PLANAR VARIATIONS IN NORMAL ANISOTROPY IN MILD STEEL STRIP

by

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SUMMARY

After a short discussion on the significance of planar variations of normal anisotropy, ('R' value) and associated earing in mild steels, the published literature on the subject has been reviewed. Previous work on earing formation in deep drawing was broadly divided into the macroscopic and crystallographic approaches. The control of earing potential in mild steels was studied with reference to process variables such as hot finishing temperature, coiling temperature, cold reduction, annealing conditions and composition. Finally, the testing methods available for earing measurement were assessed.

Several important points emerged from the literature survey to form the basis for subsequent experimental work. Firstly, it was apparent that there was a need for an accurate earing test, simulative of the deep drawing operation. A test originally proposed for aluminium, was examined as to its suitability for mild steels, and various parameters, such as test piece dimensions, tool geometry, lubrication, were evaluated. A test specification was developed and used in subsequent experimental work. Secondly, the relationship between planar variations of normal anisotropy and earing behaviour required a quantitative assessment. Thirdly, there was a need for a statistical evaluation of earing tendency across the width, and along the length of commercially produced mild steel coils.

Material from three sources was examined and the main conclusions were:-

(a) the planar variations of 'R' value correlated well with the profiles of deep drawn cups. However, the correlation became much more significant when 'R' values determined in tension in a radial direction within the sheet, were considered in relation to the circumferential hoop stress that creates earing in a typical deep drawn blank. This was particularly important for rimming steels.

(b) Although there were certain trends of variation, earing was relatively uniform across the width and along the length of typical coils, except at the ends, and, in the case of rimming steels, the extreme edges.

(c) The variation in earing was greater between coils of nominally the same composition and process history, than within a given coil.

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"Anisotropy in sheet metal can arise from three sources: internal stresses, mechanical fibering, and crystallographic texture. Anisotropy arising from these different sources is displayed in different ways. Internal stresses and mechanical fibering produce more or less isolated anisotropic effects. The Bauschinger effect and low transverse ductility are the principal manifestations of anisotropy arising from these two sources, respectively.

Anisotropy arising from crystallographic texture is characterized by different elastic moduli and flow strengths in different directions in the metal. Consequently, for a highly textured material the stress strain curves corresponding to different test directions are not coincident. This behaviour is not a rare occurrence. In fact, it is difficult to produce a sheet metal that does not exhibit this behaviour to some degree. ------ A material having these differences in the plane of the sheet would be expected to form ears, i.e. a scalloped edge, if drawn into a cylindrical cup. It is this manifestation of crystallographic anisotropy that is most generally recognized".

R.L.Whiteley.(1)

INTRODUCTION

A material that exhibits unequal properties when tested in different directions is said to be anisotropic. Planar variation in the anisotropy of sheet is best seen as the waviness, or "earing", of the rim of deep drawn cylindrical cups. This feature is usually undesirable in deep drawn articles, which are normally required to have a perfectly flat rim before further processing can be performed. A trimming operation is therefore necessary, plus a scrap allowance on the original blank size, which must be large enough to ensure the required cup height after trimming. An industrial application of this is shown in Fig.1. With pronounced earing, production difficulties are likely to arise with the stripping of cups from the punch during the return stroke. This may lead to jamming, particularly with continuous forming operations, as the ears are likely to become more pronounced on redrawing. Less obvious than the waviness of the cup profile, but equally prevalent, is the variation in the cup wall, as it is viewed down the drawing axis. This again, if excessive, and punch/die clearances are low, may lead to jamming or excessive tool wear.

Although the degree of earing found in any deep drawing operation is influenced by tooling geometry, the dominant factor upon which earing depends is the anisotropy of the sheet material. This preferred orientation in the strip

1	2	3	4	5	6
Blank & Cup	Face	Pierce location holes	Pierce pockets	Pierce bore	Form wings

Fig. 1(a) Sequence of operations in the manufacture of a roller bearing cage

Fig. 1(b) First and second operations, illustrating the necessity for a trimming operation is due to the production of texture during fabrication, since, like wire, it is inevitably highly textured as a consequence of the directional nature of the processing. Intermediate or subsequent annealing treatment may tend to randomise this texture, but this is not always so. More often the heat treatment, essential for softening the material, may introduce a new texture, or accentuate the one already present. As a result, most sheet metals possess a distinct texture, and hence exhibit a distinct anisotropy.

Many workers have investigated the influence of process variables on textures and associated earing characteristics, but the information obtained has often been a by product of investigations upon drawability.(2,3,4). Again, much more work has been carried out on the textures, associated mechanical properties, and earing behaviour of the non-ferrous metals.(5) It has been pointed out also,(6,7) that there is very little information generally available on the variation of mechanical properties and textures along the length, or across the width, of commercially produced strip.

Most of the work on earing has been conducted with cylindrical cups. Firstly because the geometry and forces involved are more uniform and the assessment is relatively simple, and secondly because the conditions under which many components are manufactured can be directly simulated. With the increasing tendency to produce such articles continuously from coils of strip, there is a need for a standardised earing test. Factors such as tooling geometry, blankholder pressures and lubrication need thorough investigation. The effect of these variables on the earing of aluminium has been investigated by several workers,(8,9,10,) and a standardised earing test for aluminium proposed.(11) One of the objects of this programme was to examine the suitability of the test for mild steel.

The research programme undertaken therefore investigated to what extent mechanical properties can be correlated with earing tendency of steel sheet; and the reproducibility, or otherwise, of earing across the width and along the length of commercially produced coils of strip, and between sheets of nominally the same chemical composition and process history.

SECTION 2. LITERATURE SURVEY

2.1. The deep drawing operation, and development of theories of earing information

The force dstribution in deep drawing leading to earing in anisotropic sheet is illustrated in fig.2. In the flange of a developing cup is a circumferential compressive stress (y) which is at its maximum at the periphery of the blank, decreasing towards the die throat, and being replaced by a radial drawing force (x) which is zero at the periphery of the blank, and a maximum at the die throat. The compressive or hoop stress could lead to buckling of the sheet, but a blankholder pressure, acting at right angles to the sheet surface (z) is usually applied to suppress this wrinkling. The material then accommodates the reduction in blank circumference, by thickening. This blankholder pressure is of secondary importance, since ears tend to form even when it is absent. Its influence on earing measurement is discussed later in section 2.3.1.

The fundamentals of the deep drawing process can be simplified by neglecting this thickening. The deformation in the flange can then be considered as plane strain, since there is no change in thickness (in the z direction, $d\epsilon_z = 0$), but changes in the x and y directions, under radial tensile and circumferential compressive stresses respectively. This is illustrated in the reference element (fig.2), shown before

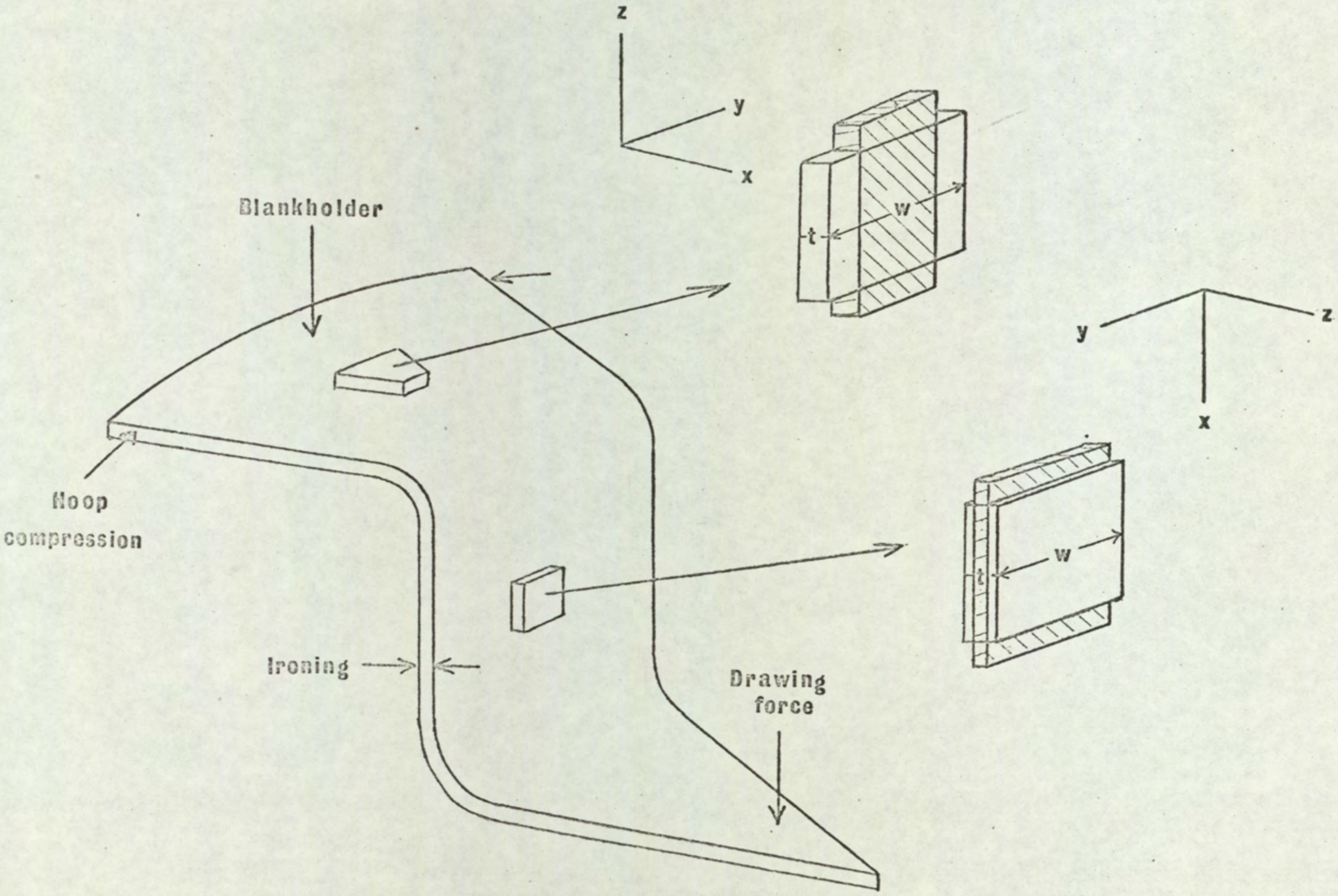
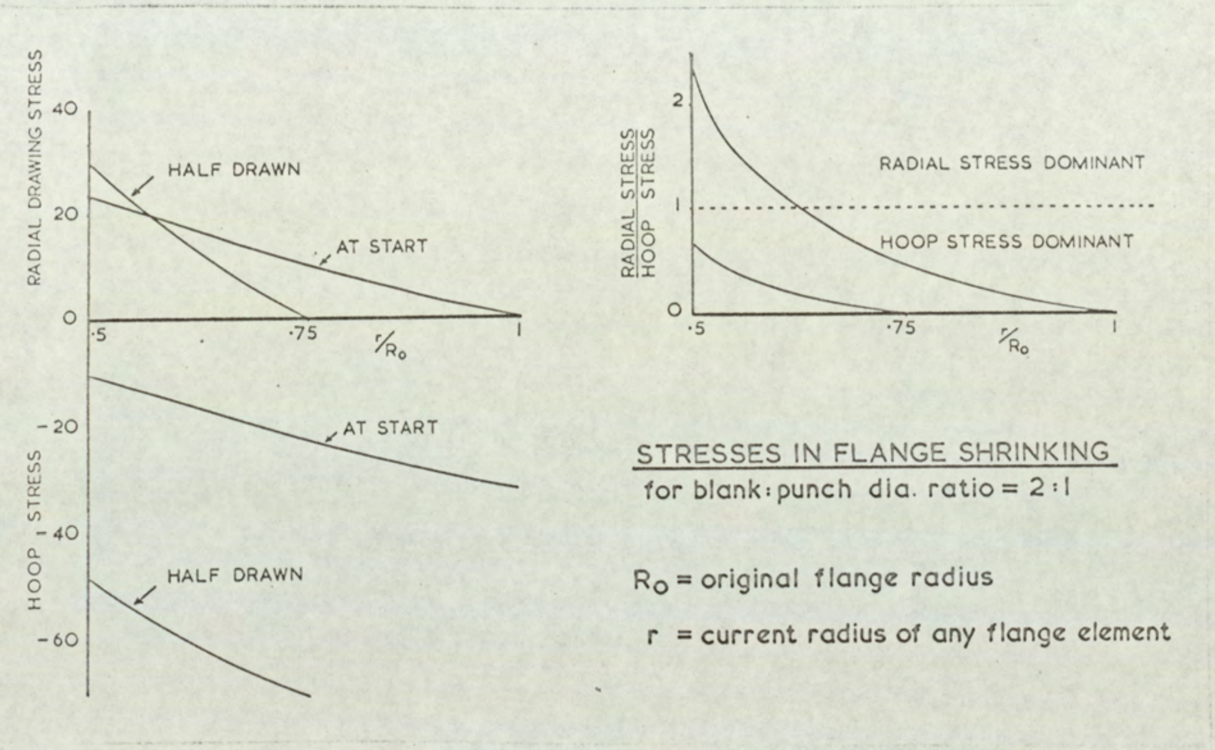


Fig. 2. Stress distribution in deep drawing.

(unshaded) and after (shaded) strain. In the cup wall, plane strain conditions are more nearly realised, since the rigid punch prevents changes in the circumferential direction ($d\epsilon_y = 0$). Stresses are now tensile in both the x and z directions, and drawing failure usually occurs over the punch nose radius by necking in the through-thickness, or z direction. The implications of this are discussed later.

The distribution of the circumferential or hoop stress, and the radial drawing force have been calculated by Chung and Swift.(12) (Appendix A.), Figure 3, derived by Wright(13) from Chung and Swift's work shows, after allowance for friction, the relative magnitude of these forces in an annealed mild steel blank with a drawing ratio of 2.0. It also shows that the ratio of radial stress to circumferential stress, varies from 0 at the rim of the blank to approximately 2.3 just before the rim of the die. Thus in the outer regions of the flange where earing first shows itself, the circumferential stress is dominant.

If, however, the sheet is not isotropic, then it is likely to exhibit different flow strengths in the plane of the sheet, leading to earing in the drawing process. The forces operating on similar segments of the original blank are the same, and each segment may be assumed to deform without change in volume. If the segment has a crystallographic arrangement with respect to the forces operating,



STRESSES IN FLANGE SHRINKING
for blank : punch dia. ratio = 2 : 1

R_o = original flange radius

r = current radius of any flange element

Fig. 3. Relative stress magnitudes in flange shrinking (Wright).

that will lead to a relatively small strain in the radial direction (x), it will tend to form a trough in the final cup profile. The material will also show a relatively large thickness strain in the (z) direction in order to maintain constant volume. A segment which showed a larger radial strain in the outer flange region will tend to form an ear.

Attempts to analyse anisotropy in sheet materials, as evidenced by earing behaviour, can be broadly divided into (a) a macroscopic approach, by examining the influence of various mechanical properties, and (b) a crystallographic approach. In both approaches, a cup drawing test of the Swift type has been employed to correlate the findings with directly observable earing behaviour.

2.1.1. The macroscopic approach to earing behaviour

The macroscopic explanation of earing behaviour, in terms of the influence of mechanical properties, has been one of continual evolution. The earlier attempts were only partially successful, mainly because of over-simplification of the deformation process involved.

Cook and Richards (14) carried out an analysis with copper having a complete cube texture, (100) [001], and showed good agreement between minimum true stress and elongation, and ears occurring at 0 and 90° to the rolling direction.

Phillips and Dunkle (15) confirmed these findings with tough pitch copper, annealed at high temperatures after heavy reductions, which showed a maximum elongation at the 45° direction, but developed ears at 0 and 90°. On the other hand, the same workers found with mild steel that the greatest earing tendencies were found in material with a maximum strength and minimum elongation at 45°, but that the ears again occurred at 0 and 90° to the rolling direction. This anomaly was explained on the grounds that two different lattices were involved. They also found that the material showing the maximum differences in tensile properties within a given strip does not necessarily develop the highest ears. The steel rolled 40% prior to annealing gave the maximum directional variations, but developed ears only one third as high as in the material rolled 69%; and at 45° instead of 0 and 90° to the rolling direction.

Baldwin, Howald and Ross (16) pointed out that the lack of success in completely explaining earing behaviour was not surprising, in that ears are due to anisotropy in the rates of deformation of the metal in the radial, circumferential and "thickness" directions of the original blank. Thus it was not feasible to expect correlation with tensile strength and total elongation, which are attributes of metal rupture.

By considering the triaxial deformation involved, Baldwin et al, were able to show that a distinct relationship existed between σ , a function of width and thickness strain at different angles to the rolling direction, and ear height of copper. They showed that the values of σ were a maximum at 0 and 90° for material that eared at 0 and 90°, and likewise were a maximum at 45° for strip with ears at 45°.

Other workers(17) in the 1945-50 period were actively engaged investigating triaxial deformation effects in press forming operations. The work was mainly directed to understanding and improving the drawability of materials. However, considerable data relevant to earing behaviour was a by product of the investigations. It is therefore proposed to briefly outline the background of this work.

Plastic anisotropy - 'R' ratio

Referring again to fig.2, and the mechanism of the deep drawing process. Failure of the cup occurs when the metal at some zone in the wall, usually over the punch nose radius, can no longer support the punch load required to draw in the remainder of the flange. Thinning in the (z) direction occurs, followed ultimately by failure. Therefore any material property which strengthens the sheet preferentially in this (z) direction should be advantageous in the deep drawing process.

A convenient measure of the properties in the thickness of the sheet is the plastic strain ratio, R. This can be defined as the ratio of width strain to thickness strain of a test specimen strained to a given extension in a uniaxial tensile test. Various techniques for obtaining 'R' values are discussed later in section 2.3.2. Usually, however, by assuming constant volume relationships during the test, width and length measurements are substituted for width and thickness measurements. Then

$$R = \frac{\ln \frac{w_0}{w_1}}{\ln \frac{w_1 l_1}{w_0 l_0}}$$

For an isotropic material, the flow strengths are the same in the x, y and z directions, and the strain ratio = 1 at all angles to the rolling direction. Increasing the normal anisotropy of the material a) increases the resistance to thinning in the cup wall, and b) decreases the resistance to flow in the flange of the cup, in deep drawing. Both these features are advantageous in improving the drawability. Lankford, Snyder and Baucher (17) showed with automobile components, made in aluminium killed steels, that material which gave unsatisfactory press performance had lower R values in the longitudinal direction than satisfactory material.

Whiteley, Wise and Blickwede (18) developed this work; showing the relationship between drawability, as measured in the Swift cupping test where drawing predominates, and normal plastic anisotropy, with a number of mild steels of both killed and rimming qualities. The drawing ratio increased linearly with increasing average R value, to give a coefficient correlation of 0.83. Since then other workers (19, 20) have confirmed the high correlation between the drawing ratio and average R value for mild steels, especially when using polythene lubrication to minimise frictional effects.(20) The relationship between drawability and average strain ratio has now been shown to apply to other sheet metals.(1,21) This is illustrated in fig.4.

When strain ratios are determined from tensile tests taken at different angles to the rolling direction, then if $R_0 = R_{45} = R_{90}$, only normal anisotropy is present. Such materials are not common. Usually $R_0 \neq R_{45} \neq R_{90}$, the normal anisotropy varying with the angle of testing, i.e. the material shows anisotropy in the plane of the sheet as well as normal to the sheet. It is this planar anisotropy that Baldwin et al,(16) showed to be related to earing.

Usually the anisotropy found in sheet metals is a combination of both normal and planar anisotropy, although it is more convenient to consider the two components of anisotropy separately. The expressions most commonly used are:-
Normal anisotropy $\bar{R} = \frac{1}{4}(R_0 + 2R_{45} + R_{90})$. A number of ways have been suggested for defining planar anisotropy. A convenient expression is $\Delta R = \frac{1}{2}(R_0 - 2R_{45} + R_{90})$. However the relationship $\frac{R_{0,\ 90} - R_{45}}{R\ (Av)}$ has been shown to be related to the earing behaviour of several metals(13,21) (fig.5.).

While a high value of normal anisotropy with associated

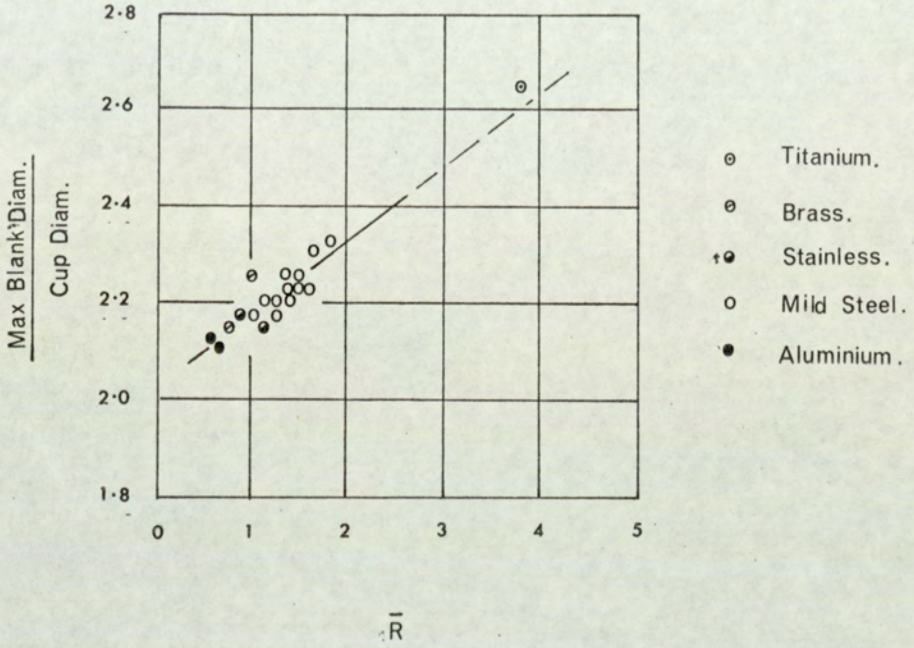


Fig. 4. Relationship between drawability, as evidenced by a cupping test of the Swift type, and average strain ratio. (after Whiteley).

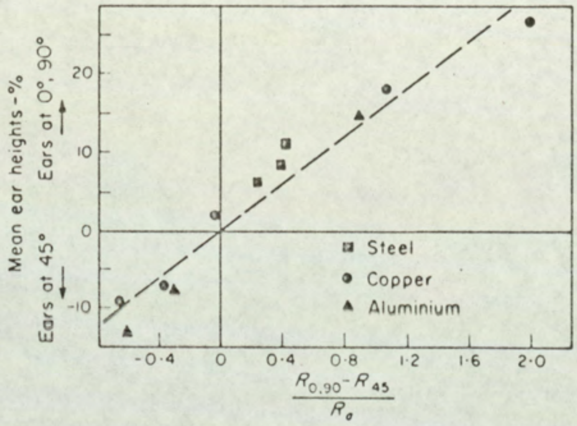


Fig. 5. Relationship between ear height and planar variations in normal anisotropy. (Wilson and Butler[21])

low planar anisotropy is desirable, it is not the only property that sheet must possess for successful forming. If the geometry of the component is such that some stretch forming is involved, then the level of strain at which plastic instability, or necking occurs, depends to some extent on the work hardening capacity of the metal.

Work hardening index - 'n' value

The work hardening capacity of a metal can be described in a number of ways, for example the yield - tensile ratio. The larger the difference between the yield point and ultimate tensile strength, the higher the work hardening capacity is said to be. This definition is not sufficiently precise,(17) largely because the tensile strength, as conventionally measured, is a fictitious stress. Also, the observed value of the yield point may be subject to variation due to differences in prior cold work, e.g. temper rolling.

A much more convenient parameter is the work hardening index of a metal 'n', in which there has been considerable interest in recent years.(17,19,22) The index is obtained in terms of true stresses and strains, by the relationship:-

$$\sigma = k \epsilon^{n}$$

where σ = true stress

K = strength coefficient

ϵ = true strain

n = work hardening index.

This relationship is generally applicable to low carbon steels for plastic strains in the range beginning just above the yield point elongation, up to maximum load. The various techniques for obtaining 'n' are discussed later.

In operations where some stretching is involved, significant correlations between 'n' and performance have been found. Lilet (19) found correlation of 0.658 with the Erichsen test. Most drawing operations involve a measure of stretch forming, and Lankford et al(17) suggested that a useful drawing performance factor would be R x n. Crane(23) confirmed that a correlation of 0.66, at a significance level of 1%, existed between R x 'n' and Erichsen limiting drawing ratio.

Several workers (24,25,26) have shown that 'n' is not a constant value, but varies with the test direction in relation to the rolling direction, in a manner analogous to Δ R.

Previous work on the relationship between earing and R and 'n'

Some of the earlier attempts to explain earing behaviour had included preferred orientation studies. Bourne and Hill(27) considered such attempts premature, since, for one thing it is not known how the operative glide system in an individual grain, is influenced by the constraint of neighbouring grains. These workers argued that a more practical approach was to measure the macroscopic properties of the anisotropic sheet in simple tests, and attempt to predict the behaviour in a more complex stress system. They concluded that only the plastic stress-strain properties which incorporate a) work hardening, and b) the relations between the ratios of the components of the stress and the plastic strain increment are of importance. In a simple deep drawing or cupping operation, the second property is likely to predominate in controlling the position of the ears. The relevant test, therefore, is the measurement of strain ratios at various angles to the rolling direction.

Following earlier work by Hill,(28) the hypothesis was suggested that ears develop at positions where the strain ratio, R, is a maximum for uniaxial stress in the circumferential direction. An alternative theory, supported by the experimental evidence of Baldwin et al,(16) was that ears form at positions where R is a maximum for uniaxial stress in the radial direction. Of the two relationships, the circumferential one can be most easily explained, if it is accepted that in a multi-slip system, such as exists in most cubic metals, strain ratios obtained from tension tests reflect strain ratios operating in compression. Since in deep drawing the dominant stress in the outer part of the flange is circumferential compression, high strain ratios, at right angles to the angle of testing, (i.e. transposed 90° to the circumferential position would reflect relatively large strains in the width of the specimen. This would correspond to an ear position. Conversely, low strain ratios at right angles to the angle of testing would reflect a smaller width strain, and correspond to a trough.

