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The testing of steel for deep drawing

- by -

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Deep drawing is a generalised term for the process which transforms a flat sheet of metal into a complex shape; it is more rationally termed sheet metal forming. The range of complex shapes produced for subsequent assembling into, for example, a motor-car body is too complex for immediate analysis and so, initially, the production of a simple shape has been studied (Fig. 1) and the operation subdivided into three modes, namely:

1. Drawing
2. Stretching
3. Bending and unbending under tension

even though the fundamental difference between these is not clear, and it is in these terms that the process will now be described.

Drawing

This can be defined as radial extension coupled with circumferential shrinkage (Figure 2).

Stretching

This is stretching under biaxial tension and can be characterized as radial extension with no circumferential shrinkage (Figure 3).

Bending and unbending under tension

This bending (Figure 4) takes place over a radius, be it that of the punch or the die, while the tension is imposed by blankholder restraint on the one hand and the moving punch on the other. During this process, the blank is bent on to the radius as it flows over the die throat, for example, and unbent off again as it becomes the cup wall.

Let us now synthesize these three modes of plastic deformation into the simplest of sheet metal forming operations, the drawing of an axisymmetrical cup from a circular metal blank. This is the simplest sheet forming operation which can be envisaged, though it is complex compared with, say, a wire-drawing operation, where each element undergoes approximately the same deformation. In the forming of a cup, different zones of the blank are subjected to different stress systems, while some experience different stress systems in turn.

Referring to Figure 5, the blank is divided into three zones X, Y and Z. The outer zone X, consists of material in contact with the die, the middle zone Y, material unsupported at the beginning of the operation and the inner zone Z, material in contact with the punch.

As the drawing proceeds, X is drawn in towards the die radius under a radial stress. As the radius is decreasing a compressive hoop stress is developed, which will tend to:

(i) Thicken the blank
(ii) cause wrinkling of the blank

The sum of the compressive hoop stress and the radial stress during the operation is substantially constant and so the hoop stress can be reduced by increasing the radial stress. This is the function of blankholder pressure. Clearly there is an optimum blankholder pressure above which - for a given blank - failure occurs and below which the flange or wall of the component is wrinkled.

As X passes on to the die radius it is thinned by plastic bending under tension and similarly as it is straightened off the radius. Approximately, the work done in bending a metal is proportional to the flow stress and the thickness, and inversely proportional to the radius round which it is bent.

If thinning during bending takes the material past its instability strain, failure will occur as the metal leaves the die radius. Finally, the inner parts of zone X are thinned by stretching between the punch and the die.

Now to consider zone Y. The outer part of this zone is thinned by bending and unbending over the die radius and the inner part is thinned by bending and unbending over the punch radius. Between these two parts is a region which is stretched in tension between the punch and the die.

Consider finally zone Z. This is subject to stretching over the punch nose. The strain depends on the punch nose form and friction and the position of the fracture is markedly influenced by friction. When stretching over a hemisphere low friction will result in fracture near the pole. High friction on the other hand will give fracture in the skirt of the component at a high load, with little thinning over the nose.

Summarizing, the following processes occur:

1. Radial drawing
2. Bending and unbending over the die radius
3. Stretching between die and punch
4. Bending and unbending over the punch radius
5. Stretching over the nose of the punch

Zone X experiences 1, 2 and 3, zone Y, 2, 3 and 4, and zone Z, 3, 4 and 5. Process 1 thickens the sheet, processes 2, 3, 4 and 5 thin it.

In a study of industrial pressins, imprinted with a fine grid (Fig. 6) before forming, it is found that these are formed by a combination of plane strain, this can be associated with flange and wall deformations and strain induced by a biaxial stress system; this can be associated with stretching over the punch nose.

If it is accepted that these are the strains involved in any sheet metal forming operation, it would now be profitable to list the ways in which materials fail and then to see whether material properties, in the widest sense can be tailored to avoid failure as far as possible.

The ways in which failure can occur are by:-

1. The presence of surface imperfections
2. Bad shape of the finished component
3. Fracture

1. By surface imperfections is meant the generation of an uneven surface during the sheet metal forming operation. This can be due to many causes and may be further divided into:

1. Physical factors
2. Metallurgical factors

By physical, is meant imperfections which result from rolled-in scratches, fleck scale, surface laminations and the like, whereas the second category contains phenomena resulting from discontinuous yielding and an unsuitable grain size, both of which can be studied from the stress-strain curve of the material.

2. Bad shape refers to buckling and elastic recovery which, though both controllable in part by the tool design and setting, are also related to the shape of the basic stress-strain curve of the material.

3. Fracture is when a material splits due to insufficient ductility. This is clearly a function of material properties, the stress strain curve again, but, as is often not realized, also can be controlled by changing the frictional conditions between the tools and the metal sheet.

Surface Imperfections

It is not proposed to deal at length with this aspect of sheet metal forming failure. Defects in rolled strip are illustrated and briefly described in 'Surface defects in ingots and their products, ISI special report No. 63. In general, gross laminations will produce splits, (Fig. 7) while skin laminations (Fig. 8) will 'open up' during forming and produce an unacceptably rough surface for subsequent painting and so finishing extras have to be agreed. Fleck scale (Fig. 9) has been a very troublesome defect in the past, and in its heavy form can cause stress concentrations from which a split will start.

Many other surface defects such as wrench marks, sticker marks, coil breaks, etc., are basically stretcher-strain markings, produced by the critical straining of the sheet during processing.

A coarse grain size produces the well-known 'orange peel' effect (Fig. 10) but this is uncommon in the steel sheet now produced for car bodies; the final cold reduction of about 70% giving a grain-size ASTM 7 - 8, while at most ASTM 5 - 6 is necessary to produce this phenomen. The yield-point elongation (Fig. 11) characteristic of an annealed-last rim-steel is the result of the stress required to maintain plastic flow, being lower than that required to initiate it. The observed fall in load after the U.Y.P. is associated with the formation of Lüders lines, also termed stretcher-strain markings.

This phenomenon of discontinuous yielding results from the presence of small concentrations of solute atoms. There exists a driving force which attracts these solute atoms to dislocations and if the appropriate time/temperature conditions are allowed, an atmosphere of solute atoms will form round each dislocation. These dislocations will take no further part in slip and there will be consequently a low concentration of mobile dislocations in the lattice. When a stress is applied a few mobile dislocations will be formed at sites such as precipitate particles, grain boundaries and the like in the pre-yield micro-strain region. The upper yield-point marks the critical stress at which these few dislocations start to move. Then, multiplication by the usual mechanisms ensues, resulting in a very rapid rate of increase of mobile dislocations. For a given strain-rate, the stress will now relax, since the stress required to move a dislocation is related in velocity and consequently the flow stress for propagation of plastic flow (lower yield point) will be lower than that required for initiation. Within a grain, an avalanche of dislocations will pile up against a boundary until the stress concentration at the head of the pile-up unpins sources in the next grain and the process is repeated. Clearly, grain-size is an important factor in the absolute value of yield-point and in the extent of the yield-point elongation, and is shown in Fig. 12, for a range of commercial steels and diagrammatically in Fig. 13.

The yield point elongation can be temporarily removed by pre-straining or by temper rolling approximately 1%. However, ageing before retesting will produce a hardening - 5 and 6 in Fig. 11. This is slow for steel at 20°C - perhaps weeks - but full ageing can be produced in about 1 hour at 100°C. This yield point return will not only produce stretcher-strain markings on a panel, but the steel will show a higher yield point and reduced ductility, both deleterious to successful sheet metal forming as will be shown later.

However, there are many pressings where surface smoothness is unimportant and in these cases annealed-last steel, not liable to strain-age hardening, is commonly used. It is thus very important to determine the effect of sharp yield-point, yield-point elongation and roller levelling on the formability of this type of steel. This problem has been investigated, and the long-established press-shop dictum that a low value of the ratio of lower yield-strength to tensile strength is desirable for good press shop performance was confirmed. In the case of a valance panel, Fig. 14 which persistently gave 50% splits with steel having a LYS/TS ratio of about 0.8; this dropped to < 5% after roller levelling, which lowered the LYS/TS to about 0.7. This had the effect of changing the stretcher-strain markings from the type shown in Fig. 15(a) to those in Fig. 15(b). The lower value of LYS/US ratio allowed work hardening to develop so that material could be drawn-in from feeding areas and produce a more even distribution of strains over a general region of the pressing rather than strain with intense work-hardening in localised bands. This effect is demonstrated in Fig. 16.

Another surface phenomenon is exhibited by under temper-rolled material and can be confused with the 'orange-peel' finish produced by a coarse grain steel, though a closer examination shows that the pattern is related to the rolling direction of the sheet. Lightly skin-passed sheet has bands of yielded material as shown in Fig. 17 and naturally these age harden. With subsequent working, these hard bands stand proud of the sheet.

The surface roughness of a sheet is also of great importance in sheet metal forming. The present practice is, in general, in annealed-last material, to use a sheet of 50-80 μ inch CLA with an open texture with isolated narrow peaks on a relatively smooth base. A temper-rolled sheet has a different texture with many more peaks/in. and is actually supplied in the range 30-90 μ inch CLA. The roughness of a well-used cast-iron tool is about 10 μ inch CLA. In forming it is important to consider the number, shape and distribution of asperities in conjunction with their behaviour in contact with the punch, blankholder or die; this is a whole new subject currently being studied. However, certain general conclusions can be drawn. Figs. 18(a) and (b) show the effect of roughness on scoring and Figs. 19(a) and (b) show the effect of roughness on shape control; the mechanical properties of these sheets were approximately the same. The loss of control of the 30 μ inch CLA sheet is obvious; increase in blankholder pressure will eventually lead to splits. The much higher friction of the 60 μ inch CLA sheets can be reduced by the application of a lubricant, whereas the addition of an anti-lubricant such as paraffin to a slick sheet is not a practical proposition.

Figure 20 shows the relationship between surface roughness and paint thickness. This indicates that no subsequent finishing troubles should be experienced. Figure 21 shows the relationship between image clarity and surface roughness for the normal British paint system, and it can be seen that unacceptability is not reached until wet sanding is omitted with an, at present, non-standard 2 - coat paint system.

Bad shape of the component

A pressed component may have an acceptable surface finish, no splits, but yet fail due to bad shape. This can be subdivided into:

1. Springback (elastic recovery)
2. Buckling

1. An allowance is made in the original tool design for this behaviour but different batches of material may show different springback behaviour.

