## INDUSTRIAL ADMINISTRATION AND ENGINEERING PRODUCTION GROUP

# AN ANALYSIS OF REDUNDANT DEFORMATIONS IN ROTARY PIERCING

By T. Z. Blazynski, B.Sc. (Eng.) (*Associate Member*)*, and I. M. Cole, B.Sc. (Eng.) (*Graduate*)†

In rotary piercing, as in most other metal-working processes, there occur redundant deformations, i.e. deformations which are not essential to the required change of shape of the workpiece. Since these deformations are responsible for unnecessary additional straining of the material and can impose limitations on the range of applications of the process, it is important to establish their nature and the way in which they vary with piercer conditions. Means can then be devised of reducing them and hence reducing the severity of the process. This investigation, based on work carried out on a specially designed experimental mill and using wax as model material, was concerned with three types of deformation, viz. circumferential shear, longitudinal shear, and shear due to twist. The incidence and pattern of these deformations for two-roll barrel piercers, both with freely rotating and with driven plugs, are analysed and the probable reasons for their occurrence are given. Methods of calculation of redundancy in the system are derived which enable all redundant deformations in rotary piercing to be compared with each other and, if necessary, with redundant deformations in other processes. General conclusions concerning the pattern and flow for various conditions of rotary piercing are set out and discussed.

### INTRODUCTION

THE FIRST STEP in the manufacture of a seamless steel tube is the production of a bloom, i.e. a tubular hollow body, obtained by piercing a solid bar or billet. This operation is usually carried out by means of a rotary piercer, employing two driven rolls of barrel (Mannesmann), disc (Stiefel), or cone type, and a piercing plug which is held in the required position between the rolls by a bar (Fig. 1*a*). The rolls are set obliquely to each other, and inclined at equal angles to the mill axis (Fig. 1*b*). The billet is subjected to oblique rolling until it reaches the plane of the plug point, where rotary piercing commences; the already pierced metal will then be cross-rolled between the outlet zones of the rolls and the plug, with a resulting decrease in the wall thickness of the bloom.

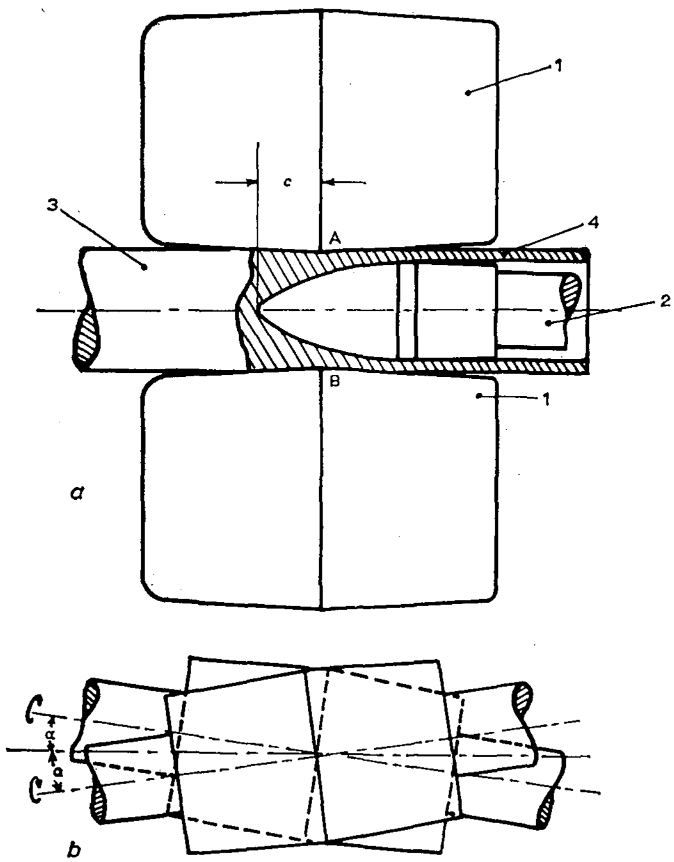
The success of the piercing operation depends, primarily, on the absence of cavitation in the worked metal. Cavitation or internal fracture of the workpiece occurs, under certain conditions, in the oblique zone, and results either in complete fracture of the metal or the formation of major defects which cannot be eliminated. Several theories have been proposed to account for the phenomenon of cavitation. These are based either on the assumption that the basic cause of cavitation is the stress concentration in front of the plug point or on the assumption that a high strain concentration in that zone is responsible for the initiation of the crack. Siebel (1)‡ and Plyatskovsky (2) present the one point of view and Teterin (3) the other.

The appearance of cavitation limits not only the range of materials which can be pierced but also the magnitude of the deformations which can be imposed on the worked metal in a two-roll mill. In addition, there also exists the problem of other imperfections caused by the mechanics of the process which, in turn, are dependent upon the geometry of the tools and tool settings. Any such

*The MS. of this paper was first received at the Institution on 30th November 1962 and in its revised form, as accepted by the Council for publication, on 9th May 1963.*

* *Department of Mechanical Engineering, The University, Leeds 2.*
† *Department of Mechanical Engineering, College of Advanced Technology, Birmingham 4.*

‡ *References are given in Appendix II.*




1 roll
2 plug
3 billet
4 bloom
AB gorge
*c* plug advance
oblique setting of rolls.
*a* roll inclination angle.

*Fig. 1. Diagram of two-roll barrel piercing*

imperfections, e.g. laps and cracks, are unlikely to be completely eliminated in subsequent operations and it is therefore essential to avoid conditions of overstrain at this initial stage of the tube-making process.

In considering the mechanics of the rotary piercing process it becomes apparent that the various hypotheses proposed for the stress pattern so far are based on very simplified assumptions which, owing to the complexity of the process, cannot be verified experimentally. The only observable and measurable quantity in metal working is deformation and, hence, the only readily calculable parameter is strain. The redundant strains are of special significance in the piercing process because control of their magnitude and pattern of variation with piercer conditions will lessen the severity of the process. The incidence of cavitation and various other faults will be reduced. The main object of this work was, therefore, the analysis of redundant deformations based on the investigation of piercing conditions in a two-roll Mannesmann-type piercer.

Both the limitations in the range of piercing conditions of existing production mills and the great number of billets to be rolled in order to obtain a fairly comprehensive picture of the effect of process variables on redundant deformations made it necessary to use a model material and a specially designed experimental mill. A subsidiary object of this paper was, therefore, the discussion of the technique of investigations, together with the theoretical problems which it presents.

## NOTATION

| | |
|---|---|
| $A_1$ | Cross-sectional area of billet. |
| $A_2$ | Cross-sectional area of bloom. |
| $a$ | Angle of roll inclination. |
| $b$ | Ratio of billet diameter to gorge diameter. |
| $c$ | Advance of plug. |
| $D_1$ | Diameter of billet. |
| $D_2$ | Diameter of bloom. |
| $E_1$ | Generalized essential strain. |
| $E_2$ | Total generalized strain. |
| $e_1$ | Radial essential natural strain. |
| $e_2$ | Longitudinal essential natural strain. |
| $e_3$ | Tangential essential natural strain. |
| $\bar{e}_1$ | Redundant circumferential shear strain. |
| $\bar{e}_2$ | Redundant longitudinal shear strain. |
| $\bar{e}_3$ | Redundant shear strain due to twist. |
| $k_1$ | Component redundancy factor for circumferential shear. |
| $k_2$ | Component redundancy factor for longitudinal shear. |
| $k_3$ | Component redundancy factor for shear due to twist. |
| $K$ | Redundancy factor. |
| $r$ | Mean radius of bloom. |
| $t$ | Mean wall thickness of bloom. |
| $w$ | Speed of roll, rev/min. |
| $\alpha$ | Angle of longitudinal shear. |
| $\beta$ | Angle of circumferential shear. |
| $\gamma$ | Twist helix angle. |

*Sign convention*

Shear strains are regarded as positive if they occur in the clockwise direction from the datum line and as negative if they occur in the counter-clockwise direction.

## METHOD OF ANALYSIS

### Consideration and discussion of types of deformation

The deformations which occur in the piercing of a billet can be divided into:

essential, i.e. necessary in the conversion of a solid billet into a hollow bloom;

redundant, i.e. not essential to the change of shape of the workpiece.

The essential deformations are determined solely by the geometry of the system and are therefore constant quantities for any particular billet–bloom transformation. Three principal essential plastic strains are associated with the change in shape, viz. longitudinal, a measure of the elongation during piercing; tangential, produced by

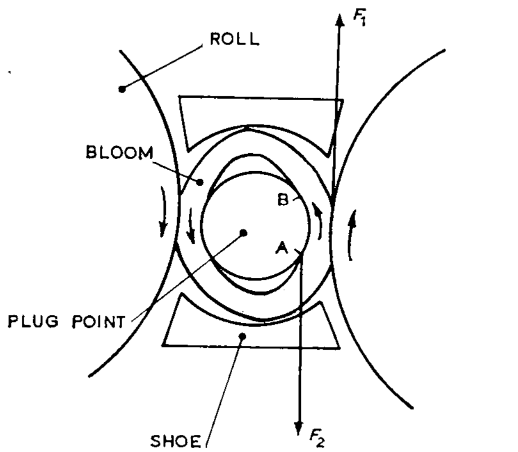



*Fig. 2. Mechanism of origin of circumferential shear strain*

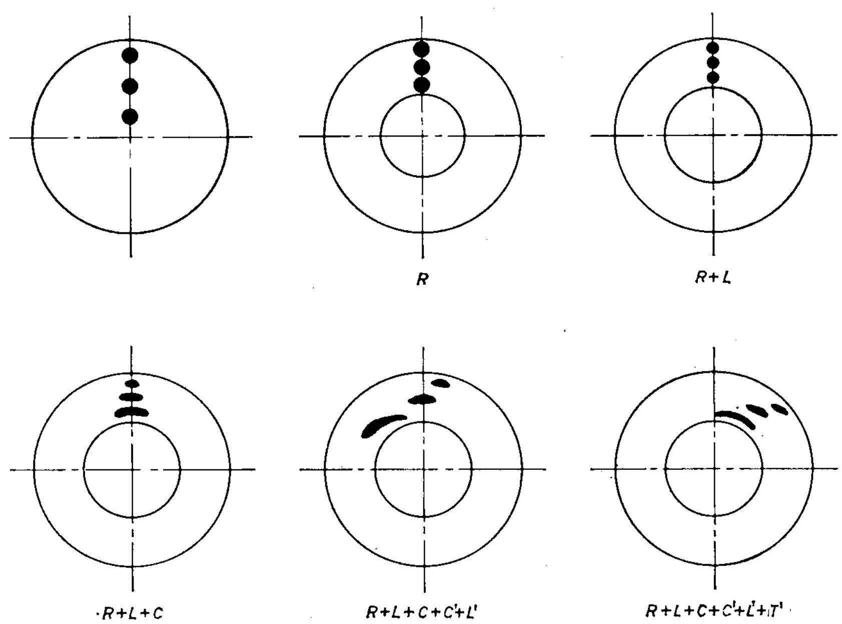
the change in diameter of an elementary tubular shell, it being assumed that the billet is composed of an infinite number of such shells; radial, corresponding to the reduction of wall thickness.

Three types of redundant deformation occur in the process. These are: circumferential shear strain; longitudinal shear strain; shear strain due to twist. The origin of circumferential redundant strain is somewhat uncertain, but a plausible explanation has been advanced by Holmquist (4), and is explained with reference to Fig. 2. This shows, diagrammatically, a vertical section through the plug nose for a two-roll system. Ovalling of the bloom during rolling results in a limited arc of contact AB with the plug; consequently the pressure exerted by the rolls on the bloom causes the plug to indent the workpiece, producing a hump at, say, A. The hump can then be expected to produce a resistance $F_2$ to the passage of the bloom through the narrowing space between the plug and the rolls along the mill pass as far as the gorge*. This resistance is overcome by the tractive force $F_1$ exerted by the roll on the outer surface of the bloom. The two parallel forces form a couple which is responsible for the tangential shearing of the bloom. The appearance of the tangential forces $F_2$ on the plug is possible, of course, only because of the constraint imposed on the plug by the rather complex system of pressure produced by the variations in both axial and tangential velocities of the billet and bloom along the axis of the pass.

Longitudinal shearing strain is caused by the existence of the two opposing forces acting on the billet: a forward longitudinal component of the force exerted by the roll on the outer surface of the billet and a backward longitudinal force exerted by the plug on the bore.

Twisting is due to the fact that, as the ratio of billet diameter to roll diameter is not constant along the pass, the condition of pure rolling is not satisfied. The difference between the tangential velocities of the billet and the roll must be accommodated either by twisting of the material or slipping of the roll, or both effects combined. Several

* *For the definition of the term 'gorge' see Fig. 1.*




*R* radial essential strain.
*L* longitudinal essential strain.
*C* tangential essential strain.
*C′* circumferential redundant strain.
*L′* longitudinal redundant strain.
*T′* redundant strain due to twist.

*Fig. 3. Effect of essential and redundant deformations*

factors will influence the extent to which either of these effects will occur. It is apparent that they will depend on frictional conditions, mill settings, and tool profiles.

The effect of essential and redundant strains on a set of markers in an experimental billet is represented diagrammatically, and not to scale, in Fig. 3. This shows a vertical section of the billet being subjected to the strains, the sequence in which they are shown being entirely arbitrary. The effect of longitudinal redundant shear is absent from the set because it can only be shown in a section taken at right angles to the one considered, and by the use of a different type of marker, as discussed later.

## Model material

In order to study the deformation in a metal-working operation it is necessary that the interior of the workpiece should be marked. In this way relative displacements can be measured and strains calculated. Sectioning and grid-scribing techniques used successfully in extrusion, for example, are impracticable for the rotary piercing of hot steel. The use of irradiated inserts in full-scale steel billets is unsatisfactory since this rather cumbersome method proves inadequate owing to the very poor resolution near the inner and outer surfaces of the bloom. For these reasons an analysis of deformations in rotary piercing has to be based on a model material simulating the behaviour of hot steel. This really means making the widely accepted assumption that there are laws of plastic flow to which the hot metal, the model material, and all other plastic materials conform.