The experimental work of Bourne and Hill(27) with copper and brass, showed earing positions close to angles for which R was a maximum in radial tension, thus supporting the radial hypothesis of Baldwin et al(16) although Bourne and Hill could supply no theoretical explanation for this.

On the other hand, Wilson and Butler(21) found that some rimming steels and cube textured aluminium, which showed a marked difference in the R maxima in the directions parallel and transverse to the rolling direction; also developed a two fold symmetry in the ears, those in the 0° positions differing considerably in height from those at 90°. However the taller pair of ears lay in a direction which showed the lesser of the two R maxima in uniaxial tension. In other words, the heights of individual ears could be related to R values if the directions in which the latter were measured were referred to circumferential, rather than radial directions in the blank.

Other work,(24,25,26,29) that has been carried out on the relationships between planar variations of R and n, and earing of mild steels is qualitative, and in some cases inconclusive or even contradictory. Thus Pomey (24) broadly confirmed the findings of Wilson and Butler,(21) but the work of Lilet and Wybo,(25) summarised in fig.6, was too qualitative and insufficiently detailed to add significant support to either

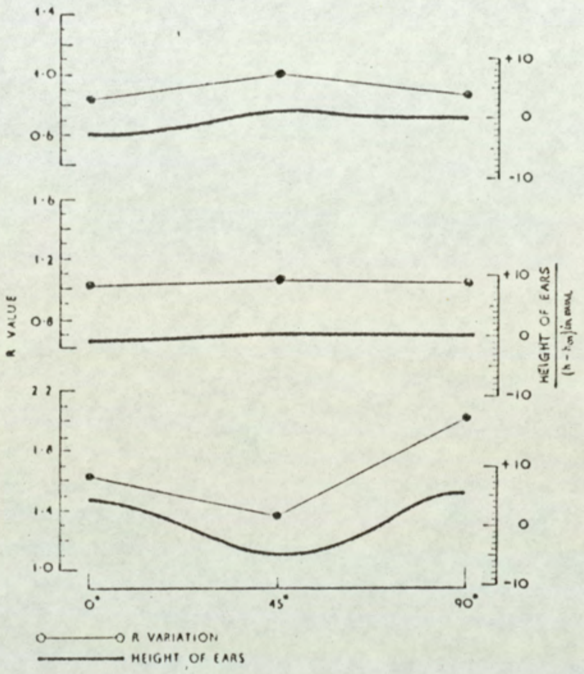


Fig. 6. Connection between the shape of the curve showing variation of R value and the location of earing. (Lilet and Wybo[25])

theory, although the lower set of two curves in fig.6. tends to support the radial position theory.

Basically three different forms of earing behaviour exist in mild steels, viz:-

(1) Cups exhibiting earing at 0° and 90° to the rolling direction. This is most commonly the case in commercially produced mild steels, and is accompanied by a minimum R value at 45°.

(2) Cup profiles showing earing at 45°, when the variations of R pass through a maximum at 45°.

(3) More rarely, cups showing a fairly uniform profile and associated uniform R.

The various factors leading to these different forms of earing in mild steels are discussed in section 2.2.2. Pomey and Grumbach (26) showed graphically the relationship between planar variations of R and ear position for the above three forms of earing behaviour, and confirmed that planar variations in n show a similar relationship with ear position. Pomey(24) found that the relative variations of n were considerably smaller than those of R. $\frac{\Delta n}{\bar{n}}$ was of the order of 0.05 to 0.1 while $\frac{\Delta R}{\bar{R}}$ was frequently between 0.2 and 0.9 in extra deep drawing quality mild steel sheet.

It therefore appears accepted that R value varies with cup height in relation to the angle of testing, and that n shows a similar type of relationship. Considerable uncertainty exists however, as to whether cup profile correlates most accurately with R values obtained from tensile tests taken radially to the rolling direction, or with R values transposed to a tangential or circumferential position relative to the angle of testing. Wilson(30) has pointed out that this is almost certainly a consequence of the failure to take into account the crystallographic nature of deformation, although the macroscopic approach can provide useful approximations in cases of practical interest. He suggested that further experimental work, aimed at defining the limits of its accuracy in particular cases is needed.

2.1.2. Crystallographic approach to earing

Some of the earlier work relating earing with textures, particularly in non-ferrous metals, has been reviewed by Underwood.(5) Much of the accumulated data has been utilised in arriving at production conditions which result in a texture balance, and associated low earing characteristics. This is discussed in section 2.2. However, up to the present time, no serious theoretical analysis relating texture and earing directly has yet appeared, although several useful associations have been reported.

Burghoff and Bohlen(31) observed that the $\{111\}$ pole figures for samples of α brass, giving cups with four ears at 45°, and six ears at 0° and 60° to the rolling direction, had four and six areas respectively of dense pole population around the periphery. In the former case these areas were in the rolling direction and at 90° to it, and in the latter case they were at 30° and 90° to the rolling direction.

Wilson and Brick(32) also found with brass that ears occurred in directions remote from peripheral concentrations of $\{111\}$ poles.

With mild steels much of the work relating earing to preferred orientations has emerged as a by product of studies into deep drawability and associated normal anisotropy. By a simple analysis, Burns and Heyer(2) showed how a cube-on-corner texture, where the cube diagonal, or strongest direction, is oriented normal to the sheet, should be a favourable texture for high strain ratios. Conversely, a cube on face texture, with the weakest crystal direction $[100]$ oriented normal to the sheet, should be unfavourable for high strain ratios. They also produced pole figure data, showing that aluminium killed sheets, with high strain ratios, did have a pronounced cube-on-corner texture.

Whiteley and Wise(3) took this work a stage further, and by means of inverse pole figure techniques, measured the relativ intensities of cube-on-corner, cube-on-edge, and cube-on-face textures with material cold reduced differing amounts. Relationships between earing and processing variables such as amount of cold reduction (fig.7) were also established.

Thus, at reductions between about 25% and 90%, ears

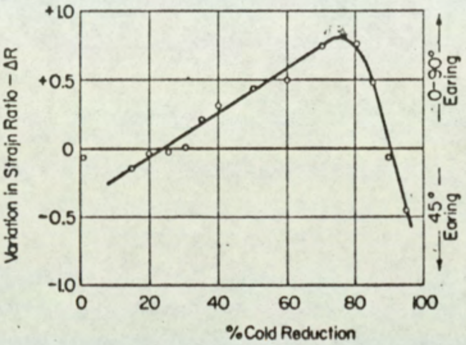


Fig. 7. Effect of cold reduction prior to annealing on the earing behaviour of a rimming steel. (Whiteley and Wise[3])

develop at 0° and 90°, but below and above these reductions ears are formed at 45° to the rolling direction. Dilamore and Roberts(33) have pointed out that comparing this data with the pole figures at different amounts of cold reduction obtained by Heyer et al,(29) indicates that 0° and 90° earing corresponds to textures containing components of {110} ⟨001⟩ and a spread about {111} ⟨110⟩ . Earing at 45° corresponds to a texture consisting of major {100} ⟨012⟩ components.

In recent work, Angeli, Crussard et al(34) are reported (24) to have established that ears occur at positions where the density of the ⟨100⟩ axes is most intense. From the distribution of ⟨100⟩ axes, and measurement of deformation during the deep drawing of a cup, these workers deduced a mechanism of formation of ears for steels with principal orientations (100) ⟨011⟩ and (110) ⟨001⟩ . The position of ears depends on the proportions of these two orientations, calculated by the density of axes at 0° and 45°, the first giving ears at 45°, and the second at 0° and 90° to the rolling direction.

In a more fundamental approach, Tucker(35) working with single crystals of aluminium of a number of different orientations, predicted earing behaviour quite accurately. His analysis involved a number of simplifying assumptions, and by adapting these to suit body centred cubic metals, Vieth and Whiteley (36) investigated different orientations of iron single crystals. They found that the cube-on-corner orientation seemed to produce the least amount of earing or planar anisotropy.

Thus although the relationships between earing and preferred orientations in mild steel are still not fully understood and theoretically explained, certain crystallographic requirements for deep drawing mild steel can be defined.(37) These are a high density of $\{111\}$ $\langle 110 \rangle$ and $\{111\}$ $\langle 112 \rangle$, bringing about a high $\bar{R}$ value, and relatively small $\triangle R$ value. On the other hand, a higher density of $\{100\}$ $\langle 011 \rangle$ and $\{110\}$ $\langle 001 \rangle$ leads to a lower $\bar{R}$ and a larger $\triangle R$ value.

2.2. Formation and control of earing in commercially produced materials

Roberts(6) has reviewed the variables affecting the textures found in sheet metals, dividing them into material and process variables. In commercial practice, textures giving acceptable levels of earing are achieved by balancing certain production variables. The ease with which this can be achieved varies from metal to metal.

2.2.1. Non-ferrous metals

Generally, close packed hexagonal metals tend to develop pronounced textures more readily than either body or face centred cubic metals, because of the small number of slip systems available. With commercial purity zinc strip, the preferred orientations in both the cold worked and annealed conditions were found to be similar,(38) with (0001) poles oriented in the rolling direction, at about 65° to the plane of the strip. Both annealed strip and material rolled in one direction, exhibited pronounced 0° and 180° earing, but cups drawn from cross rolled zinc strip, showed four smaller ears, at 0° and 90° to the rolling direction. By cross rolling, with reductions of 15%, material was produced with an almost random structure, which was virtually free of earing. Evans et al(39) have reported the earing behaviour of some other non-cubic metals such as uranium and plutonium.

The earing behaviour of copper, aluminium and their alloys has been reviewed by Underwood.(5) The control of earing in copper can be achieved by balancing the amounts of "cube" and "rolling" texture. If the penultimate reduction is small, followed by a high final reduction, then cube texture [100] (001), predominates in the final annealed strip, giving ears at 0° and 90° to the rolling direction. Baldwin(40) showed that there is an approximately linear relationship between the heights of the 0° and 90° ears and the percentage of cube texture.

However, if the penultimate reduction is high followed by a small reduction, the cube texture is in a more metastable condition, and after final annealing, the recrystallisation texture will be largely of the "retained rolling" type [110] (001), with ears forming at 45° to the rolling direction. By selection of suitable material gauges, rolling schedules and annealing treatments it is therefore possible to achieve a "balanced" texture, giving essentially flat topped cups. The actual amount of cube texture required to produce a "balanced" texture is of the order of 10 to 20%. Cook and Richards(41) showed that a final rolling reduction of between 25 and 50%, after a high temperature intermediate anneal, followed by a relatively low temperature final anneal, was conducive to the production of material with low earing characteristics.

Yen(42) investigated the effect of annealing temperatures, and found that with increasing final annealing temperature, the ear position could be changed from 45° to 0° and 90° at about 230° C. The heights of these ears then increased with annealing temperature up to about 540° C, but then decreased, with the earing reverting to the 45° type at about 870° C. The increase and decrease of the 0° and 90° ears was accompanied by a rise and fall in the amount of cube texture.

Annealing temperature has also been found to have a pronounced effect upon the earing of brass. Generally the height of the ears increases with increase in final annealing temperature, and decreases with the temperature of final interstage annealing. Increases in the penultimate and final rolling reductions are found to increase the heights of the ears. Cook and Richards(43) concluded that a large initial grain size was conducive to the production of rolled and annealed strip with low earing behaviour.

The most common type of earing in brass is associated with an annealing texture, similar to the rolling texture $(110)[\bar{1}12]$ (32). This produces four ears at 45° to the rolling direction. A variation of this texture produces six ears at 0°, 60° and 120° to the rolling direction.

The earing behaviour of aluminium and its alloys is extremely complex, being influenced by the whole range of material and processing variables. Wright (13) has reviewed the effect of these variables, and considers that earing may be regarded as a continuous variable, ranging from high ears at 45° to the rolling direction, until at low levels of 45° earing, additional small ears at 90° appear. These increase in magnitude as the 45° ears disappear. Variations in fabrication procedure favour either the 45° or 90° earing behaviour, depending upon whether they support a rolling or annealing texture.

2.2.2. Mild steel

In the commercial production of deep drawing quality mild steel, process conditions are primarily adjusted to yield as high a value of normal anisotropy as possible. At the same time certain production variables must be balanced to give acceptable levels of planar anisotropy. These two requirements are not always compatible.

Thus in achieving consistent $\bar{R}$ values, processing must be controlled to maximise the $\{111\}$ component and minimise other components such as the $\{100\}$. The important variables are by now well appreciated. These are:-

(a) Hot finishing temperature
(b) Coiling temperature
(c) Cold reduction
(d) Annealing conditions
(e) Composition

The effects of these variables on earing behaviour, are as follows, although it is often difficult to divorce completely earing behaviour, as revealed by planar anisotropy, from deep drawing performance, as revealed by normal anisotropy.

Hot finishing temperature

Hot rolling, carried out in the austenite region, is followed by the transformation, producing a metal essentially without preferred orientation. If the rolling is continued into the region, unfavourable orientations for a high normal anisotropy are produced.

When considering the effect upon earing behaviour, it has been observed(44) that a low finishing temperature results in a product with pronounced planar anisotropy. Whiteley and Wise,(3) again using amount of cold reduction as the controlling variable, showed that the situation was more complex. Figs. 8 and 9 show their findings for rimmed and aluminium killed steels respectively. The effect of lowering the finishing temperature was to depress the entire level of the R curve, which became more pronounced as the finishing temperature decreased below 1450° F (790° C). In lowering

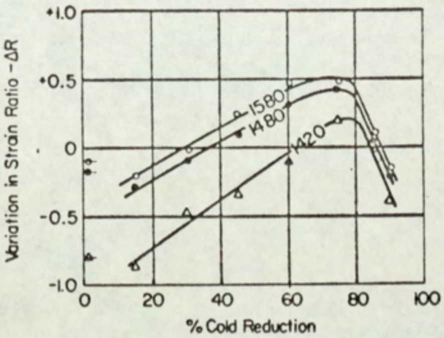


Fig. 8. Variation in ΔR as a function of prior cold reduction, for a rimming steel finished at the temperatures (^{o}F) shown. (Whiteley and Wise[3])

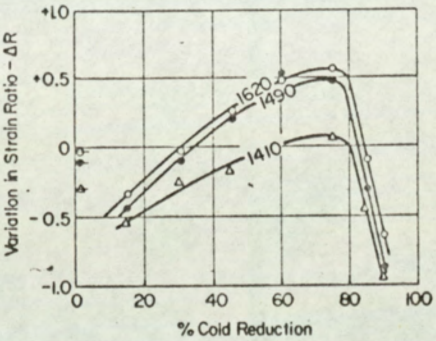


Fig. 9. Variation in ΔR as a function of prior cold reduction for an aluminium killed steel finished at the temperatures (^{o}F) shown. (Whiteley and Wise[3])

the $\triangle R$ curve, the range of cold reductions producing 0° and 90° earing, i.e. with positive $\triangle R$ values, was reduced, while the range of cold reductions that produce 45° earing was extended. Whiteley and Wise suggested that eventually 45° earing would be produced for all levels of cold reduction, if the finishing temperature was below 1400° F (760° C). From their experimental data, they proposed the interrelation between finishing temperature and amount of cold reduction necessary to produce non-earing characteristics in both rimming and aluminium killed steels, (Fig.10). However it is likely that other factors such as coiling temperature, will have some effect on earing behaviour of certain mild steels.

Coiling temperature

Whiteley, Wise and Blickwede(18) reported on the effect of hot mill coiling temperatures on the average R values for aluminium killed steels, coiled at temperatures between 1070°F (570°C) and about 1275°F (690°C). They observed that the $\bar{R}$ value increased as the coiling temperature was lowered. In the case of rimming steels(3), coiling temperature had little effect on $\bar{R}$, provided the finishing rolling temperature was high. The difference in behaviour between stabilised and rimming steels is generally attributed to the precipitation of aluminium nitride in the former. The hot coiled stabilised material will precipitate most of the aluminium from solution as aluminium nitride. The cold coiled material, having cooled rapidly before coiling, will have retained much of the aluminium

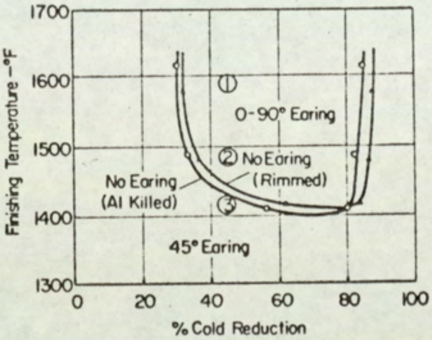


Fig. 10. Relationship between finishing temperature and cold reduction likely to produce non-earing behaviour in rimming and aluminium killed steels. (Whiteley and Wise[3])

in solution.

Whiteley and Wise(3) reported that planar anisotropy in both aluminium killed and rimming steels, was not affected to any marked degree by coiling temperature. On the other hand, Atkinson et al,(4) working with stabilised steels, while confirming that the normal plastic anisotropy was lowered by raising the coiling temperature, found that planar anisotropy was lowered also.

Cold Reduction

The amount of cold reduction was the controlling variable used in their investigations by Whiteley and Wise(3) and Atkinson et al.(4) This major variable has a marked effect not only on normal anisotropy but also on planar anisotropy. Besides influencing the amount of earing produced, cold reduction affects the position at which ears are formed in relation to the rolling direction, as indicated in section 2.1.2. For reductions below about 25% ears are formed at 45°, increasing in magnitude as amount of cold reduction decreases. Between about 25% and 90% cold reduction ears are produced at 0° and 90°, increasing in size up to about 75% cold reduction, and then decreasing to zero at about 90% reduction. Above this figure, ears again occur at 45° increasing in magnitude as the amount of cold reduction is further increased. The critical reductions to ensure absence of earing are necessarily arbitrary, as other factors such as composition and annealing conditions have an affect.

Annealing conditions

After cold reduction, the sheet is annealed to bring about recrystallisation and ensure adequate ductility for subsequent forming. The cold rolled and annealed steel sheet is then usually temper rolled, i.e. given a final cold reduction of about 2%, to improve surface finish and retard the return of a yield point during any subsequent strain ageing. Crane(23) has reported that ageing has some influence on planar variations of normal anisotropy.

The batch annealing cycle following cold reduction typically consists of(45):-

(1) Slow heating up to a peak temperature of 680 - 700°C

(2) Prolonged soaking, dependant upon coil size, at temperature.

(3) Slow cooling down to the stripping temperature of about 130° C.

With the very slow heating rates used, recrystallisation occurs in the range 550 - 600° C. The resulting grain size is not, however, sufficient to ensure adequate ductility. Prolonged soaking is therefore necessary to induce further grain growth. With stabilized steels, the desirable strain ratios obtainable are associated with the precipitation of aluminium nitride. Richards(46) has stated that the annealing cycle for this material must include a minimum period of about 2 hours between 500° C and the soaking temperature to ensure optimum strain ratios.

Slow cooling ensures maximum precipitation of carbon and nitrogen, and from a practial point of view, the elimination of quench ageing effects. Sufficiently low dissolved carbon contents can also be achieved, effectively eliminating strain ageing due to carbon. Higher nitrogen solubility levels prevent the complete elimination of strain ageing unless a strong nitride former, such as aluminium in stabilised steels, is present. Work on open coil annealing has shown that greater than normal ageing tendencies are found in E.D.D. rimming and stabilised steels when the total cooling period is reduced to about 16 hours.

Against this background of rigid metallurgical requirements in the annealing treatment, there appears little opportunity for independently influencing earing characteristics. However, Matsudo(37) showed that certain annealing conditions did affect earing behaviour. His main conclusions were: (a) Planar anisotropy in aluminium killed steels hardly varied at heating rates of 500 ~ 240°C/hour. A sudden increase in planar anisotropy occurred at rates of 240~180°C/hour, becoming almost constant again below 50°C/hour. With rimming steels, no effect on planar anisotropy was found by varying the heating rate. (b) Soaking time at the annealing temperature increased planar anisotropy when heating had been at the rate of 500 ~ 240°C/hour. There was hardly any effect at other cooling rates. (c) Soaking at a sub-recrystallisation temperature of 500° C, followed by rapid heating (500° C/hour) to the annealing temperature not only improved normal anisotropy as indicated by Richards, but also decreased ear height and altered ear position, yielding six ears.

The annealing treatment may also be utilised to bring about transformations in the steel sheet, partly by modifying steel compositions.

Composition

The precipitation of a new phase before or during annealing may change the final texture, provided that this precipitation does not take place before cold rolling. This essentially accounts for the differences in normal and planar anisotropy between stabilised and rimming steels.

The rapid cooling to a low coiling temperature of hot rolled aluminium killed stabilised steels effectively retains much of the aluminium in solution, to be precipitated later as aluminium nitride. It has been suggested that the aluminium inhibits the recovery process, which would normally occur during the slow heating involved in box annealing, and thus recrystallisation nuclei in the same orientation as the hot rolled metal do not have any particular growth advantage. If a recrystallisation texture similar to the rolling texture were formed, this would lead to material with low $\overline{R}$. In the absence of recovery, the growth rate of new grains is governed by the formation and growth of nuclei favoured for growth into the various components of the deformation texture, leading to recrystallisation textures with a strong cube-on-corner component, and associated high $\overline{R}$ value.

On the other hand, a high $\overline{R}$ is not obtained when rate of heating to the annealing temperature is rapid. Richards has suggested that for optimum $\overline{R}$ in a stabilised steel, recovery at 450 - 500° C should take place before recrystallisation, and that the heating rate around this temperature should be very low in order to allow time for recrystallisation to occur.

Although there is some uncertainty on the exact mechanism of the aluminium precipitation, the characteristic recrystallised microstructure of stabilised steels is of elongated or pancake grains. Elements other than aluminium can bring about the precipitation effect. Leslie(48) showed that copper additions caused the precipitation of ϵ phase during soaking at 500° C, resulting in elongated or pancake grains. However, Whiteley and Wise(49) found difficulty in consistently reproducing the desired structure with copper additions. This pancake structure was formerly thought to be the reason for the superior deep drawing properties of stabilised steels. More recently greater importance has been attached to the associated textures produced by precipitation effects when using addition elements.

Stabilised steels have certain economic and technical drawbacks, such as low ingot yield and relatively high planar anisotropy, compared with rimming steels. This had led to considerable development with rimming steels. For example, small additions of copper, phosphorus and antimony(50,51,52) have all been shown to improve the normal anisotropy of rimming steels and reduce the planar anisotropy. Unfortunately, at the normal carbon and nitrogen levels found in this type of steel, the work hardening coefficient is reduced by these additions, and phosphorus(52) also tends to cause embrittlement.

However when used in conjunction with decarburising and denitriding annealing treatments, by open coil annealing in wet hydrogen, the improvements in normal and planar anisotropy are achieved, without the deleterious effects on work hardening. Currently, interest is being shown in the use of copper bearing low carbon steels, with significantly reduced planar anisotropy,(52,53) although this work has not yet been translated into full scale commercial production

2.2.3. Variation of earing potential in commerially produced mild steels

Very little information is available in the published literature on variation of earing in commercially produced materials. Atkinson et al(4) have pointed out that planar plastic anisotropy is usually the unavoidable adjunct of normal plastic anisotropy, and that planar anisotropy is developed to the greatest extent in materials which show the most pronounced normal anisotropy.

Whiteley and Wise(3) showed that the effect of mill variables on planar anisotropy closely parallels their effect on normal anisotropy.

Thus the practices most likely to produce non-earing behaviour are not consistent with the attainment of good drawability.

If the generalisation that planar anisotropy will vary proportionally with normal anisotropy is accepted, then some qualitative evidence of earing variation in commercial steels is available. Wilson and Butler(21) showed how R values, in the rolling direction, varied across three wide deep drawing quality rimming steel sheets. As might be expected, the maximum variation occurred towards the edges. Crane,(23) investigating the variation of mechanical properties including $\overline{R}$ across the width of steel sheets, reported that the properties in the major central portion of the width were quite uniform. There was, however, a small but definite change in properties at the edges, corresponding with the rim of the original ingot. This worker also reported that $\overline{R}$ value changed markedly at the one end of coils, probably due to variations in rolling speeds, coil temperature, etc.

Any transverse and longitudinal variation in earing behaviour of coils would be of interest to a user simultaneously producing a number of small articles from wide strip. Often wide strip is slit into narrower widths to suit customer requirements. It is obviously desirable that earing potential, together with other parameters such as gauge and hardness, should be as constant as possible.

2.3. Test for measurement of earing

Willis and Blade(11) have pointed out the need for a standardised earing test, that meets the following requirements:

(a) Rapid sampling and testing.
(b) Minimum of sample preparation.
(c) Directly stimulates normal conditions of earing.
(d) Requires minimum of operator skill.
(e) Can be performed on wide range of testing equipment, with as many materials as possible.

Thus while the cupping test seems the logical answer, yielding information on both earing and drawability, other non-simulative tests have been used. For example, magnetometer tests have been used to determine anisotropy,(2,24) but the results are difficult to interpret quantitatively, and the test is only applicable to magnetic materials. The 'R' value test, originally developed to measure 'normal' anisotropy, can be used to determine planar anisotropy from tensile tests taken in the strip plane at different angles to the original rolling direction of the material. However for a routine test the method is probably too time consuming to be of general interest. The Knoop hardness test has been used,(61) but correlation with press shop behaviour has not been established. Tear length tests have been found to be too dependant upon the operator's technique. It is obviously very important that the test selected shall be as reproducible as possible, with minimum variation due to the operator. Thus the deep drawing cupping test has become widely accepted as a measure of both earing and drawability (8.21).

2.3.1. Simulative tests. The cupping test.

If cups are drawn from constant diameter blanks of sheet, then using a standard set of drawing tools, the ears produced will be a direct measure of the earing characteristics of the materials tested. On the other hand, cups drawn from blanks taken from the same sheet, but deep drawn using a variety of tooling dimensions and drawing conditions, will show different earing performance. It is therefore necessary to specify the test procedure for measuring earing potential. As discussed by Wright,(13) this can be achieved by three methods. In the first, cups of unknown earing behaviour could be drawn using any convenient hybrid tooling, and compared with similarly produced cups from standard sheets of known earing behaviour. Whilst attractive for its economy of test equipment, the test would require a wide range of consumable standards of differing gauge and composition. In the second method, tooling and test procedure is rigidly specified, so that results from one machine are only comparable with those obtained from a similar machine. This method is impractical because of the rigid control of so many variables.