Referring to Figure 22, it can be seen that when the load is released, the total strain ϵ_t is reduced to ϵ_p owing to the elastic recovery ϵ_r. Springback will therefore be greater the greater the area under the curve, consequently it will be greater the higher the yield-stress and flow curve, the lower the elastic modulus and the greater the plastic strain.

Buckling or wrinkling can occur in pressing where incorrect blankholder pressure is applied, but a state of affairs can obtain where whatever pressure is used, buckling or splitting will result. In the flange of a pressing, instability sets in in the range

$$0.46\left(\frac{t_o}{D_o}\right) \leq \frac{\sigma_\theta}{E_o} \leq 0.58\left(\frac{t_o}{D_o}\right)$$

and the number of waves formed lies between the limits

$$1.65\left(\frac{a}{b}\right) \leq n \leq 2.08\left(\frac{a}{b}\right)$$

where σ_θ = hoop stress

t_o = initial material thickness

D_o = initial blank diameter

b = flange breadth

a = mean flange radius

$E_o = \dfrac{4EP}{(\sqrt{E} + \sqrt{P})^2}$

E = elastic modulus

P = appropriate slope of the σ vs. ϵ curve

σ = true stress

ϵ = true strain

The effect of material properties on buckling has not been systematically studied but in the pressing of temper-rolled rim-steel, the increase in yield point with ageing is a most important parameter involved with buckling. Figures 23 a, b and c, 24 and 25 and Table 1, show the effect of ageing for 1 hour at 100°C on pressings and properties.

Table 1

	Yield Strength		Tensile strength		Uniform elongation	
	L	T	L	T	L	T
Steel 1 fresh	12.0	12.4	20.2	20.5	20.3	24.8
Steel 1 aged	15.1	15.7	20.7	21.0	22.3	20.0
Steel 2 fresh	13.9	14.9	20.5	20.6	22.5	21.5
Steel 2 aged	17.9	18.5	21.3	21.0	22.0	17.7

The strain ratio r, which will be dealt with in more detail later, also has an effect on flange wrinkling (Fig. 24). This is probably because higher r steels have higher values of the elastic modulus (Fig. 25) and from the equations quoted above it is clear that modulus will affect wrinkling.

The most important cause of failure in sheet metal forming operations is, of course, failure by fracture. From the analysis of the sheet metal forming process given earlier, it can be seen that failure can be caused by plane stress or biaxial stress, and so it is important to know under which of these stress systems the part has failed. The critical region of the stamping is thus imprinted with a fine grid and measurements made after forming to fracture will answer this question. If failure is due tc plane strain, with the punch restraining metal flow circumferentially, then the properties of the material in the through-thickness direction become all-important. In drawing, failure usually occurs at one or other of the necks shown in Fig. 26, and it is the through-thickness properties in this area, the thinnest part of the cup, which will dictate the depth of cup which can be drawn, for it is this region which must sustain the drawing load imposed on the flange by the die and blankholder. Clearly, if some resistance to thinning could be built into a metal, then its performance in a pressing operation would surely be enhanced. It is now well-known that the through-thickness strength can be increased relative to the strength in the plane of the sheet by altering the crystallographic texture of the material. This can be demonstrated using the extreme example shown in Fig. 27 for hexagonal close-packed materials. In these metals the slip direction is normally a ($<1\bar{2}10>$). If the three a directions are all in the plane of the sheet ((0001)) slip can produce no strains normal to the sheet surface, and thus no thinning.

It is important to have a test which can measure this property and conveniently this can be accomplished during the tensile test. The parameter characterizing the ability of a sheet to resist thinning, the ratio of width strain to thickness strain, designated r, is calculated at a specified elongation and a specified angle to the rolling direction, e.g.,

$$r_{45°} = \frac{e_{width}}{e_{thickness}}$$ (measured at 15% elongation)

With the ideal texture described above no thinning should occur so $r = \infty$ would be expected. $r = 1$ indicates complete uniformity of properties in the x, y and z directions, i.e. an isotropic material, while $r \neq 1$ indicates anisotropy, $r > 1$ showing a resistance to thinning and $r < 1$ a preference for thinning. So, wall failures and failures over sharp radii can be delayed by using material of higher strain ratio <u>r</u>. The strain ratios in deep drawing steels can vary from less than 0.5 to greater than 2, and this has a significant effect on the diameter of blank which can be drawn, as Fig. 28 shows.

Systematic study of the thermal and mechanical treatments used in sheet steel production have established the broad principles on which high <u>r</u> steels can be produced and these are summarized below.

1. It is not generally possible to produce high <u>r</u> rim-steels. Consequently, most of the work has been concentrated on Al-killed steels.

2. Strain-ratio increases with increasing cold reduction up to about 70% and then decreases (Fig. 29). The further <u>r</u> departs from unity, the greater the planar anisotropy. This correlates with the earing behaviour of the material when pressed into axisymmetrical shapes; ears corresponding to directions of high <u>r</u>.

3. <u>r</u> average decreases with decreasing hot mill finishing temperature.

4. <u>r</u> average increased with decreasing hot mill coiling temperature.

The reason for this phenomenon is crystallographic preferred orientation and attempts have been made to correlate <u>r</u> with preferred orientation in carbon steels. Burns and Heyer predict <u>r</u> - assuming sheet single crystals and <111> slip - for (100)[011], (110)[001] and (111)[110] orientations. The results from this highly idealized model were in qualitative agreement with results measured on polycrystalline specimens. Further work to refine this model has not produced a significant improvement in the predicted values, and subsequent work on Al and certain alloys has been no more successful. The effect of grain boundaries and the grain size effects in commercial materials are in all probability the reason for the lack of quantitative agreement, though the general relationship between r and crystallography is unquestioned.

The deformation caused by biaxial tension is typified by metal stretching over the nose of a punch. Stretching failures are probably the most common types of failure in a sheet metal forming operation. In this case the general work hardening behaviour of the metal is all-important. Consider a punch-stretching operation. The nose of the punch contacts the steel sheet, this deforms, work hardens and transfers the load to the next element of the sheet. This process continuing until the metal cannot sustain the steadily increasing load and so instability followed by fracture results. In a simple tensile test on temper-rolled steel, the load-elongation curve is of the form shown in Fig. 30. a is the point of instability, and the elongation e_u is termed the uniform elongation. These steels have true-stress true-strain curves which can conveniently be described by the equation:

$\sigma = K\epsilon^n$ where K is a constant and n is termed the work hardening exponent.

Thus, the slope of the log-log plot of the σ, ϵ curve is n.

It can be shown that, at maximum load, the limit of uniform elongation

$$\frac{d\sigma}{d\epsilon} = \sigma$$

So,

$$\frac{d\sigma}{d\epsilon} = \sigma = K\epsilon^n$$

Also,

$$\frac{d\sigma}{d\epsilon} = nK\epsilon^{(n-1)}$$

Therefore

$$K\epsilon^n = nK\epsilon^{(n-1)}$$

and at maximum load, ϵ, usually written ϵ_u equals n, the work hardening exponent.

Furthermore, true strain is related to engineering strain thus:

$$\epsilon_u = \ln(1 + e_u)$$

It is this parameter, whether n or e_u, which is the present measure of the work hardening capacity of sheet steel. A relationship between e_u and $D_{S_{max}}$, which is the depth to failure in a simple punch-stretching operation is shown in Figure 31. The correlation here is not as good as the r vs. cup-drawing relationship, and this is probably due to the fact that it is more difficult to measure a property at instability (e_u) than one during the period of uniform elongation (r), that the relationship of r to stretch formability is not properly understood, and that the ductile fracture behaviour of sheet metal in biaxial tension has yet to be studied. Nevertheless, as will be shown later, the correlation between press-shop performance and the r and n values in sheet steel is good enough for these parameters to be used with confidence.

In sheet steel the ratio of lower yield strength to ultimate strength is used as a ductility parameter, and assuming again $\sigma = K\epsilon^n$, and defining lower yield-strength as 0.002% proof strength, it can be shown that

$$\frac{LYS}{TS} = \left[\frac{k}{n}\right]^n$$

The approximate truth of this relationship is shown in Fig. 32.

To sum up. Broadly, the material properties requires for the successful forming of steel sheet are known, and these are the plastic strain ratio, r and a measure of the work hardening behaviour, whether it be e_u, ϵ_u, n or LYS/US, for these are all inter-related for a $\sigma = K\epsilon^n$ - type material.

The properties required for successful sheet steel forming from the point of view of:

1. Surface contour
2. Buckling
3. Elastic recovery
4. Fracture

have been discussed.

How shall they be measured?

These properties - apart from surface roughness - are:-

1. Modulus
2. Extent and type of discontinuous yielding
3. Lower yield strength
4. 4. Strain ratio
5. Work hardening parameter [n, e_u ....]

Many tests exist, and the relationship between these tests and the behaviour of sheet steel in a production press must be established. Many simulative tests have been invented (Table 2) and work has shown correlation between a given pressing and a certain simulative test, but this may be fortuitous. It has been pointed out that there is a scale effect which operates in all simulative testing, the various factors involved in the tools may be capable of simulation, but it is not possible to 'scale down' the metal sheet under test for it would not then be the metal used on the actual component - so we have the parodox of the unreal simulative test'. Again, in tests of this type the blankholding loads, and the friction/lubrication conditions are extremely difficult to standardize and this leads to a wide scatter of results. It is thus better to know the fundamental material properties required for successful sheet metal forming and then measure these in a well-controlled accurate tensile test. Thus modulus, to the limits of accuracy required here, can be measured as can all the other properties listed above.

Care must be taken to ensure uniform testing conditions when measuring yield strength in an annealed-last steel, for its value is very sensitive to strain rate and to the number of Lüders fronts operating. In fact, the worst combination of these two factors will produce a difference in LYS of 4 tons/in^2 with a difference in TS of only 0.5 tons/in^2. Laboratories wishing to compare results must operate similarly and it is suggested that centre-punch marks be made on the test-piece before testing to initiate two operating Lüders fronts (Figures 33, 34 and 35).

Yield strength in temper-rolled steels presents very little difficulty.

