THE SANDWICH ROLLING OF THIN HARD STRIP.

by

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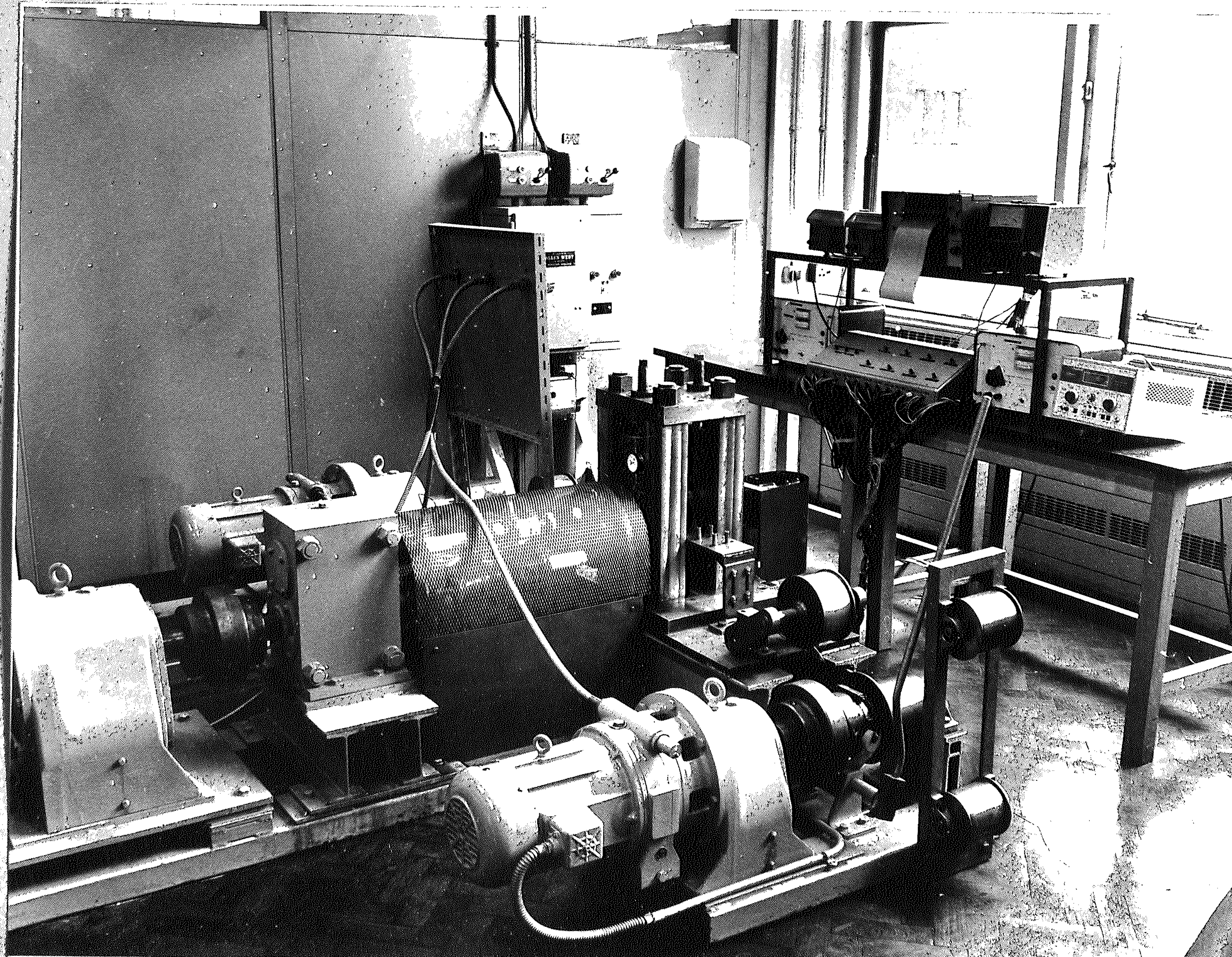
The fact that the clad is discarded usually in practice makes the sandwich rolling process economically unattractive except for the production of thin sheets of very expensive metals. It is desirable therefore that the clad material should be cheap and easily recoverable. Plastic appears to satisfy these requirements and the possibility of using it as a clad was briefly considered.

It was concluded that a considerable reduction in the roll force and torque can be achieved by carefully selecting the process parameters, the most significant being the clad-sandwich thickness ratio, the clad-matrix hardness ratio, and the frictional conditions at the clad-matrix interface. The results of experiments involving the use of plastic clads were encouraging and further work is necessary in this direction.



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NOMENCLATURE.

P	The roll force.
T	The roll torque.
σ	Stress in the workpiece.
τ	Shear stress.
q	Additional stresses induced in the clad and matrix of the sandwich as a result of cladding.
μ	The coefficient of friction.
H	Initial thickness of the workpiece.
h,H	Final thickness of the workpiece.
$\bar{Y}$	Mean yield stress of the workpiece.
Y	Yield stress of the workpiece.
k	Yield stress in shear of the workpiece.
D	The roll diameter.
R,Ro	The roll radius.
R'	The radius of the deformed arc of contact.
θ	The angle of bite.
r	Pass reduction.
w	Width of the workpiece.
δ	Draft.
B	Proportion of clad in the sandwich.
p	Vertical stresses.

Suffices.

m,h	The hard metal.