The third method of testing, after examination of the relative importance of variables affecting an earing test, seeks to control them according to their influence upon the accuracy of the test, within practical specification limits; in order to produce a widely acceptable earing value from different machines. This appears to be the most logical approach to a standardised earing test. Such a test has been proposed for aluminium,(11) but requires examination as to its suitability for mild steels.

Several workers(8,9,10) have investigated the variables in cup drawing tests, Wright(10) concluding that with aluminium sheet, reduction ratio, and tool clearance compared with sheet thickness, were the most important factors. Punch geometry had a moderate influence, blankholder pressure, lubrication and die profile, while requiring some control, had relatively little effect on earing.

Influence of reduction ratio

Some disagrement exists over the most suitable definition of reduction or draw ratio, which can be expressed either as the ratio of blank diameter to punch diameter D.R.(p) or as the ratio of blank diameter to die diameter D.R.(d). Provided

that the thickness of the sheet, and thus the die clearance, is small compared with the punch diameter, the difference between the two ratios will also be small.

As materials of increasing thickness are tested, either the punch diametermust be reduced, or the die diameter increased, to accommodate the increased clearance that is necessary. It is therefore convenient to adopt the draw ratio convention that utilises the tool dimension which is held constant; but exactly comparable conditions are only achieved if the sheet thickness : punch diameter ratio is also kept constant, and tool sizes all varied in exact proportion. This would obviously lead to an infinite number of tool sets, and in a practical test some compromise is necessary.

The work of Siebel and Mack(9) indicates that it is preferable to vary the die diameter and keep the punch diameter constant, since this allows cups to be drawn with an almost constant mean height and trough height when the sheet thickness : punch diameter ratio varies from 1:150 to 1:12.

In contrast, when the punch diameter is altered, keeping the die diameter constant, the mean cup height is also altered. This latter method was advocated by Willis and Blade,(54) who claim that where earing is measured using the constant die dimensions and the D.R.(d) convention, more satisfactory extrapolation can be made between different gauges of the same material.

Percentage earing increases with reduction ratio or blank diameter. Blade and Pearson(8) found a direct linear relationship which extrapolated back to zero earing at a theoretical draw ratio of 1.0. (fig.11.). On the other hand, Wright(10) found that the percentage earing increased at a slightly accelerating rate with increasing reduction ratio (fig.12). Siebel and Mack(9) suggested that for aluminium, percentage earing, $E = n(D.R._{(d)} - 1)^X$ where X varied from 1.0 for recrystallised material to 1.5 for fully cold worked material.

Maximum sensitivity in an earing test would be achieved by drawing cups from as large a blank diameter as possible, Blade and Pearson(8) recommending a $D.R._{(d)}$ between 1.7 and 1.8. The difficulty lies in specifying a common blank diameter to give maximum sensitivity without ever exceeding the critical blank diameter of any material. This requires experimental determination for mild steel.

Influence of clearance

The second major variable to be controlled in an earing test is the clearance between the punch and walls of the die. When this is less than the thickness of material passing through, ironing takes place. Then a modified extrusion process occurs to reduce thickness of the cup wall to the clearance. If the initial thickness of the blank is more than the clearance, ironing occurs throughout the draw.

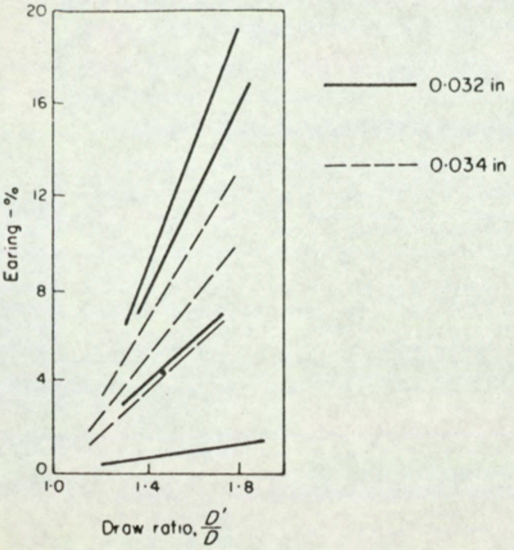


Fig. 11. Effect of reduction ratio on percentage earing of various aluminium sheets (Blade and Pearson).

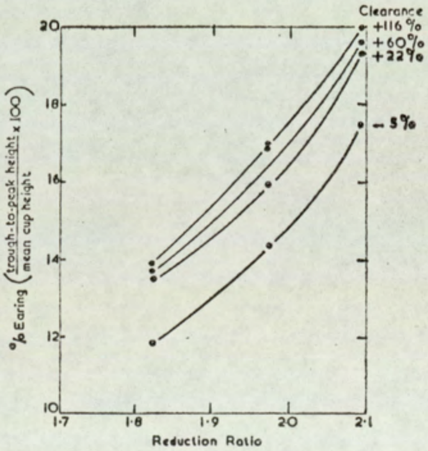


Fig. 12. Effect of reduction ratio on percentage earing of various aluminium sheets at different clearances (Wright).

In other cases the initial thickness of the blank may be smaller than the clearance, but towards the end of the draw the increasing thickening, brought about by the continually reducing blank periphery, may make the clearance inadequate in the upper walls of the cup.

The deep drawing of a cup from a circular blank involves a symmetrical pattern, and any wedge shaped segment will contain the same volume of material, after drawing, as any other segment of the same area. Thus a segment containing an ear will be thinner than one containing a trough. Therefore the thicker material under a trough will be the first area to suffer ironing as clearance decreases. Ironing then, tends to raise the troughs while the peaks remain comparatively untouched, decreasing the apparent ear height and percentage earing.

With increased clearance beyond the point at which no ironing occurs, the mean cup height and apparent percentage earing may again decrease. This may be due to the reduced tendency to stretch the blank over the punch nose, but is suggested to be mainly due to the tendency of the cup walls to thicken during drawing and barrel, or bulge outwards slightly, which could occur on stripping from the punch. The latter operation can also cause a splaying outwards of large ears, as the clearance between punch and die increases. Again, the last part of the flange to bend over the die radius, i.e. the ears, may remain splayed out, and not straighten as drawing is completed, if the clearance between punch and die is excessive. Fig.13 illustrated these effects on cups drawn from the same material, under identical drawing conditions, except for differences in clearance.

The optimum clearance depends upon the purpose for which the drawn cups are intended. For industrial applications, clearances of 10 - 20% are common, yielding a more uniformly walled cup. In an earing test the optimum clearance is that which gives the highest sensivity and accuracy of measurement, a clearance which avoids ironing, and yet is not so excessive as to allow barrelling of the cup or outward splaying of the ears during stripping. Blade and Pearson(8) recommended a clearance of 70%.

The draw ratio has some influence on the optimum clearance in that larger draw ratios require greater clearance because more extensive flange thickening occurs. Siebel and Mack(9) showed that the optimum clearance to avoid ironing also depended upon sheet thickness, t. With a draw ratio of 1.82 the optimum clearance for 0.50 m/m thick sheet was 1.7t; for 1.0 m/m sheet 1.5t, and for 2.0 m/m sheet 1.3t. These two workers produced an empirical formula to relate the influence of both sheet thickness and draw ratio on optimum clearance.

$$C = D.R_{(p)} - (D.R._{(p)} - 1.25)(20\alpha - 100\alpha^2)$$

where C is the factor by which the sheet thickness must be

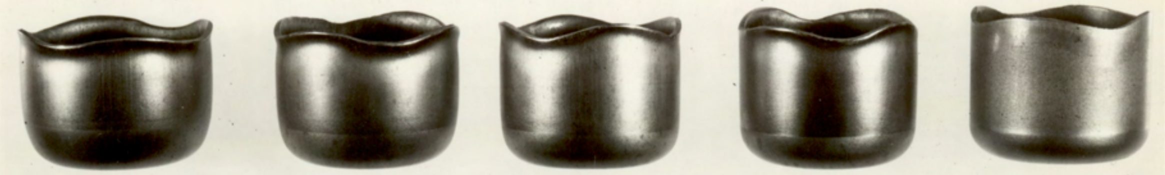


Fig. 13. Effect of clearance upon cup formation. Clearances, reading from left to right, are 134%, 92%, 50%, 29% and 8% respectively.

multiplied to determine optimum clearance, and α is the ratio strip thickness : punch diameter. This formula is applicable for sheet thickness : punch diameter ratios $<$ 1 :12 and draw ratios of $\sim$1.5 - 2.0.

Wright(10) investigated the effect of clearance for various reduction ratios using 0.036" super purity aluminium. His work showed that earing increases with clearance; very rapidly at negative and low clearances and progressively less with increasing clearance. This is shown in Fig.14. Beyond about 50% clearance further increases have negligible effect. On the other hand, he showed, fig.15, that earing can start to decrease again for reasons previously discussed.

It therefore appears that both ~~a~~minimum and maximum clearance needs to be specified in an earing test if a high degree of sensitivity and reproducibility is to be achieved. This clearance range must obviously be chosen from a practical viewpoint to avoid an excessive number of punches to accomodate slightly different sheet thicknesses. Wright(10) suggested a clearance of between 50 and 100%; the test under investigation,(11) adopts approximately the same clearance range.

Influence of tool geometry

Wright(10,13), extensively examined the effect of punch and die geometry. He concluded that compared with reduction ratio and clearance, punch geometry has only a moderate effect, and die geometry a minor effect on earing assessment in a

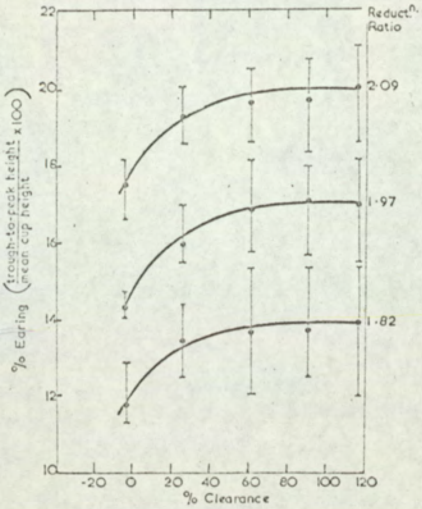


Fig. 14. Effect of percentage clearance between punch and die on percentage earing (Wright).

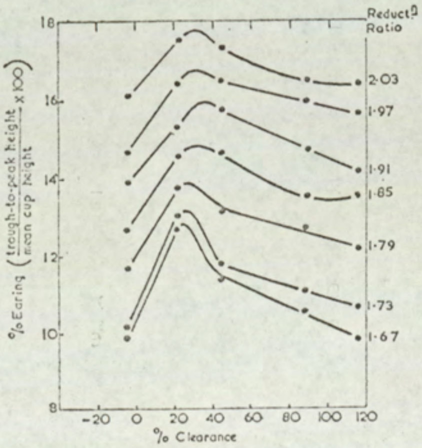


Fig. 15. Effect of percentage clearance between punch and die on percentage earing under difficult cup stripping conditions (Wright)

cupping test. He examined the effect of varying punch diameter between 24 and 32 mms, with both a constant punch nose radius of 4.5 mms, (fig.16) and a varying nose radius, such that the punch dia : nose radius ratio was constant at 7 : 1, (fig.17). His work with material 0.036" thick showed that provided the punch diameter : nose radius ratio is maintained constant at about 7 : 1, the effect of varying punch diameter around 28 to 33 mms is small. In the proposed earing test the punch diameters are in the approximate range of 32 to 39 mms. to accommodate material between 0.106 and 0.007" thick. Thus Wright's findings are of interest in assessing the proposed test specification, where the tooling dimensions give a punch diameter : nose radius ratio which varies between 5 : 1 for thicker material, to 13 : 1 for thinner gauges. The ratio with 0.036" in thick material is approximately 7.3 : 1.

The ideal punch nose radius was suggested by Willis and Blade(11) to be eight times the material thickness, although this may have to be reduced to accommodate thicker gauges without excessive stretch forming. In fact radii stipulated in the proposed test, range between 2.2 and 16.7 times the material thickness.

Punch geometry appears to need further investigation to clarify some of the above uncertainty.

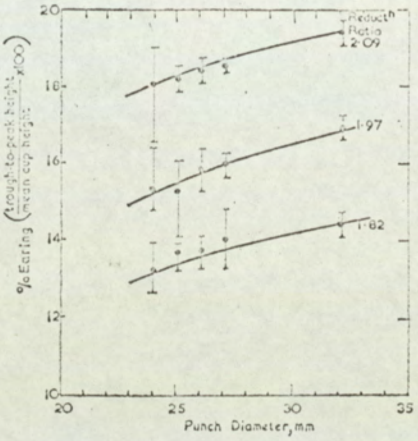


Fig. 16. Effect of punch diameter on percentage earing for three reduction ratios (Wright)

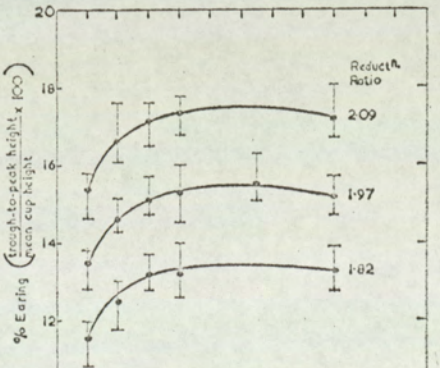


Fig. 17. Effect of punch diameter, with constant punch diameter: nose-radius ratio, on percentage earing (Wright)

Influence of blankholder pressure

During the drawing operation the circumference of the blank must continually shorten as the material is drawn into the die mouth. Assuming constancy of volume, this shortening must be accompanied by a) wrinkling or buckling, or b) thickening of the material flange. If the upper face of this flange is unconfined, the circumferential hoop stresses produced in the flange of the partially formed component may be of sufficient magnitude to force the material out of its original plane, producing a series of radially disposed waves or wrinkles. Once wrinkling has commenced, it is extremely difficult to eliminate, and can lead to splitting of the cup wall as the folds enter the gap between punch and die. It is known that(55, 56) certain materials are more prone to wrinkling than others, aluminium being particularly susceptible.

Geckeler(57) carried out a mathematical analysis into wrinkling behaviour, developing an expression for the critical stress at which buckling occurs. While Baldwin and Howald(58) reported good experimental agreement with Geckeler's theory, Sanders and Loxley(56) found some disparity. The latter's experimental results suggested that when applied to brass and steel, the theory over-estimated the danger of buckling, and that greater reductions that those predicted were possible without folding taking place. However with copper and aluminium the reverse appeared to be the case. Relatively thick blanks may undergo a definite reduction in diameter before folding, but thinner blanks suffer insignificant reduction before beginning to fold. Theoretically, buckling may be suppressed, by reducing the flange dimension or increasing the material thickness, since either raises the critical stress for buckling.

From a practical point of view, it is rarely possible industrially to modify the blank dimensions; while in an earing test the desirability of having as large a blank as possible has been demonstrated, and sheet thickness is a fixed property of the material under test.

The commonly practised alternative therefore, is to physically suppress any wrinkling tendency by means of a blankholder. This causes the shortening of the circumferences of the blank to be accompanied by thickening. Thus there must be a balance between the blankholder and the circumferential compressive forces. Too low a blankholder force would not prevent wrinkling, while too high a force would act as a 'back tension', opposing the drawing force by increasing the friction between the die face and cup flange. This would result in malforming the ears of the cup, which in extreme cases might be drawn into points. Between these two extremes there exists a plateau of blankholder pressures, along which the optimum blankholder force lies for the material being deformed, under the prevailing drawing conditions.

Although a considerable amount of knowledge exists industrially on blankholder forces, it is generally empirical, based on accumulated experience of specific applications. Sachs(59) found that the minimum pressure required to suppress wrinkling increases rapidly as the curvature of the die increases, and the blank thickness decreases. He stated that a blankholder pressure of 10 - 20 kilograms/sq.cm. was sufficient to prevent wrinkling in steel, and that where sheets are thicker than 3% of punch diameter, such pressures have little effect on drawing capacity. Later, the same worker(60) proposed that blankholder pressures should be between 1/50th and 1/200th of the sum of the yield strength and tensile strength of the material.

Recent workers, investigating more specifically the effect of blankholder force on earing assessment, are nearly all of the opinion that its effect is relatively minor compared with reduction ratio and clearance, although Fukui(62) stated that it plays an important role in earing behaviour. Seibel and Mack(9) found that blankholder pressure was only significant with relatively thin sheets at a sheet thickness : punch diameter ratio $<$ 1 : 35, and then only if the force was excessively above the minimum required to suppress wrinkling. Wright(10) concluded that provided the load is insufficient to cause distortion of the ears, the slight increase in mean cup height and percentage earing with increased blankholder pressure is negligible. Willis and Blade(11) suggested that the minimum force to suppress earing of a particular material be found by preliminary trials, and a 20% allowance be then added to this figure.

However all this work was carried out with aluminium, and is thus not directly applicable to the earing of mild steel. Moreover about half the tooling sets of the proposed test(11) have sheet thickness : punch diameter ratios of around or < 1 : 35. Again, Wright's work is only marginally below this ratio and was carried out at 22% clearance, which is not conducive to accurate earing measurement, or conclusive for thinner gauge material.

Influence of lubrication

The influence of lubrication on the drawability of materials is a perennial subject in the technical press. Less is known of its effects on ear formation, although it is generally accepted as being one of the minor variables. Wright(10) found in a pilot study with aluminium, that mean cup height decreased slightly, while ear height and percentage earing increased slightly, with increasingly effective lubrication. Because of this lack of published information, it would seem that experimental work is necessary to determine if lubrication requires more rigid control than suggested in the earing test under examination,(11) where choice of lubricant is left to operator discretion.

2.3.2. Non-simulative tests. The tensile test.

Although lacking some of the essentials of a routine test, e.g. rapidity of sampling and testing, some non-simulative tests do offer certain attractions. The tensile test has long been recognised as yielding basic deformation data on a material. In more recent years, effort has been concentrated on relating this basis data to specific metal working processes, by a study of the stress systems involved. As outlined in earlier sections, planar variations of strain ratio R, and to a lesser extent work hardening index 'n', have been of interest in studying earing characteristics of a metal.

Determination of Strain Ratio R.

The significance of planar variations of R on the earing behaviour of sheet metals, has largely been established from tensile tests carried out at different angles to the rolling direction.

R value, or ratio of width to thickness strain, is given by the relationship,

$$R = \frac{\log_e \frac{W_o}{W}}{\log_e \frac{t_o}{t}}$$

where W_o and t_o are the initial width and thickness, and w and t the width and thickness of the test piece after a given extension.

Experimentally,(25) it is difficult to measure accurately the variation in thickness of a strip test piece under tensile stress. Also, variations in initial strip gauge can produce errors of the order of 12-15%.(20)

By assuming, however, that constant volume is maintained in the test piece throughout, R can be calculated from the changes in length and width, by substitution in the constant volume equation.(2)

i.e. $$\frac{t_o}{t} = \frac{l.w.}{l_o w_o}$$

and therefore

$$R = \frac{\log_e \frac{W_o}{W}}{\log_e \frac{l.W}{l_o W_o}}$$

Lilet and Wybo(25) have examined the substitution technique, using sensitive measuring equipment, and reported that no change in volume could be detected up to maximum load.

The level of strain at which R value is measured is important. Wright(63) found that zinc, with its limited slip systems, showed considerable variation of R with amount of strain. In the case of mild steel, it has been reported(17, 23) that R value does not vary significantly with increasing strain up to maximum load. However, Lilet and Wybo(25) found that with low strains of the order of 7 to 10%, R values were scattered due to lack of accuracy in the logarithmic calculation of the very small deformations measured. Between 10 and 25% elongation, R value diminished slowly and smoothly, the greatest variation arising at the high strain values due to the onset of necking. Grumbach and Pomey(26) found it advisable not to exceed 24 or 25% strain in mild steel, and determined R at 20% strain.

These two workers(26) also examined the influence of test piece dimensions. They found that a satisfactory compromise between accuracy of measurement, which involves the largest possible measuring basis, and heterogeneity of metal properties under investigation, requiring as small a test piece as possible, was achieved using test pieces with a gauge length of 50 mm. and a gauge width of 12.5 mm.

Atkinson and Maclean(20) recommended that the following principles be observed for accurate determinations of R.

i) The gauge length of the sample should be as large as possible.

ii) The applied extension should approach the limit of uniform elongation.

iii) Width and length strains should be measured in preference to width and thickness strains.

iv) Width measurements should be made at intervals not greater than a ½" apart along the gauge length.

(v) The measuring technique should be very precise; for example to guarantee a maximum possible error of ± 0.1 in a strain ratio value of 2, accuracies of ± 1 in 2,000 in length measurement, and ± 1 in 1,500 in width measurement, are required in a sample extended 20%.

These reqommendations were followed as closely as possible in the experimental work described later.

Determination of work hardening index, 'n'

Lankford, Snyder and Bauscher(17) determined the work hardening coefficient n from the relationship $\sigma = k\epsilon^n$

By plotting log true stress against log true strain, i.e. $\log_e \sigma = \log_e K + n \log_e \epsilon$, a straight line was obtained in all cases between 2 and 20% strain in aluminium killed steels. The slope of the line gave the value of 'n'. Crane(23) has found that the relationship holds with rimmed steel, but that the log/log plot deviated from a straight line below 5% and above 17% strain.

The acceptance of a limited linear range of strain found by the above workers, would appear to confirm and yet circumvent the findings of Voce.(64) He objected to the use of the power function on the grounds that a better fit to experimental stress/strain curves, over longer ranges of strain, could be obtained by using an exponential function.

Heyer, McCabe and Elias(46) proposed the determination of 'n' using a stepped tensile test piece. This method does not require measurements to be taken during the test, and therefore lends itself to investigations at high strain rates and non-ambient temperatures. However the test was found to be unsatisfactory for detecting planar variations in 'n'. They found that the ten inch long sample required for the test contained large variations in material thickness and properties. This was particularly pronounced in samples taken in the diagonal and transverse directions, and led to erratic results.

It is apparent from the foregoing survey that information is required on a number of aspects of earing behaviour in mild steel. For instance, a reliable test for measurement of earing, suitable for industrial application, is required.

Once such a test has been established, it can be used to examine two aspects of earing that are of interest in commercially produced mild steels. Firstly, the relationship between such mechanical properties as planar variations of normal anisotropy R, and work hardening coefficient 'n', and earing behaviour can be quantitatively investigated. This work should have a strong statistical approach in order that some of the present uncertainty can be clarified, and limits of accuracy established. Secondly, a statistical survey can be carried out on the reproducibility of earing tendency across the width, and along the length, of coils of mild steel strip of nominally the same chemical composition and process history.

3.0. EXPERIMENTAL METHOD

3.1. The materials examined.

All the material used in the investigation, came from commercially produced deep drawing quality mild steel coils. Both rimming and stabilised steels were examined, of nominally the same chemical composition and process history. The chemical analyses and production schedules of the material are summarised in tables 1 and 2. Ten coils were investigated, from three strip producers. Only single sheets of the first two samples were supplied, but in the remainder, five portions from the full width of the strip, each approximately five feet long, were supplied from each coil. These portions were from the start, quarter, half, three-quarter and finish end of the coils.

Rimming steel samples 1 and 4 were analysed at the edge, as well as the centre; and in samples 5 to 8 inclusive, analyses of all five portions of each coil were supplied. As found by Crane,(23) the variation in analysis across the width and along the length of coils was negligible, and for brevity, these analyses are omitted.

Because of the delays involved in obtaining, delivering and testing material from commercial production, no attempt was made to investigate any possible influence of strain ageing on the earing behaviour of rimming steels.

TABLE 1. Chemical Analysis of Materials examined

Sample	Material	C	S	P	Mn	Ni	Cu	Sn	Al (total)	Al (Sol)	N
1	Rimming 47" x .048"	.065	.020	.009	.32	.053	.048	.010	-	-	.0057
2	Stabilised 39$\frac{1}{2}$" x .047"	.058	.023	.007	.28	.055	.063	.010	.055	.049	.0048
3	Stabilised 59" x .042"	.080	.025	.011	.33	.030	.085	.010	.060	.046	.0036
4	Rimming 52" x .043"	.050	.017	.019	.35	.025	.020	.010	.016	.01	.0030
5	Stabilised 38" x 0.036"	.060	.023	.010	.28	.020	.020	.010	.050	-	-
6	Stabilised 48" x 0.031"	.056	.020	.013	.28	.020	.020	.010	.050	-	-
7	Rimming 42" x 0.036"	.044	.027	.019	.31	.020	.020	.010	trace	-	-
8	Rimming 48" x 0.049"	.039	.023	.011	.27	.020	.020	.010	.005	-	-
9	Rimming 36" x 0.048"	.059	.019	.008	.37	.035	.034	.011	-	-	.0028
10	Stabilised 36" x 0.036"	.059	.019	.009	.38	.029	.029	.010	.056	-	.0059

TABLE 2.

Sample	Material	Gauge (ins.)	Nominal % Cold Redn.	Hot Finishing Temp. (°F)	Coiling Temp. (°F)
1	Rimming	.048	57	1690 - 1650	1090 - 1050
2	Stabilised	.047	58	1740 - 1700	1100 - 990
3	Stabilised	.042	55	1630 - 1570	1080 - 980
4	Rimming	.043	62	1660 - 1540	1120 - 1090
5	Stabilised	.036	62	1590 - 1500	1080 - 1020
6	Stabilised	.031	63	1650 - 1570	1150 - 1075
7	Rimming	.036	62	1640 - 1560	1100 - 1030
8	Rimming	.049	57	1700 - 1600	1080 - 1000
9	Rimming	.048	56	1590 - 1560	1230 - 1010
10	Stabilised	.036	57	1670 - 1600	1300 - 1230

Inevitably there was some variation in both the time the samples awaited investigation, and the ambient temperature during this period. These variations were minimised by storing the material together in one place, and examining it as quickly as possible after receipt. The stabilised steels were all aluminium killed.