The strain ratio r, can be measured at 15% elongation during a normal tensile test. As r is defined:

$$r = \frac{\epsilon_w}{\epsilon_t} = \frac{\log_{10}\left({}^{w_o}/w_{15}\right)}{\log_{10}\left({}^{e_o}/e_{15}\right)} \qquad \begin{array}{l} \epsilon = \text{true strain} \\ e = \text{thickness} \end{array}$$

If constant volume is assumed, then:

$$r = \frac{\epsilon_w}{\epsilon_l - \epsilon_w} = \frac{\log_{10}\left({}^{w_o}/w_{15}\right)}{\log_{10}\left({}^{wl}/l_o w_o\right)}$$

So, length and width may be measured, giving more accuracy than measuring a change in thickness. It is important that a long enough test piece is used, so that end-effects do not cloud the results. The centre half-inch on a standard 2-inch tensile test specimen, or a 2-inch gauge length on a standard 8″ gauge-length will prove satisfactory.

A far as elongation is concerned, uniform elongation can be measured on a fractured eight-inch gauge-length test piece if the sections associated with necking are ignored. It can also be measured from the load-elongation curve if the effects of the gripped ends are first proved to be unimportant.

As steel is a metal with a $\sigma = K\epsilon^n$-type stress-strain curve another method can be used.

If, $\sigma = K\epsilon^n$

then $$n = \epsilon_u = \frac{\log \sigma_u - \log \sigma_2}{\log \epsilon_u = \log \epsilon_2}$$

when σ_2 and ϵ_2 are the stress and strain at an arbitrary point below maximum load. This reduces to:

$$\frac{\sigma_u}{\sigma_2} = \left(\frac{\epsilon_u}{\epsilon_2}\right)^{\epsilon_u}$$

and substituting

$$\frac{P_u(1+e_u)}{A_o}$$, where A_o is the original cross sectional area

of the testpiece, for σ_u, and similarly for σ_2, and $\ell_n(1+e_u)$ for ϵ_u, etc., then

$$\frac{P_u}{P_2} = \left[\frac{1+e_2}{1+e_u} \quad \frac{\ell_n(1+e_u)}{\ell_n(1+e_2)}\right]^{\ell_n(1+e_u)}$$

From this equation curves of the type shown in Figure 36 can be plotted, and e_u read off for a given P_u/P_2 and e_2. It can readily be seen that this, when standardised will give rapid results; subsequent work on deep drawing steels has shown that this method agrees well with the log-log plot, the former giving higher results by about 0.002.

Finally, it is important to show that these parameters r and [n, e_u....] do bear some relation to press shop performance. Figure 37 shows the correlation between r and [n, e_u ....] and an r-dependent pressing (Blower Housing).

Figure 38 represents an [n, e_u ....] dependent pressing (Door Panel) while Fig. 39 shows the results for a pressing (Instrument Panel) which requires minimum values of both r and [n, e_u] for satisfactory production. Clearly, these parameters are important in the pressing of sheet steel. A last word on the future of testing, and simulative testing in particular. The use of polyethylene film as a lubricant in these tests - the avoidance of metal to metal contact using a low shear-strength film - has changed the situation.

The important change is what is being simulated.

If a simulative test can be used, not as an attempt to copy press-shop conditions, but as a quick method of determining a property which would otherwise take far longer to determine by, say the tensile test, then simulative testing can be of great value. Remembering the important sheet metal properties discussed earlier - can simulative tests determine r and [n, e_u ...] with accuracy? Fig. 28 showed the familiar graph of r vs. ldr published first in 1960, and it is clear that the degree of scatter makes the Swift flat-bottomed cup test, as carried out in this work unsuitable for determining r quantitatively. Further work, however, using oiled-polyethylene lubrication have reduced the scatter to such an extent as to make this test a practical method of estimating r in a quality-control laboratory, if not for research purposes. (Fig. 40).

In the case of elongation measurement, stretch-forming tests have for many years been used as a rough measure of 'ductility'. However, investigations using the Erichsen test and polyethylene and limited to a single material in different tempers, show good correlation between height of cup at fracture and e_u (Fig. 41). Finally, some workers have evolved a special extensometer which is mounted on a sheet specimen during hydraulic bulging and enables a stress-strain curve to be plotted for balanced biaxial tension. Surely the wheel has turned full circle when a modified simulative test yields information from which the stress-strain curve of the metal is simply plotted. However, this instrument is comparatively new and more results from its use are awaited.

To sum up. Broadly, the material properties required for successful sheet metal forming are known and can be measured using a tensile test. Simulative tests, not respectable for some years, are achieving a new respectability, as their test parameters correlate more and more significantly with basic material properties such as work hardening behaviour and plastic strain ratio.

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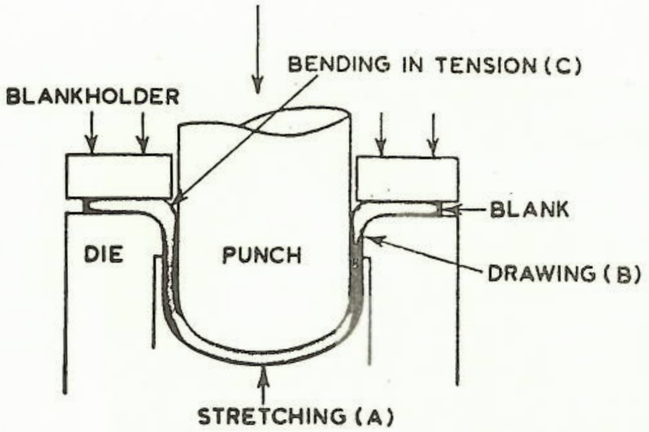


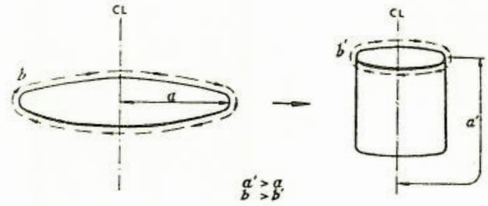


FIG. 2 DRAWING

The fundamental methods of deformation in a pressing operation

FIG. 1 FORMING OF AN AXISYMMETRICAL CUP

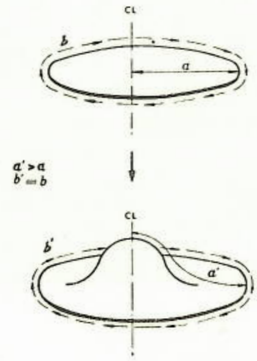
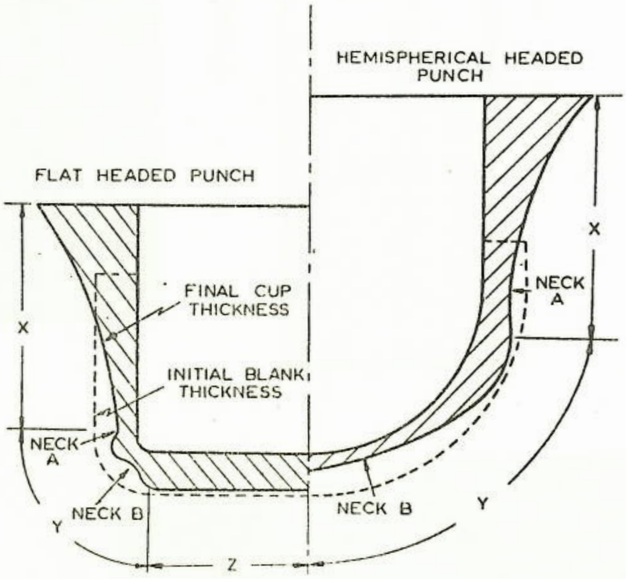


FIG. 3 STRETCHING



Sections through drawn cups.
(Thickness changes greatly exaggerated.)