The nature of the investigation undertaken precluded the use of soft metals such as lead or aluminium and the choice lay therefore between Plasticene and waxes. General characteristics of wax as model material make it preferable to Plasticene for the investigation of the rotary metal-working processes where special insert-making and bloom- or tube-sectioning techniques are necessary. These characteristics are: standard conditions can readily be obtained by melting and casting to the desired shape and size despite the presence of a small amount of thixotropy; dyeing of wax can be carried out without altering its mechanical properties, and accurate inserts can be made by special casting techniques; although for working experiments wax must be heated to slightly above room temperature, sectioning by normal machining methods can be very readily carried out after cooling. These properties have been used by Assel (5), who based the design of his tube-elongating mill on the results of wax-rolling experiments, and by Holmquist (4) in his studies of piercing. The satisfactory simulation by paraffin wax of the properties of hot metal was studied by Bodsworth *et al.* (6), in connection with their extrusion experiments. For the present work a mixture of four waxes was used, based on Holmquist's composition slightly modified. The mixture consisted of 8 parts by weight of carnauba wax, 8 parts of beeswax, 40 parts of ceresin wax, and 44 parts of paraffin wax. The mechanical properties of the material, for a range of temperatures between 75 and 110°F, were ascertained by means of torsion tests for two equivalent strain rates of 0·124/s and 4·2/s. It was found that the best correlation between wax and steel at piercing temperatures was obtained at a temperature of 100°F. The relation between temperature and maximum torque for both strain rates (Fig. 4) shows the susceptibility of wax to temperature changes. The discrepancy existing between the stress–strain curves of the two materials indicates that, although the pattern of redundant deformations for a given metal-working operation will remain the same for both, the magnitude of these deformations may not necessarily be the same, at least for high strains. The torsional tests also confirmed that the use of Neutral red chloride and Toluidine blue dyes did not alter the mechanical properties of the wax.

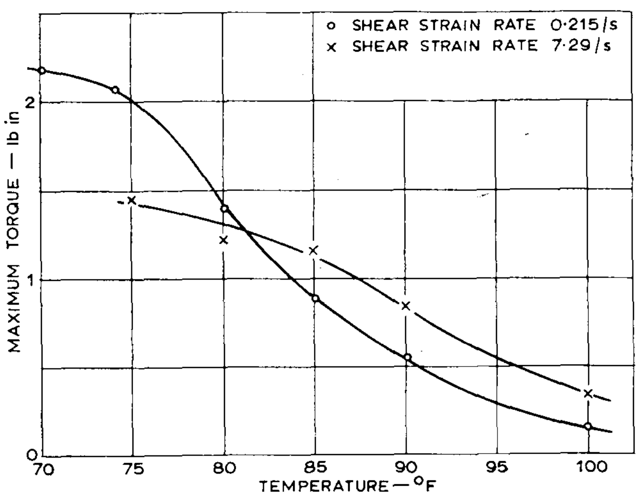



*Fig. 4. Variation of maximum torque with temperature*

## Numerical analysis

The mean values of the essential strains are given by the following general expressions, derived from the definitions of the respective strains:

$$\text{radial strain} \qquad e_1 = -\ln \frac{D_1}{2t} \quad . \quad . \quad (1)$$

$$\text{longitudinal strain} \quad e_2 = \ln \frac{A_1}{A_2} \quad . \quad . \quad (2)$$

$$\text{tangential strain} \quad e_3 = \ln \frac{2(D_2-t)}{D_1} \quad . \quad (3)$$

In a similar way the redundant strains can be described by means of expressions based on the definitions of these strains. The three redundant strains are thus given by the following expressions:

$$\text{circumferential shear strain } \bar{e}_1 = \frac{\beta r}{t} \quad . \quad (4)$$

$$\text{longitudinal shear strain} \quad \bar{e}_2 = \cot \alpha \quad . \quad (5)$$

$$\text{shear strain due to twist} \quad \bar{e}_3 = \tan \gamma \quad . \quad (6)$$

An interesting problem can arise over the significance of the values of the various shear angles measured from the deformed billets. The assumption made in every metal-working operation is that, in the absence of redundant deformations, vertical planes in any section of the undeformed material will remain vertical after the deformation has taken place and that the initial angular position of an element of material with respect to some datum in any vertical plane considered will also remain unchanged. Consequently, any observed deviation from these principles constitutes proof of the existence of redundant deformation and, when expressed in terms of physical measurements, provides a measure of the deformation or shear strain. The physical significance of such a direct measurement could, however, be misleading in some cases, since it depends on the order in which the deformations take place. To clarify this point it is necessary to consider the two extreme cases. If it is supposed that all essential deformations take place first and are followed by redundant deformations, then, clearly, measurement of a physical entity will give the magnitude of the redundant deformation directly. If, however, redundant deformations precede the essential, the measurement of the same physical entity made on the deformed material will differ from that obtained in the first case, the difference depending on the magnitude and direction of the essential deformation which affects the entity considered. As a simple example of the problem involved one may consider the essential and redundant strains in rotary piercing. In the first case a vertical plane through the billet that would remain vertical in the absence of redundant longitudinal deformation will, when considered again, say at a section of the plug nose where piercing begins, be inclined at an angle to the horizontal, the angle being a measure of the longitudinal redundant deformation. If, however, the redundant deformation is followed by the essential, the observed angle will be distorted and, in this particular case, will be larger than the true angle caused by the redundant deformation.

It is not known in what order, if any, the essential and redundant deformations occur at any instant in any given section along the pass in the rotary piercing process. Consequently, in order to evaluate the physical significance of measurements made in this investigation, a method of correcting for the influence of the essential deformations on the redundant has been obtained for the second case discussed above. This method is shown in Appendix I.

Although the magnitude of strains involved in the process can be estimated, the influence of the process variables on the strains can be assessed only if a method of arriving at a redundancy factor for the given set of conditions is available. This appears to be possible if the concept of the generalized total strain is used; the generalized increment of plastic strain is defined by the equation

$$\overline{\mathrm{d}\epsilon^{p}} = +\sqrt{\tfrac{2}{3}}\,(\mathrm{d}\epsilon_{ij}{}^{p}\,\mathrm{d}\epsilon_{ij}{}^{p})^{\frac{1}{2}} \quad . \quad . \quad (7)$$

It is often held that equation (7) can be applied only to those cases where the principal axis does not rotate relatively to the element considered and to the strain paths where strain ratios remain constant, this part of the statement being important when stresses are being considered. It has, however, been shown by Davis (7) and Roš and Eichinger (8) that non-adherence to the stated postulates results in small errors of no more than 5 per cent (Roš). In view of the magnitude of the possible errors involved in the experimental part of this work it was felt fully justifiable to base the calculations on equation (7) although, strictly, the conditions in rotary piercing are to a certain extent at variance with the assumptions made in arriving at this expression. Even with these reservations equation (7) proved a very useful and the only available tool for the purpose of the present investigation. It follows from this equation that the generalized strain when essential deformations only are considered will be given by:

$$E_1 = \sqrt{\tfrac{2}{3}}\,(e_1{}^2+e_2{}^2+e_3{}^2)^{\frac{1}{2}} \quad . \quad . \quad (8)$$

and the generalized total strain

$$E_2 = \sqrt{\tfrac{2}{3}}\left[e_1{}^2+e_2{}^2+e_3{}^2+2\left\{\left(\frac{\bar{e}_1}{2}\right)^2+\left(\frac{\bar{e}_2}{2}\right)^2+\left(\frac{\bar{e}_3}{2}\right)^2\right\}\right]^{\frac{1}{2}} \quad . \quad . \quad . \quad (9)$$

Ideally the values of strains used in both equations should be those calculated from considerations of small incremental changes taking place along the pass. Since such procedure would preclude any possibility of a comprehensive survey of piercing conditions it is necessary to simplify the issue by considering a reasonable number of sections and then to obtain the values of strains by integrating along the pass; reversals of strains, if any, will thus be accounted for. It should be realized, of course, that in every case the strains used in both equations are mean values across the whole or a large portion of the cross-section.

The assessment of the contribution of any of the redundant deformations towards the total amount of redundancy in the process can then be made by means of component redundancy factors defined as follows:

$$k_1 = \frac{\bar{e}_1}{E_1}\ \text{(circumferential)} \quad . \quad . \quad (10)$$

$$k_2 = \frac{\bar{e}_2}{E_1}\ \text{(longitudinal)} \quad . \quad . \quad . \quad (11)$$

$$k_3 = \frac{\bar{e}_3}{E_1}\ \text{(due to twist)} \quad . \quad . \quad . \quad (12)$$

A measure of total redundancy in the process will be given by means of the redundancy factor $K$.

$$K = \frac{E_2}{E_1} \quad . \quad . \quad . \quad . \quad (13)$$

## Measurements

The determination of redundant deformations necessitated the use of the two different types of billet shown in Fig. 5. Type 'a' with eleven red and one blue longitudinal filaments was obtained by casting wax in a metal mould with

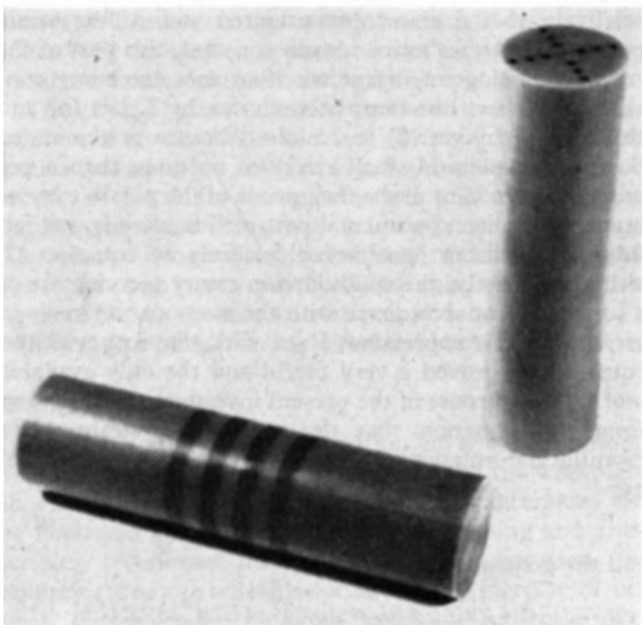


*Fig. 5. Type 'a' and type 'b' wax billets*

steel cores which were withdrawn after solidification and then forcing in liquid coloured wax under pressure to give a homogeneous bond. (This method is essentially the same as that used by Holmquist (4).) Type 'b' was made by 'welding' together previously machined wax discs by passing a hot wire between them. Both types of billet were finally machined to a size of 6 in long and 1.625 in diameter. To obtain the necessary numerical data at least one billet of each type had to be pierced for any piercing condition investigated. The assumption that essential deformations in both billets are identical was proved correct by a series of exploratory piercing trials. Furthermore, the piercing was stopped by means of an instantaneous release mechanism incorporated in the experimental mill and the various stages of the piercing operation could be examined. The procedure adopted was as follows. A line, perpendicular to the undeformed bank of filaments containing the blue marker, was inscribed on the surface of every 'a' billet, which was then sectioned transversely (Fig. 6); 'b' billets were sectioned longitudinally. The six transverse sections of the 'a' billet and the longitudinal section of the 'b' billet were photographed and prints of seven-times magnification made on a photographic paper stabilized with aluminium sheet to prevent distortion. All measurements were then made on the photographs.

The 'a' billet was used for the determination of twist and the 'b' billet was used for the calculation of longitudinal shear strain. The circumferential shear strain was determined by using these two quantities in conjunction with measurements of relative angles of displacement obtained from the 'a' billets.

It follows from the usual analysis of the effect of a twisting couple on a cylindrical bar (Fig. 7*a*) that the shear strain $\bar{\varepsilon}_3$ due to twist is given by

$$\bar{\varepsilon}_3 = \tan\gamma = \frac{r\theta}{L} \quad . \quad . \quad . \quad \text{(6a)}$$

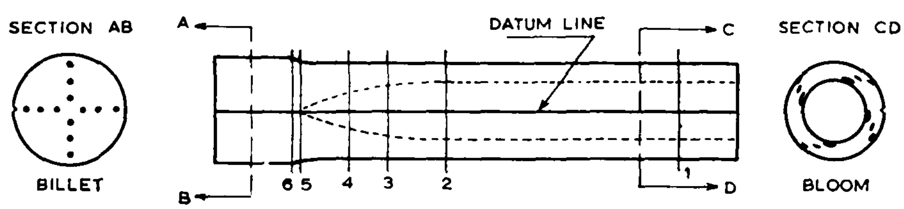
The method of measurement of the angle $\theta$ and radius $r$ on the wax billets is shown in Fig. 7*b*. The angles between the datum line and the centres of corresponding filaments are measured on two consecutive sections which are a distance $L$ apart. (N.B. Fig. 7*b* shows only one bank of filaments, whereas in practice the measurements were made on four banks.) The angle $\theta$ is then defined as follows:

$$\theta = \tfrac{1}{3}\sum(\delta_2-\delta_1)+(\epsilon_2-\epsilon_1)+(\lambda_2-\lambda_1) \quad . \quad \text{(14)}$$

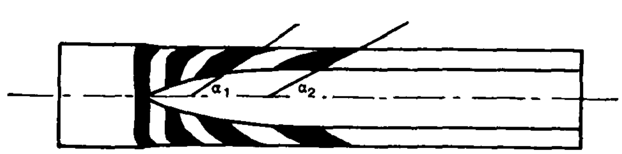
The radius $r$ is the arithmetic mean of radii $r_1$ and $r_2$.

The longitudinal shear strain was determined as follows. The distance of any transverse section from the plug point was determined from the corresponding 'a' billet and a mean line, tangential to the boundary between red and white wafers in the 'b' billet for that section, was determined; the angle between this line and the longitudinal axis was measured. This angle is a direct measure of longitudinal shear and its cotangent gives the strain (equation (5)). The angle is shown in Fig. 6.