The coils from which the samples were taken varied in length between 3,200 and 8,600 feet. The width varied between 36" and 59", and the nominal gauges between 0.031" and 0.049".

3.2. Establishment of a cupping test to measure earing. Assessment of controlling variables

Section 2.3 of the foregoing literature survey has shown the attractions of a cupping test as a means of assessing the earing behaviour of a material. However, uncertainties such as the relationship between earing and reduction ratio need to be clarified, and parameters such as optimum clearance range further investigated.

Asimow and Crombie(65) pointed out that most of the work on deep drawing, and associated phenomena such as earing, has been done on material with a thickness of the order of 1.5 - 2.5% of the blank diameter, whereas in industrial operations thicknesses are often only of the order of 0.1% of the blank diameter. With such scaled down research, the significance of clearance, lubrication and blankholder pressures, which become increasingly important as the blank surface increases in relation to its thickness, was clouded.

The experimental work carried out in this research programme, was on material with thicknesses at the lower end of the Asimow-Crombie range, i.e.a thickness of the order of 1.1% - 1.7% of the blank diameter. This limitation was necessary because of restricted plant availability. Never the less, the work is relevant to industrial practise, since this is the dimensional range of many deep drawn articles of cup form. For example, the roller bearing cages shown in fig.1. have a thickness : blank diameter ratio of 1.3%. Again, better reproducibility can be obtained if a number of tests can be performed on a relatively small area of material. A thoroughly standardised earing test, based on small cylindrical cups, also allows comparative tests to be made on batches of material with minimum wastage.

Such a test, originally proposed for aluminium,(11) was investigated as to its suitability for mild steel, and formed the basis of the experimental work in earing measurement.

Cup drawing throughout was performed on the Erichsen Electrohydraulic Sheet Testing Machine, shown in fig.18, which has the following specified performance:-

Drawing: Maximum punch load 40,000 kg.
Maximum punch travel 12 cms.
Maximum blankholder pressure 5,000 kg.
Speed range 0 - 25 cms per minute.

Fig. 18. The Erichsen sheet testing machine

Blanking was carried out in the cylindrically shaped blanking press to the left of the Erichsen machine. A range of tools to produce blanks, differing in diameter by 1 mm was available; and for each blank diameter, three blanking dies to cover varying blank thicknesses viz: 0.1 - 1.0 mm; 1.1 - 2.0 mm and 2.1 - 3.0 mm. This provision is designed to minimise edge burr and work hardening when blanking different material gauges.

The blanks, suitably lubricated, were drawn and individually measured on the jig shown in fig.19. This consisted of a horizontally rotating clamp, calibrated from 0 to 360° around the periphery. The clamp was fitted with three spring loaded plungers to ensure that the cup was located centrally beneath the dial gauge. A small permanent magnet located in the bottom of the clamp assisted in securing the cup.

Measurement was carried out by locating each cup with the rolling direction of the original blank in line with the 0° mark on the rotating base. On rotating the base, the height of the cup wall could be measured at any angle to the original rolling direction by means of the dial gauge, calibrated to read to 0.01 mm.

By measurement of ear peaks and troughs, average ear height (h_e) and trough height (h_t) could be calculated. From this data, the following was calculated for each cup.

Fig. 19. Jig for measurement of earing

1) Ear height, from $(h_e - h_t)$

2) Mean cup height, from $\frac{(h_e + h_t)}{2}$

3) Percentage earing.

Two alternative ways of expressing this value are in general use. The first, expressed in terms of trough height h_t, is obtained from the relationship $\% E(_t) = \frac{h_e - h_t}{h_t} \times 100$

The second method, expressed in terms of mean cup height, is given by $\%E(m) = \frac{h_e - h_t}{\frac{1}{2}(h_e + h_t)} \times 100$

This appeared to be a more logical way of expressing percentage earing, and is the convention adopted throughout the work.

3.2.1. Reduction ratio

Earing increases with reduction ratio, although as shown in figs.11 and 12, there is some uncertainty about the exact relationship. Thus optimum measuring accuracy is obtained by using as large a blank diameter as possible, without exceeding the critical blank diameter of the material. The reduction or draw ratio D.R (d) chosen, will depend upon the tooling dimensions.

The die diameter as originally proposed by Willis and Blade(65) was 40 mm. This was later modified(11) to 45 mm, with a consequent increase of approximately 5 mm in all punch diameters. It was argued that this larger die diameter was more convenient, taking into account the type of machine or press suitable for laboratory use. To make it smaller would introduce difficulties in measuring earing accurately, involving the use of excessive punch radii with thicker gauge material to avoid premature drawing failure, so that little flat would exist at the cup base. Stretching, rather than true deep drawing, would then contribute a significant part to the deformation mode.

While it is agreed that these are valid and desirable features, it was found that the 45 mm diameter die was in fact too large for any of the experimental drawing equipment available. Therefore the originally proposed(65) tooling dimensions were adopted for the experimental work. These details are shown in Table 3.

During preliminary trials the critical blank diameters of a number of mild steel sheets were determined. The method used relies on the fact that the punch pressure, necessary to draw the cup completely, rises linearly with increasing blank diameter up to the critical blank diameter. Further increases in blank diameter beyond this require an approximately constant, or even falling(21) punch load to fracture. If the slope of the punch load curve plotted against blank diameter is determined, together with the fracture load; extrapolation to the point of intersection gives the critical blank diameter.

TABLE 3.

Dies	Die Throat dia.	Die Blend Radius
Die No.1. (Materials 0.65 mm thick and above)	40 mm	5 mm
Die No.2. (Materials below 0.65 mm thick)	40 mm	2.5 mm

Material Gauge		Punch diameter	Punch Profile radius
mm	ins.	mm	mm
2.7 - 2.03	0.106 - 0.080	31.9	6
2.02 - 1.53	0.0795 - 0.0605	33.94	6
1.52 - 1.15	0.060 - 0.0455	35.44	6
1.14 - 0.86	0.045 - 0.034	36.58	5
0.085 - 0.65	0.0335 - 0.0265	37.43	5
0.64 - 0.48	0.025 - 0.019	38.08	4
0.47 - 0.35	0.0185 - 0.014	38.59	4
0.34 - 0.25	0.0135 - 0.010	38.98	3
0.24 - 0.18	0.0095 - 0.007	39.28	3

The accuracy of this method increases with the number of blanks tested, particularly at blank diameters close to the point of intersection. Svahn(67) studied statistically the dispersion of testing values, using 3, 6, 10, and 50 test blanks, to determine the limiting drawing ratio, on a variety of metals including mild steel. He found that an accuracy of 0.5% on blank diameter was possible using six blanks. It was found in this present work, that under constant drawing conditions, using six blanks at diameters closely adjacent to the intersection, the critical blank diameter of a sheet could be satisfactorily established to within a millimeter.

The critical blank diameter of the different mild steel samples, varied between 74 and 80 mms. This is equivalent to limiting draw ratios of between 1.85 and 2.00 where:

$$\text{L.D.R.(d)} = \frac{\text{C.B.D.}}{\text{Internal die dia.}}$$

It was therefore decided to adopt a D.R.(d) of 1.80, i.e. to use a 72 mm diameter blank for all earing tests. This blank size was thought to be sufficiently conservative to allow complete cups to be drawn from all commercial mild steel sheets, and yet be sufficiently sensitive for earing measurement. Should it be found that this proposed draw ratio exceeds the limiting draw ratio of a particular batch of material, then a smaller diameter blank, say 70 mms. can be used.

A series of tests with different diameter blanks should then produce a relationship for the material, which can be extrapolated for comparative purposes, to the percentage earing at the 72 mm level.

In view of the discrepancy between the findings of other workers,(8,9,10) with aluminium, these relationships were established experimentally for both stabilised (sample No.3.) and rimming (sample No.4.) steels. Blanks ranging in diameter from 56 to 75 mm were drawn, using the appropriate tooling laid down in Table 3. Light mineral oil lubrication was used, together with a blank holder pressure just above the minimum required to suppress wrinkling. Blanks were taken from as small an area of sheet as possible, in order to minimise the effect of material variation.

Duplication of the tests were carried out according to the schedule in Table 4.

Blank dia. (mms)	No. of samples
56 - 66	3
67 - 71	4
72 - 75	5

Greater scatter was found in the results as the blank diameter increased. More samples were therefore taken of the larger blank sizes, in an attempt to obtain more accurate average earing values.

Results from both stabilised and rimming steels were submitted to a curve fitting computer programme.

3.2.2. Clearance

Preliminary trials were carried out on 0.047" material from sample No.2. Dies of differing internal diameter were used together with a 35.4 mm punch, so that clearances of 8, 29, 50, 92 and 134% were obtained. Percentage clearance being derived from:- $\frac{100\,(D - P - 2t)}{2t}$

where D is the internal diameter of the die

P is the diameter of the punch, and

t is the sheet thickness.

A blankholder load of 700 kg was used, and was not adjusted for variations in area of contact with the blank caused by changes in the die size or blank diameter.

Blanks of three different diameters, 70, 72 and 74 mm were drawn at each clearance, giving reduction ratios of 1.75, 1.80 and 1.85, when calculated on blank diameter : internal die diameter of 40 mm, the die size specified in the earing test under examination. The cups shown in fig.13 were drawn from the 72 mm blanks at the different clearances. Graphs of percentage earing against percentage clearance indicated that the optimum clearance for maximum earing, and hence maximum measuring sensitivity, is approximately 60%.

In order to determine this optimum value more precisely, an extended experimental programme was carried out, using material from sample 3. The area of sheet chosen was particularly consistent in gauge, which only varied between 0.0418 and 0.0422", thus minimising scatter in clearances due to variation in thickness of individual test blanks. Bias, from either inherent earing variation in the material or the sampling sequence, was minimised by sampling according to a modified Youden(68) square.

The pattern of blank selection with respect to drawing clearance and position in the sheet is shown in fig.20. Blanks of 70, 72 and 74 mm were again drawn in triplicate at each clearance. A 36.58 mm diameter punch (table 3) with constant 5 mm radius nose, was used in conjunction with a series of dies with internal diameters of 39.00, 39.25, 39.50, 39.75, 40.00, 40.25, 40.50, 40.75, 41.00 and 41.25 mms. With a material gauge of 0.0420", accurate to ± 0.5%, the above tooling allowed clearances of 14, 25, 37, 49, 61, 72, 84, 95, 108 and 118% respectively. The blankholder load was maintained constant at 600 kg.

The earing data obtained was subjected to multiple regression analysis, by means of a computer programme, to determine the relationship existing between earing and clearance, at reduction ratios appropriate to the test under examination. The last two clearances viz 108% and 118% were omitted from

30"
R.D. ↑

27"

Blank Size	Sample										
70 mm	A	1	2	3	4	5	6	7	8	9	10
72 "	A	1	2	3	4	5	6	7	8	9	10
74 "	A	1	2	3	4	5	6	7	8	9	10
72 "	B	8	9	10	1	2	3	4	5	6	7
74 "	B	8	9	10	1	2	3	4	5	6	7
70 "	B	8	9	10	1	2	3	4	5	6	7
74 "	C	4	5	6	7	8	9	10	1	2	3
72 "	C	4	5	6	7	8	9	10	1	2	3
70 "	C	4	5	6	7	8	9	10	1	2	3

Blank No.	1	2	3	4	5	6	7	8	9	10
Clearance %	72	14	84	25	95	37	108	49	118	61

Fig. 20. Pattern of blank selection, with respect to clearance and sheet position.

the analysis in order to simplify the relationship, since such clearances are in excess of the recommended range of 50 - 100%.

3.2.3. Tooling geometry

Die profile radius was found by Blade and Pearson to have no effect on earing, and in the proposed test under examination, only two die profiles are recommended. (See Table 3, page 74). The sharper profile is necessary with thinner gauge material to prevent "leaning out" of cup ears which would introduce a small error in measuring earing. The influence of die profile was therefore not investigated, since its effect is generally accepted as being small, and only relevant to thinner gauges outside the range of material examined in this programme of work.

The influence of punch nose radius was investigated with blanks of 1.80 and 1.85 D.R.(d), to determine the optimum radius for earing measurement. The punch diameter employed was 35.44 mm with radii of 2, 4, 6, 8 and 10 mm. Each test was carried out in triplicate.

3.2.4. Blankholder pressure

Blankholder pressure is considered to be a minor variable in earing measurement, and hence only a limited experimental programme, appropriate to the material gauges under investigation, was carried out. 72 mm diameter blanks, i.e. D.R.(d) 1.80, were drawn from sample No.3, with increasing blankholder loads. These ranged between 250 kgs and 3000 kgs. In each case the blank was lubricated on either side with a light mineral oil. Drawing was carried out on the Erichsen machine previously described, in which the required blankholder pressure is hydraulically applied.

The effect of altering the blankholder pressure on both earing characteristics and measurement was noted.

3.2.5. Lubrication

The effect of four common lubricants of different character was investigated. The lubricants examined were:-

a) Light mineral oil - Cosmolubric H.

b) Polythene sheet, 0.001" thick.

c) Polytetrafluoroethylene, (P.T.F.E.) - in the form of a proprietary anti-seizure aerosol spray.

d) Grease - Shell barbatia No.2.

Preliminary pilot trials were carried out on two different mild steel sheets of unknown origin and process history. Twenty samples were blanked from each sheet, shuffled to minimise any inherent earing bias in the material, and divided between the four lubricants. In each case both sides of each blank were lubricated. The polythene films, blanked out at the same time as the steel samples, were held in place during the drawing operation by a small particle of grease at the centre of the blank.

Results of the pilot trial, summarised in Table 5, indicated a certain ordering in the effectiveness of lubricants on ear formation.

Table 5.

Lubricant	% Earing (Average of five tests)	
	Sheet A.	Sheet B.
Polythene	4.13	8.61
P.T.F.E.	3.99	8.69
Oil	4.69	8.88
Grease	5.19	9.05

Polythene and P.T.F.E. produced the lowest earing, while grease resulted in the highest earing. It is possible, therefore, for some error to be introduced in assessing the earing characteristics of a material if lubrication is not kept constant and it was decided to investigate further this parameter.

Two sheets were examined, samples 1 and 2 in Table 1. Four adjacent, three inch wide strips were taken across each strip. Apart from variation in lubricants, tooling and deep drawing procedure were the same for all samples. If it is accepted that earing characteristics will not vary significantly along a one foot length of sheet, then the experimental work should show (a) the effect of different lubricants on earing, enabling a cup formed with one lubricant to be compared with cups taken from the same position in the sheet width, but formed with other lubricants, and (b) provide data as to earing tendency across the width of two samples, which could be used in other sections of the research programme.

3.2.6. Established cupping test procedure

As a result of the experimental work on the variables affecting earing measurement in a cupping test, some modifications were found necessary in the test under examination. The drawbacks found, and the recommendations for their improvement are discussed in sections 4.1 and 4.2.

For convenience, the main specification modifications are summarised here, as these were progressively incorporated into the experimental work, and subsequently used for all earing measurements:-

(1) The blank diameter for mild steel is recommended to be 72 mms, i.e. a D.R.(d) of 1.80.

(2) Optimum clearance for D.R.(d) of 1.80 is approximately 55%. Recommended that the clearange range be 40 - 80%.

(3) Tooling geometry as laid down in table 3 appeared satisfactory for medium gauge materials of the order of 0.040".

(4) The recommended practice of determining the minimum blankholder pressure to suppress wrinkling and then adding a 20% allowance appeared satisfactory for medium gauge mild steels.

(5) Lubrication has a greater influence than credited for in the proposed test. A common lubricant should be specified, and a light mineral oil was recommended for adoption.

3.3. Relationship between planar variations of mechanical properties and earing.

3.3.1. The Tensile test

As discussed earlier, the two parameters whose relationship with earing are to be examined are strain ratio 'R' and work hardening coefficient 'n'. Data for both these material properties is obtained from tensile tests taken at different angles to the original rolling direction of the material. These were carried out in the following manner.

Test piece dimensions

It was necessary to compromise between accuracy of measurement during testing, and the need to use as small a test piece as possible when making a detailed survey of the variation of properties within a sheet.

Previous workers,$^{(23,26)}$ had found that a gauge section of 2" x $\frac{1}{2}$" was a suitable compromise for the tensile testing of sheet metal. It was therefore decided to use the British Standard test piece shown in fig.21.

Test piece selection and preparation

Test piece blanks, slightly larger than 6" long x 1" wide, were cut with a band saw from the sheets to be tested. The selection of test pieces was as set out in fig.22. This allowed for the investigation of mechanical properties every $22\frac{1}{2}^{0}$ to the rolling direction of the sheet. The circular blanks fitted between the radiating test piece blanks, were

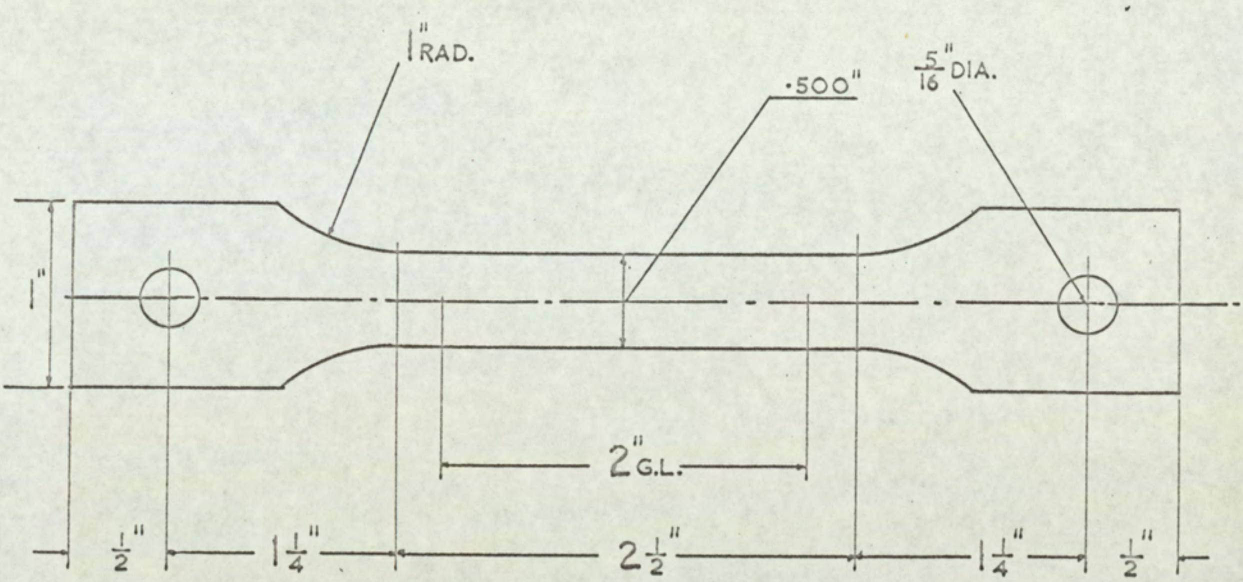


FIGURE 21 THE TENSILE TEST PIECE

for cupping tests. This sampling arrangement was designed so that a complete survey of planar variations of material properties, together with accompanying comparative earing tests, could be taken from an area approximately thirty inches square in the centre of the strip, thus minimising any variation of properties due to the heterogeneity of the material. With the rimming steel from sample 1, in addition to the centre pattern, half circular patterns were cut from the edges of the sheets. The right hand edge arrangement is shown in fig.22. The mirror image of this edge pattern was repeated on the left hand side. By combining the two edge patterns, it was envisaged that planar variations at the edge of a rimming steel sheet could be compared with planar variations at the centre.

The test pieces were milled to size from the 6" x 1" blanks, by means of light, high speed cuts, to reduce any work hardening effects on the test piece edges, which were finally dressed with a fine file.

Tensile testing throughout was performed on a Hounsfield Tensometer. The machine was fitted with a motorised drive to give a constant strain rate of $3\frac{1}{4}$ inches/hour. A Variac was fitted to the power supply to ensure smooth starting and restarting.

Test Procedure

Before commencement of testing, the gauge length of each

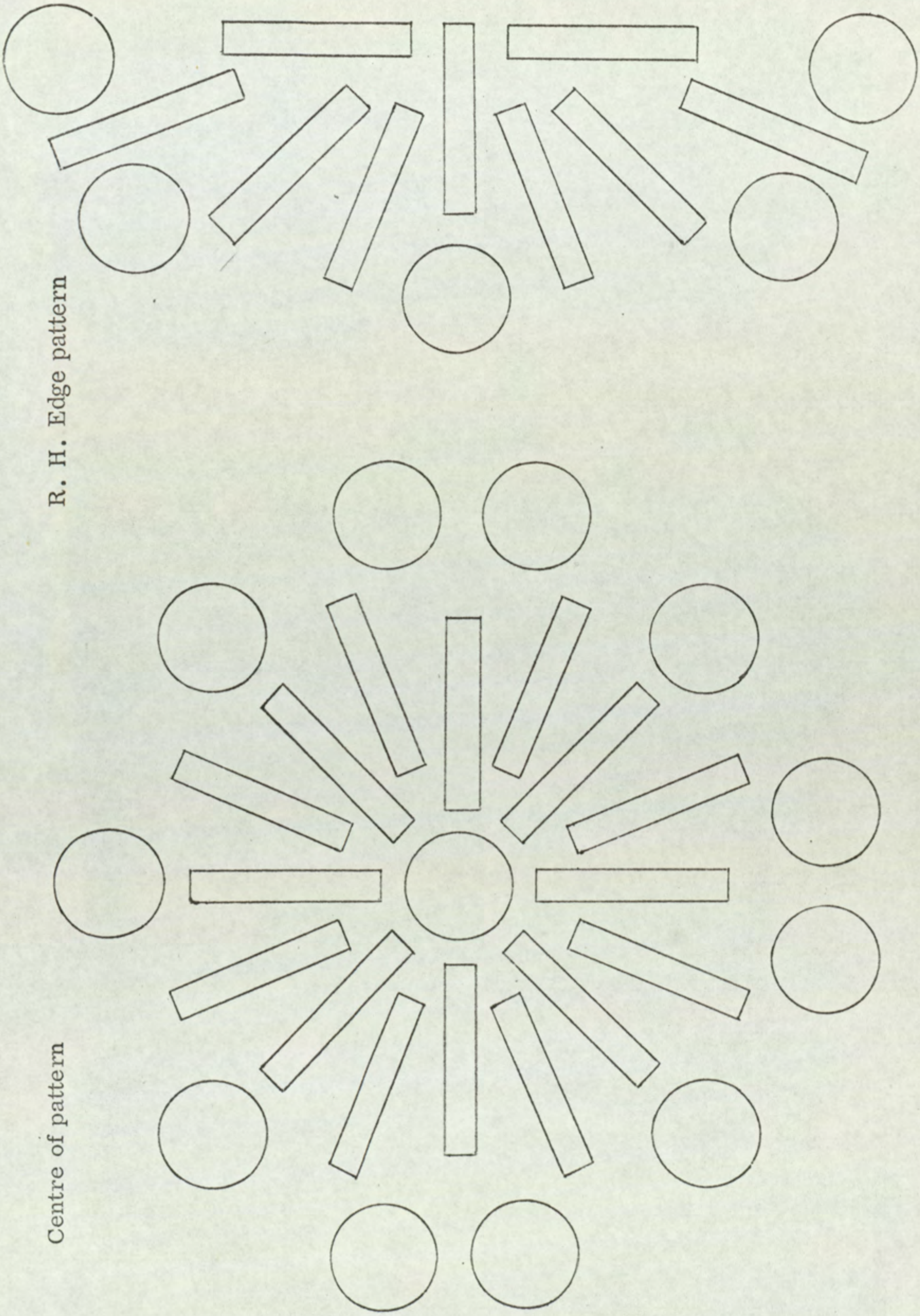


Fig. 22. Arrangement of test pieces.

specimen was marked with shallow scribe marks. Strain measurements prior to, and during the tests, were made directly from these gauge marks by means of a cathetometer fitted with a vernier attachment to measure to 0.002 mms. The gauge width measurements were taken at five equally spaced intervals along the gauge length and averaged. Measurements were made with a vernier micrometer calibrated to 0.0001". Load measurements were taken directly from the Hounsfield machine. The layout for testing is shown in fig.23.

3.3.2. Planar variations in normal anisotropy R.

R values throughout were calculated from length and width measurements, by the substitution technique, thus eliminating thickness measurements.