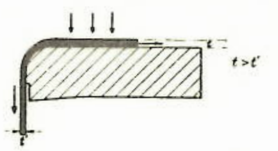


FIG. 4 BENDING UNDER TENSION

FIG. 5 THE SHEET METAL FORMING OPERATION

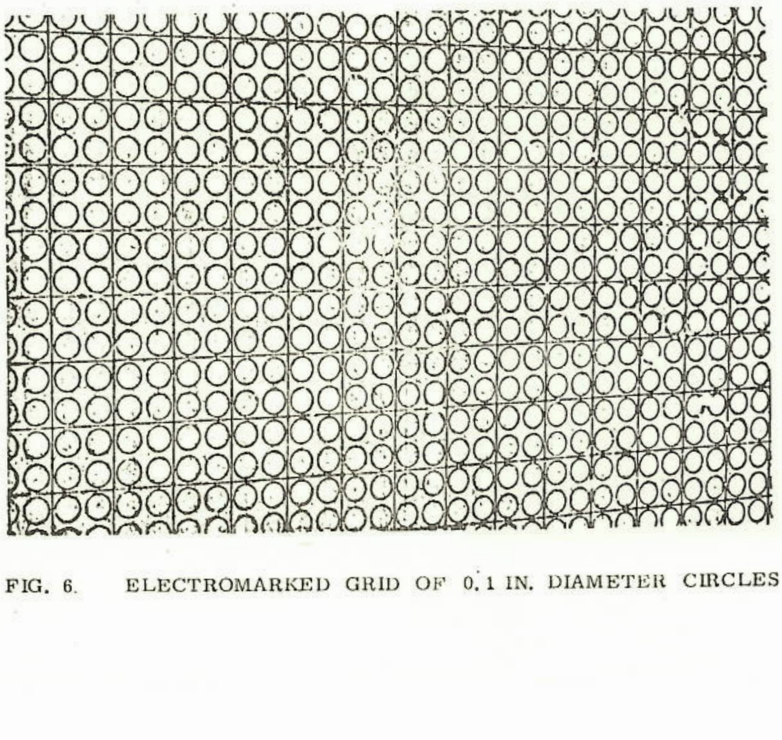


FIG. 6. ELECTROMARKED GRID OF 0.1 IN. DIAMETER CIRCLES

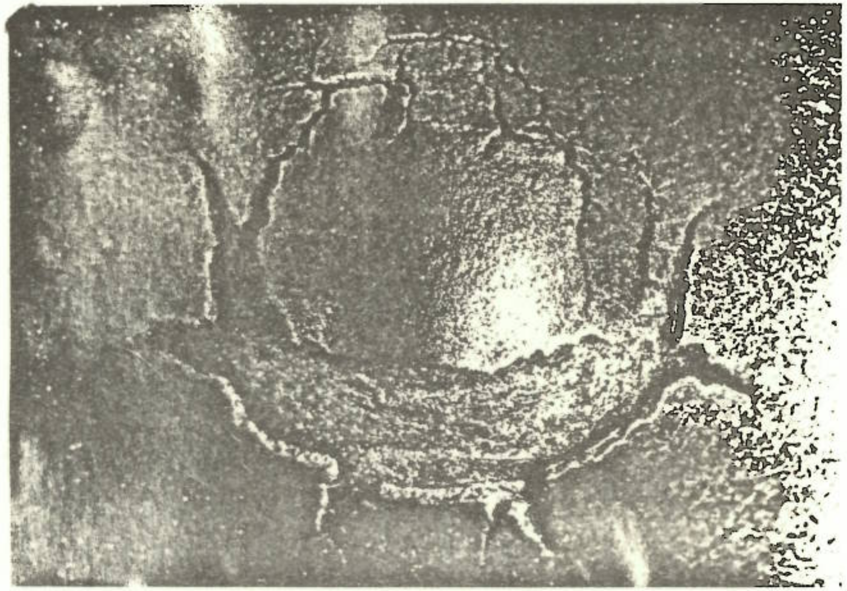


FIG. 7 SPLIT PRESSING, DUE TO PIPE LAMINATION

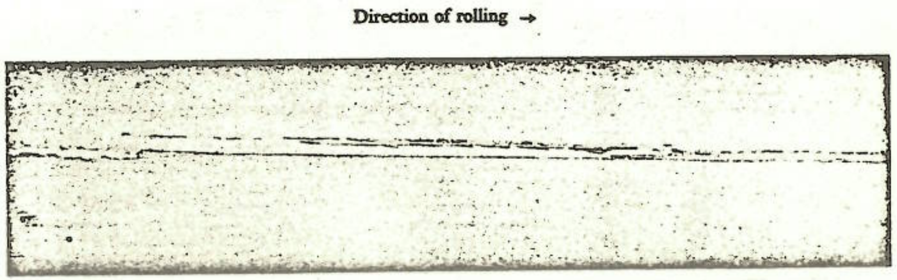


FIG. 8 OPENED UP SKIN LAMINATION

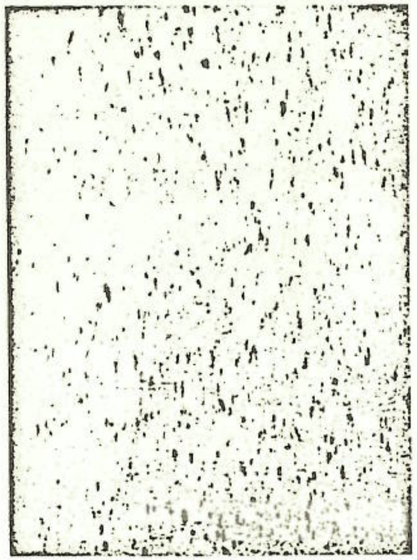


FIG. 9 FLECK SCALE

FIG. 10 COARSE SURFACE RESULTING FROM LARGE GRAIN SIZE

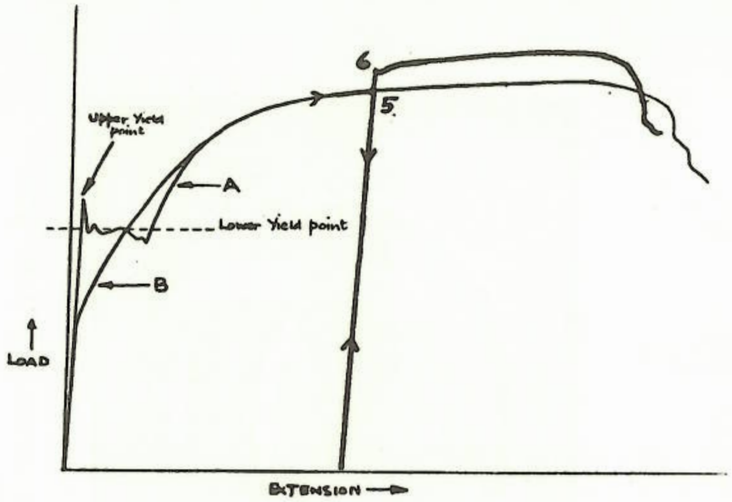


FIG. 11 LOAD/ELONGATION CURVE OF AN ANNEALED-LAST STEEL

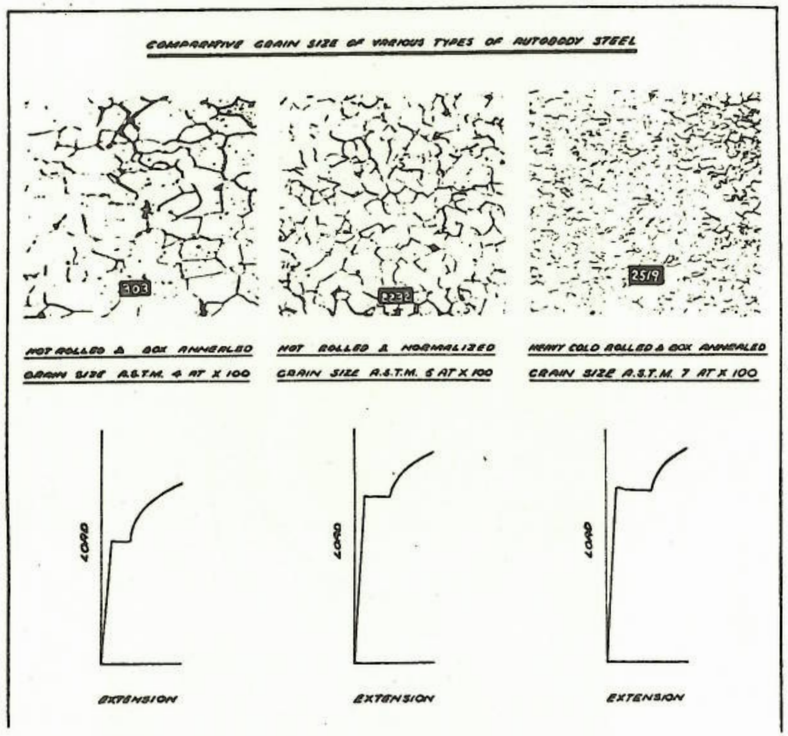


FIG. 12 EFFECT OF GRAIN SIZE ON YIELD-POINT ELONGATION

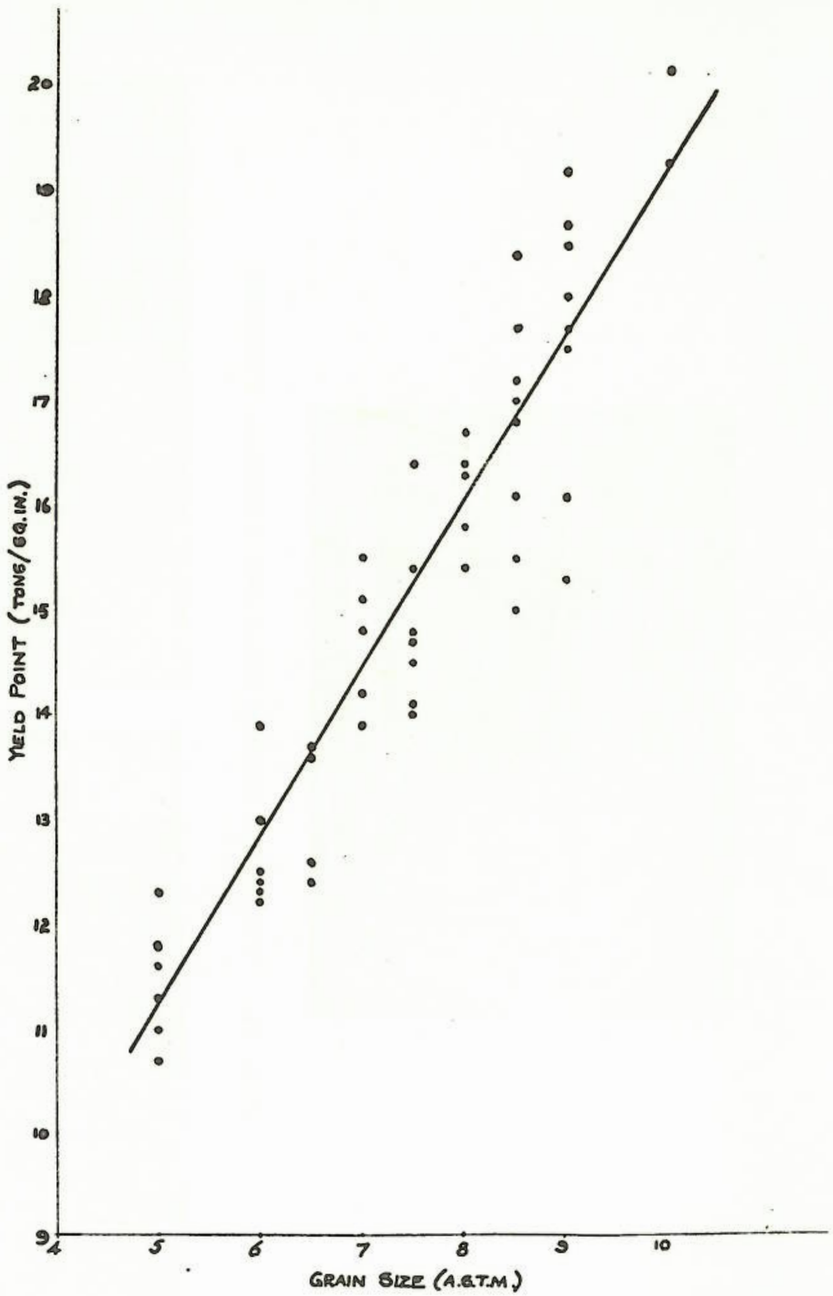


FIG. 13 EFFECT OF GRAIN SIZE ON YIELD STRENGTH