Since the total angular displacement of a filament from




*a* Type 'a' billet, showing positions of transverse sections




*b* Type 'b' billet, showing a longitudinal section used for the determination of longitudinal shear

*Fig. 6. Sectioning of wax billets*

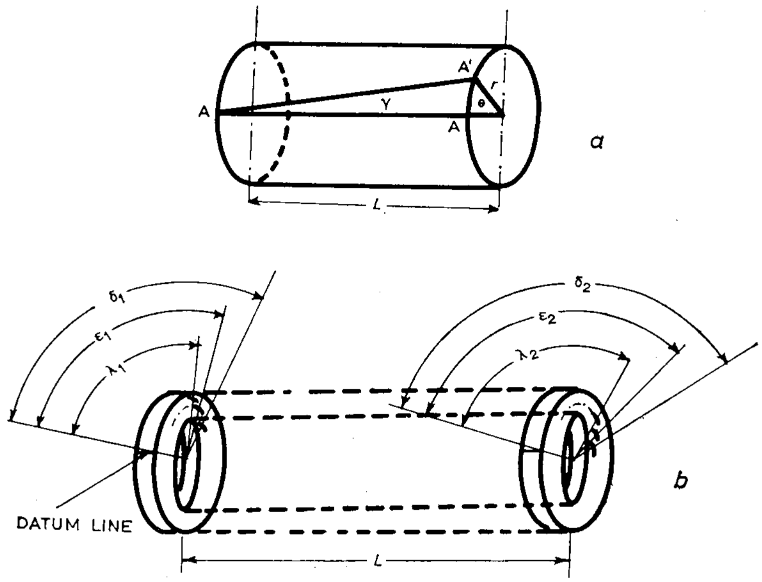



*Fig. 7. Determination of the angle of twist*

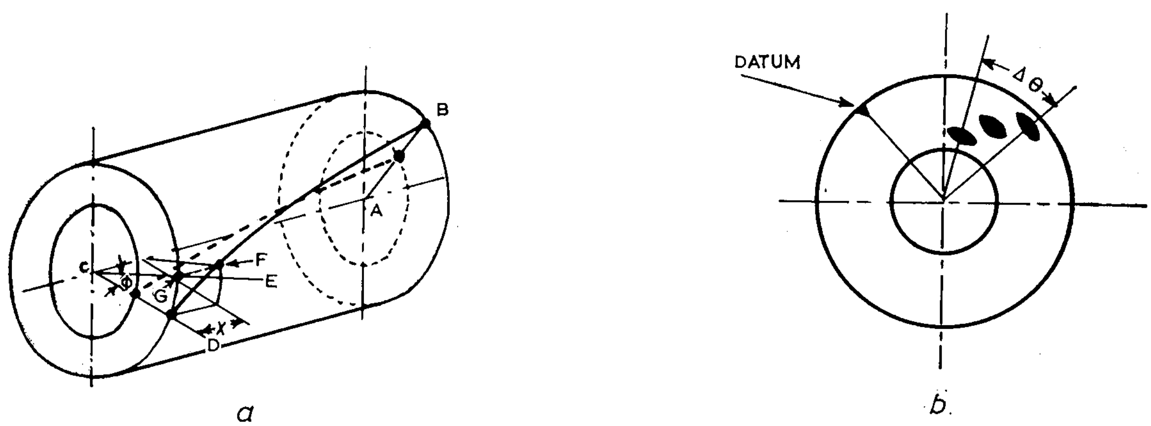



*Fig. 8. Determination of the angle of circumferential shear*

the datum line in a transverse section is composed of the combined displacements due to twist, longitudinal shear, and circumferential shear, a relation between the first two has to be determined in order to arrive at the value of the circumferential strain. A simple geometrical construction, due to Holmquist, can be used for this purpose (Fig. 8). When two filaments only are considered, the ends of which lie along the radial line AB, it is seen that if there were no longitudinal displacement in addition to torsional deformation these ends would lie on the radial line CD in the other plane of the section. However, when the outer surface is displaced a distance $x$ relative to the inner surface, a point F on the outer filament is moved to G. The angle between the radial line CE through G and the radial line CD is equivalent to the angular displacement due to both twist and longitudinal shear. This angle is equal to the product of twist in radian measure per unit length and the longitudinal displacement $x$. Let $\phi$ be this angle, $\Delta h$ be the radial distance between the inner and outer filaments, and $\Delta\theta$ (see Fig. 8*b*) be the relative angular displacement. From equation (6a)

$$\phi = \frac{\theta x}{L} \qquad (15)$$

and by the use of equation (5)

$$\cot\alpha = \frac{x}{\Delta h} \qquad (16)$$

Hence $\phi$ can be determined for any section and the angle of the circumferential shear is given by

$$\beta = \Delta\theta - \phi \qquad (17)$$

This value can then be used in equation (4) to obtain the circumferential strain.

## EXPERIMENTAL DETAILS

The results of the work are based on measurements made on 160 rotary-pierced wax tubes. The work was carried

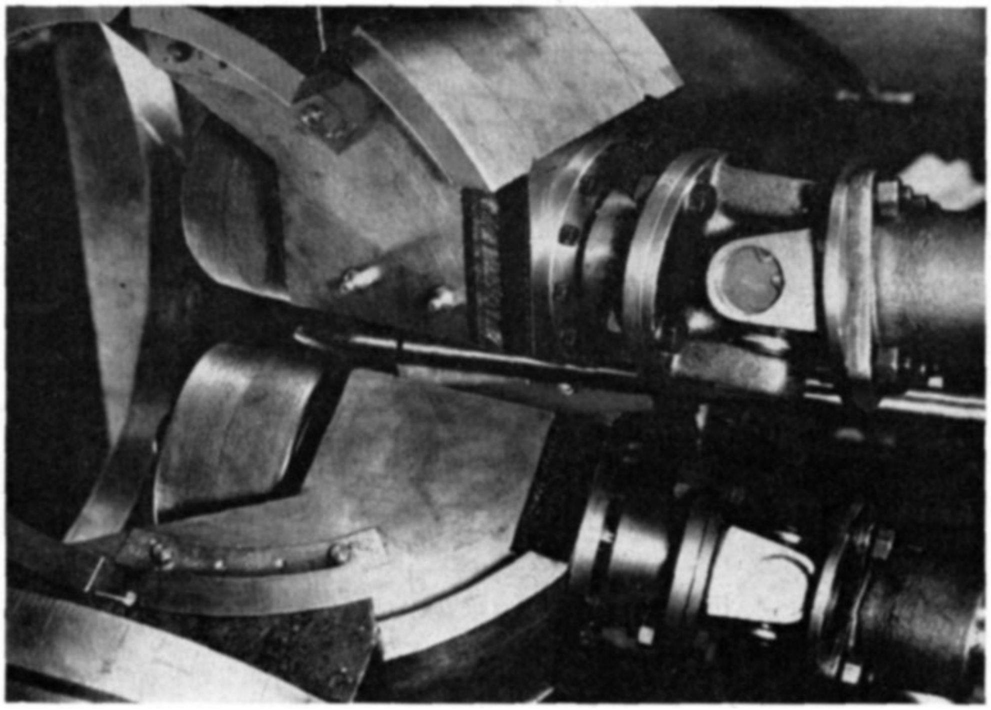


*Fig. 9. Set-up of experimental mill (with guides removed)*

out on an experimental mill with a quick-release mechanism. All tools were made from Tufnol; profiles were based on standard tools and can be seen in Fig. 9 which shows the set-up of the experimental mill. Two Tufnol guides were employed and their profile is shown in Fig. 10.

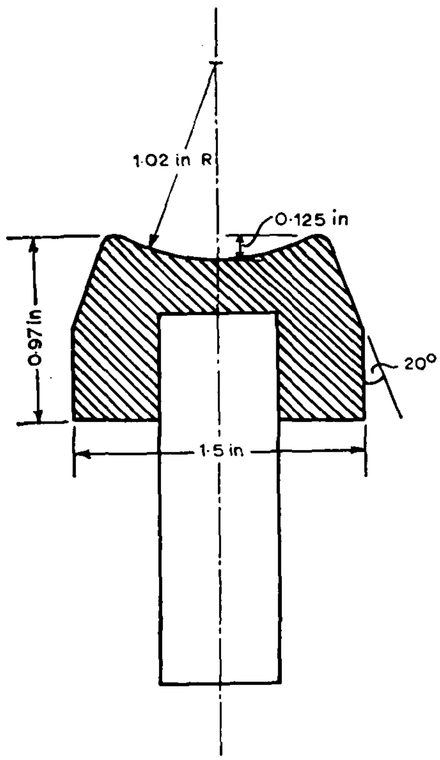



*Fig. 10. Guide profile*

The investigations were primarily concerned with the redundant deformations occurring with a freely rotating plug bar. In view of the claims put forward by Holmquist (9), that forced rotation of the plug bar in the direction of rotation of the billet reduces laps and other faults in the bloom, i.e. apparently reduces the redundant deformations, this condition was examined for one position of the plug and all angles of roll inclination. The plug bar was overdriven by 25 per cent in excess of the theoretical rotational speed of the bloom, i.e. in excess of the speed corresponding to the size of the gorge if circumferential slip is neglected.

To confine the investigations to reasonable limits a selection of variables had to be made. The following were considered the most important:

roll inclination angle $a$;
plug position $c$, defined as the distance from the plug point to the gorge;
magnitude of essential deformation represented by the ratio $b$ of billet diameter to gorge diameter;
effect of driving the plug bar.

It was found convenient to keep the following variables constant: roll profile, plug profile, roll speed ($w = 40$ rev/min was chosen), and guide profile. The following range of each variable was investigated:

roll inclination angle, $a = 8°, 10°, 12°, 16°$;
three plug positions for each angle, $c = 0{\cdot}42$ in, $0{\cdot}52$ in, $0{\cdot}62$ in;

five essential deformations for each plug position, $b = 1{\cdot}05, 1{\cdot}10, 1{\cdot}15, 1{\cdot}20, 1{\cdot}25$;

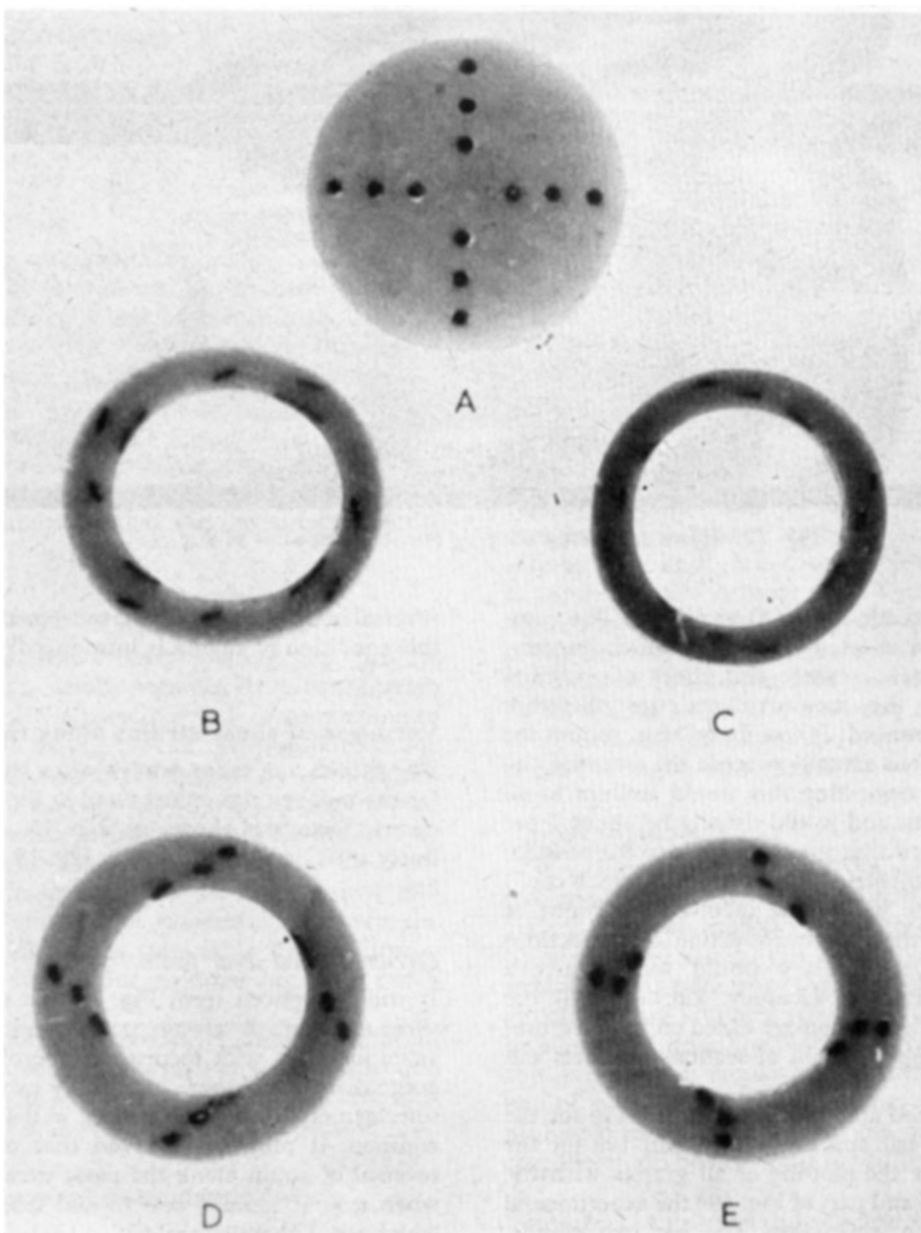
driven plug bar (25 per cent over-drive) for $c = 0{\cdot}52$ and $a = 8°, 10°, 12°, 16°$.