In the earlier work of the programme, namely on samples 1 and 2, (Table 1) several calculations of R were made during a test to determine whether R varied with strain. Each test was halted just beyond the elastic limit and on three further occasions at approximately 3% strain intervals, up to just before maximum load. It was found that R did not vary appreciably with strain. This is illustrated for a rimming steel, sample 1, in fig.24. NB. The test piece at 67½° to the rolling direction is omitted to avoid confusion with the 22½° test piece. It was also noted that the average of the four R values up to maximum load was very close to the

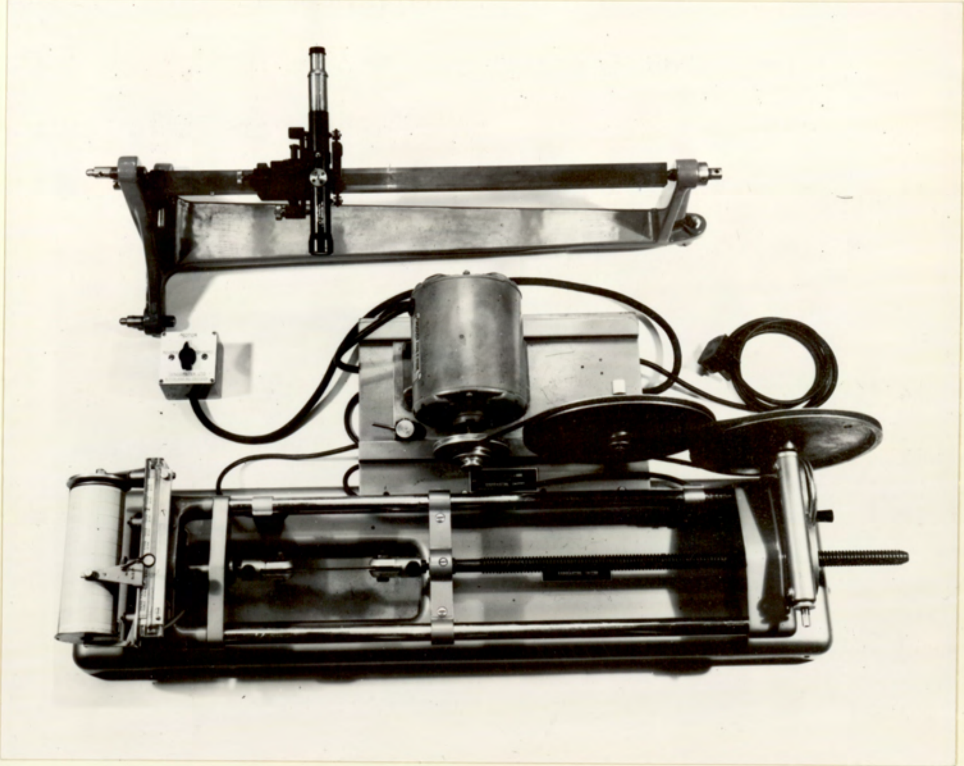


Fig. 23. The tensile test equipment

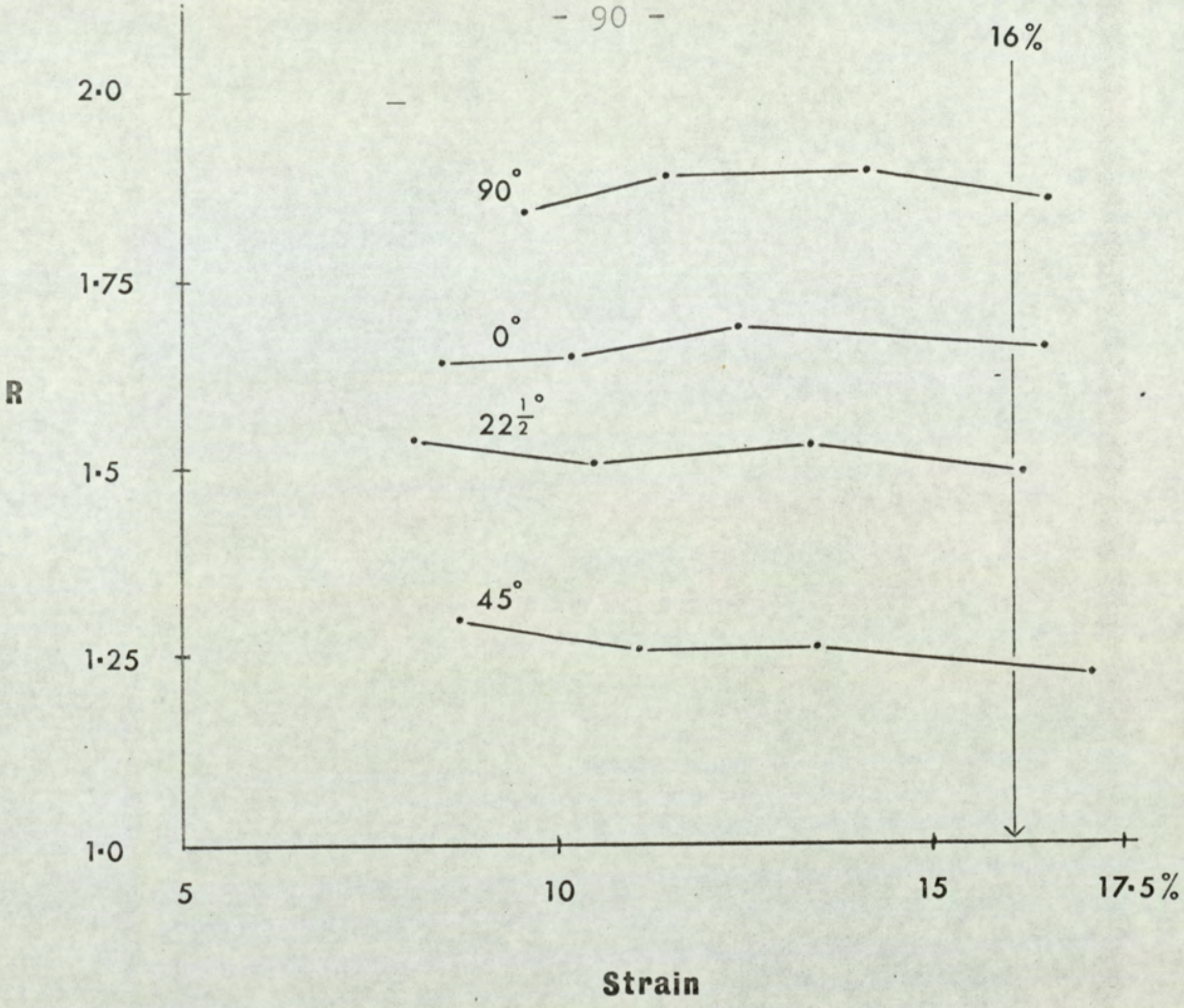


Fig. 24. Variation of R value with percentage strain, at different angles to the rolling direction.

R at 16% strain. This later value was obtained by intrapolation of the graphical results. Table 6 shows the two sets of R values for the centre of sample 1.

The 16% strain level was selected after consideration of previous workers findings, and recommendations that R should be measured as close as possible to maximum load. A further factor in deciding the strain level for measurement, was that the data might also be required for calculations of 'n'. Crane(23) had found that the graphical method it was proposed to employ for determining 'n', deviated from a straight line relationship above about 17% strain in rimming steels.

Since R did not vary appreciably over the range of strain employed; and because coincident work on planar variations of n and associated earing behaviour proved disappointing, and was abandoned, the need for the tensile test to be interrupted at intervals was removed. It was therefore decided to use a standardised technique, and in subsequent work R was calculated from length and width measurements taken before loading, and at 16% strain.

3.3.3. Planar variations in work hardening coefficient 'n'.

It was proposed to determine 'n' from the relationship $\sigma = k\epsilon^{n}$. Although this technique has been criticised by Voce, other workers, as indication in section 2.3.2, have found it a satisfactory technique.

TABLE 6. Comparison of average R value at four strain levels, and R at 16% strain; Rimming Steel Sample 1.

Angle to rolling direction of sheet	0°	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½
Average R value of four tests at approx. 8%, 11%, 14% and 17% strain	1.66	1.51	1.25	1.60	1.87	1.44	1.17	1.39	1.76	1.33	1.10	1.35	1.75	1.36	1.18	1.37
R value at 16% strain	1.68	1.51	1.21	1.58	1.87	1.40	1.16	1.38	1.76	1.37	1.10	1.34	1.74	1.35	1.17	1.34

From the plot of true stress against true strain, i.e. $\log_e \sigma = \log_e k + n \log_e \epsilon$, the slope of the line provides the coefficient 'n'. True stress was obtained from conventional stress by the relationship $\sigma = \frac{P}{A_0}(1+e)$, and true strain from $\epsilon = l_n(1+e)$, where P = applied load A_0 original cross section area and e = nominal strain, ins. per in. The stress and strain data was obtained from the tensile tests used to determine R, but additional data, calculated at the midpoint of the strain increments, was also utilised. Load measurements were taken directly from the scale of the machine.

A likely source of inaccuracy$^{(48)}$ in this graphical method of determining 'n' is the fitting of a straight line to the experimental points. Straight lines were therefore fitted by the system of least squares, using a computer to process the data.

The work on planar variations of 'n' and associated earing behaviour was confined to samples 1 and 2, and not pursued further, since the results proved disappointing.

Coincident with the determination of planar variations in normal anisotropy and work hardening coefficient, the circular blanks shown in fig.22. were subjected to cupping tests, in accordance with the specification summarised in section 3.2.5. Normally, twelve cups were taken from each sheet position. The height of the wall of each cup above the base, was accurately measured every $22\frac{1}{2}^{\circ}$ to the original rolling direction of the sheet, with the jig shown in fig.19. The height of the walls of the twelve cups, at known angles to the rolling direction, was then averaged, and this average profile compared with the profile of the planar variations in R and n.

3.4. Relationship between cup profile and wall thickness

It was pointed out earlier that planar anisotropy not only results in a variation in the profile of a deep drawn cup, but also in a variation of wall thickness. Wright(13) showed how the wall thickness varied, and qualitatively demonstrated how this was related to the cup profile. It was therefore considered worthwhile to investigate, on a more quantitative basis, the relationship between cup profile and wall thickness in cups drawn from anisotropic material.

From the experimental work in section 3.3, the profiles of twelve closely adjacent cups, drawn from the centre of a stabilised steel sheet, Table 1, sample 2, were known. These profiles were averaged, and the cup selected for examination whose profile corresponded most closely with the mean profile. Table 7 shows the profile data of these twelve cups, and the cup chosen from them for examination. The wall thickness of this cup was then measured by means of a vernier micrometer, every 30°, and also at 45°, 135°, 225° and 315° to the rolling direction, at heights of 10,

TABLE 7. Profile data of cups drawn from stabilised steel sheet, sample 2.

Angle to rolling direction		0	22½	45	67½	90	112½	135	157½	180	202½	225	247½	270	292½	315	337½
Wall heights of twelve cups drawn from Sample 2. (mms)	Max	31.13	30.07	28.90	30.58	31.94	30.20	28.88	30.31	31.24	29.98	28.83	30.34	31.48	30.11	28.62	30.46
	Min	30.14	29.17	27.69	29.02	30.47	29.08	27.56	29.50	30.11	28.56	27.70	29.05	30.46	28.69	27.52	29.24
	Av:	30.78	29.52	28.44	29.83	31.25	29.66	28.49	29.82	30.66	29.29	28.31	29.84	30.99	29.27	28.12	29.79
Height profile of selected cup (mms)		30.40	29.66	27.69	29.19	31.47	30.04	28.88	29.61	30.61	29.83	28.59	29.78	31.02	28.87	27.62	29.50

15, 20 and 25 mms. above the base. The accurate positioning of these measurements was achieved with a series of lightly inscribed horizontal and vertical guide lines around the walls of the cup.

The profile of the cup was then graphically compared with the variation in wall thickness, at the four positions up the cup wall, and coefficients of correlation calculated.

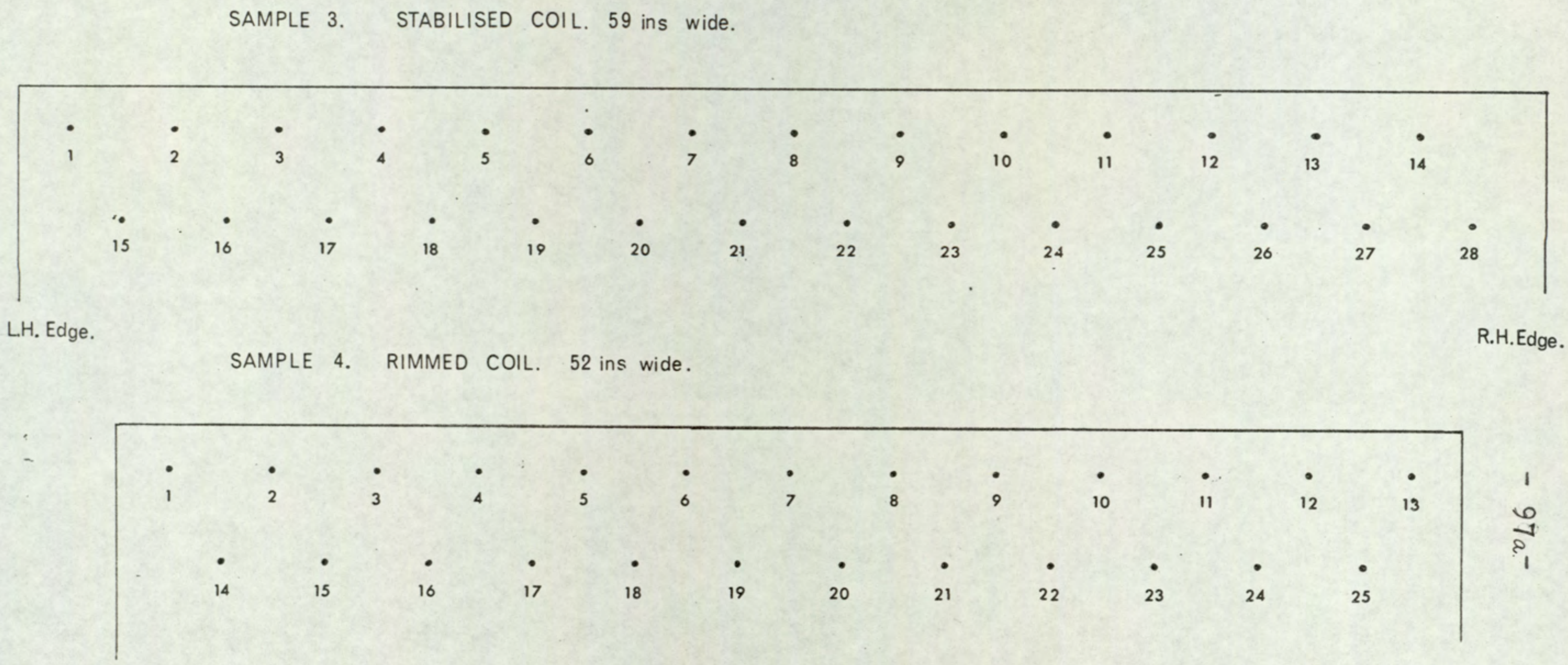
3.5. Variation of earing across the width and along the length of commercially produced mild steels.

Because of the lack of published data on the variation of earing in commercial mild steels, it was decided to carry out surveys on both stabilised and rimming quality steels. Earing variation across the width and along the length of coils was examined, and statistically analysed.

Some data was available on width variation in sheets 1 and 2, and as a by product of the investigation on the effect of lubrication on earing. With the coil samples, full width sheets were available from the start, one quarter, half, three-quarters and end positions, of coils several thousand feet long. By comparing the variation in earing across the width at each of these positions, the variation along the length of the coil could be ascertained.

Four coils were investigated, sample numbers 3, 4, 5 and 7, from two suppliers. One rimming and one stabilised coil were taken from each source.

Cupping tests, in accordance with the experimentally established procedure, were taken across the widths of both rimming and stabilised coil samples, at the five positions along the coil length. The sampling pattern was as set out in fig.25. By combining the results of rows A and B, earing could be assessed from blanks taken at the equivalent of 2" centres across the width. Comparison of the five width surveys for each coil showed the variation of earing along the coil lengths.



Scale: 4 mms = 1 inch.

Fig. 25. Pattern of blank selection across width of coils.

4.0. RESULTS AND DISCUSSION

4.1. Effect of variables in a cupping test on the measurement of earing

A review of the available methods of assessing earing has shown the attractions and wide acceptance of cupping tests. Such a test has been proposed for measuring the earing of aluminium, and it was this test which has been examined both for its general suitability, and when applied to mild steels. The literature survey has shown that the influence of certain parameters, i.e. reduction ratio, clearance, tooling geometry, blank holder pressure and lubrication, required further experimental study. This experimental work has been detailed in section 3.2, and the results are described and discussed in the following sections.

Reduction Ratio

Percentage earing increases with reduction ratio. Therefore maximum earing, and accuracy of measurement, would be achieved by using blanks at the critical blank diameter of the material. However, this would involve determining the critical blank diameter of each sample, defeating the requirements of speed and simplicity of testing. Again, direct comparison of the earing characteristics of different samples would not be possible. The more practical alternative is to decide upon a universal blank diameter, as close as possible to the smallest critical blank diameter likely to be found in commercially produced materials.

The selected diameter of 72 mms, ie a reduction ratio of 1.80 when using the 40 mm die specified in table 3, was found to be below the critical blank diameter of all the materials tested. The lowest critical blank diameter found was 74 mms, or a reduction ratio of 1.85. Thus the 72 mm blank would appear to be a satisfactory compromise between accuracy of measurement, and not exceeding the critical blank diameter of the material.

The earing of any steels with a critical blank diameter below 72 mm, when using the prescribed tooling, would have to be assessed by using a smaller blank. The value obtained, could then be converted for comparative purposes, to the earing level obtainable with a 72 mm blank, if the relationship between percentage earing and reduction ratio were known.

It is on this point that previous workers,(8,9,10) who all investigated aluminium, are in some disagreement.

From a geometrical viewpoint, the linear relationship suggested by Blade and Pearson,(8) appears the more unlikely. As the reduction ratio increases, then the area of the blank contributing to the walls of the cup, and hence earing, increases as the square of the increase in blank radius. It might be expected, therefore, that as the reduction ratio increases, the percentage earing will increase at the "slightly accelerating rate" found by Wright,(10) or according to a relationship of the type found by Siebel and Mack.(9)

The experimental results with mild steel confirm this, although the accuracy of more complex relationships over a linear one was only marginal. Figure 26 summarises the experimental data for a rimming and a stabilised steel. Both the average and range of earing are shown, for blank diameters between 56 and 75 mms, equivalent to reduction ratios of 1.40 to approximately 1.90. The complete data was submitted to linear and quadratic curve fitting computer programmes and the optimum relationships obtained are shown in Table 8. In both cases the quadratic relationship was marginally superior to the linear. The solid curves in fig.26 were constructed from the quadratic functions.

However, such levels of statistical accuracy are not experimentally warranted, because of the wide scatter in the results, especially at the higher reduction ratios. This scatter was due to both experimental error and the inherent earing heterogeneity of the material. From a practical viewpoint therefore, the linear relationship would appear to be adequate for comparative purposes in an earing test.

It is likely that the departure from linearity will

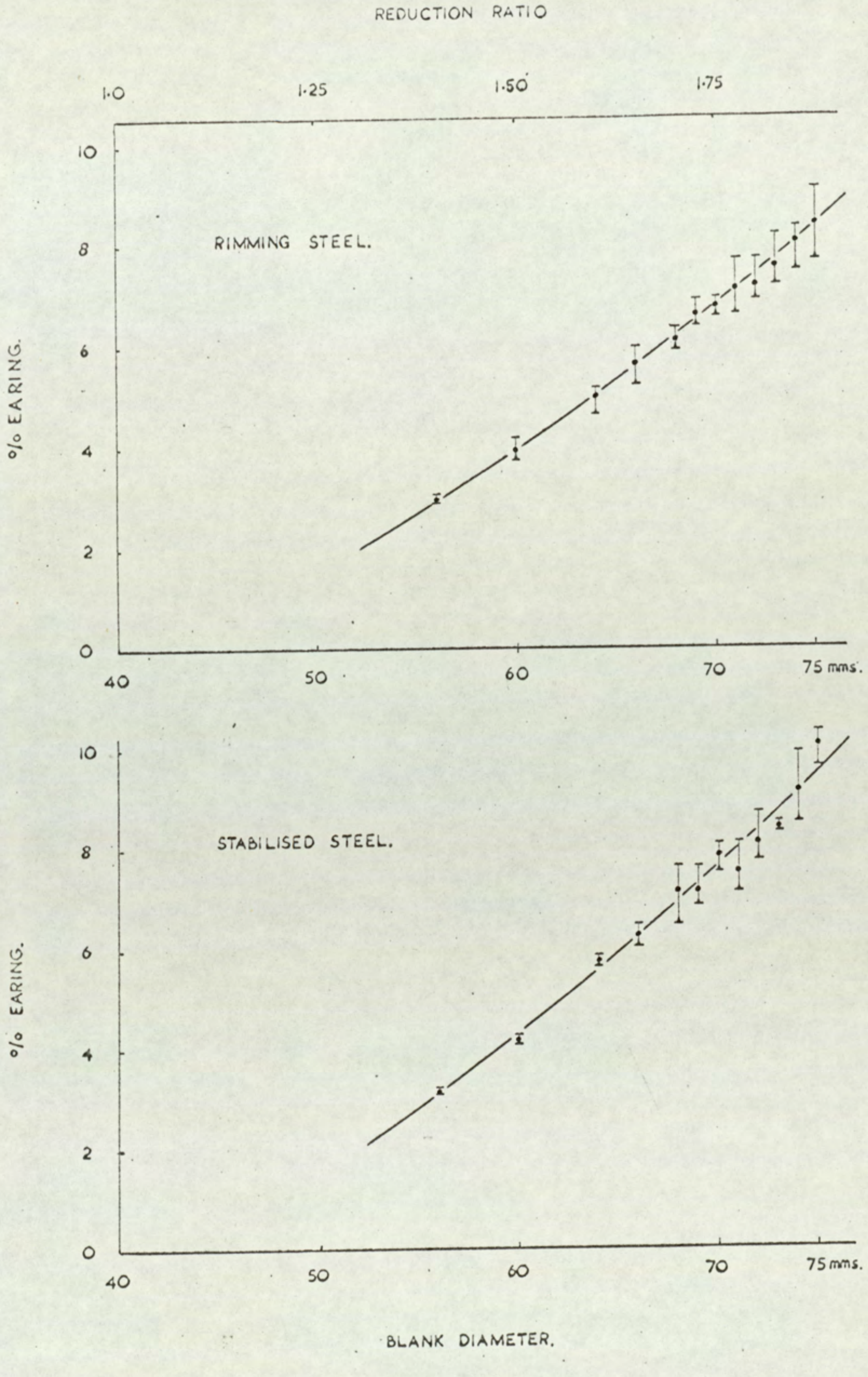


FIG 26. EFFECT OF REDUCTION RATIO ON PERCENTAGE EARING.

TABLE 8. Relationship between % earing and reduction ratio

Material	Relationship	Constants for Optimum Relationship	Sum of Squares Accounted for %	% earing with 72 mm dia Blank	
				Derived $(x = 72)$	Experimentally Determined Av:
Rimming	$E = mx + c$	$E = 0.287x - 13.30$	95.13	7.36	7.18
	$E = mx^2 + c$	$E = 0.00216x^2 - 3.90$	95.52	7.30	
Stabilised	$E = mx + c$	$E = 0.337x - 15.95$	94.09	8.31	8.08
	$E = mx^2 + c$	$E = 0.00256x^2 - 4.94$	95.63	8.33	

tend to become more pronounced for materials with a greater earing potential than mild steel, i.e. as the constant m is increased. This would be particularly so at increased reduction ratios, i.e. as x, the blank diameter is increased.

Clearance

As the reduction ratio increases, then greater clearance between the punch and die will be required to accommodate the increased thickening of the blank flange. Thus the optimum clearance to give maximum earing, and hence measuring sensitivity, will also increase with increased reduction ratio. This was indicated by the work of Wright, fig.25, page 53, but required quantitative assessment.

As described in section 3.2.2. the relationship between percentage clearance and percentage earing was investigated at reduction ratios of 1.75, 1.80 and 1.85. The data was subjected to multiple regression analysis and a relationship obtained, of the form:-

$$\% \text{ Earing} = a + bx + cx^2 + dy^3 + exy \quad \ldots\ldots (1)$$

where x = blank diameter (mms)

y = percentage clearance

From the experimental data, the actual relationship obtained was:-

$$\% \text{ Earing} = 262.4 - 7.38X + 0.053X^2 - 0.31 \times 10^{-5}y^3 + 0.405 \times 10^{-3}Xy \quad \ldots\ldots (2)$$

The relationship (2) above was calculated at blank diameters of 70, 72 and 74 mms, for clearances between 0 and 100% in increments of 10%. The data obtained produced the three curves shown in fig.27. Superimposed are the average experimental values.

For any particular blank diameter x, let

$$a + bx + cx^2 = \alpha$$

$$exy = \beta y$$

$$\text{and } dy^3 = \gamma y^3$$

$$\text{Then \% earing} = \alpha + \beta y + \gamma y^3 = Ex$$

$$\therefore \frac{dEx}{dy} = \beta + 3\gamma y^2$$

At stationary value, i.e. the peak or optimum clearance,

$$\frac{dEx}{dy} = 0$$

$$\therefore 0 = \beta + 3\gamma y^2 \qquad \therefore y^2 = \frac{-\beta}{3\gamma}$$

But β is + ve, γ is - ve

$$\therefore y = \pm \sqrt{\frac{\beta}{3\gamma}} \qquad \ldots\ldots (3)$$

Substituting blank diameters of 70, 72 and 74 mms for x in (2) above, optimum clearances of 55.2%, 56.0% and 56.7% were obtained.