FIG. 14 VALANCE PANEL SHOWING TYPICAL FAILURE

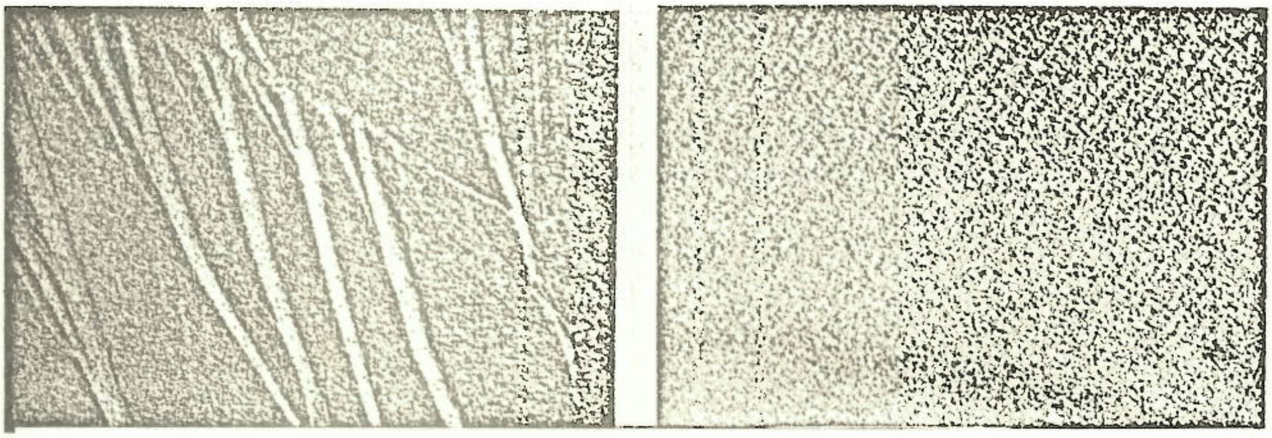


FIG. 15 (a) STRETCHER STRAIN PATTERN OF STEEL USED FOR FIG. 14 PRESSING

(b) AS FIG. 15(a) BUT ROLLER LEVELLED

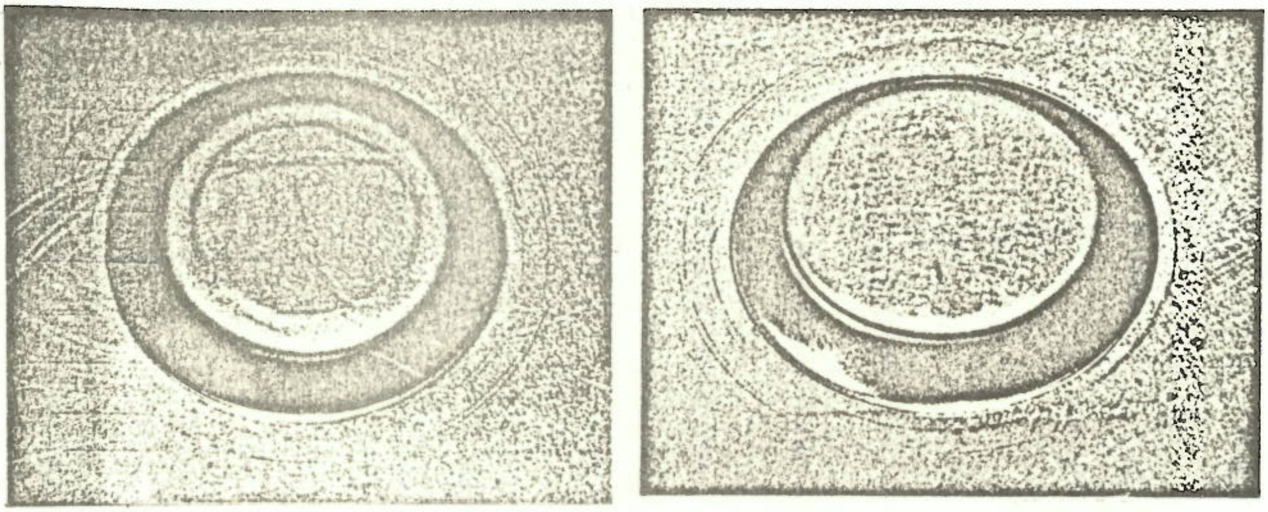


FIG. 16 DIFFERENCES BETWEEN PRESSED ROLLER LEVELLED AND NON ROLLER LEVELLED ANNEALED-LAST STEEL

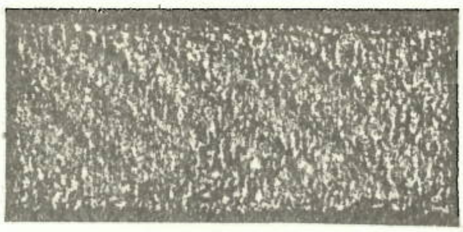


FIG. 17 YIELDED BANDS THROUGH THICKNESS OF UNDER-TEMPER ROLLED SHEET

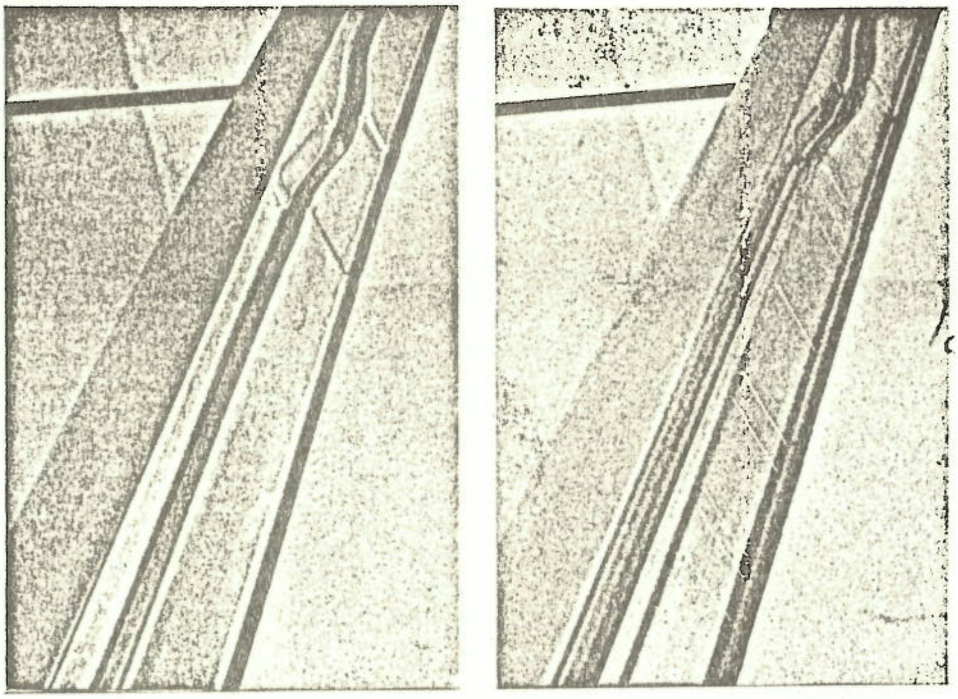


FIG. 18 (a) SCORED SILL PANEL PRESSED FROM 20 CLA STEEL
(b) SILL NOT SHOWING THIS DEFECT PRESSED FROM 60 CLA STEEL

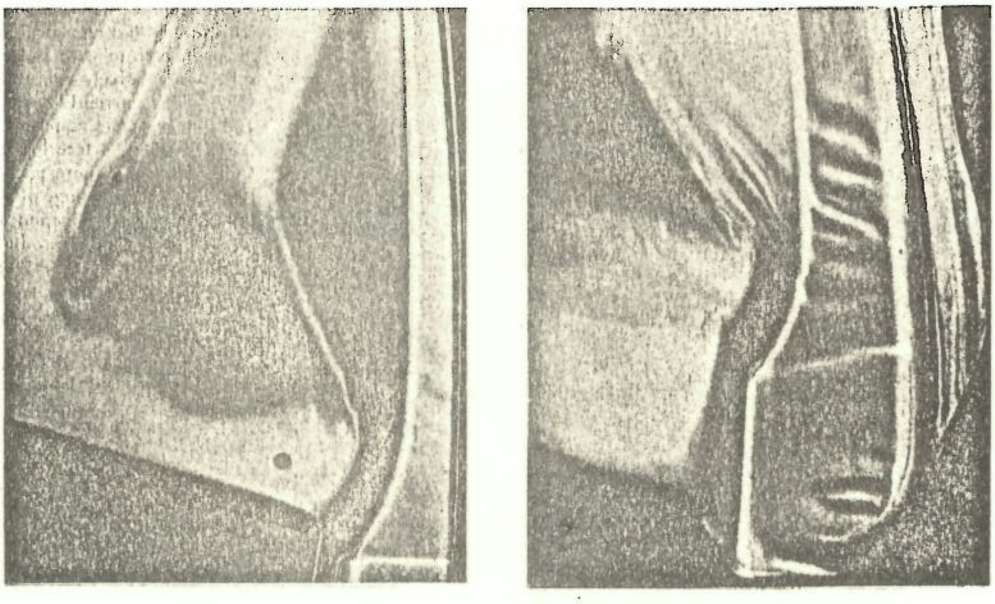


FIG. 19 (a) BUCKLES IN 30 CLA STEEL
(b) EVIDENCE OF CONTROL IN FORMING 65 CLA STEEL. PROPERTIES AS FIG. 19(a)