The spacing of guides was adjusted to create conditions in which the worked material would be in contact with the guides and the removal of ovality achieved. The correct spacings were found experimentally and the following were employed:

for $b = 1{\cdot}05$: spacing 1·700 in;
for $b = 1{\cdot}10$ and $1{\cdot}15$; spacing 1·675 in;
for $b = 1{\cdot}20$ and $1{\cdot}25$: spacing 1·650 in.

## DISCUSSION OF RESULTS

To determine the significance of the experimental data obtained from the rolling tests a comparison was made between the values obtained when redundant deformations were said to follow the essential and those obtained when




A undeformed billet.
B freely rotating plug bar ($a = 8°$, $b = 1{\cdot}25$, $c = 0{\cdot}52$).
C driven plug bar (same conditions as for B).
D freely rotating plug bar ($a = 10°$, $b = 1{\cdot}05$, $c = 0{\cdot}52$).
E driven plug bar (same conditions as for D).

*Fig. 11. Effect of driving the plug bar*

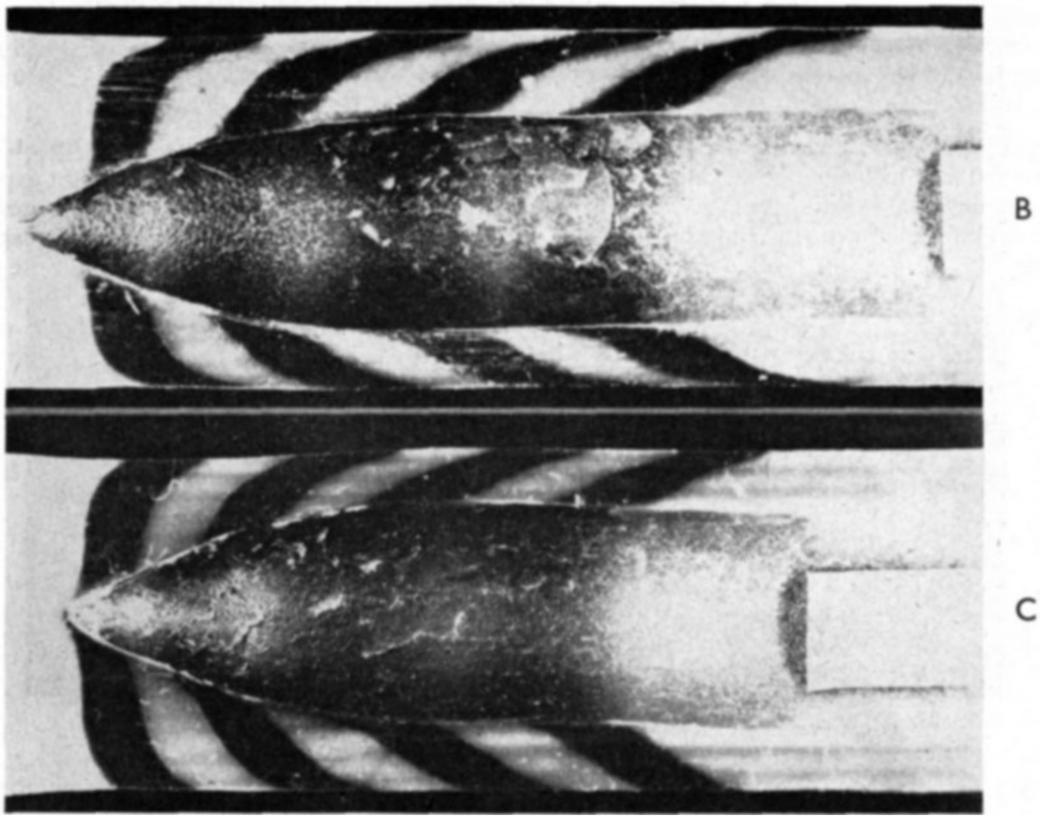



*Fig. 12. Effect of driving the plug bar (conditions as in Fig. 11)*

they were said to precede them (Appendix I). The comparison was based on selected blooms for which the conditions of rolling were severe: the effect of essential deformations upon the measurements was therefore expected to be pronounced. It was found that, should the redundant deformations actually precede the essential, the error introduced by neglecting this would amount to no more than 10 per cent and would usually be about 7 per cent. It was recognized that the magnitude of the possible error was small in comparison with the errors which could be introduced by the use of the involved technique of measurements, and that the introduction of corrections which might not be necessary would merely give a semblance of unwarranted accuracy. Consequently the results discussed in this section are based on the measurements made on the photographs of sections of billets and blooms.

The results obtained are shown in Figs 13–17*b* for the freely rotating plug bar and in Figs 18 and 19*b* for the driven plug bar. For the plotting of all graphs with the exception of Fig. 17*b* and part of Fig. 19*b* the experimental points shown in each were used. The last two graphs, representing the variation of redundancy factor with roll inclination angle, show derived curves obtained from mean curves in Figs 17*a* and 19*b*.

A pictorial illustration of the effects of driving the plug bar is afforded by Figs 11 and 12 which show a marked reversal in the direction of the movement of filaments when this condition of rolling is introduced.

## Variation of shear strains along the pass

The variation of redundant shearing strains along the pass for the mill settings enumerated in the section on Experimental Details is shown in Figs 13, 14, and 15 for the freely rotating plug bar and in Fig. 18 for the driven plug bar.

### *Circumferential shear strain*

It will be noticed from Fig. 13 that the circumferential shearing strain is always positive and that its absolute value increases with increasing ratio of billet diameter to gorge diameter *b*, there being only two exceptions to this rule, namely for $a = 16°$ and $c = 0{\cdot}42$ and $0{\cdot}52$ in. In addition, it may be observed that usually there is no reversal of strain along the pass; exceptions again occur when $a = 16°$ and $c = 0{\cdot}42$ and $0{\cdot}52$; they also occur when $a = 12°$ and $c = 0{\cdot}62$.

The variation of the circumferential shear strain along the pass when the plug bar is driven is represented in Fig. 18. It appears from the graphs that over-driving the plug bar by 25 per cent of its theoretical speed completely changes the pattern of this strain for various mill settings. In general the strains are negative, although there is usually a small positive increment near the plug nose, followed by a reversal in direction further along the plug. When $a = 16°$ and $b = 1{\cdot}25$, however, the strain remains negative throughout. It is also noticeable that the absolute magnitudes of strains when the plug bar is driven are very much smaller than the corresponding magnitudes when the plug is freely rotating. Except when $a = 8°$ and $b = 1{\cdot}25$ the magnitude of the strain, for any given $b$, does not vary much with increasing angle of roll inclination.

The trend towards the change of orientation of the strain when the plug is driven is illustated in Fig. 11, although it must be realized that photographs reproduced there show the cumulative effect of all three redundant strains and not only that of the circumferential strain.

*Longitudinal shear strain*

The changes along the pass for various conditions of rolling are shown in Figs 14 and 18. In both the strain invariably increases with $b$ and no reversals are noticed. The influence of driving the plug is very slight. In general, it may be said that in this case the strains for corresponding mill settings are slightly lower. It can also be observed that, although there usually exists a longitudinal redundant strain in the section corresponding to the plug point, there is none at a distance of 0·4 in from this section. The position is very similar to that for the circumferential strain.

*Shear strain due to twist*

Fig. 15 shows that with a freely rotating plug bar the strain due to twist is generally negative. Reversals of strain are common and there is usually a peak corresponding to some section on the middle part of the plug. Unlike the other two redundant strains the magnitude of the strain due to twist does not vary directly with $b$. Driving the plug bar changes the pattern radically (Fig. 18). For $a = 8°$ and 12° the strains are mainly positive and for the other two angles of roll inclination they are both positive and negative but very small. The comparison between the driven and free plug bar is favourable to the former, showing that the strains due to twist are very much smaller.

However, since the magnitudes of strains are small when considered in conjunction with circumferential and longitudinal strains it can be concluded that twist contributes little to the total redundancy of the process.

## Variation of component redundancy factors

The component redundancy factors have been introduced as a measure of the degree of redundancy introduced by individual strains and consequently they indicate the importance of the respective strains in the process. The results are represented in Fig. 16 for the freely rotating plug bar and in Fig. 19*a* for the driven plug bar.

*Circumferential shear strain*

Within the range of mill settings investigated and for a freely rotating plug bar the factor $k_1$ is always positive and the curves never intersect the $x$ axis. It follows, therefore, that it is not possible to eliminate the circumferential shearing strain in two-roll barrel piercing. It is also noticeable that the factor $k_1$ increases with increasing $b$. When the plug bar is driven, however, the component redundancy factor is negative except in the graph for $a = 16°$ where the curve intersects the $x$-axis. The shift in the relative position of the corresponding curves from the first quadrant to the fourth indicates that with a suitable over-drive (less than 25 per cent) it would be possible to roll with $k_1 \simeq 0$ for a wide range of mill settings. This desirable condition can only be achieved with the over-drive of 25 per cent when $a = 16°$, $b = 1{\cdot}22$, and $c = 0{\cdot}52$.

*Longitudinal shear strain*

The component redundancy factor $k_2$ is always positive for both free and driven plugs and increases with increasing $b$. It should be noticed that for comparable rolling conditions the absolute values of $k_2$ are invariably smaller when the plug is driven.

*Shear due to twist*

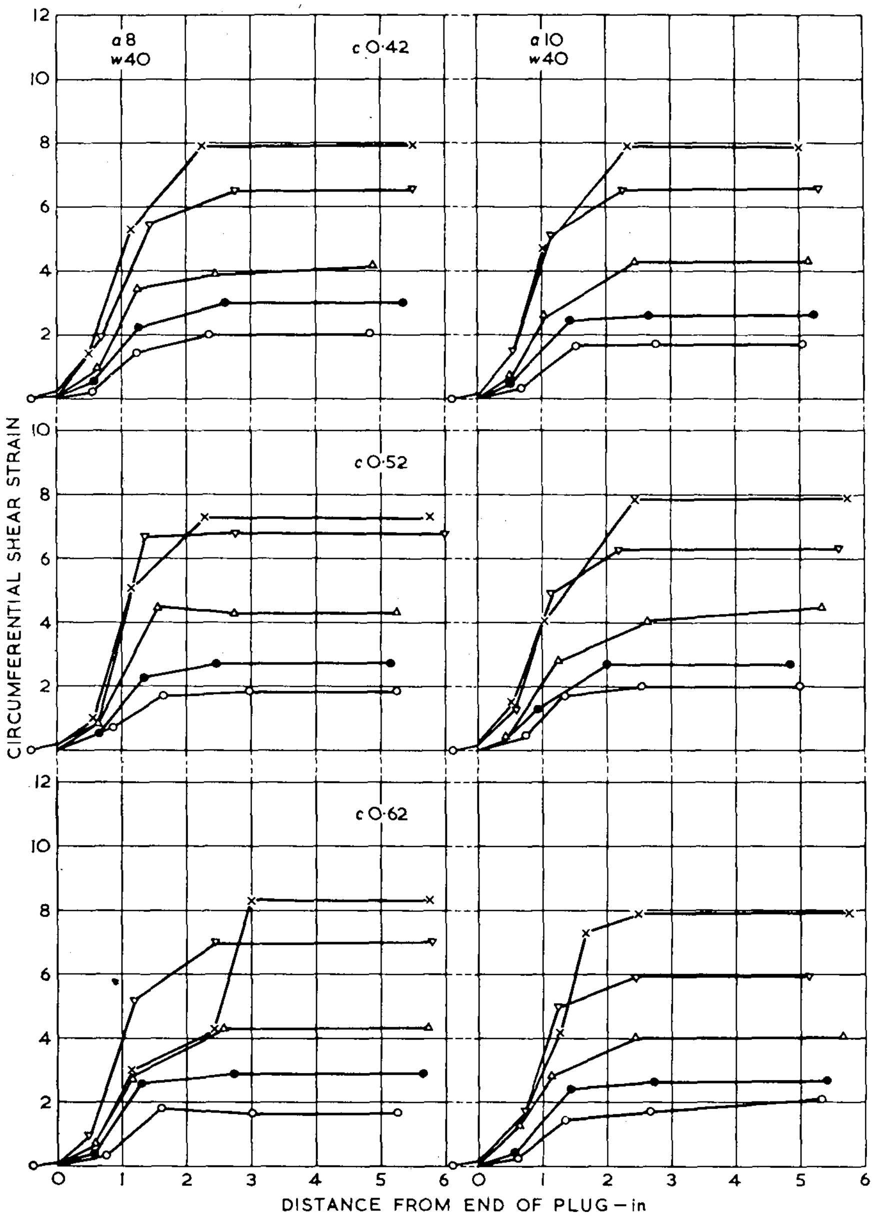
Fig. 16 indicates that for the freely rotating plug the component redundancy factor $k_3$ always remains negative and that, as with $k_1$, it is not possible to achieve conditions in which it would become zero. The situation is different when the conditions induced by driving the plug are considered: $k_3$ becomes zero for $a = 8°$ and $b \simeq 1{\cdot}07$ and for $a = 10°$, 12°, and 16° and $b \simeq 1{\cdot}12$. It is found however that, so far as the relative magnitudes of $k_3$ are concerned, the roll inclination angle of 8° gives the worst effect, making $k_3$ rather high.

*General comments*

When the considerations of the influence of the three redundant strains on total redundancy in piercing are summarized two aspects of the process become obvious: (i) none of the strains can be eliminated or significantly reduced at any time when the plug rotates freely but either circumferential strain or strain due to twist, or both, can be eliminated when the plug is driven provided that suitable over-drive is employed; (ii) with the possible exception of $a = 8°$ for the driven plug, shear due to twist is negligible in comparison with the other two strains and can, therefore, be neglected for all practical purposes.

## Variation of redundancy factor $K$

The redundancy factor $K$ is the measure of total redundancy in the process resulting from the interaction of the three redundant strains. Its variation with $b$ for varying $a$, and with $a$ for constant $b$, is shown in Figs 17*a* and 17*b* for the free plug and in Fig. 19*b* for the driven plug.




*a* roll inclination angle, degrees.
*b* ratio of billet diameter to gorge diameter.
*c* plug advance, in.
*w* roll speed, rev/min.