Thus slightly varying the reduction ratio around the selected ratio of $1.80_{(d)}$, i.e a 72 mm diameter blank, has little effect upon the optimum clearance. With the blank and tooling dimensions proposed and under examination, this

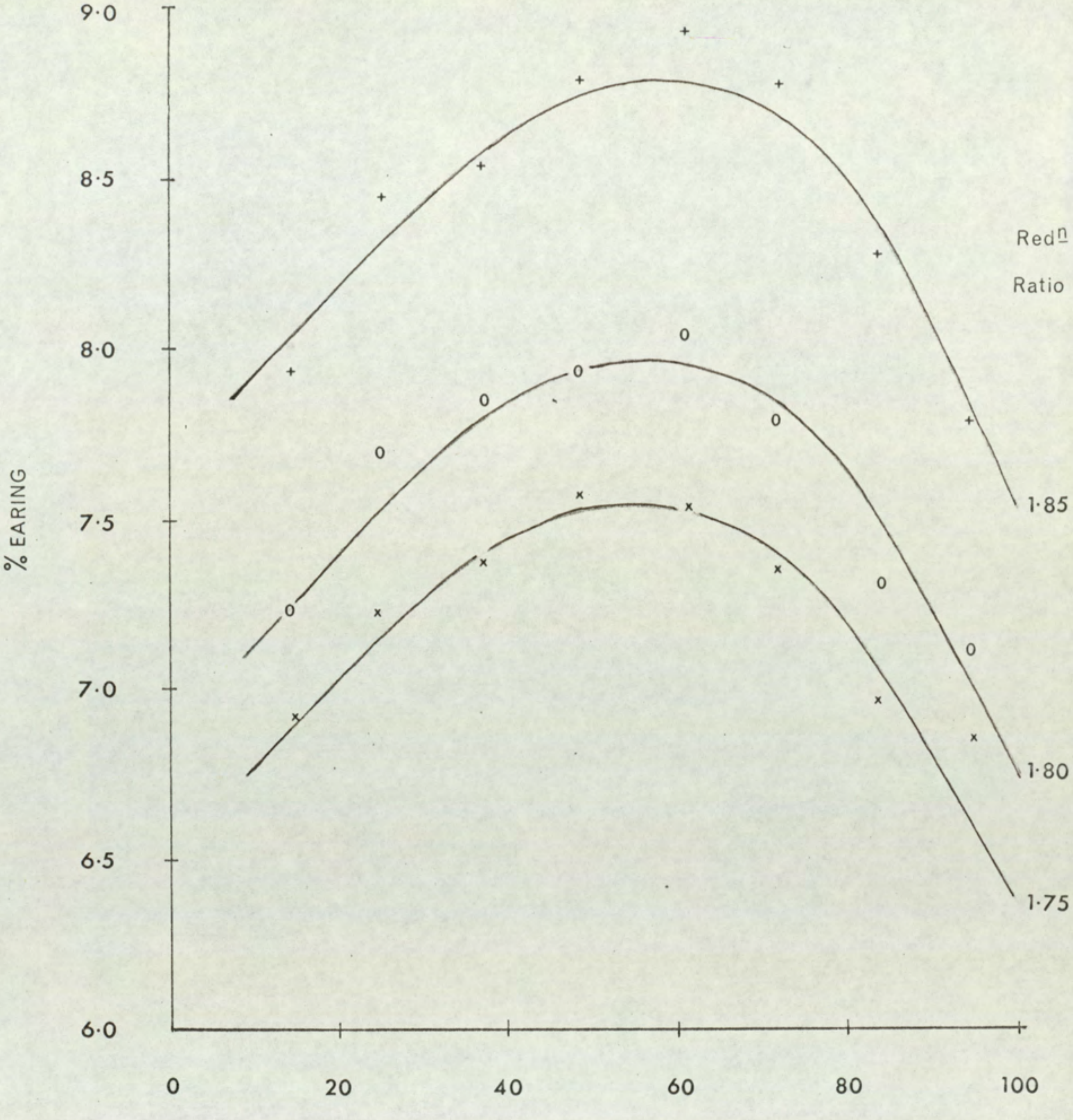


Fig. 27. Relationship between percentage earing and percentage clearance at different reduction ratios.

clearance is between 55 and 60%.

However, such a close tolerance would lead to an infinitely large number of punches, to accommodate an equally infinite number of material gauges. Differences in gauge within a coil were subsequently found to account for variations in clearance of between 44 and 62% in one instance, and 49 and 70% in another, when using the tooling specified in table 3.

On the other hand, figs. 15 and 27 indicate that the clearance range of 40 to 100% suggested by other workers might be too wide, particularly at the upper end of the range, where cup stripping conditions are likely to have a varying influence. In specifying clearance tolerances in an earing test, it will therefore be necessary to compromise between accuracy, and an acceptable number of punches. From the calculated data, used to produce the curves in fig.27, it can be seen that with a 72 mm diameter blank, at 57% clearance, the material showed an earing level of approximately 8.0%. Widening the clearance range to 40 - 80% lowered the earing measurement to 7.65% at 80% clearance, i.e. introduced a possible error of the order of 4% at an earing level of 8.0%. Increasing the upper clearance to 100% lowered the measured earing to 6.75%, an error of 14%.

Taking into account the clearance range about the nominal tooling found in commercially produced coils, an acceptable compromise between accuracy and convenience would be a clearance range of 40 to 80%. This would necessitate probably doubling the number of punches specified in table 3, to cover the full range of material gauges. However many industrial users of strip concentrate on products with a much narrower range of gauge, and would not be unduly embarrassed by the increased number of punches required.

Tool Geometry

The experimental data obtained from the investigation of the influence of punch nose radius on earing measurement is summarised in table 9 and fig.28. These also include the two ratios proposed as criteria for determining optimum punch geometry, i.e. punch nose radius : material thickness, and punch dia : nose radius.

It can be seen that too small a punch nose radius, viz. 2 mms, is likely to cause premature cup failure with blanks close to the critical blank diameter of the material. As the punch nose radius increases, the curves in fig.28 are flattening out. That is, percentage earing is becoming less sensitive to variation in the punch nose radius. While this is a desirable feature, minimising the influence of one variable in the earing test, the percentage earing itself is lowered. Thus measuring sensitivity is sacrificed. A compromise is necessary between these conflicting features. The proposed test specified a punch nose radius of 6 mms for

TABLE 9. Influence of punch geometry on earing measurement

Punch Radius (mms)	D.R. (d)	Blank dia. (mms)	Punch Nose Radius: Material Thickness (Willis & Blade)	Punch Dia: Nose Radius (Wright)	Ears Height (mms)		Cup Height (mms)		% Earing	
					Average	Range	Average	Range	Average	Range
2	1.80	72	1.6:1	17.7:1	2.51	2.465 2.57	27.75	27.49 28.055	9.06	8.97 9.16
	1.85	74					All cups failed			
4	1.80	72	3.3:1	8.9:1	2.43	2.37 2.52	28.18	28.155 28.21	8.61	8.41 8.93
	1.85	74			2.755	2.73 2.79	30.51	30.465 30.54	9.03	8.95 9.16
6	1.80	72	4.9:1	5.9:1	2.435	2.42 2.46	29.18	29.14 29.20	8.34	8.30 8.42
	1.85	74			2.735	2.675 2.775	31.50	31.32 31.61	8.69	8.46 8.86
8	1.80	72	6.6:1	4.4:1	2.50	2.40 2.565	30.24	30.21 30.27	8.26	7.93 8.48
	1.85	74			2.74	2.71 2.78	32.47	32.46 32.49	8.45	8.35 8.56
10	1.80	72	8.2:1	3.5:1	2.525	2.395 2.64	30.97	30.95 31.00	8.15	7.74 8.51
	1.85	74			2.83	2.67 2.91	33.23	33.15 33.345	8.54	8.09 8.77

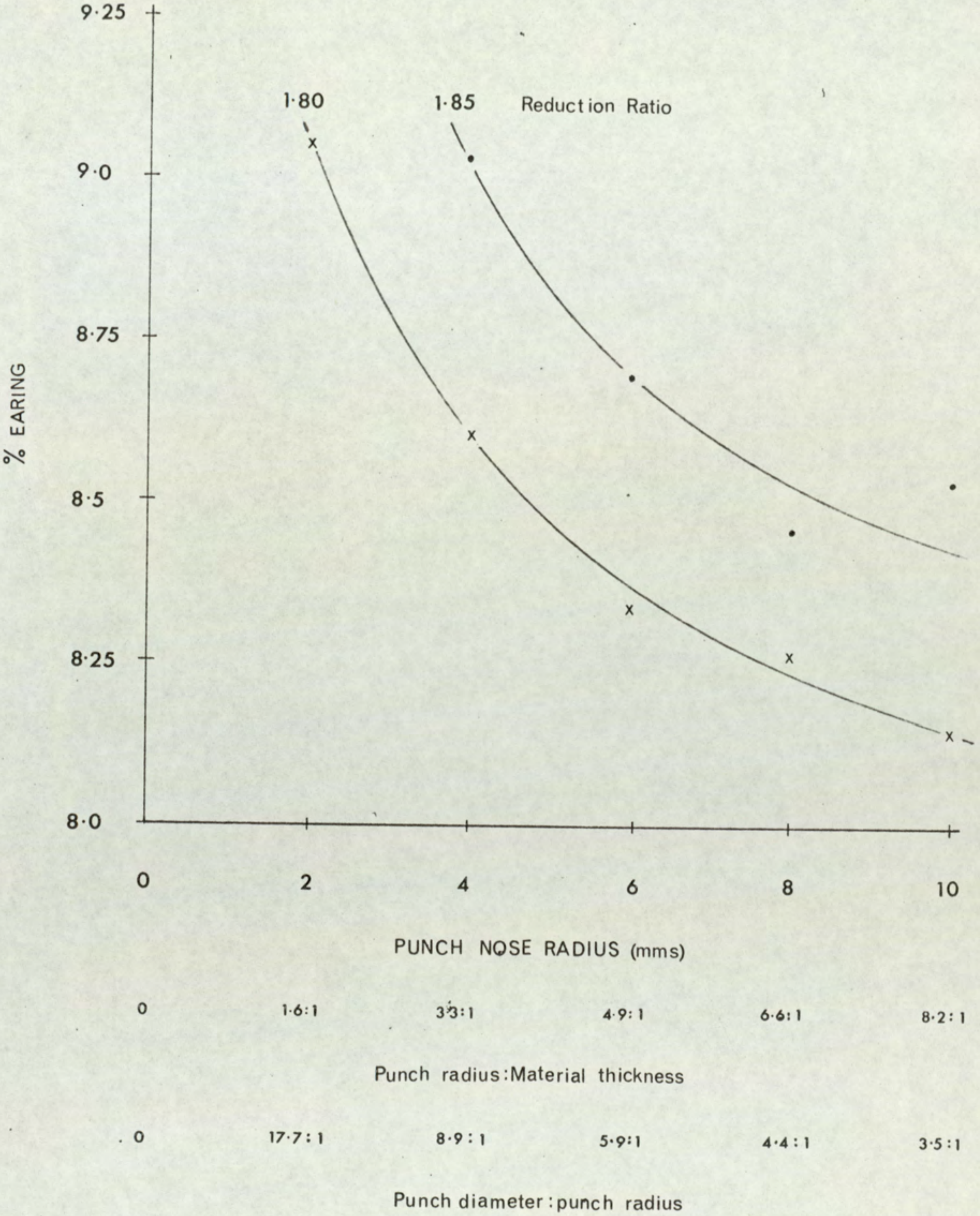


Fig. 28. Effect of punch nose radius on percentage earing.

for material 0.048" thick. Wright's punch diameter : nose radius ratio of approximately 7 : 1 would therefore appear to be a satisfactory criterion for medium gauge material. This would require a punch nose radius of 5 mms, when applied to the 35.44 mm punch appropriate for 0.048" mild steel. From fig.28 it can be seen that such a punch nose radius is a reasonable compromise on the gradient of the curves connecting percentage earing and punch nose radius.

This method of calculating the nose radius is more satisfactory for medium gauge materials, than the criterion of a punch nose radius : material thickness ratio of 8 : 1 suggested by Willis and Blade. However, more detailed experimental work on the influence of punch nose radius is required, with material gauges outside the range investigated in this programme.

Blankholder pressure

Only a limited experimental programme was carried out on the influence of blankholder pressure on earing, since it is generally accepted as being one of the less important parameters.

The results of the experimental work are summarised in table 10 and fig.29. It will be seen from table 10 that while cup height increased, the ear height and percentage earing decreased slightly with increasing blankholder pressure. Either some ironing was produced under the pressure plate by

TABLE 10. Influence of blankholder load on ear formation

B/H Load kgs	B/H Load per unit area of blank kgs/sq.cm.	Ear Height mms	Cup Height mms	% Earing	Cup Formation
250	6.1	2.69	28.58	9.41	Badly wrinkled
300	7.4	2.64	28.65	9.22	Wrinkled
400	9.8	2.67	28.80	9.20	Slightly wrinkled
500	12.3	2.73	28.83	9.47	Satisfactory
750	18.4	2.52	28.87	8.73	"
900	22.1	2.38	29.06	8.19	"
1000	24.6	2.55	29.33	8.68	"
1100	27.0	2.49	29.44	8.45	"
1200	29.5	2.43	29.38	8.27	"
1500	36.9	-	-	-	) Ears too badly distorted for measurement
2000	49.1	-	-	-	
2500	61.4	-	-	-	
3000	73.7	-	-	-	Cups failed during drawing

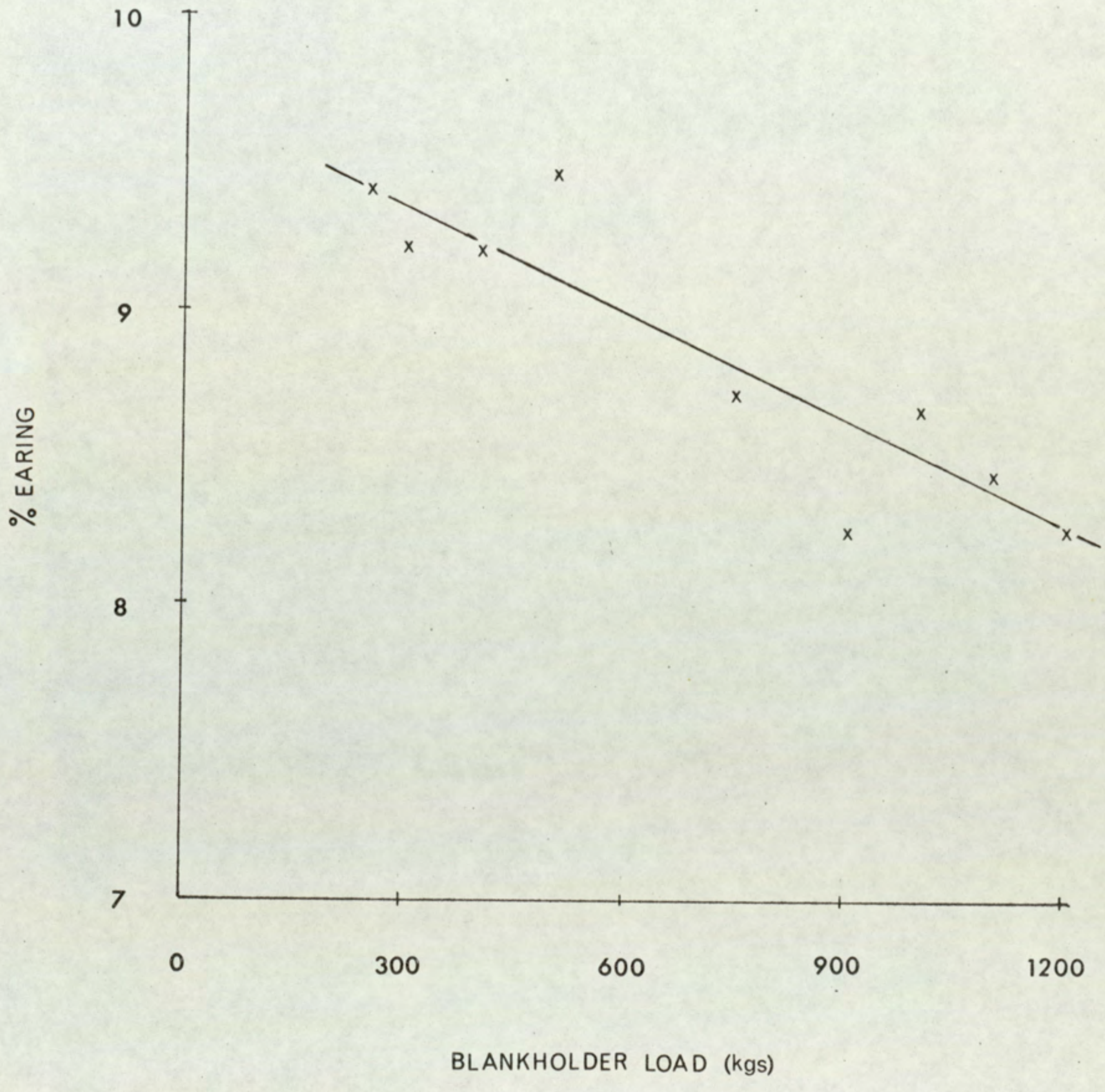


Fig. 29. Effect of blankholder load on percentage earing.

the increasing blankholder load, or the increased friction resulting in back tension, caused the stretch component of drawing to increase. In either case this resulted in a taller cup without adding to the ear height. This broadly supports the findings of other workers,(69) that within limits, drawability increases with blankholder load. The decrease in earing found with increasing blankholder load is in contrast with Wright's findings with aluminium.

From table 10, the minimum pressure to suppress wrinkling was 12.3 kgs/sq.cm. for 0.042" gauge mild steel. Adding the 20% allowance recommended by Willis and Blade gives 14.8 kgs/sq.cm. This compares favourably with the minimum blankholder force of 10 - 20 kgs/sq.cm. found by Sachs to suppress wrinkling.

The recommended 20% safety margin above the threshold blankholder force would appear to be adequate, since on the basis of this limited data, the error introduced in measuring earing would only be of the order of 1% at an earing level of 9.0%. A greater safety allowance would increase measuring error, and be unnecessary in view of Sanders and Loxley's findings that steel is less susceptible to wrinkling than aluminium. However the influence of blankholder pressure on earing measurement requires verification with thinner gauges of mild steel, since Wallace(70) showed that the minimum blankholder pressure increased rapidly with decrease in blank thickness.

Lubrication

Preliminary trials had indicated a certain ordering in the effectiveness of lubricants on percentage earing, and the investigation was extended further to examine this effect.

The results of the experimental work described in section 3.2.5, are summarised in fig.30. Although there was some scatter in the order of effectiveness with individual results, generally the tendency was for grease to yield the highest percentage earing values, and P.T.F.E. and polythene the lowest. This work confirmed the earlier preliminary trials; and showed that lubrication has a small but measurable effect on ear formation. The variation between the lubricants examined, is probably of the order of ± 2% at a 10% earing level. It is therefore considered desirable that this parameter should be more closely specified in any earing test, if only as to type of lubricant e.g. polythene sheet or mineral oil.

In deciding the choice of lubricant, the effect on drawing load was noted. This data, obtained when drawing cups from samples 1 and 2, is summarised in table 11. It was noted that the order of increasing drawing force requirements of the lubricants, was virtually the same as the order of increasing influence upon earing.

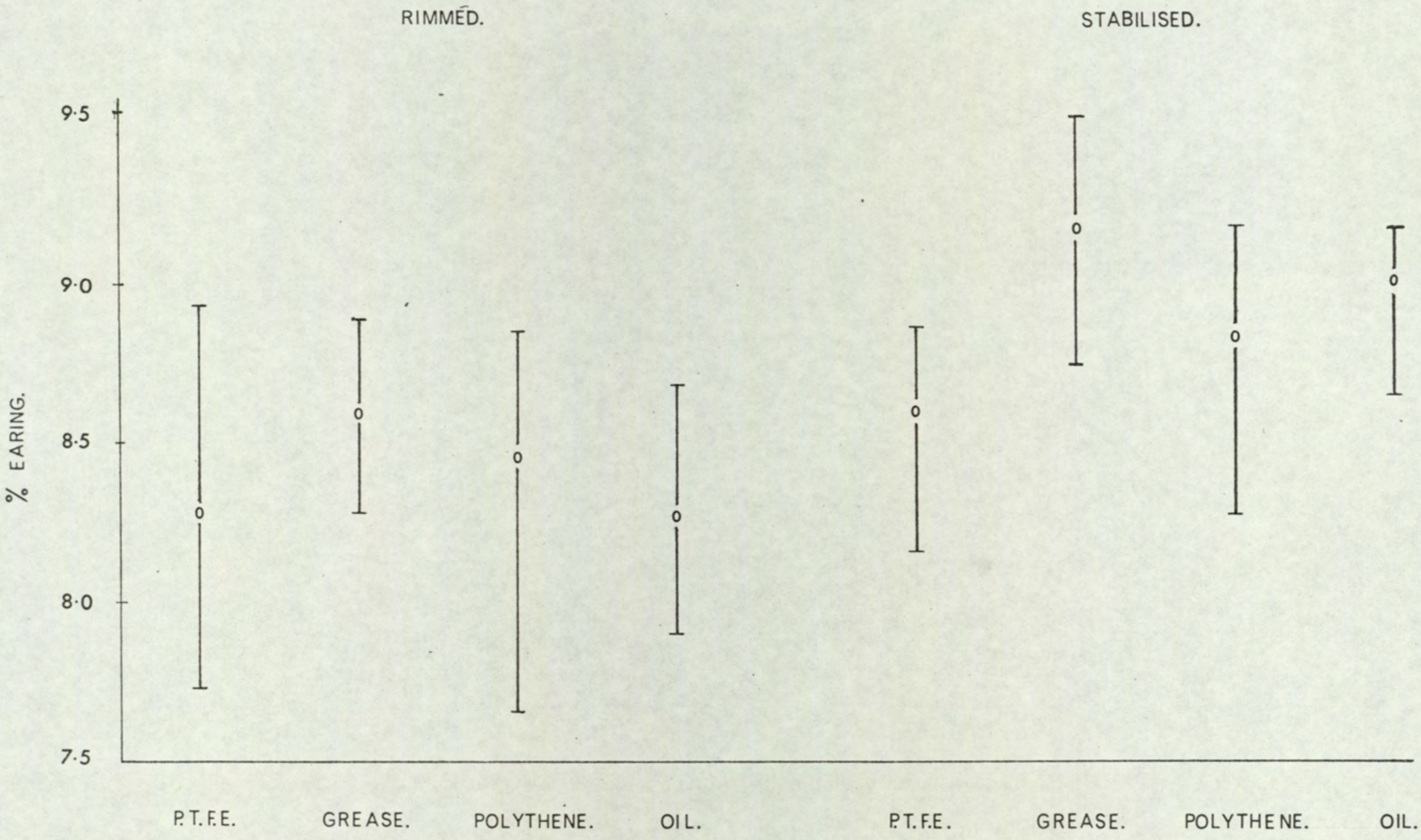


Fig. 30. Effect of lubrication upon the percentage earing of two steels.

TABLE 11.

	Sample 1. RIMMING STEEL 0.048"		Sample 2. STABILISED STEEL 0.047"	
Lubricant	Drawing Load (kgs)		Drawing Load (kgs)	
	Average	Range	Average	Range
Polythene	3707	3500 - 3850	3767	3650 - 3850
P.T.F.E.	4010	3900 - 4100	4054	3950 - 4150
Grease	4057	3950 - 4100	4187	4050 - 4250
Oil	4205	4050 - 4300	4402	4300 - 4550

The final choice of lubricant must be a compromise between cost, availability, convenience and effectiveness. P.T.F.E. and polythene are most expensive, inconvenient to apply and not always readily available. In addition they produce the lowest earing, which is not conducive to accurate measurement, although this feature might prove useful in suppressing earing commercially. Grease and oil are both readily available, cheap and convenient to apply. Oil was chosen since a) it was more convenient than grease when a large number of tests were required, b) is intermediate in its effect, neither suppressing nor unduly influencing earing behaviour, and c) other workers (69) found it to be most satisfactory for deep drawing purposes, and recommended its use where light blankholder forces were employed.

4.2. Specification for a cupping test to measure earing

The test originally proposed for aluminium is satisfactory for measuring the earing of medium gauge mild steels, with the following reservations and recommendations:-

1. The blank diameter for mild steel should be 72 mms, i.e. a D.R.(d) of 1.80. This is a reasonable compromise between the accuracy requirements of as large a blank as possible; and the convenience of a standard blank size, which will not exceed the critical blank diameter of the material. The relationship between blank diameter and

percentage earing is sufficiently linear for extrapolation to 72 mms should this dimension be above the critical blank diameter of the material under test.

2. Optimum clearance for D.R.(d) of 1.80 is 55 - 60%. It is considered that the specified range of 40 - 100% is too wide for accurate measurement, particularly at the upper end of the range. It is recommended that a clearance range between 40 and 80% is an acceptable compromise between convenience and accuracy. Accordingly, the number of punches listed in table 3 will have to be increased, to accommodate the reduced gauge ranges.

3. Tooling geometry as set out in table 3 is satisfactory for medium gauge materialsof the order of 0.040". However the influence of punch nose radius requires further investigation, particularly with thinner gauges of material.

4. The recommended practice of determining the minimum blank holder pressure necessary to suppress wrinkling, and then adding a 20% allowance, appears satisfactory for medium gauge mild steels. Further investigation is required, as to the effect of material gauge on the minimum blankholder load to suppress wrinkling, under the conditions of this particular test; when it is likely that a more quantitative specification for blankholder pressure will emerge.

5. Lubrication has a greater influence than credited for in the proposed test. A common lubricant should be specified,

and a light mineral oil is recommended for adoption.

An assessment of the reproducibility of the test is difficult, since it must take into account both the variation of earing potential between samples, and the experimental error. The possible extent of some of these latter errors has been discussed. It is submitted that the adoption of the above modified specification will considerably reduce the level of these experimental errors, which should be at a minimum or constant level, if the test is to be discriminatory for earing variation.

The reproducibility attainable was indicated in the subsequent work on earing variation in commercial coils. Twelve cups, which showed earing contrary to the general trend across strips, were re-tested immediately adjacent to the original blank position, thus minimising material variation. Although the re-testing was undertaken because the first results were in some doubt, ten of the twelve were within 9% of the original earing values of approximately 8%. Seven of the twelve were within 2% of the original value.

4.3. Planar variations in normal anisotropy, R, and work hardening index n.

In section 2.1 it was shown that uncertainty existed in the macroscopic approach to earing behaviour. Some workers had found a 'radial' relationship between the positions of ears and the maxima in R values; other workers had found that the relationship was better when the R values were transposed from a 'radial' to a 'circumferential' position. Accordingly, as described in section 3.3, from each sample, the average profile of twelve cups, was compared with the planar variations of R obtained from tensile tests taken in the radial position from the same sheet. A total of ten samples, five stabilised and five rimming, were examined. With both types of steel, ears were always found at 0, 90, 180 and 270° to the rolling direction. This was consistent with the processing history of the material.