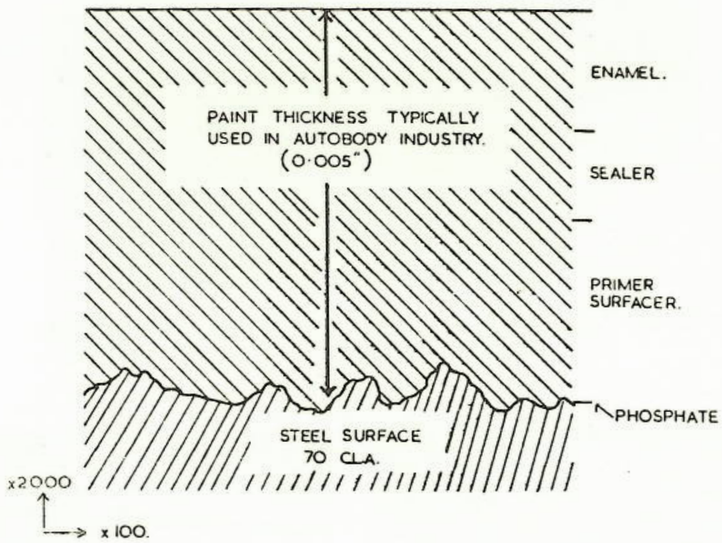


FIG. 20 RELATIONSHIP OF SURFACE ROUGHNESS AND NORMAL PAINT FINISH

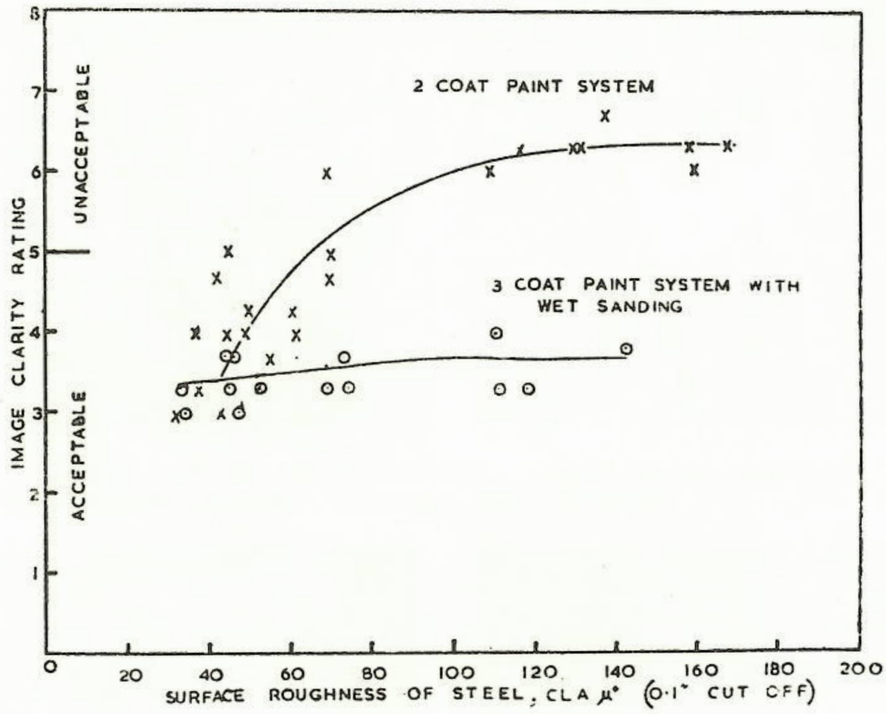


FIG. 21 RELATIONSHIP BETWEEN IMAGE CLARITY AND SURFACE ROUGHNESS

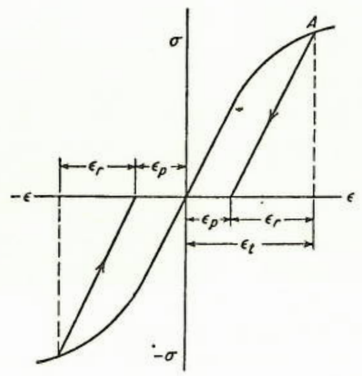


FIG. 22 ELASTIC RECOVERY

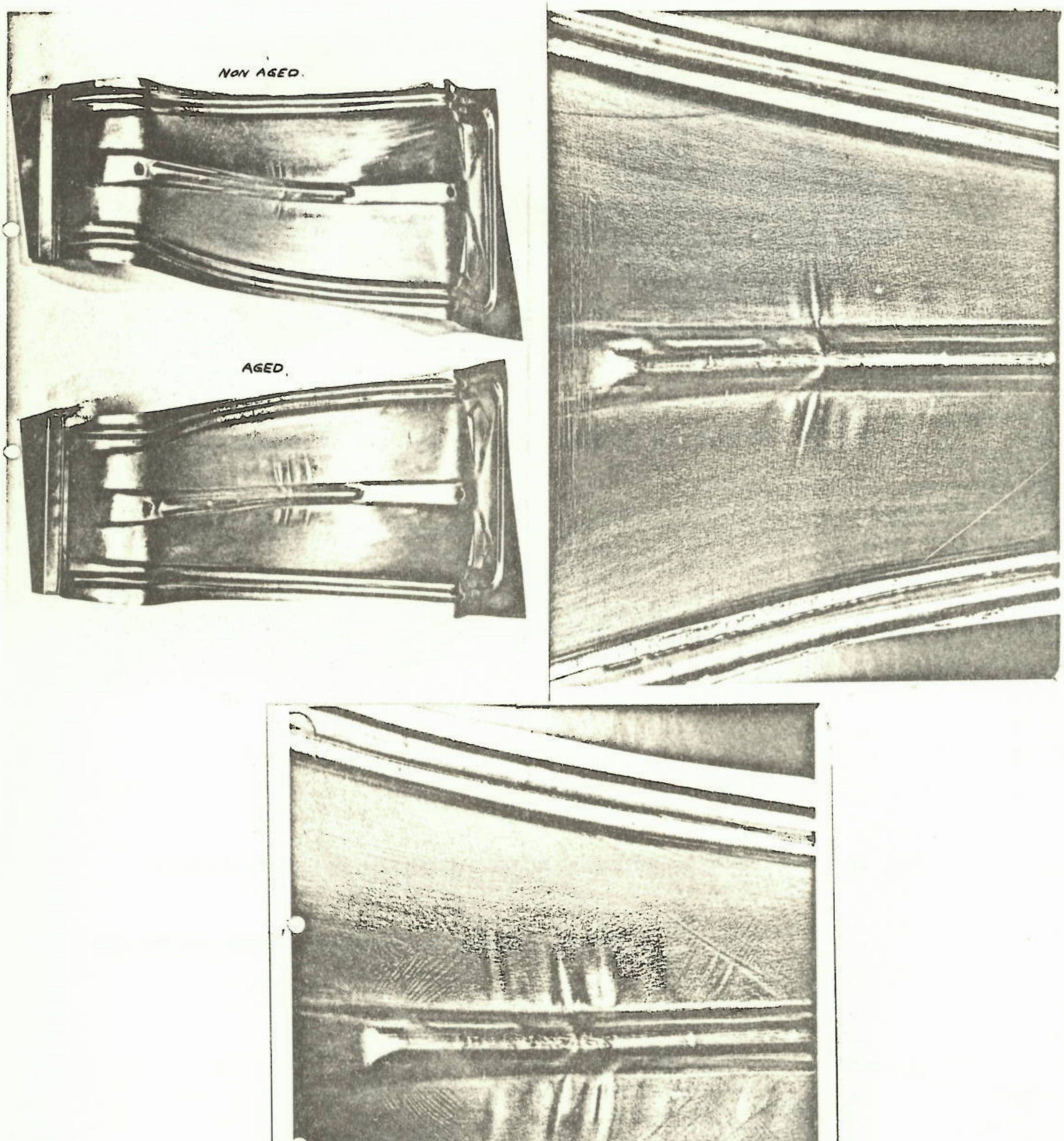


FIG. 23 (a) PRESSINGS IN STEEL
(b) ENLARGEMENT OF PART OF PRESSING FROM FRESHLY TEMPER ROLLED STEEL
(c) ENLARGEMENT OF PART OF PRESSING FROM AGED STEEL

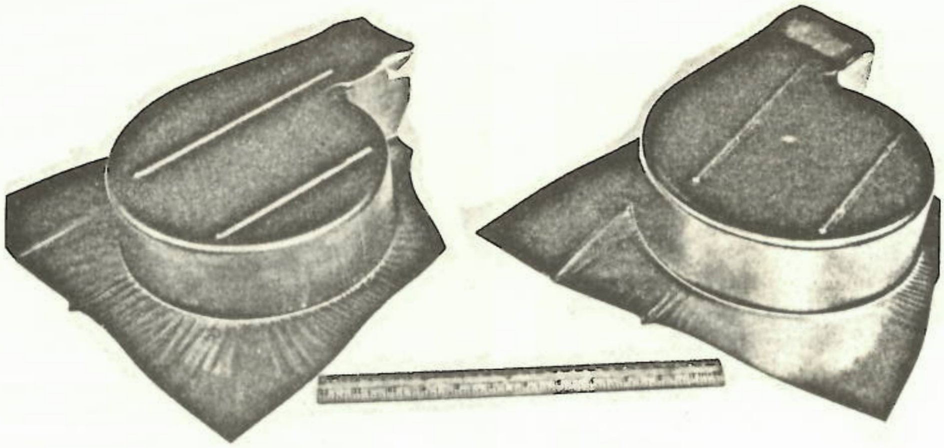


FIG. 24 EFFECT OF STRAIN RATIO ON FLANGE WRINKLING

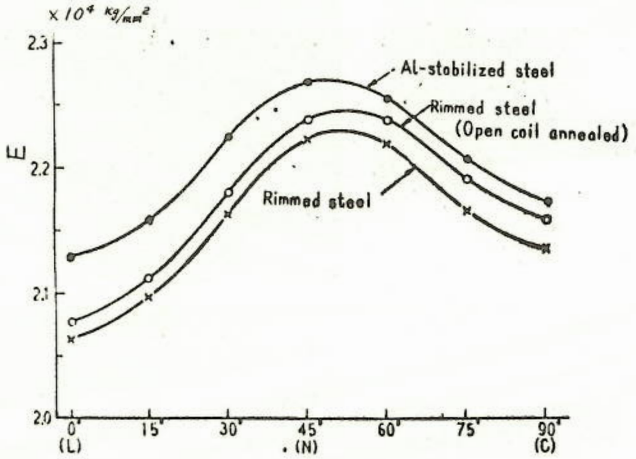
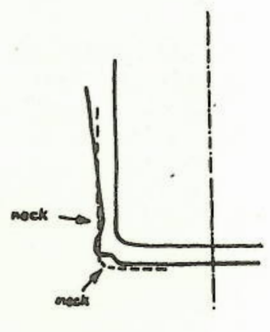