● *b* 1·05 ○ *b* 1·10 △ *b* 1·15 ▽ *b* 1·20 × *b* 1·25

*Fig. 13. Variation of circumferential shear strain along pass*

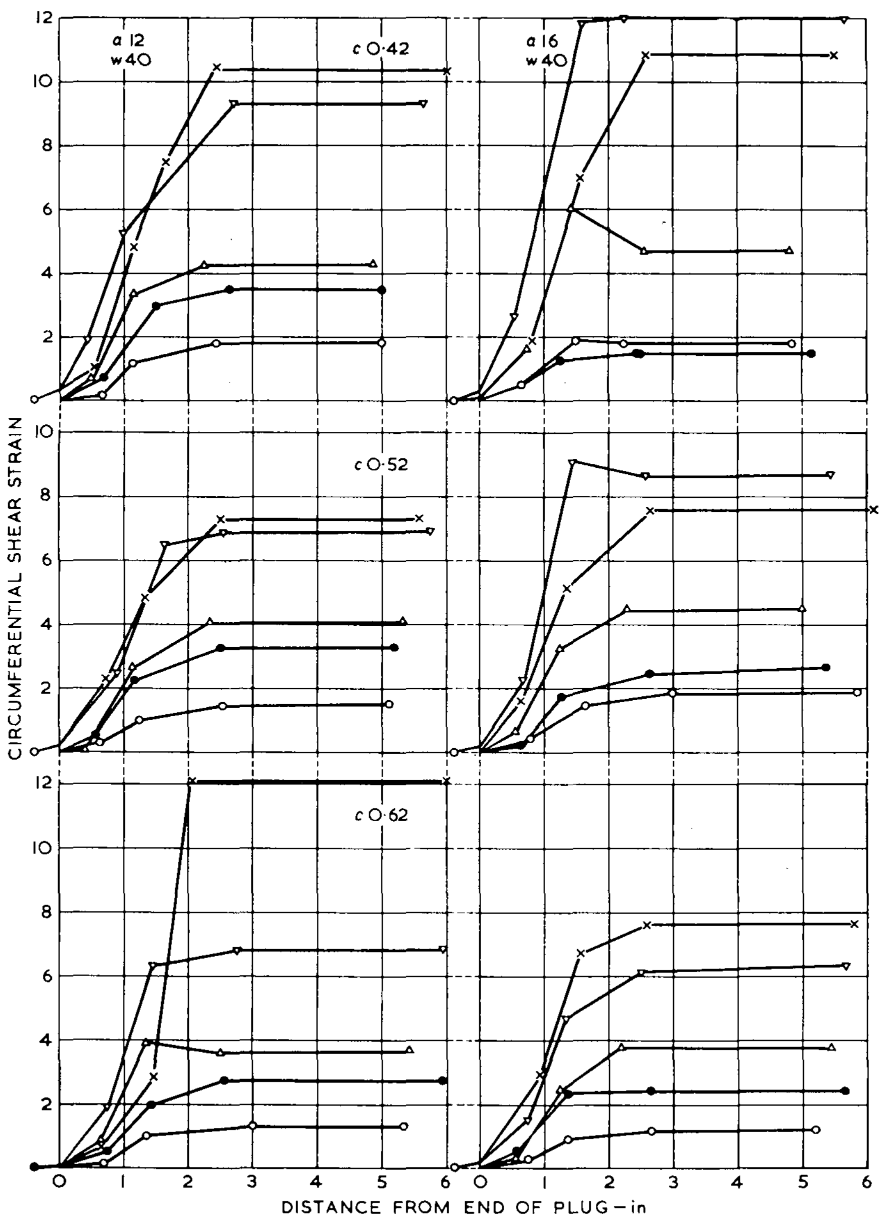
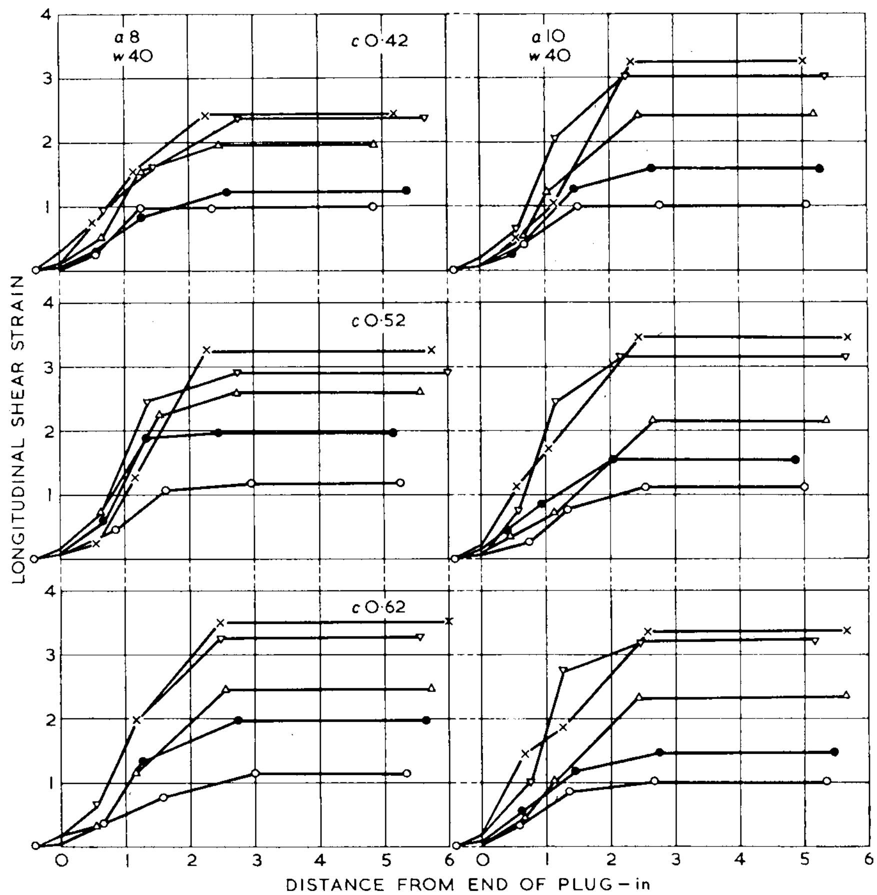

a 12
w 40
c 0·42
a 16
w 40
c 0·52
c 0·62
CIRCUMFERENTIAL SHEAR STRAIN
DISTANCE FROM END OF PLUG – in

*Fig. 13—contd.*




*a* roll inclination angle, degrees.
*b* ratio of billet diameter to gorge diameter.
*c* plug advance, in.
*w* roll speed, rev/min.
● *b* 1·05 ○ *b* 1·10 △ *b* 1·15 ▽ *b* 1·20 × *b* 1·25

*Fig. 14. Variation of longitudinal shear strain along pass*

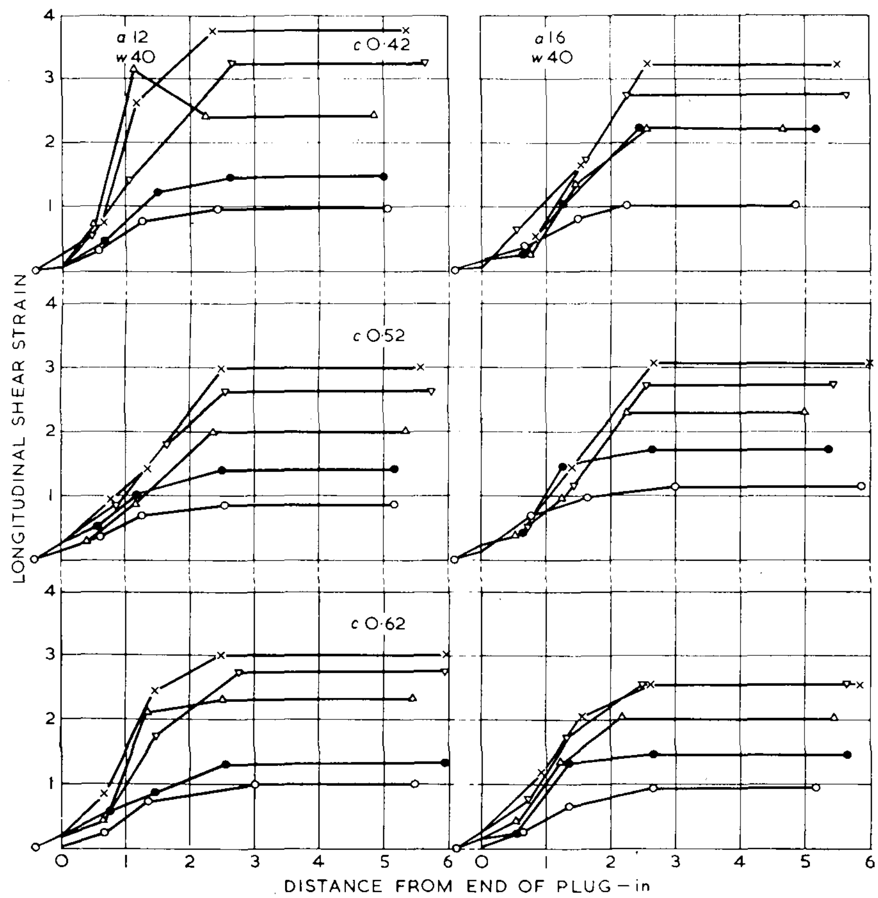
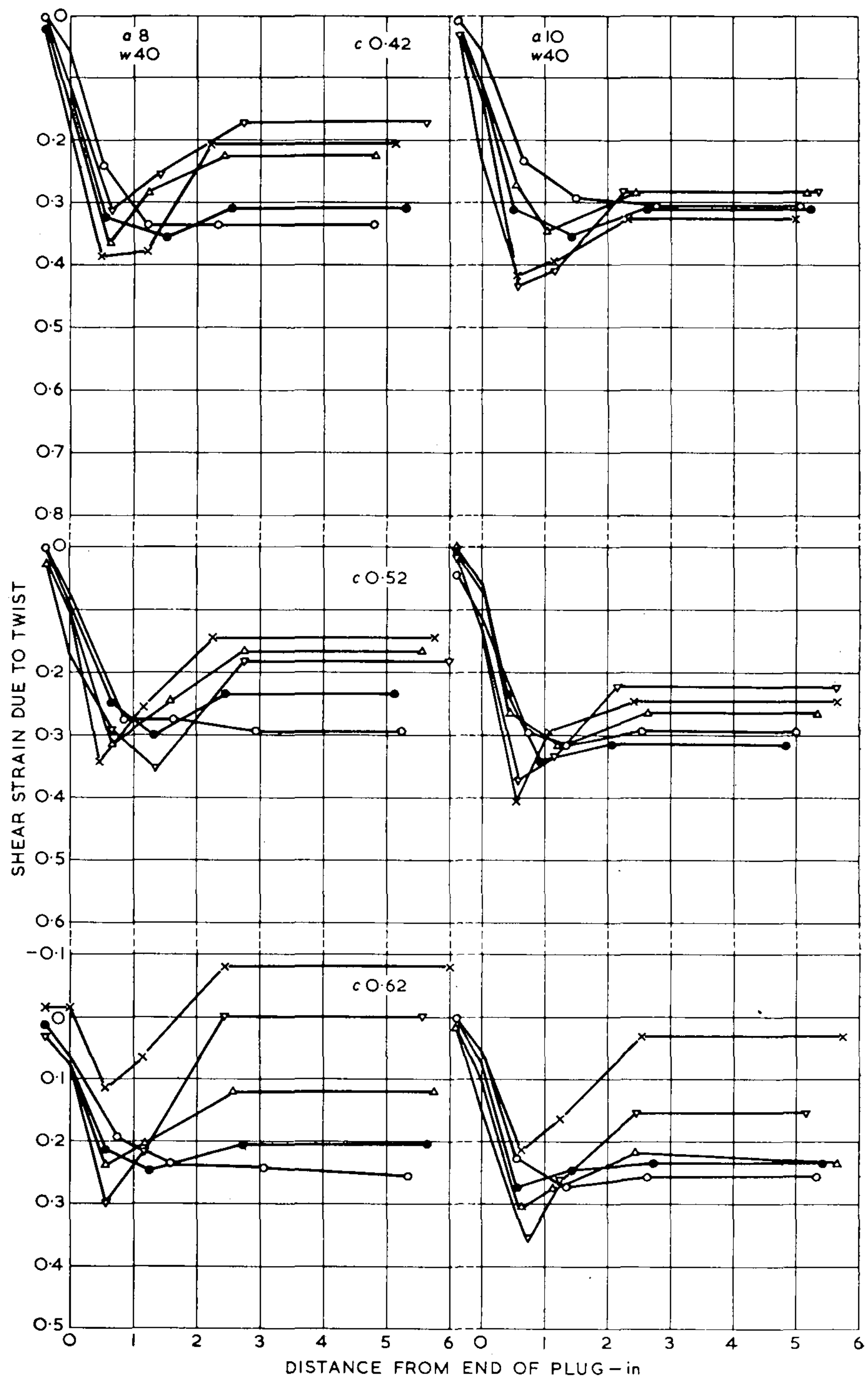

a 12
w 40
c 0·42
a 16
w 40
c 0·52
c 0·62
LONGITUDINAL SHEAR STRAIN
DISTANCE FROM END OF PLUG – in

*Fig. 14—contd.*




*a* roll inclination angle, degrees.
*b* ratio of billet diameter to gorge diameter.
*c* plug advance, in.
*w* roll speed, rev/min.
● *b* 1·05 ○ *b* 1·10 △ *b* 1·15 ▽ *b* 1·20 × *b* 1·25