With the stabilised steels, the ear positions appeared to coincide with the maxima in R values, and trough positions with the minima in R values, taken in the plane of the sheet. This is illustrated for a stabilised steel, sample 3, in fig.31. The taller pair of ears occurred at 90° and 270° to the rolling direction, which was also the position of the taller pair of R values. It was found that this 'radial position of R' relationship appeared to apply for all the stabilised steels. However it was noticed with three of the stabilised steels, samples 2, 3 and 5, that although the tallest pair of ears formed at 90° and 270°, which coincided with the two maxima in R values; in each case the tallest ear occurred at 90°, while the maximum R value occurred at 270°. Similarly in sample 3, the lowest trough was at 135°, but the maximum R value was transposed 180° to 315°. This anomaly in the minima of trough and R values did not however apply to all the stabilised samples. Generally,

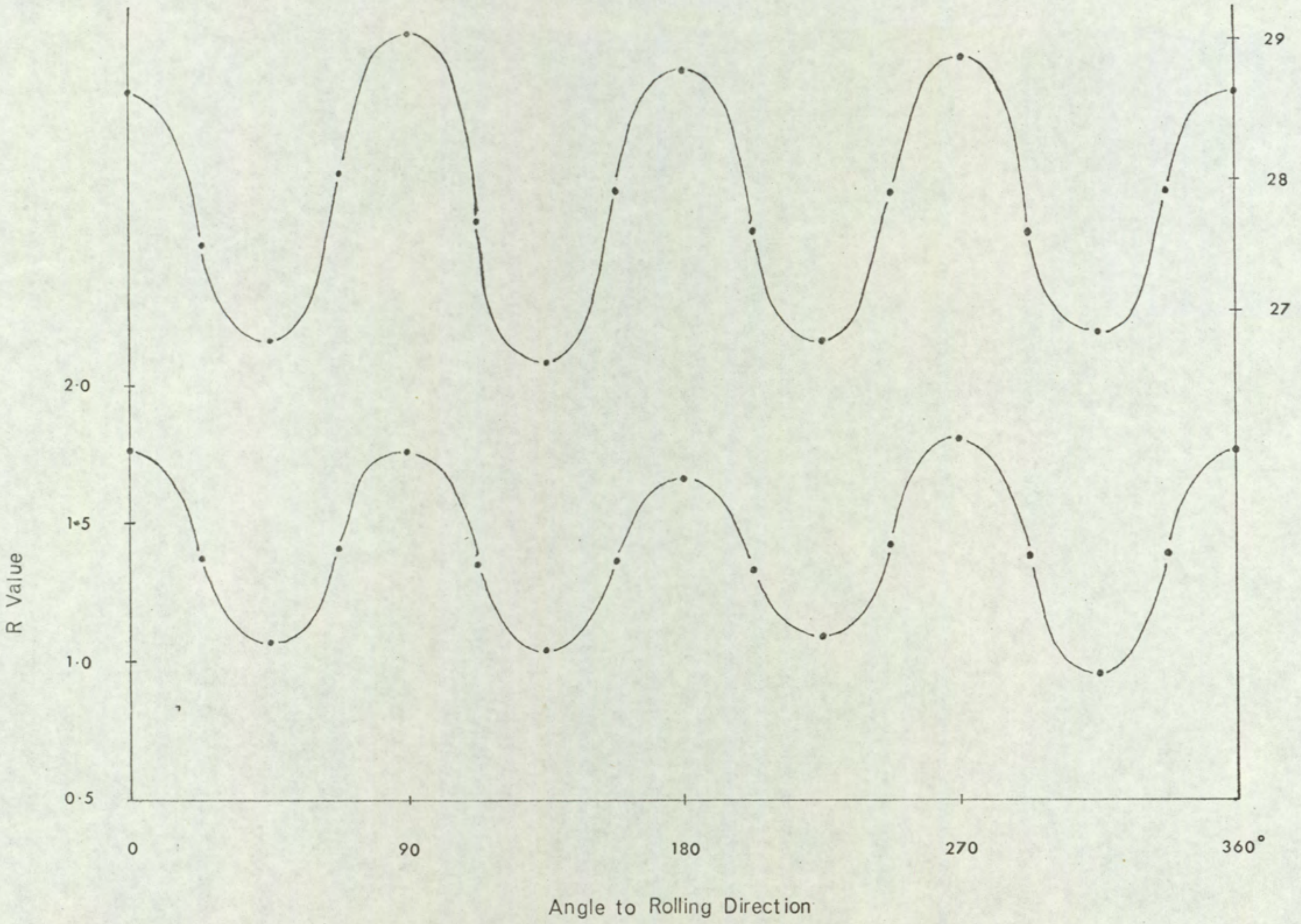


Fig. 31. Planar variation of R and average cup profile of stabilised steel, Sample 3.

there was not a great deal of variation in the ear and trough heights of these steels.

The radial relationship between ear position and R values, was also found at both the centre and edge position of rimming steel sample 1. This was not the case with any of the remaining rimming steels, where the tallest pair of ears occurred at 0° and 180°, while the highest pair of R values occurred at 90° and 270° to the rolling direction. This is illustrated in figs. 32 and 33, for rimming steel samples 4 and 7 respectively. Except for sample 1, a much better relationship appeared likely with rimming steels if the R values were transposed from a radial to a circumferential position, that is, to positions where a tensile specimen cut parallel to the circumferential direction, would give maximum R values in relation to ear position.

In order to examine these alternative relationships more quantitatively, coefficients of correlation were calculated for the radial relationship between the two sets of data for each sample, i.e. the wall height and the corresponding R values, at the same position relative to the rolling direction. The R values were then transposed a) clockwise 90°, and b) anticlockwise 90°, to bring R into each of the two possible circumferential positions relative to the ear positions. Coefficients of correlation were again calculated (see Appendix B). These are shown in table 12.

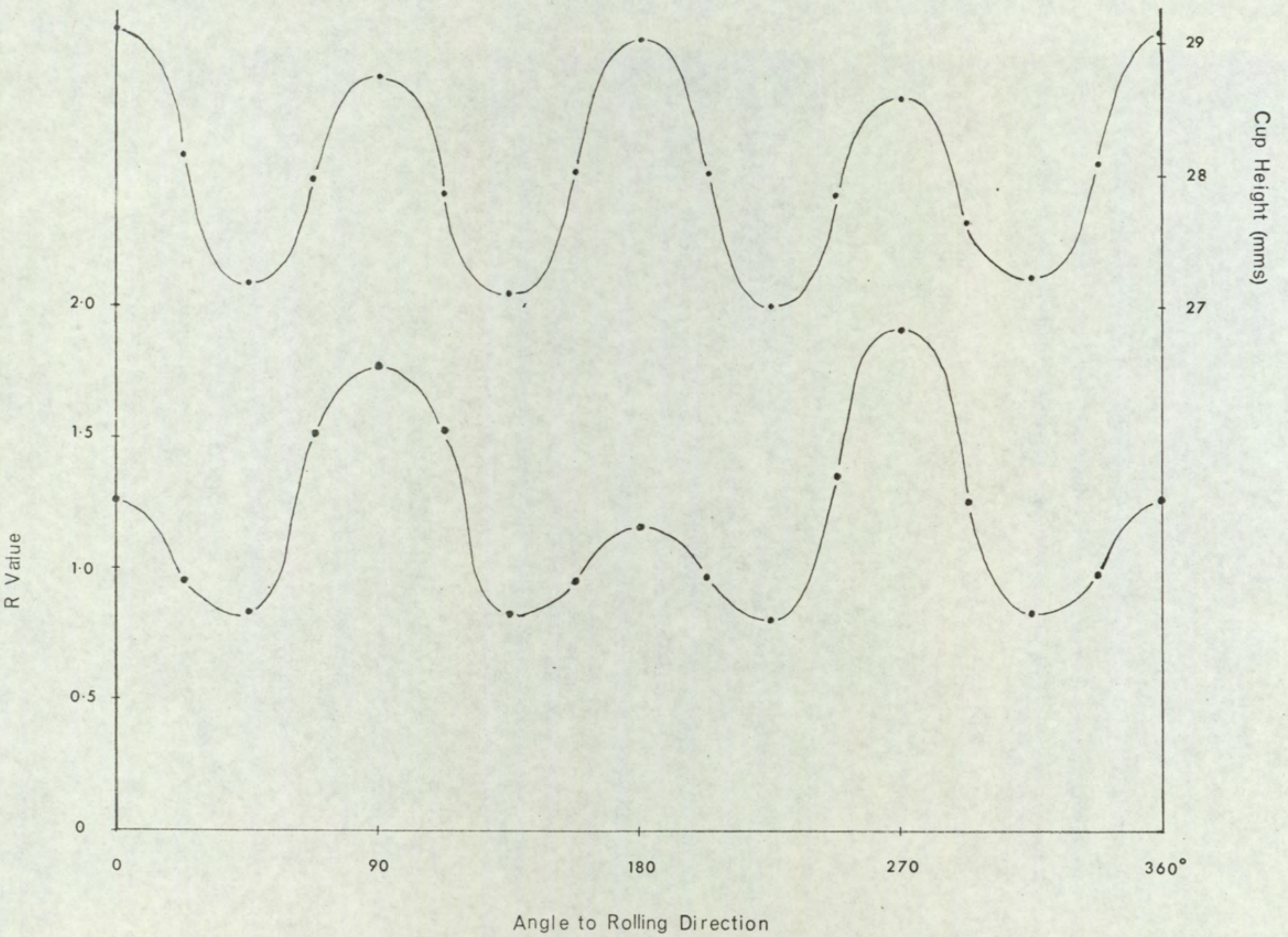


Fig. 32. Planar variation of R and average cup profile of rimming steel. Sample 4.

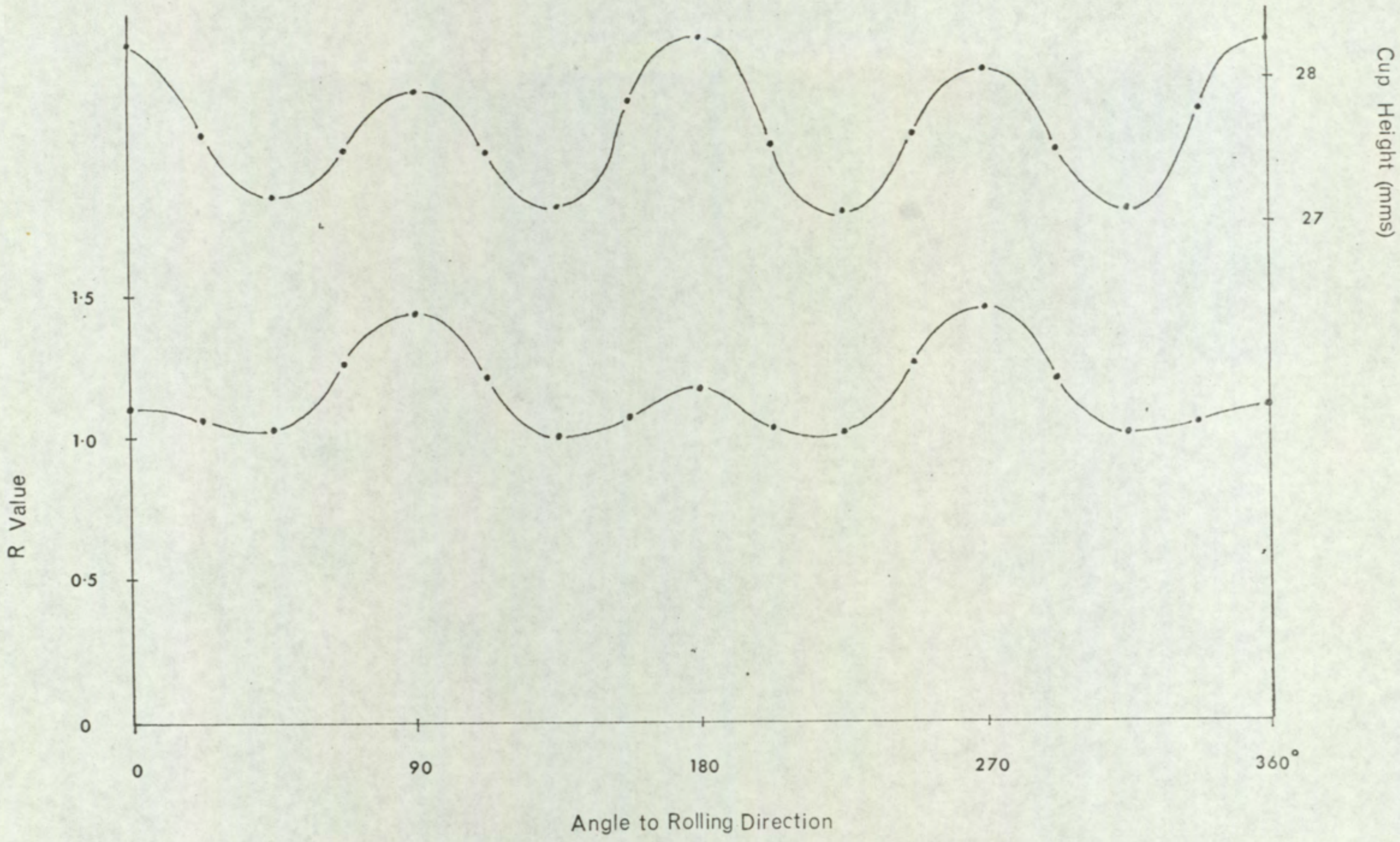


Fig. 33. Planar variation of R and average cup profile of rimming steel. Sample 7.

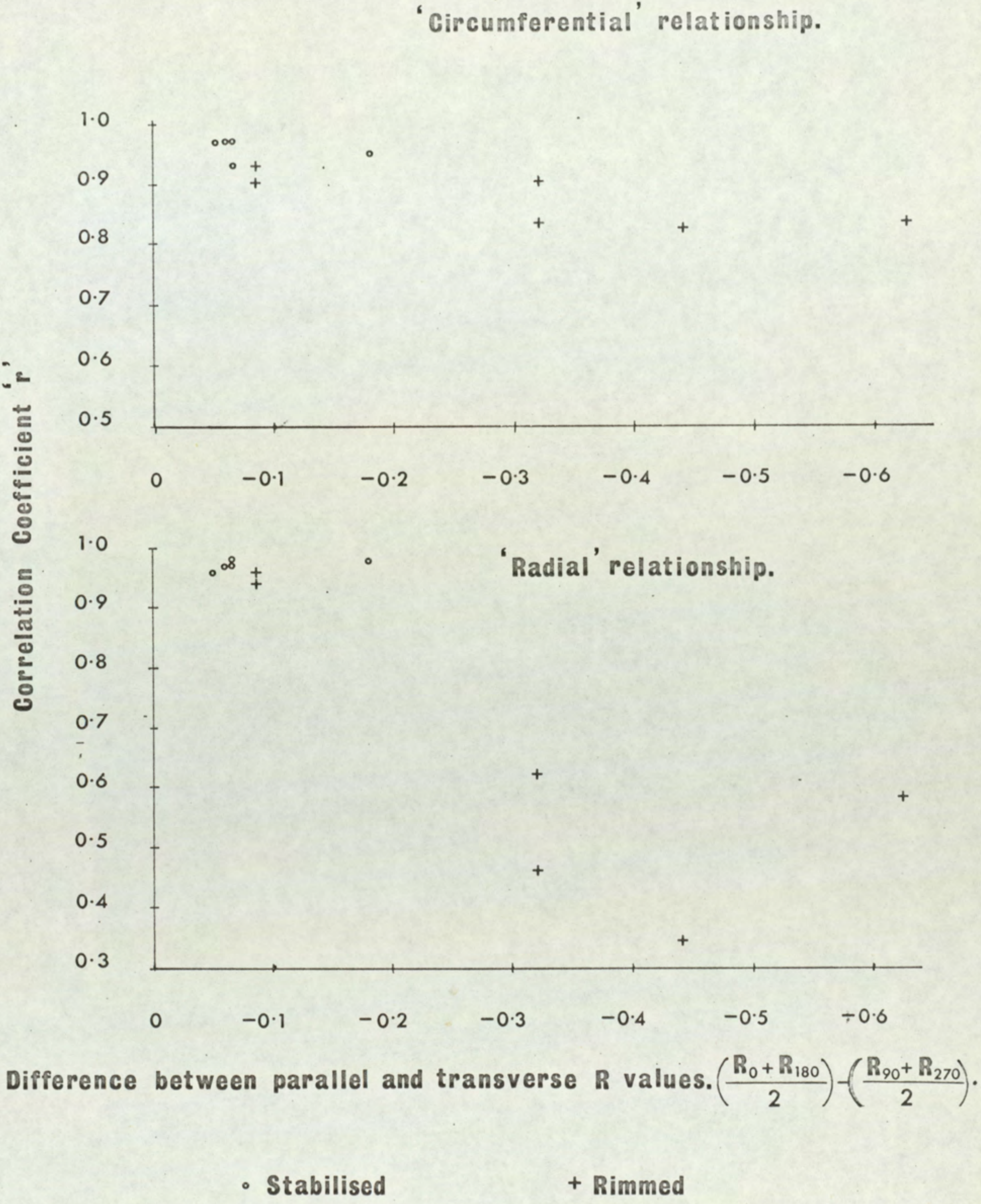
TABLE 12. Correlation between planar variation of 'R' and cup height profile

Sample	Correlation Coefficient			Difference in parallel and transverse R values
	'R' value in radial position	'R' value in circumferential position		
		Clockwise 90°	Anticlockwise 90°	$\frac{(R_o+R_{180})}{2} - \frac{(R_{90}+R_{270})}{2}$
1. Rimming				
a) Centre of sheet	.945	.93	.89	- .085
b) Edge of sheet	.95	.90	.93	- .085
2. Stabilised	.97	.93	.96	- .065
3. Stabilised	.97	.97	.96	- .065
4. Rimming	.58	.83	.84	- .625
5. Stabilised	.97	.97	.97	- .06
6. Stabilised	.96	.97	.98	- .05
7. Rimming	.46	.83	.82	- .32
8. Rimming	.62	.90	.90	- .32
9. Rimming	.34	.82	.81	- .44
10. Stabilised	.98	.95	.95	- .18

It can be seen that with all the stabilised samples except number 6, the radial relationship was marginally superior to either of the two circumferential relationships. On this latter point, there was very little difference between either of the two circumferential relationships with any of the samples. However, the correlation between the cup profile, or earing characteristics, and either the radial or circumferential relationship was so close, and both correlations so highly significant, that either appears acceptable for stabilised steels.

The significance of the correlation coefficients in table 12 was determined by Student's test. Each coefficient had been determined from sixteen pairs of data. For N = 16-2 = 14 degrees of freedom, it was found that at a probability level of 5%, the correlation coefficient r = .50; at a probability level of 1%, the correlation coefficient r = .62; and at a probability level of 0.1% the correlation coefficient r = .74. Thus all the correlation coefficients in the circumferential positions were highly significant.

For the rimming steels, except for sample 1, the circumferential relationship was markedly superior. This superiority became more pronounced as the difference between R values parallel, and transverse to the rolling direction increased. These differences are given in column 5 of table 12. Figure 34 shows these differences plotted against



'Circumferential' relationship.

'Radial' relationship.

Fig. 34. Circumferential and radial relationships.

the radial and circumferential correlation coefficients for all the samples.

Although neither relationship has complete validity, broadly, the rimming steels followed the circumferential relationship; and while either would be acceptable, the radial relationship was marginally superior for stabilised steels. The difference in the behaviour of the two types of steel is as yet unexplained. However the inconsistency can probably be attributed to different crystallographic features. Here, the findings of Watson(71), with a rimming steel exhibiting a cup profile and variation in R pattern similar to those shown in figs. 32 and 33, are of interest. He found that the steel, with a four fold symmetry of ear heights, and a two fold symmetry in R, contained a strong $\{110\}$ $\langle 001 \rangle$ component.

Thus the best general relationship between ear position and planar variations in normal anisotropy for mild steels, is the circumferential one. The relationship is readily accounted for if the stress system under which ears form is accepted as being a major circumferential compression, together with a small radial tension.

The results of the investigation into relations between earing behaviour and planar variations in work hardening index n, were disappointing. Because of the obvious lack of correlation, the work was discontinued after investigating samples 1 and 2, in favour of a more extensive investigation into the planar variations of normal anisotropy.

The correlation coefficients for samples 1 and 2 are shown in table 13. These were calculated from the wall height every $22\frac{1}{2}^{\circ}$ to the original rolling direction, and the corresponding 'n' values obtained from tensile tests taken at the same angle to the rolling direction.

TABLE 13. Correlation between planar variations of 'n' and cup height profile

Sample	Correlation Coefficient
1. Rimming	0.36
2. Stabilised	0.45

Neither of the correlations was significant at the 5% probability level. The lack of correlation may have been influenced by the experimental method employed. A recent report (72) on determinations of 'n' has attributed lack of consistency in results, to a) small deviations in the measured load, which exert a great influence on the determination of 'n', and b) lack of precision, resulting from too few data points when resolving the equation $\sigma = k\epsilon^{n}$ Further work, concentrated on relationships involving 'n', rather than utilising by product data from determinations of R, is recommended. This might show the correlation between earing behaviour and planar variations of 'n' in a more favourable light.

4.4. Correlation between cup profile and wall thickness

It was described in section 3.4 how the variation in wall thickness of a representative cup was measured for correlation with its profile. The variations in cup wall thickness, at different angles to the rolling direction of the original blank, and at various heights above the base, together with the cup wall profile, are shown in fig.35.

In the lower half of the cup the wall was thinner than the original blank thickness. Although the wall here was reasonably uniform, there was evidence of distinct thickening at positions beneath the two lowest troughs, at 45° and 315° to the rolling direction. Two thirds of the way up the cup, at position C, a definite variation in wall thickness was evident, tending towards an inverse relationship with the cup profile. The wall was significantly thicker at the 45° and 315° positions. Finally, at position D immediately beneath the troughs, the wall thickness varied inversely with wall height.

Table 14 shows how the correlation coefficient between cup profile and wall thickness became more significant as the top of the cup was approached. Because of a slight leaning out of the cup wall immediately beneath the troughs, it

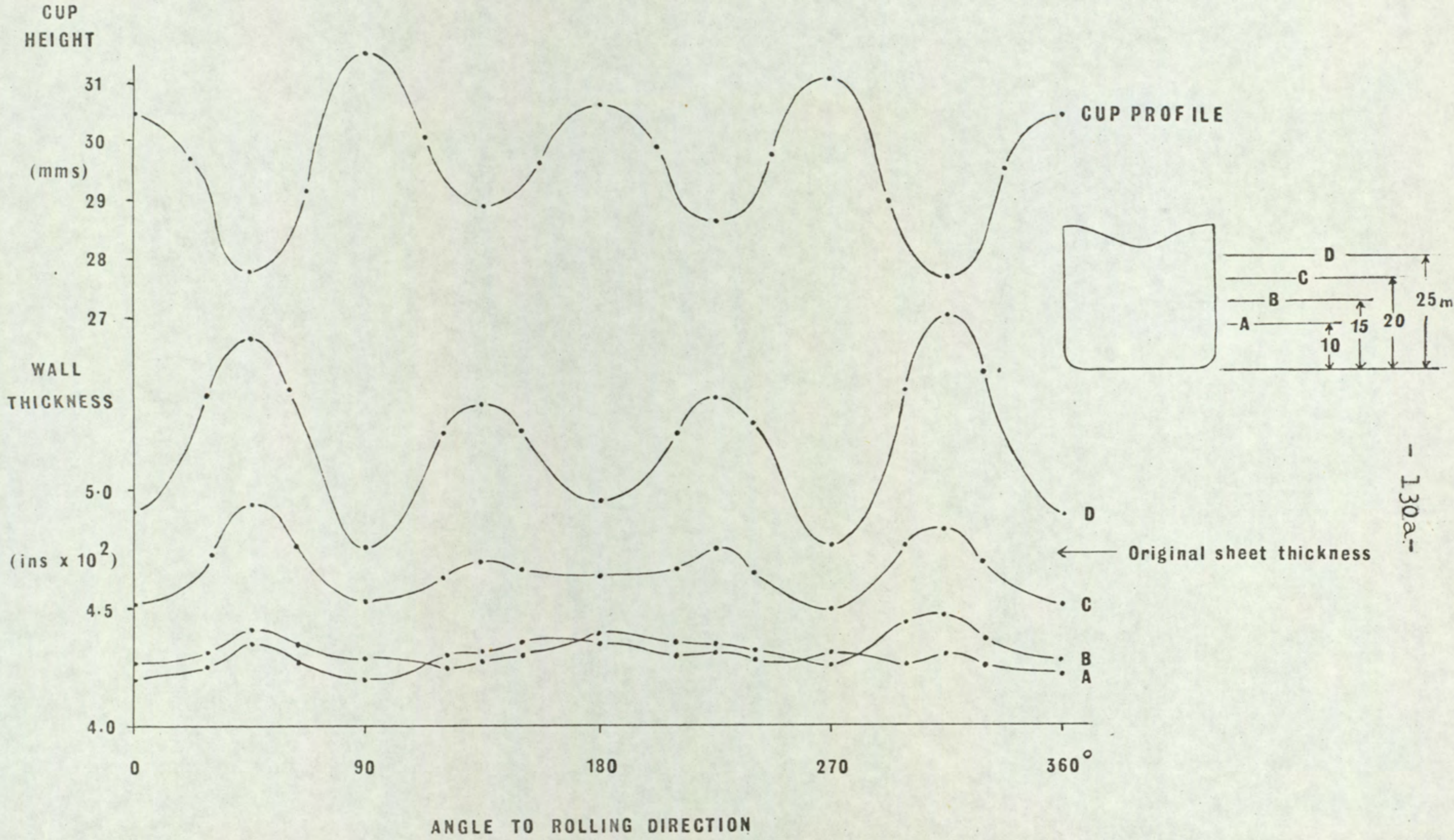


Fig. 35. Relationship between wall thickness and cup profile.

was not possible to measure variations in wall thickness higher up the cup. However it can be postulated that an inverse correlation would exist at a position immediately beneath the troughs.

TABLE 14. Correlation coefficient between cup profile and wall thickness, at four positions above the cup base

Position	Coefficient of correlation.'r.'
A. 10 mms above base	- 0.575
B. 15 " " "	- 0.707
C. 20 " " "	- 0.935
D. 25 " " "	- 0.988

These findings emphasize that in applications where a uniform component wall is essential, it may not be sufficient to eliminate the effects of earing with a trimming operation. In such applications, alternative methods of suppressing earing, by drawing with low clearances or high blankholder forces, may also produce undesirable side effects. For example, excessive die wear, scoring of the component walls or premature cup failure. The same objections apply to the possible use of differential lubrication to suppress earing. It follows that the most satisfactory means of combating undesirable earing effects is to use material essentially free of earing characteristics. Thus the incidence of earing in commercially produced mild steels is of interest.