FIG. 25 RELATIONSHIP BETWEEN ELASTIC MODULUS AND STRAIN RATIO

FIG. 26 NECKS A AND B IN A DEEP DRAWN CUP



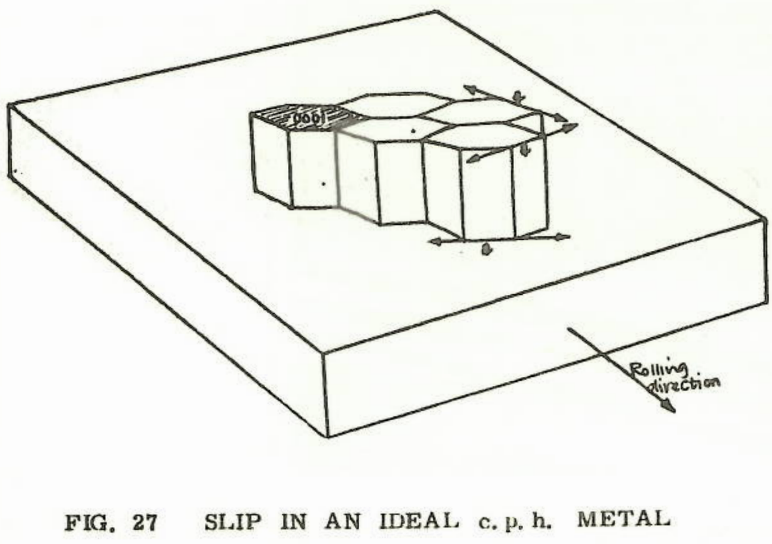


FIG. 27 SLIP IN AN IDEAL c.p.h. METAL

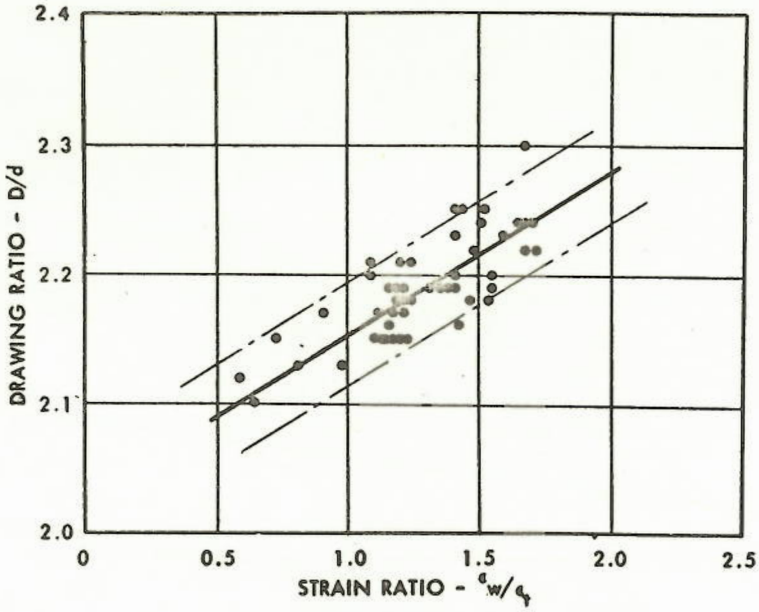


FIG. 28 LDR VS. r FOR A RANGE OF EDD STEELS

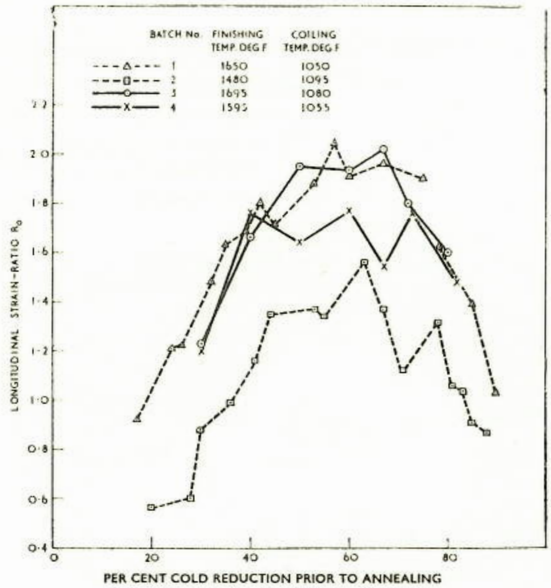


FIG. 29 EFFECT OF PERCENTAGE COLD REDUCTION ON FINAL STRAIN RATIO

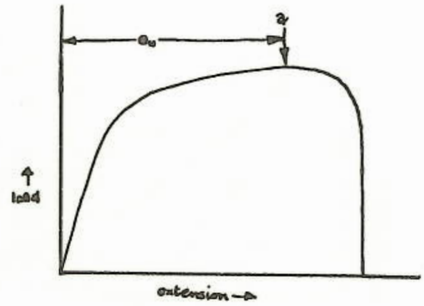


FIG. 30 TYPICAL LOAD ELONGATION CURVE WITHOUT YIELD PHENOMENON

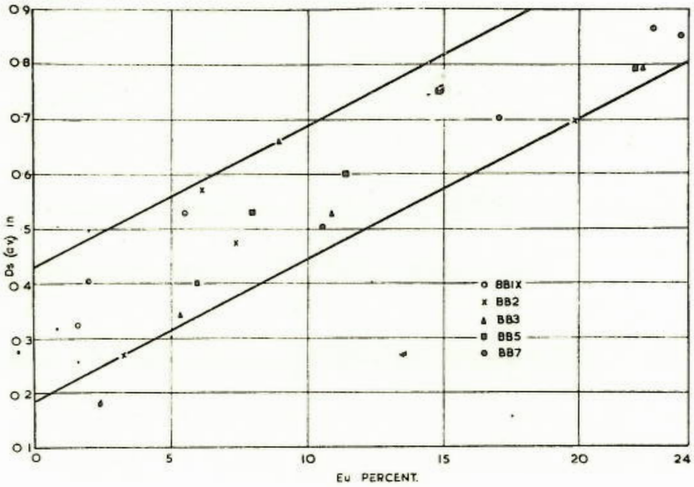


FIG. 31 RELATIONSHIP BETWEEN n AND $D_{S_{max}}$

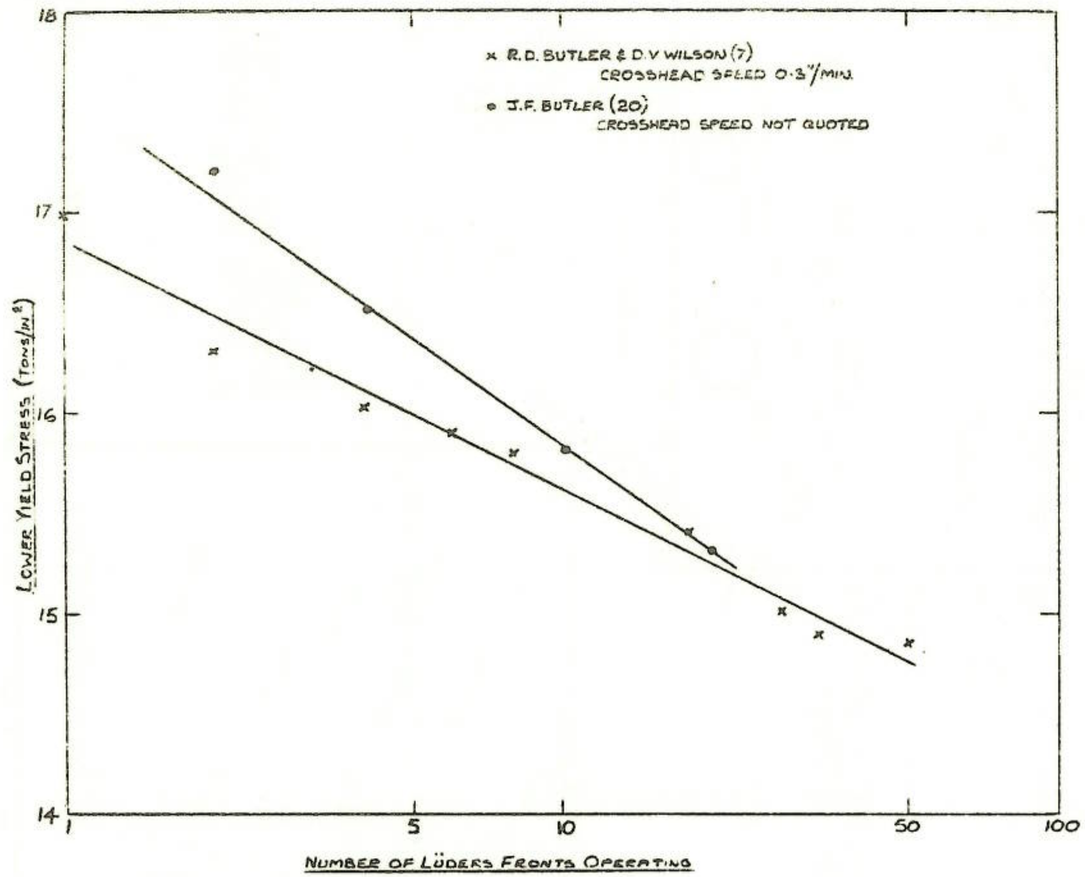


FIG. 34 EFFECT OF NUMBER OF LÜDERS FRONTS OPERATING ON LYS