*Fig. 15. Variation of shear strain due to twist along pass*

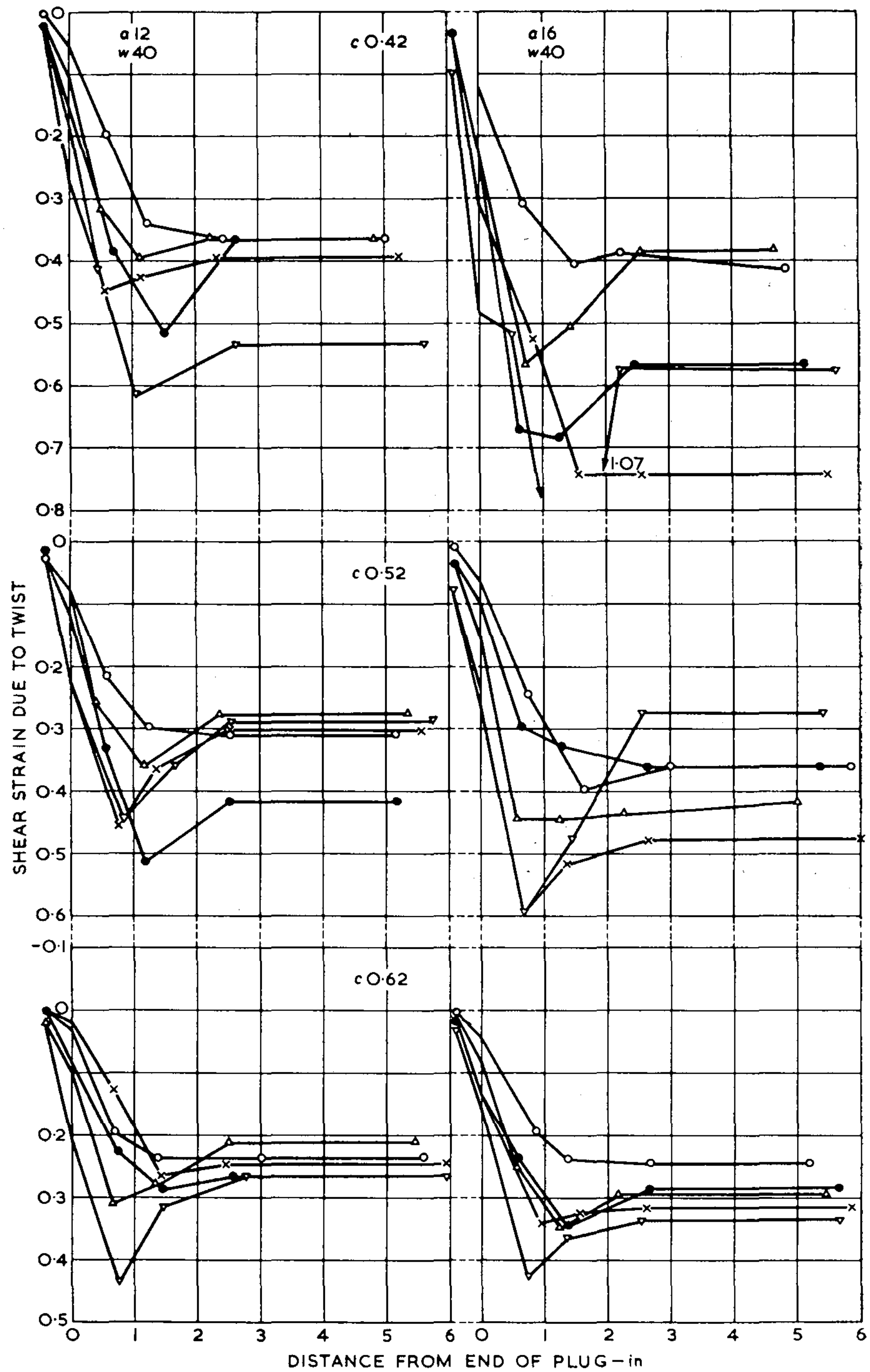
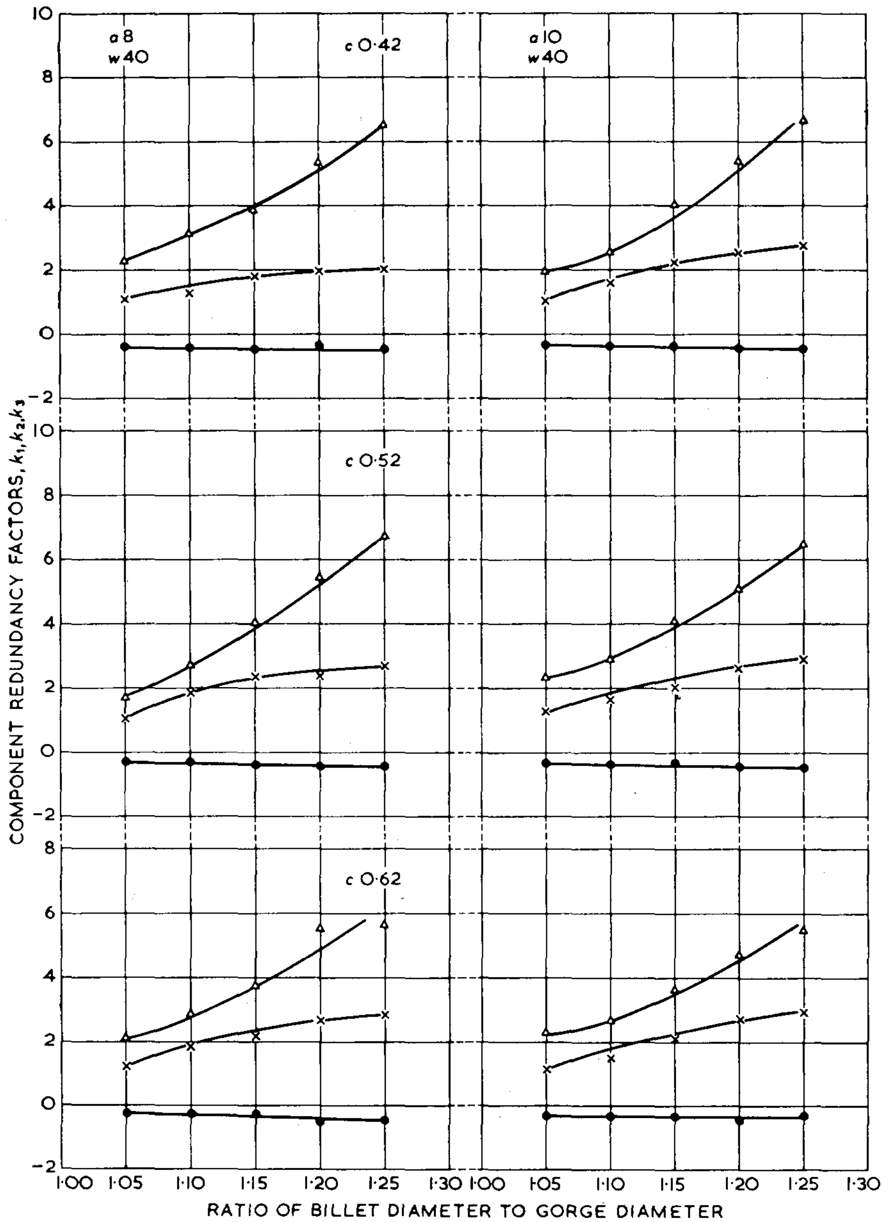

a 12
w 40
c 0·42
a 16
w 40
1·07
c 0·52
c 0·62
SHEAR STRAIN DUE TO TWIST
DISTANCE FROM END OF PLUG—in

*Fig. 15—contd.*




$a$ roll inclination angle, degrees.
$c$ plug advance, in.
$w$ roll speed, rev/min.
△ circumferential shear component redundancy factor $k_1$.
× longitudinal shear component redundancy factor $k_2$.
● component redundancy factor for shear due to twist $k_3$.

*Fig. 16. Variation of component redundancy factors with ratio of billet diameter to gorge diameter*

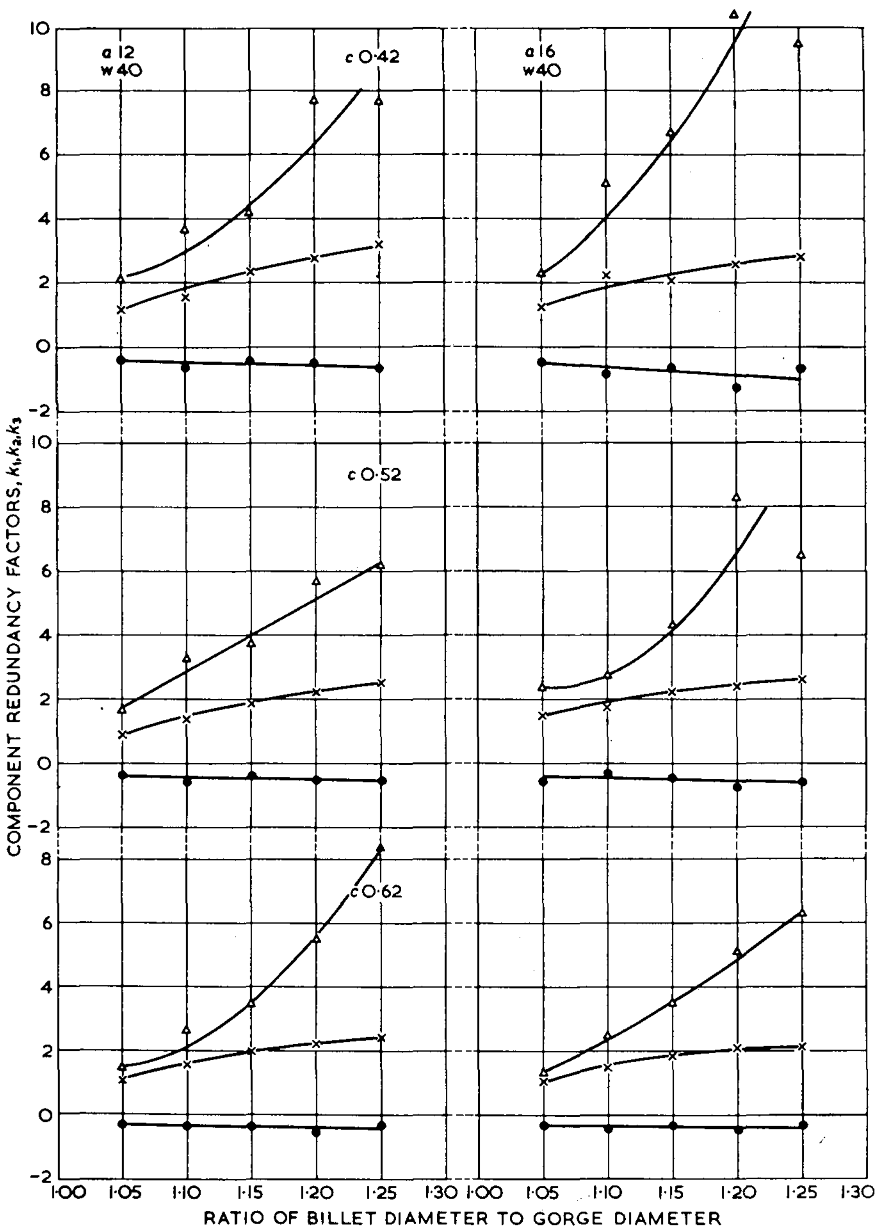
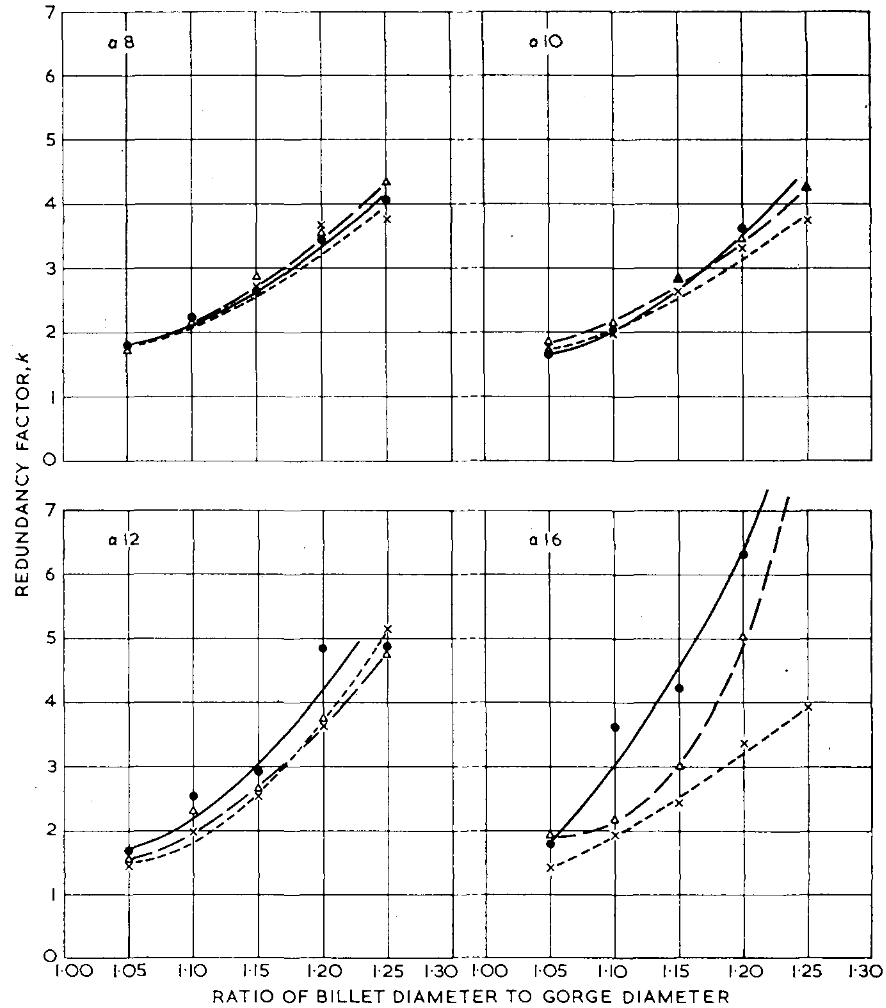
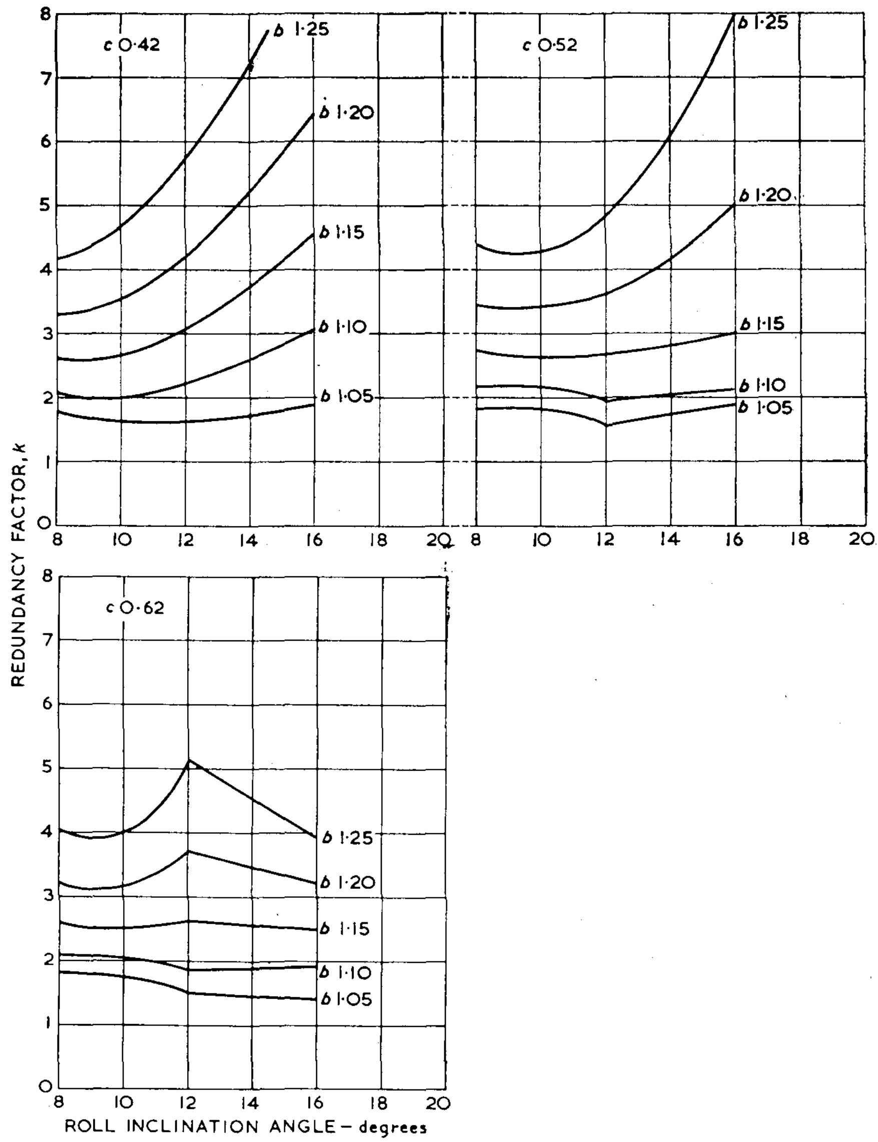