4.5. Earing variation in commercially produced mild steels

Some information on earing variation across the width of samples 1 and 2, was available from the investigation into the effect of lubrication upon earing. This is shown in fig.36; derived by taking the average of four earing values, obtained with different lubricants, from the same width position across the respective sheets. If it is accepted that earing behaviour will not alter appreciably along a one foot length of coil, then fig.36 gives an assessment of average earing across a stabilised and a rimming sheet. Earing in the stabilised sheet was very uniform, ranging from 8.7 to 9.1%, averaging 8.92%. The rimming steel was equally uniform across the mid section, but varied at the edges of the sheet.

Earing variation, both across and along the length of four coils, was investigated by means of cupping tests taken at 2" centres across the width, at five length positions in each coil. The results are shown in figs. 37 and 38.

The general characteristics of the coils were complicated by isolated anomalies in the pattern of earing behaviour. Certain of these minor variations persisted along the coil, and are of interest. For example, the earing at a position

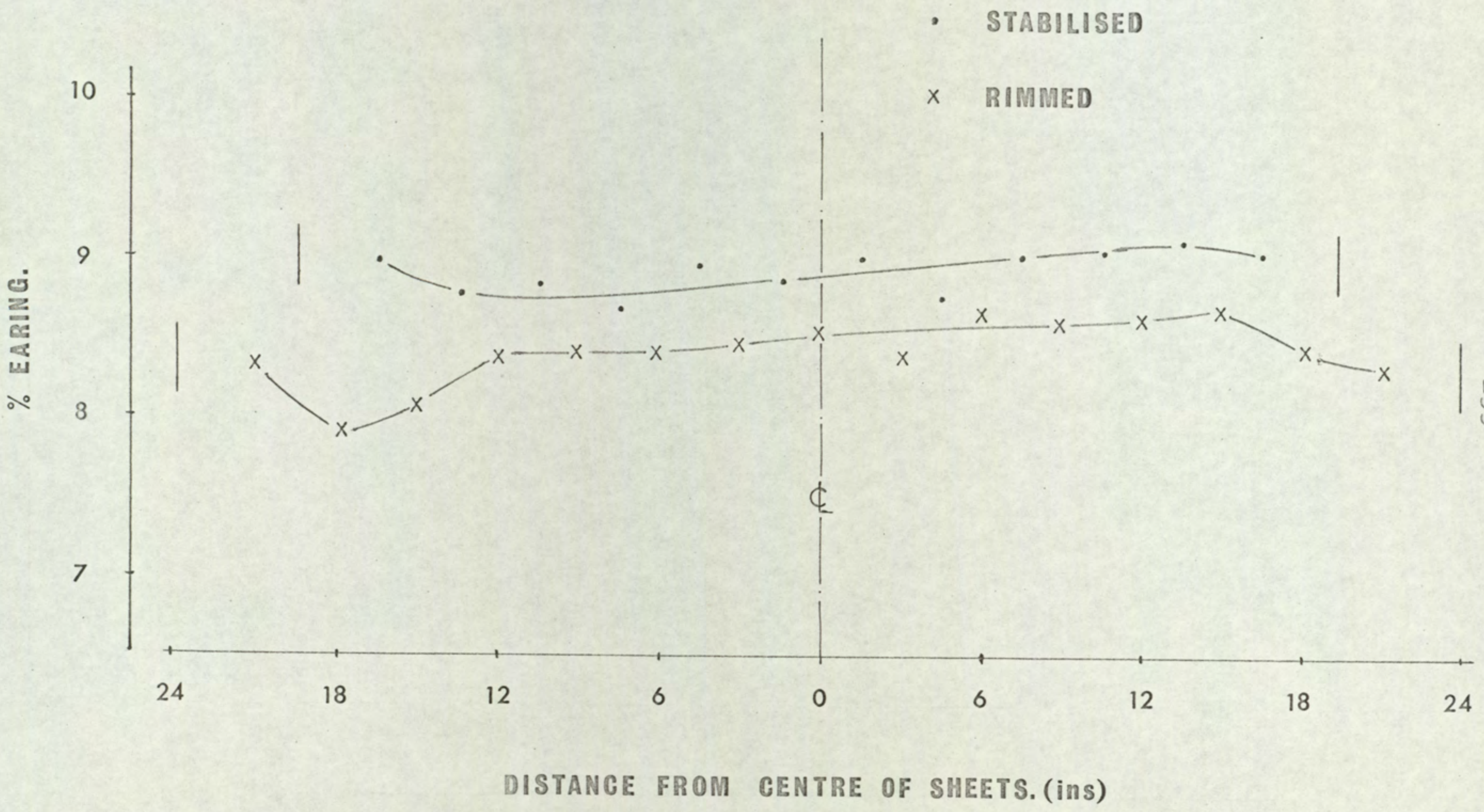


Fig. 36. Earing variation across stabilised and rimming and steel sheets

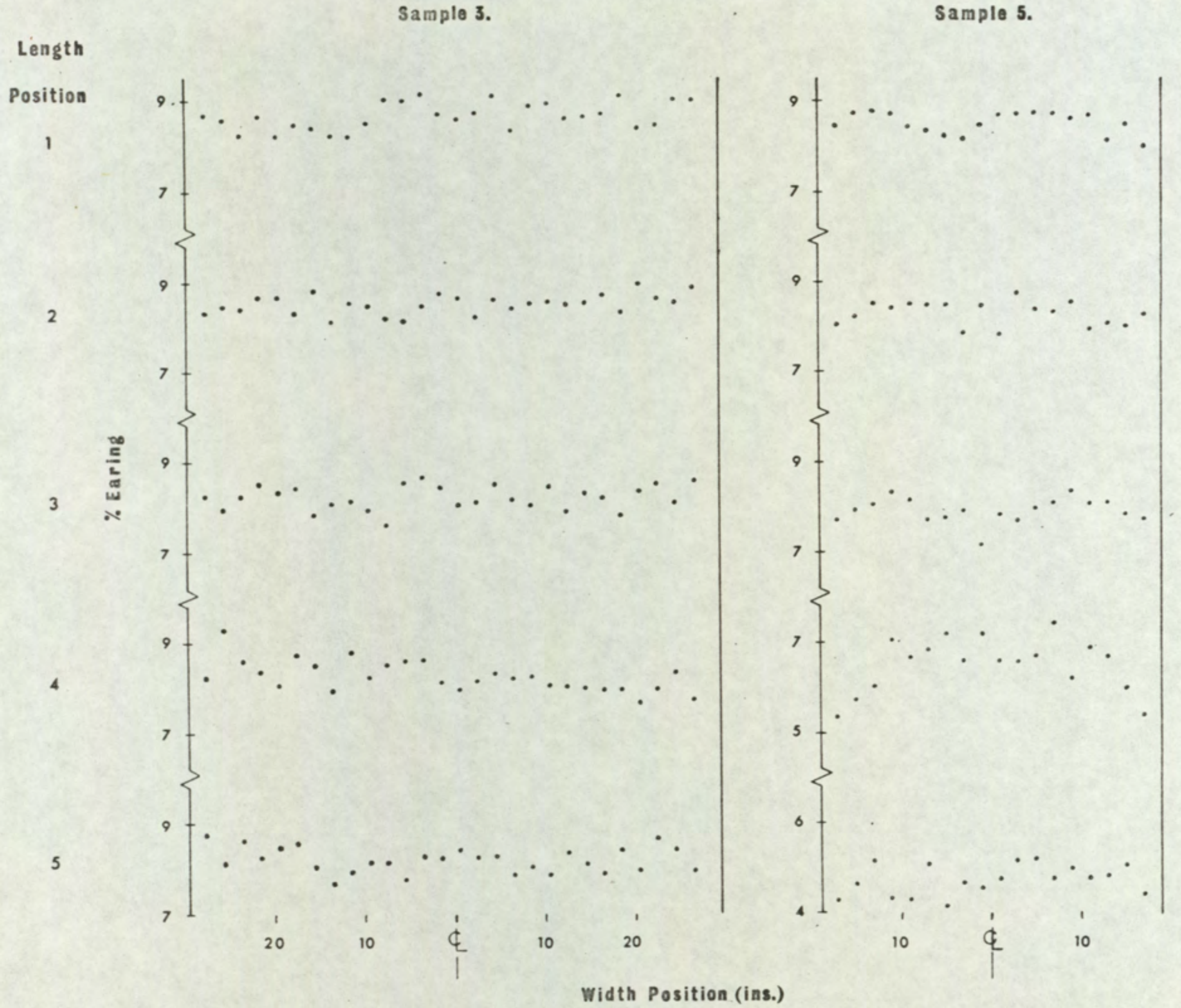


Fig. 37. Earing variation in two stabilised steel coils.

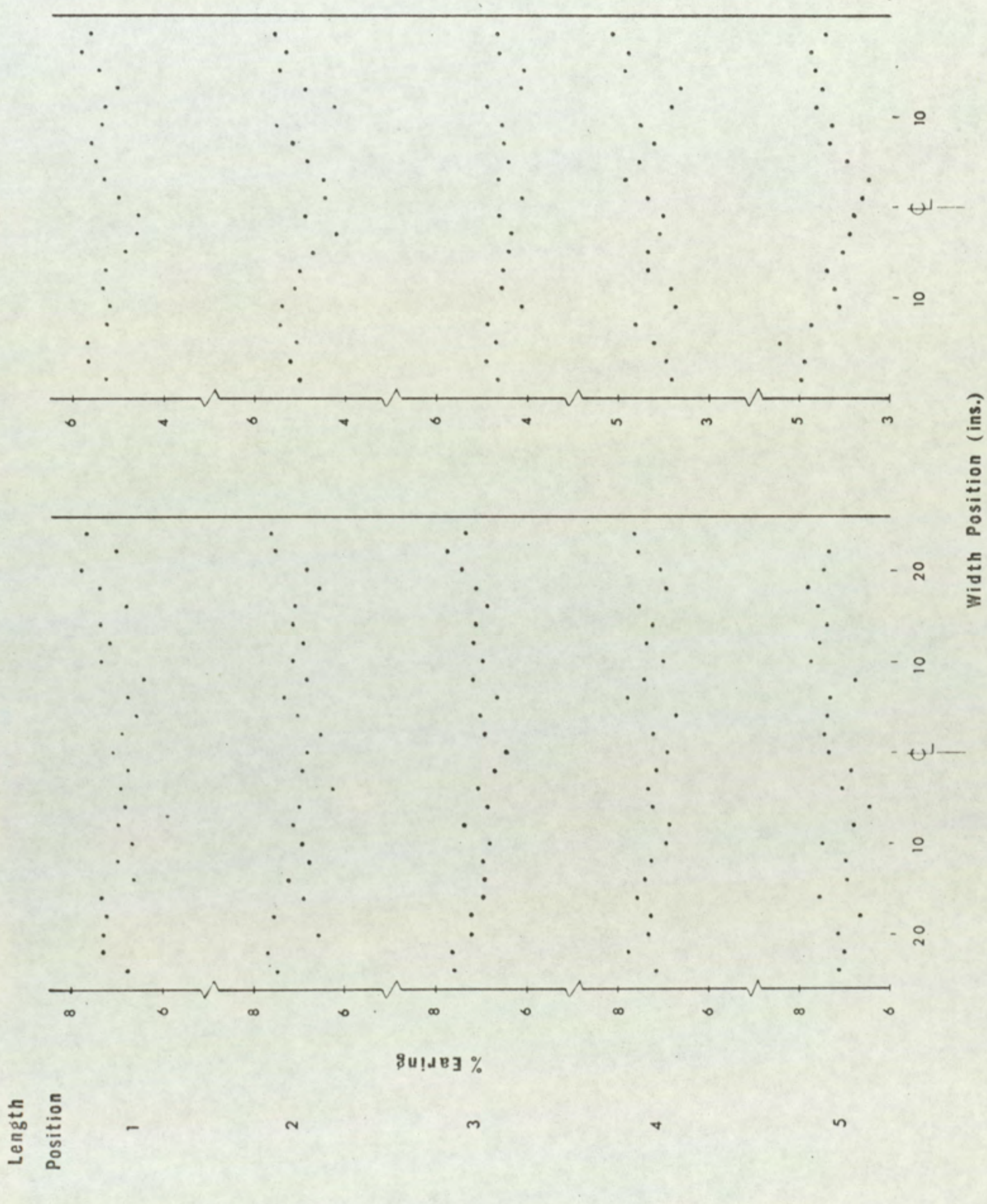


Fig. 38. Earing variation in two rimming steel coils.

ten inches from the left hand edge of sample 7, is consistently low in the second half of the coil. It is suggested that such "streaks" of deviation are probably the result of chemical heterogeneity in the material, or a minor inconsistency in processing, such as fluctuation in the cooling water spray after hot rolling.

In order to investigate general earing trends, rather than isolated variation, the earing values across each width position were grouped into five sections, and the average percentage earing for each section compared. These summarised results are shown in table 15.

Generally, the stabilised coils were more uniform across their width than the rimming, thus confirming the findings illustrated in fig.36. The rimming steels tended to yield a higher percentage earing at the edges, decreasing towards the centre. This variation at the edge can probably be attributed to the ferritic outer skin of rimming steels. The consistency of earing across the width of stabilised coils was emphasised in sample 5. Here, although the percentage earing was decreasing markedly along the length of the coil, the earing across the width was relatively uniform at each length position.

Variation of earing along the length of coils, shown in table 15, column 8, appeared to depend to a large extent upon source of supply. Samples 3 and 4, from one source,

TABLE 15. Earing, at different width and length positions, of four mild steel coils.

Sample	Position along coil	Average percentage earing at different width positions					Average earing across width %	Standard deviation across width	Coefficient of variation %
		Left hand edge section	Left hand mid section	Centre Section	Right hand mid section	Right hand edge section			
Stabilised Sample No.3. 59" x 0.042"	Start	8.51	8.52	8.93	8.74	8.83	8.70	0.31	3.56
	Quarter	8.53	8.44	8.48	8.58	8.71	8.55	0.22	2.57
	Half	8.28	8.02	8.42	8.22	8.31	8.24	0.28	3.39
	Three quarter	8.54	8.48	8.31	8.10	7.95	8.27	0.36	4.35
	End	8.46	8.08	8.21	8.01	8.31	8.20	0.29	3.53
Rimming Sample No.4. 52" x 0.043"	Start	7.21	6.85	6.89	7.05	7.37	7.08	0.34	4.80
	Quarter	7.25	7.03	6.74	7.10	7.13	7.05	0.36	5.11
	Half	7.31	7.00	6.85	7.04	7.31	7.10	0.30	4.22
	Three quarter	7.41	7.15	7.08	7.37	7.34	7.27	0.285	3.92
	End	7.10	6.92	7.22	7.35	7.45	7.21	0.35	4.85
Stabilised Sample No.5. 38" x 0.036"	Start	8.68	8.44	8.52	8.70	8.17	8.51	0.26	3.05
	Quarter	8.28	8.49	8.20	8.30	8.11	8.29	0.29	3.49
	Half	7.91	8.00	7.60	8.13	7.54	7.85	0.36	4.56
	Three quarter	6.06	6.91	6.74	6.82	6.08	6.48	0.73	11.26
	End	4.68	4.43	4.76	4.91	4.76	4.71	0.35	7.43
Rimming Sample No.7. 42" x 0.036"	Start	5.49	5.19	4.89	5.47	5.40	5.31	0.33	6.21
	Quarter	5.19	5.08	4.53	4.94	5.32	5.01	0.415	8.28
	Half	4.78	4.42	4.46	4.61	4.37	4.53	0.24	5.30
	Three quarter	4.15	4.08	4.34	4.27	4.61	4.29	0.42	9.79
	End	5.01	4.20	3.73	4.31	4.57	4.36	0.475	10.89

exhibited a greater, but more consistent earing, than samples 5 and 7 from a different source. The latter two samples varied considerably along their length, the percentage earing tending to decrease towards the end of the coils. This was particularly pronounced with sample 5. From the process history of this coil, summarised in table 2, page 66b, and the work of Whiteley and Wise, fig.9, page 33; it is probable that the low finishing temperature of this coil, particularly towards the end position, was largely responsible for the decrease in earing. However, these variations in the earing along the length, (and across the width), of coils might be due to a number of factors, namely:-

Initial raw material. Inhomogeneity, brought about by the steelmaking practice, ingot size, etc., might have a marked effect upon the earing produced in different parts of the final strip.

Processing of the strip. The process data provided by the material suppliers was essentially only a nominal record, for example, the percentage cold reduction. Both the hot rolled strip profile and cold roll profile, would affect the actual amount of cold reduction that different parts of the strip received. Again, the amount of reduction would be influenced by variations in rolling temperature and speed. Finally, variations in coiling temperature and annealing cycle, would have some effect upon earing behaviour.

The earing consistency of the first two coils, was confirmed by a statistical analysis of the complete earing data for each coil. The standard deviations and coefficients of variation of samples 3 and 4, were generally more consistent than samples 5 and 7. The coefficients of variation also confirmed that there was more variation in the earing across rimming than stabilised steels.

5. CONCLUSIONS

1. The cupping test proposed for the measurement of earing in aluminium, is suitable for use with medium gauge mild steels. Some modifications in the clearance range and lubrication specifications are recommended.
2. The relationship between percentage earing and reduction ratio is sufficiently linear for practical purposes in an earing test.
3. There is an optimum clearance between punch and die to yield maximum earing for measurement sensitivity. Increasing the reduction ratio, slightly increases this clearance.
4. The planar variations in normal anisotropy, or 'R' value, show good correlation with the profiles of deep drawn cups. This is especially the case with stabilised steels. However, with rimming steels the correlation is much more significant when 'R' values, determined in tension in a radial direction within the sheet, are transposed to the circumferential position, that is, considered in relation to the hoop stress creating earing. The circumferential relationship is the most significant for mild steels generally.
5. There is no apparent correlation between planar variations of work hardening index, 'n', and the profiles of deep drawn cups.

6. The variation in wall thickness increases towards the top of a deep drawn cup. There is a highly significant inverse relationship between cup profile, and the wall thickness immediately beneath the troughs.
7. There is more earing variation across rimming steels, particularly at the edges, than across stabilised steels. The variation of earing along the length of coils appears to differ widely, and be largely dependent upon the source of supply.
8. Generally, the earing variation tends to be greater between coils of nominally the same composition and process history, than within a given coil.

6. FUTURE WORK

The literature survey, experimental work and results, have revealed several avenues for future exploration of earing behaviour. These can be broadly divided into 'industrial' and 'academic' approaches.

In the former approach, the occurrence of earing in commercial coils requires further examination. The programme should involve a much more detailed consideration of process history than the present work, and the data be subjected to a more rigorous statistical analysis. The systematic changing of processing variables would be likely to yield information on the control of earing in mild steels, particularly if textural studies were included. It would be especially useful to concentrate on the thinner gauges of material, when the influence of certain parameters in an earing test, such as tooling geometry and blankholder forces, could also be investigated.

With the academic approach there are several possibilities. Any connection between the strain ageing and earing behaviour of mild steels, ought to be clarified. The relationships between earing and planar variations of normal anisotropy found in the present work, ought to be extended to include studies of the textures present. In a parallel field, the statistical evaluation of relationships between earing and planar variations of normal anisotropy, could be extended to other materials, for example, copper and aluminium alloys.

ACKNOWLEDGMENTS

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APPENDIX A.

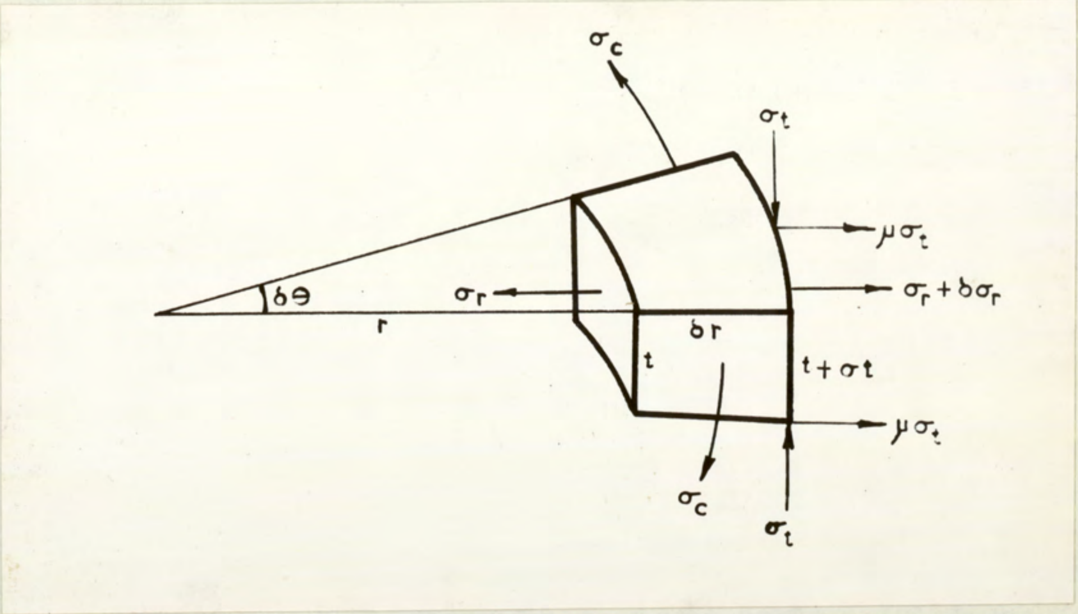

Fig. 39

The principal stresses acting on an element of the flange of a cup during deep drawing, may be defined as illustrated in fig. 39, σ_r being the radial stress, σ_c the circumferential stress, and σ_t the axial stress.

Chung and Swift(12) simplified the analysis by assuming plane stress conditions, with σ_t equal to zero. They also assumed the modified Tresca yield criterion, viz:-

$$\bar{\sigma} = \sigma_{max} - \sigma_{min}$$

Resolving forces radially (σ_r direction positive).

Assume that $\delta\theta$ is so small that $\sin \delta\theta \simeq \delta\theta$

Then half arc length $\hat{=} \quad \frac{\sin \delta\theta}{2} \times r$

$\therefore$ arc length $\hat{=} \; r\,\delta\theta$

Stress σ_r acts on area $\; t\,r\,\delta\theta$

$\therefore$ force $= \sigma_r\, t.r.\,\delta\theta.$

Similarly with radius $\;(r + \delta r).$

Arc length $= (r + \delta r)\,\delta\theta$

Stress $\sigma_r + \delta\sigma_r$ (acting in opposite direction to σ_r)

acts on area $(r + \delta r)t.\,\delta\theta$

$\therefore$ Force $= (\sigma_r + \delta\sigma_r)(r + \delta r)t.\,\delta\theta.$

Resolving circumferential forces in a radial direction.

Stress component $= \sigma_c \, \frac{\delta\theta}{2.}$

Stress acts on area $\; t\,\delta r$

$\therefore$ Force $= \sigma_c \left(\frac{\delta\theta}{2}\right) t.\,\delta r$

but there are two of these components, one either side of segment.

$\therefore$ Circumferential force resolved radially

$$= (\sigma_c\,\delta\theta)t.\,\delta r.$$

Assumed that flange thickness variation is negligible, then for equilibrium:-

$$\sigma_r\, t\, r\,\delta\theta - (\sigma_r + \delta\sigma_r)(r + \delta r)t\,\delta\theta + (\sigma_c\,\delta\theta)t.\,\delta r = 0$$

Cancelling by $\; t\,\delta\theta$

$$\sigma_r\, r - (\sigma_r\, r + r\,\delta\sigma_r + \sigma_r\,\delta r + \delta\sigma_r\,\delta_r) + \sigma_c\,\delta r = 0$$

but if $\delta\sigma_r$ and δ_r are small, then $\delta\sigma_r\,\delta r$ is negligible.

$$\therefore \; - r\,\delta\sigma_r - \sigma_r\,\delta r + \sigma_c\,\delta r = 0.$$

or $\quad - r\,\delta\sigma_r - \delta r(\sigma_r - \sigma_c) = 0.$

$$\therefore \quad \frac{\delta\sigma_r}{\delta r} = -\frac{(\sigma_r - \sigma_c)}{r} \qquad \text{------ (1).}$$

Since $\bar{\sigma} = \sigma_{max} - \sigma_{min}$

Then $\sigma_r > \sigma_t > \sigma_c$ (σ_c being compressive considered negative).

$\therefore \bar{\sigma} = \sigma_r - \sigma_c$

$\therefore Y_m = \sigma_r - \sigma_c$ - - - - - - -(2)

Substituting (2) into (1)

$$\delta\sigma_r = -Y_m \frac{\delta r}{r}$$

Integrating between limits of R and r, where R = original radius of blank and r = current radius of blank

$$\delta\sigma_r = -Y_m \int_r^R \frac{\delta r}{r}$$

i.e. $\sigma_r = -Y_m \, l_n \frac{R}{r} + C$ - - - - - - - -(3)

Where C is the integration constant, determined from the boundary condition that when R = r, then

$l_n \frac{R}{r} = 0$ and $\sigma_r = C.$

Assuming that the blankholder force acts only round the circumference of the blank, then C depends upon the frictional forces at this point.

$$\therefore C = \frac{2\mu\sigma_t}{2\pi R t} = \frac{\mu\sigma_t}{\pi R t} \quad ---- (4)$$

$$\therefore \sigma_r = -Y_m \, l_n \frac{R}{r} + \frac{\mu\sigma_t}{\pi R t} \quad ------- (5)$$

and from the Tresca criterion:-

$$\sigma_c = \sigma_r - Y_m.$$

<u>NOTE</u> R, t and possibly σ_t can all vary during the process.

APPENDIX B.

The degree of correlation between two sets of data may be measured by the product moment correlation coefficient; defined as

$$\text{Correlation Coefficient } r = \frac{\frac{1}{N} \sum (x - \bar{x})(y - \bar{y})}{\sigma_x \quad \sigma_y}$$

where $\bar{x}$ and $\bar{y}$ are respectively the mean of all the x and y values, and σx and σy are respectively the standard deviations of all the x and y values.

An r value of + 1 denotes perfect correlation between x and y, an increasing x being associated with an increasing y. When $r = -1$, this denotes a perfect inverse correlation, an increasing x being associated with a decreasing y. When $r = 0$, there is no relation between the two sets of data, x and y, which are not correlated. Intermediate values of r indicate the trend towards a relationship.

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