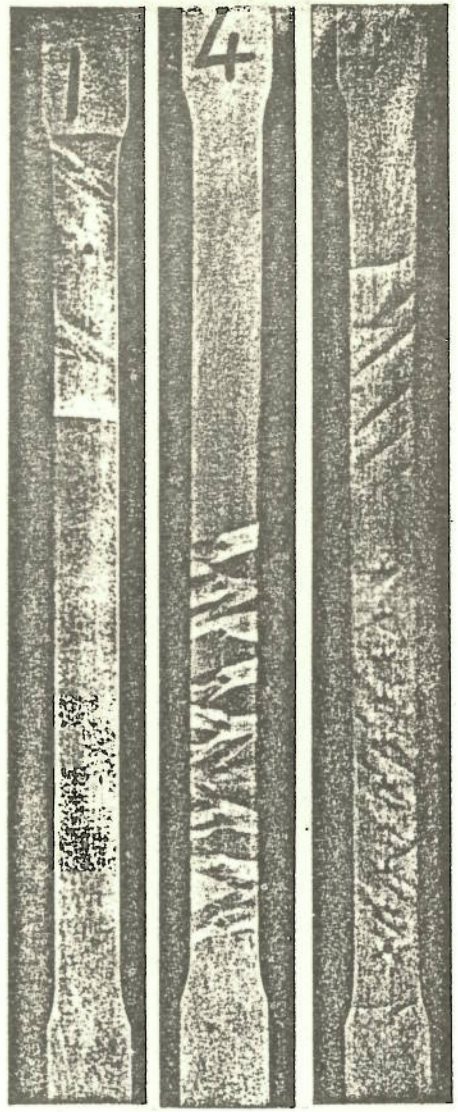


FIG. 35 DEVELOPMENT OF LÜDERS FRONTS FROM POP-MARKS

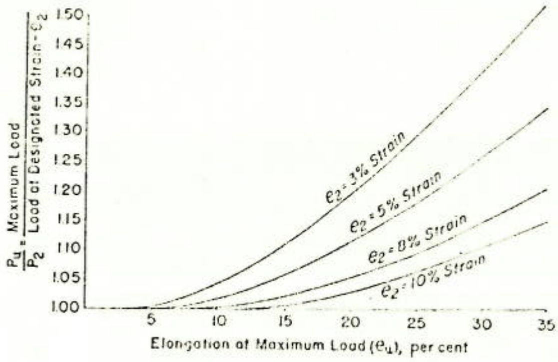


FIG. 36
CURVES FOR READING e_u
FROM THE RATIO OF TWO LOADS

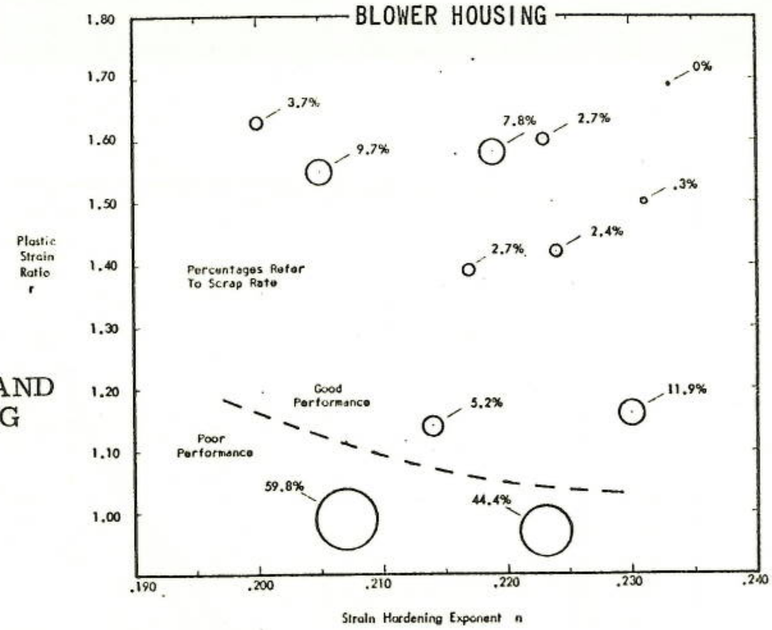


FIG. 37
EFFECT OF VARYING r AND n UPON BLOWER HOUSING

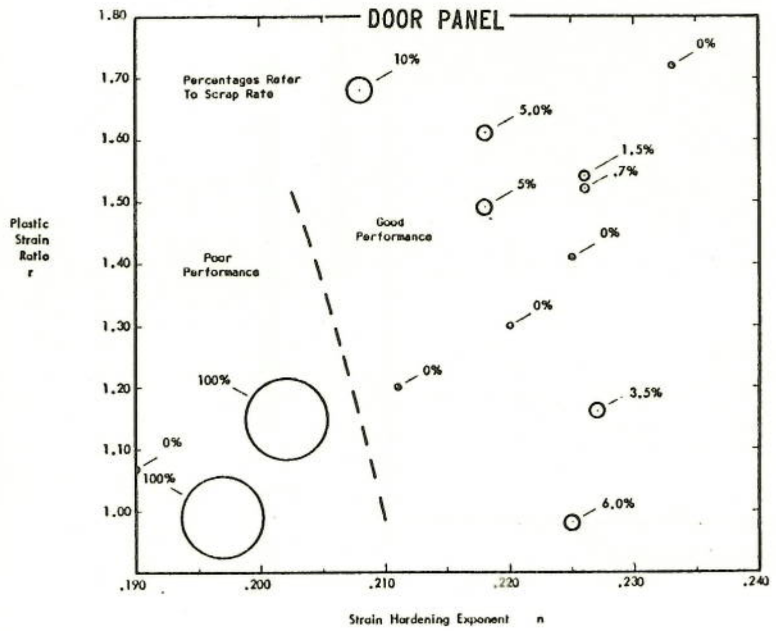


FIG. 38
EFFECT OF VARYING r AND n UPON DOOR PANEL

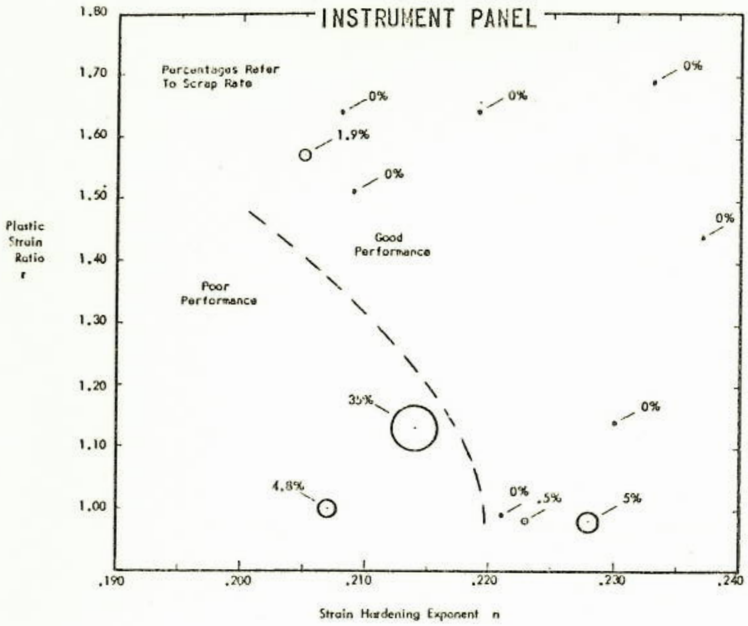


FIG. 39 EFFECT OF VARYING r AND n UPON INSTRUMENT PANEL

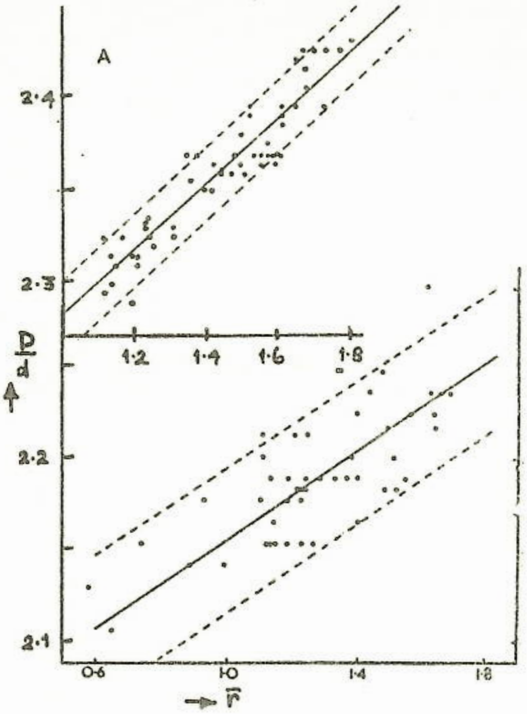


FIG. 40 EFFECT OF LUBRICATION ON SCATTER OF LDR VS. r CURVE

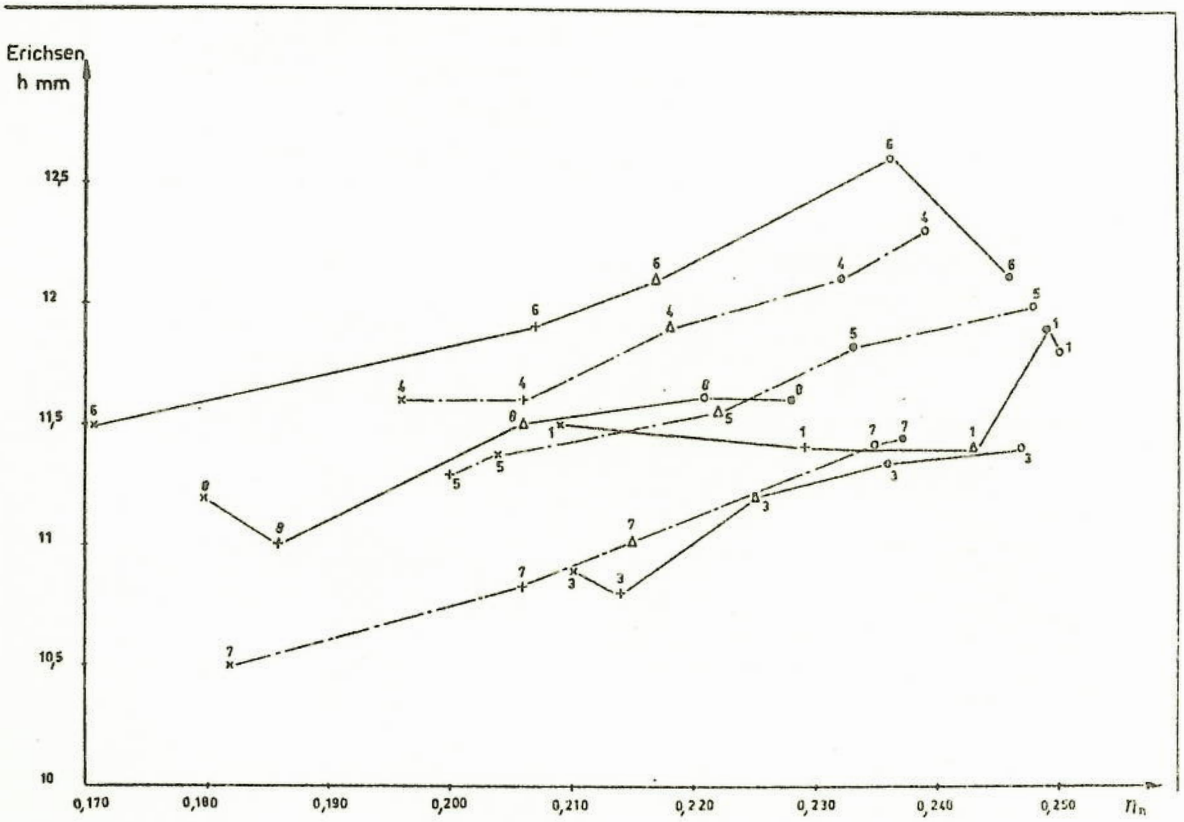


FIG. 41 HEIGHT OF CUP AT FRACTURE IN ERICHSEN TEST VS. e_u