a 12
w 40
c 0·42
a 16
w 40
c 0·52
c 0·62
COMPONENT REDUNDANCY FACTORS, $k_1, k_2, k_3$
RATIO OF BILLET DIAMETER TO GORGE DIAMETER
10
8
6
4
2
0
−2
1·00
1·05
1·10
1·15
1·20
1·25
1·30

*Fig. 16—contd.*



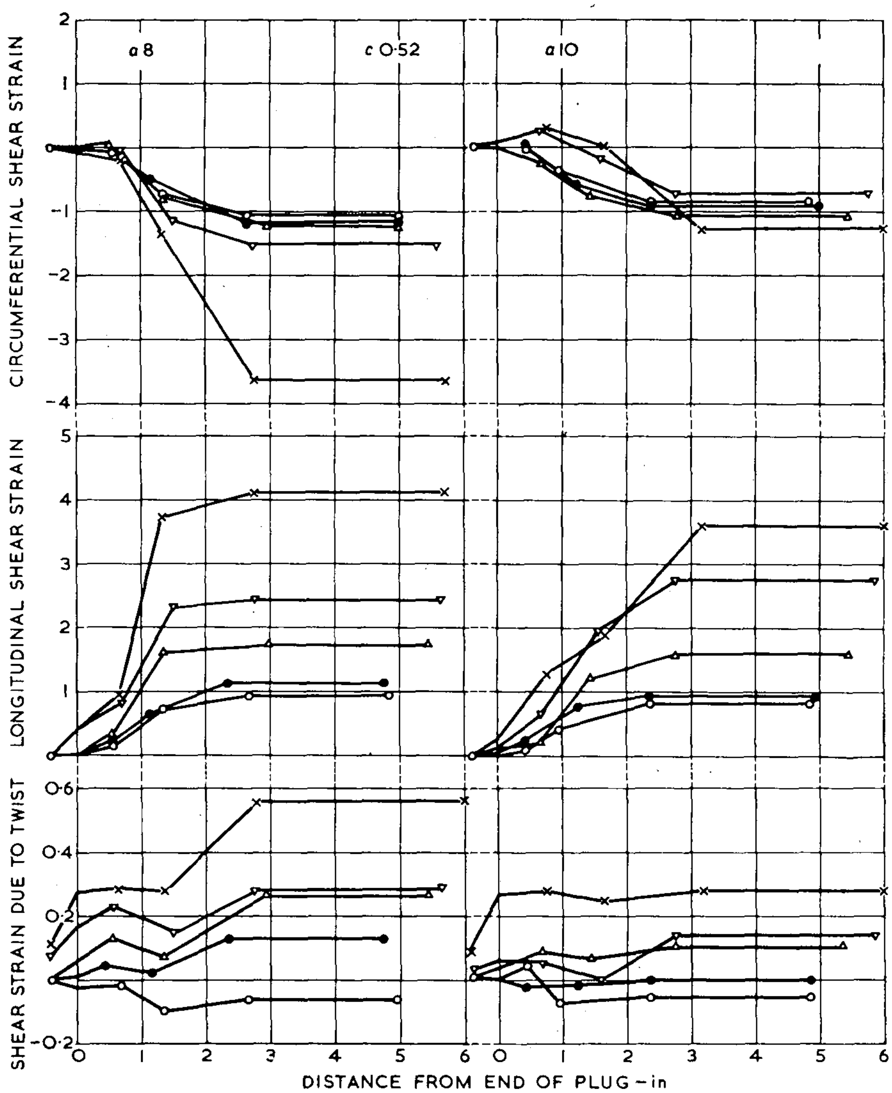

*a* roll inclination angle, degrees.
● ——— *c* 0·42.
△ — — — *c* 0·52.
× - - - - *c* 0·62.

*Fig. 17a. Variation of redundancy factors with ratio of billet diameter to gorge diameter*




*b* ratio of billet diameter to gorge diameter.
*c* plug advance, in.

*Fig. 17b. Variation of redundancy factors with roll inclination angle for constant 'b'*




*a* roll inclination angle, degrees.
*b* ratio of billet diameter to gorge diameter.
*c* plug advance, in.
○ *b* 1·05 ● *b* 1·10 △ *b* 1·15 ▽ *b* 1·20 × *b* 1·25

*Fig. 18. Variation of shear strain along pass*

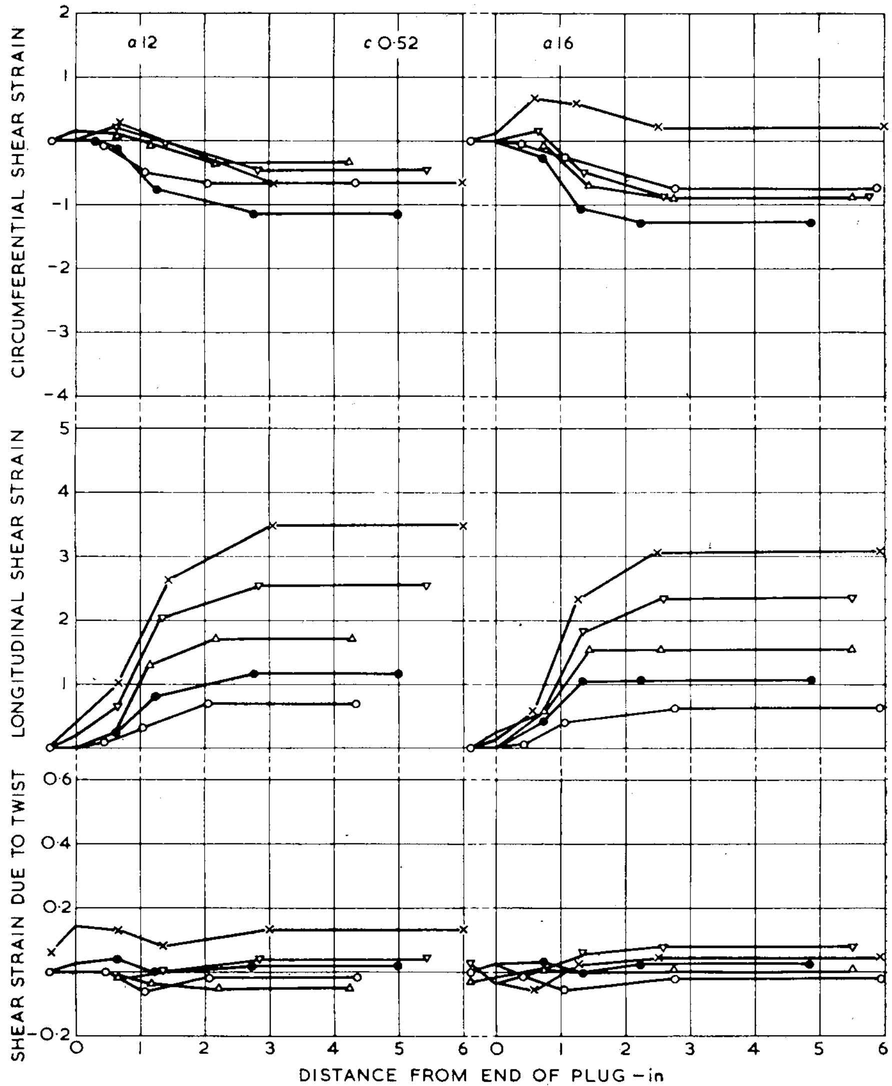
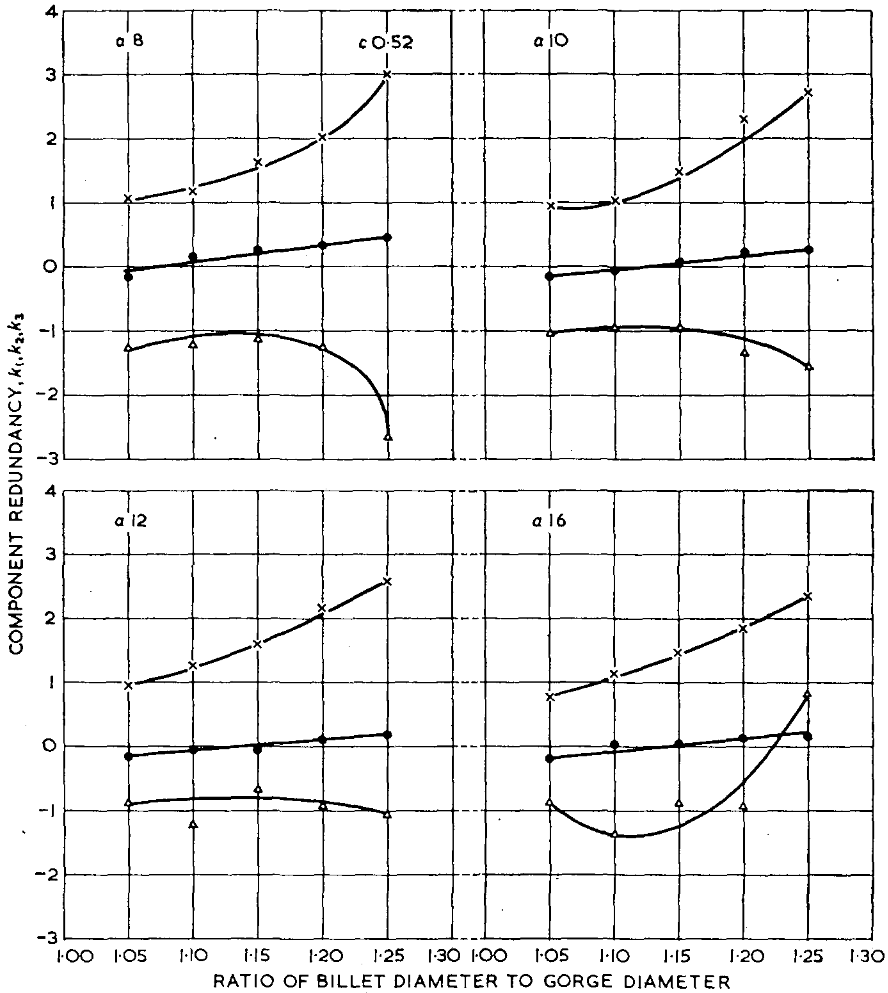

a 12
c 0·52
a 16
CIRCUMFERENTIAL SHEAR STRAIN
LONGITUDINAL SHEAR STRAIN
SHEAR STRAIN DUE TO TWIST
DISTANCE FROM END OF PLUG – in

*Fig. 18—contd.*




*a* roll inclination angle, degrees.

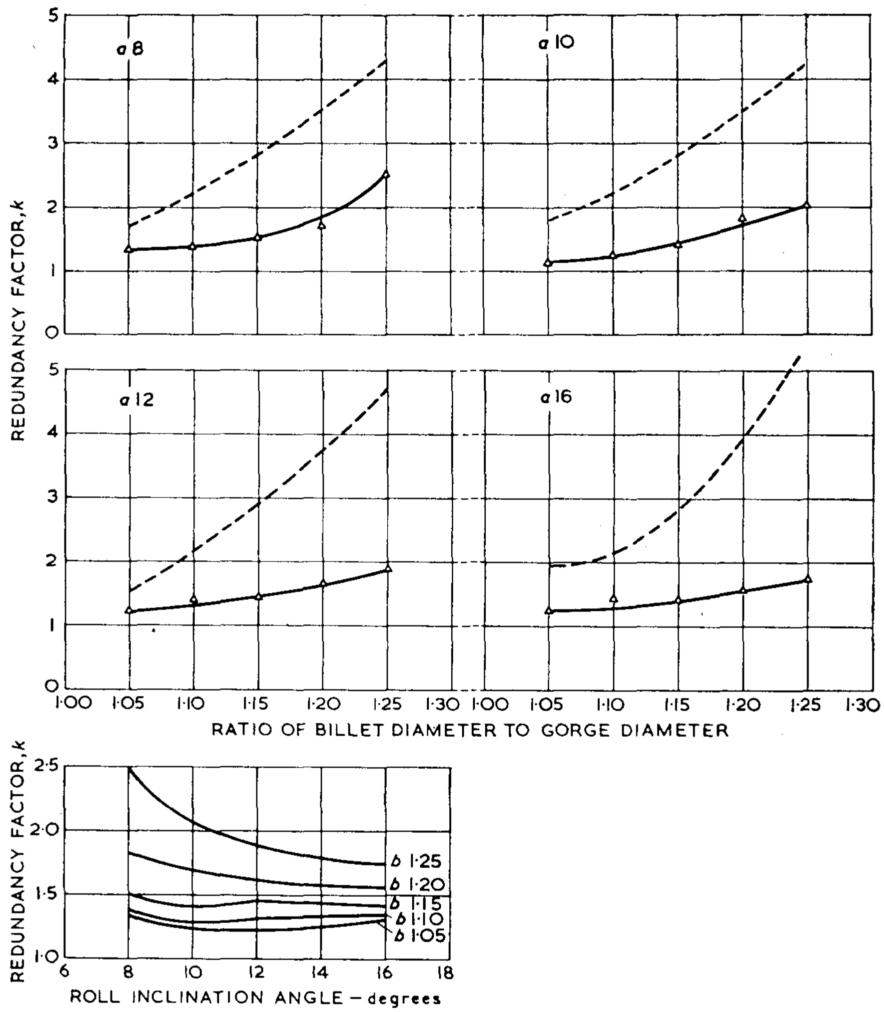
*c* plug advance, in.

△ circumferential shear component redundancy factor $k_1$.

× longitudinal shear component redundancy factor $k_2$.

● component redundancy factor for shear due to twist $k_3$.

*Fig. 19a. Variation of component redundancy factors with ratio of billet diameter to gorge diameter*




*b* ratio of billet diameter to gorge diameter.

△ ———— piercing with driven plug.

– – – – – – – piercing with freely rotating plug (see Fig. 7*a*).

*Fig. 19b. Variation of redundancy factors with ratio of billet diameter to gorge diameter and with roll inclination angle*

Considering the conditions when the plug is free to rotate one observes that for $a = 8°$ and $10°$ (Fig. 17*a*) the advance $c$ of the plug has very little influence on $K$ but that in both cases $c = 0{\cdot}62$ appears to be the best condition of piercing. For $a = 12°$ there is very little to choose between $c = 0{\cdot}52$ and $c = 0{\cdot}62$ but whereas the latter produces more favourable conditions as $b$ increases up to about 1·17, the former gives lower values of $K$ for higher values of $b$.

A direct comparison between the conditions when the plug bar is driven and those when it is free to rotate is afforded by Fig. 19*b* which shows that the advantage of driving the plug bar becomes greater for higher values of $b$, especially for $a = 12°$. In all cases, however, more desirable conditions of piercing are achieved when the plug is driven.

The optimum angle of roll inclination can be selected from Figs 17*b* and 19*b*. Fig. 17*b* shows that for constant $b$ the optimum conditions vary with the advance of the plug, and thus for $c = 0{\cdot}42$ they lie within the range of 8° for $b = 1{\cdot}25$ to 11° for $b = 1{\cdot}05$. For $c = 0{\cdot}52$ the optimum angle varies between 9° for $b = 1{\cdot}25$ and 10° for $b = 1{\cdot}15$ and remains constant at 12° for $b = 1{\cdot}10$ and 1·05. For $c = 0{\cdot}62$, if $a = 16°$ is neglected, the pattern of variation is similar to that for $c = 0{\cdot}52$. When the plug bar is driven the optimum angle can be found within the range of 16° for $b = 1{\cdot}25$ and 1·20 to 10° for $b = 1{\cdot}10$, with the exception of $b = 1{\cdot}15$ for which the best effect can be achieved by using a setting of either 10° or 16°. For $b = 1{\cdot}05$, $a = 12°$ appears to be the most desirable roll inclination angle.

In general, it should be realized that although improvements can be achieved by varying the mill settings they are of minor significance unless the plug bar is driven.

## CONCLUSIONS

The experiments with wax billets show that the redundant strains in rotary piercing on a two-roll barrel system are influenced by mill settings, and that their variation with changing rolling conditions can not be represented by means of any simple mathematical expression. Any considerations of these strains have to be based on graphical representation of their dependence upon the different variables; with the help of graphs certain general conclusions can be drawn. These are as follows.

The most important redundant strains are circumferential and longitudinal. Twist does not influence the redundancy of the process to any marked degree and for all practical purposes it can be neglected.

It is impossible to eliminate any of the redundant strains when the plug is free to rotate and only minor improvements in redundancy can be achieved by alteration of mill settings. The optimum conditions can be determined from consideration of the values of the redundancy factor $K$.

The roll inclination angle for the lowest total redundancy varies with the plug advance and to a limited extent, with the ratio of billet diameter to gorge diameter. Although an angle of 16° with a freely rotating plug appears favourable at a plug advance of 0·62, when judged by the redundancy of the process, the ridged surface produced by the rolls makes the use of this setting inadvisable.

The redundant deformation before the plug is negligible.

By driving the plug bar in the direction of rotation of the billet, it should be possible to find a range of ratios of billet diameter to gorge diameter for which circumferential strains would be approximately zero at a suitable plug-bar over-drive (less than 25 per cent of the theoretical rotational speed of the plug). By this technique the total redundancy of the process is considerably reduced.

Ovality was successfully controlled in these experiments by adjusting the guides. Eccentricity, usually appearing on the front part of the plug nose, was considerably corrected in the latter stages of rolling.

## ACKNOWLEDGEMENTS

The authors wish to thank Tube Investments Limited for permission to publish this paper and their colleague Mr D. Radford for his help with experimental investigations.

## APPENDIX I

### METHOD OF CORRECTING FOR THE INFLUENCE OF ESSENTIAL DEFORMATIONS ON REDUNDANT DEFORMATIONS

The need for correcting, if necessary, a measured quantity has already been discussed. The distortion occurring in any section will become magnified as one proceeds along the pass and consequently it is necessary, in adopting a method of correction, to consider an incremental procedure of calculation. Since the increments are small it is both convenient and justifiable to use engineering strains, provided that proper attention is paid to sign. In the following argument, $\epsilon_1$, $\epsilon_2$, and $\epsilon_3$ are engineering essential strains, longitudinal, radial, and tangential respectively.

*Longitudinal redundant strain*

With reference to Fig. 20 and considering an element of the bloom wall let us assume that as a result of longitudinal redundant deformation an initially vertical marker AB has become inclined

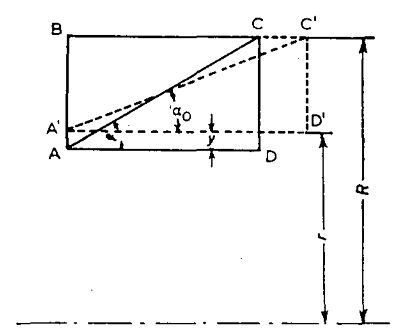



*Fig. 20*

at an angle $\alpha$ to the horizontal. $\alpha$ is then a measure of the longitudinal redundant deformation. When, however, essential deformations are superimposed on the element the change in dimensions will cause the marker AB to be inclined at an angle $\alpha_0$ to the horizontal and be coincident with line A′C′ in Fig. 20. The angle $\alpha_0$ will then be the angle actually measured.

Let $r$ be the inner radius of the bloom, $R$ the outer radius of the bloom, and $y$ the change in radius due to the change in shape of the element considered.

Then $R-r = L_2 \tan \alpha_0$ and $R-r+y = L_1 \tan \alpha$; $L_2/L_1 = \epsilon_1+1$ and hence

$$(\epsilon_1+1) = \frac{(R-r)\cot \alpha_0}{(R-r+y)\cot \alpha} \quad . \quad . \quad . \quad (18)$$

The essential radial strain is given by

$$\epsilon_2 = \frac{y}{R-r+y}$$

Substituting for $y$ in equation (18) and re-arranging one obtains

$$\cot \alpha = \frac{1-\epsilon_2}{1+\epsilon_1} \cot \alpha_0 \quad . \quad . \quad . \quad . \quad (19)$$

For incremental correction equation (19) becomes

$$\Delta \cot \alpha = \frac{1-\epsilon_2}{1+\epsilon_1} \Delta \cot \alpha_0 \quad . \quad . \quad . \quad (20)$$

where $\epsilon_1$ and $\epsilon_2$ are evaluated between two consecutive sections. Applying equation (20) to consecutive sections along the pass one arrives at the true value of the angle $\alpha$ which can then be used in a manner already discussed in equation (5).

*Circumferential redundant strain*

An apparent increase of the true angle will be observed. With reference to Fig. 21 let the angle required for the calculation of the circumferential redundant strain (equation (17)) be denoted for simplicity as $\theta$ and the angle actually measured be $\phi$; let the cross-sectional area of the element before the application of essential deformations be $A_1$ and after the change of shape be $A_2$. Since the change of shape does not imply any change in volume

$$A_1 = (1+\epsilon_1)A_2 \quad . \quad . \quad . \quad . \quad (21)$$

Hence

$$R^2\theta-(r-y)^2\theta = (1+\epsilon_1)(R^2\phi-r^2\phi) \quad . \quad . \quad (22)$$

The essential tangential strain is given by

$$\epsilon_3 = \frac{(R+r-y)\theta-(R+r)\phi}{(R+r-y)\theta} \quad . \quad . \quad . \quad (23)$$

Substituting for $y$ from equation (23) into equation (22) and re-arranging one obtains

$$\theta = \frac{(R+r)}{2R(1-\epsilon_3)-(1+\epsilon_1)(1-\epsilon_3)^2(R-r)}\phi \quad . \quad (24)$$

For incremental correction equation (24) becomes, say

$$\Delta\theta = c\,\Delta\phi \quad . \quad . \quad . \quad . \quad . \quad (25)$$

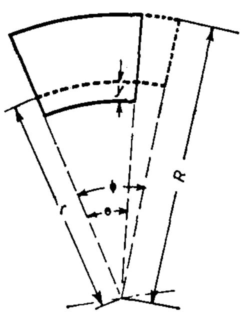



*Fig. 21*

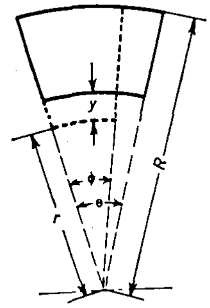



*Fig. 22*

Again the essential strains will be evaluated between consecutive sections of the billet.

*Redundant strain due to twist*

An apparent reduction of the true angle will be observed. With reference to Fig. 22 let $\theta$ be the angle required in equation (6a) and $\phi$ be the angle actually measured. Then, with the same notation as in the section on circumferential strain, the constancy of volume gives

$$R^2\theta-(r+y)^2\theta = (1+\epsilon_1)(R^2-r^2)\phi \quad . \quad . \quad (26)$$

The essential radial strain is given by

$$\epsilon_2 = \frac{y}{R-r-y} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

Substituting for $y$ in equation (26) and re-arranging one obtains

$$\theta = \frac{(1+\epsilon_1)(1-\epsilon_1)^2(R+r)}{R(1-2\epsilon_2)+r}\phi \quad . \quad . \quad . \quad (28)$$

and again for incremental corrections equation (28) will be given by, say

$$\Delta\theta = c\,\Delta\phi \quad . \quad . \quad . \quad . \quad . \quad (29)$$

## APPENDIX II

### REFERENCES

(1) Siebel, R. 'Grundsätzliche Betrachtungen zum Schrägwalzverfahren', *Stahl u. Eisen, Düsseldorf* 1927 **47**, 1685.
(2) Plyatskovsky, O. A. and Pishchikov, C. P. 'Preventing the occurrence of premature cavitation in the piercing of high-alloy steels', *Stal* 1952 No. 4, 330 (in Russian).
(3) Teterin, P. K. and Luzin, Yu. F. 'Mechanism of metal fracture during transverse rolling', *Stal* 1960 No. 10, 930 (in Russian).
(4) Holmquist, J. L. 'Investigation of the piercing process by means of model wax billets', *Iron Steel Engr* 1952 **29** (December), 53.
(5) Snee, C. E. 'Use of the modern Assel mill in production of seamless tubing', *Iron Steel Engr* 1956 **33** (October), 124.
(6) Bodsworth, C. *et al.* 'The use of paraffin wax as a model material to simulate the plastic deformation of metals', *J. Iron St. Inst.* 1957 **185**, 375.
(7) Davis, E. A. 'Increase of stress with permanent strain and stress–strain relations in the plastic state for copper under combined stresses', *Trans. Amer. Soc. mech. Engrs* 1943 **65**, A-187.
(8) Roš, M. and Eichinger, A. 'Weitere Versuche zur Klärung der Frage der Bruchgefahr', *Proc. 3rd International Congr. appl. Mech.* 1930 **2**, 254.
(9) Holmquist, J. L. 1957 U.S. Patent No. 2 780 119.