Siffices contd.

c,s	The soft material.
i	Entry to the zone of deformation.
o	Exit to the zone of deformation.
x	The horizontal plane, normal to the rolls.
y	The vertical plane.
z	The horizontal plane parallel to the rolls.
p	Plane strain condition.
f	Front tension.
b	Back tension.
n	The neutral plane.

1. INTRODUCTION.

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The modern rolling mill probably evolved from the crude, wooden, hand-driven mills used for the extraction of sugar in the early part of the fifteenth century. Some two hundred years later, mills with cast iron rolls mounted in wooden frames were being used for rolling soft, non-ferrous metals such as lead, brass and tin. It would have been difficult to roll ferrous metals on this type of mill, since it was driven by a water wheel. Development in this direction had to wait until a more suitable source of power was available. The advent of the steam engine helped to establish the rolling mill in a dominant position in industry which it still maintains.

Practical experience was far in advance of theory, as is the case in most technological innovations. The early mill user knew very little about the fundamental principles involved in the rolling process and had to depend on experience gained often through expensive failures. Even then, when a new situation arose, such experience was often found to be hopelessly inadequate.

In the last sixty years or so, major efforts have been made to understand the mechanics of the rolling process and to develop theories which enable the roll separating force, torque, and power requirements to be predicted for the benefit of the rolling mill manufacturer and user. An exact mathematical analysis of the rolling process is difficult and numerous assumptions are made often in order to derive simple equations which can be applied readily, particularly in industry where the access to a computer may be limited. Efforts have been made to develop rolling theories which take into account the effect of roll flattening often encountered in the rolling of thin hard materials.

The increasing demand for more difficult materials such as titanium and the high carbon steels in very thin gauges has provided the stimulus for the development of more sophisticated rolling mills including the Sendzimir mill, the C-B-S. mill, and the Pendulum mill. The C-B-S.

and the Pendulum mills are still at the development stage and the Sendzimir mill is often expensive and requires a high level of production to justify the capital outlay. Furthermore, the necessity to apply a high back tension to ensure that the product is of good shape often imposes a limit on the width of the material that can be rolled on the mill. Thin hard sheets can be produced at a lower cost on an existing mill by rolling them sandwiched between sheets of softer metal. The method has been applied to the production of titanium alloy sheets on a commercial scale as reported by Arnold and Whitton[1] and the results of their investigation showed that a reduction in the roll separating force of up to 60 percent could be achieved.

The object of this investigation was to determine the important parameters on which the success of the process depends and the conditions under which a reduction in the rolling load can be achieved. Most of the previous investigators have ignored the effect of cladding on the roll torque, since the reduction in the roll separating force was considered to be more important. However, the roll torque may increase as a result of cladding to the extent that it may become the limiting factor which determines the amount of reduction possible in one pass. For this reason, it was decided to include the roll torque in the list of parameters which were measured. The applicability of the sandwich method to the rolling of high carbon steels and nimonic alloys was investigated.

Since the clad material is normally discarded after use, it is desirable that it should be inexpensive. The use of ferrous and non-ferrous clads was examined and the possibility of using non-metal clads, for instance, plastic, was briefly investigated. The theoretical aspects of the process were studied and the extent to which the results of the investigation can be applied to the rolling of permanently cladded materials was considered.

The development of sandwich rolling theory is based on the assumption that both the clad and the matrix are deformed jointly. The sandwich can be treated then as a homogeneous material having the same dimensions and a mean yield stress value which can be determined from the individual yield stresses of the component materials and the proportion of the clad material in the sandwich. Any conventional rolling theory can then be applied. For this reason, and because most of the parameters which govern the conventional rolling process are also significant in sandwich rolling, the development of the sandwich rolling theories as well as the conventional rolling theories will be reviewed.

2. THE RELEVANT THEORY OF PLASTIC DEFORMATION.

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2.1. Postulates of the theory of plastic deformation.

The process of deforming a material plastically by the application of external forces is complex and does not lend itself to exact mathematical treatment. Many assumptions have to be made in respect of the properties of the material and the mechanics of the process in order to develop meaningful theoretical equations of plastic flow. Despite the simplifying assumptions, the results of theoretical analyses are often far too complex to be of much practical use and more assumptions are usually necessary in order to apply the results in practice. Some of the basic assumptions which apply to flat rolling are listed below.

(i) There is no change in the volume of a material undergoing plastic deformation.

(ii) Hydrostatic stress does not influence yielding.

(iii) The Bauschinger effect is negligible and there is no difference between the yield stress of the material in pure tension and pure compression.

(iv) The material is isotropic, that is, yielding properties in all directions are identical.

(v) Stresses due to thermal gradients in the material are insignificant.

(vi) The effect of the temperature caused by deformation on the yield stress of the material is negligible

(vii) The rate of deformation does not influence yielding.

(viii) The elastic component of the total strain is is small compared with the plastic component.

(ix) The material is rigid plastic, that is, it is inelastic and does not work-harden.

Most of the assumptions accord well with experimental evidence, or do not influence the results of theoretical analyses significantly. However, assumptions (vi) to (ix) often are not valid in flat rolling, and indeed many other metalworking processes. The rate of straining may be significant in high speed, hot working processes, the elastic and plastic strains may be of the same order, for example in temper rolling, and most metals are not rigid plastic. However, approximate corrections can be made in the development of metalworking theory to reduce the errors emanating from the assumptions.

2.2. The criterion of yielding.

When a ductile material is subjected to an external force which induces in it a simple uniaxial state of stress, the material will start to yield when the induced stress attains a critical value - the yield stress of the material under the loading conditions. However, in most metalworking processes, the state of stress is complex and it is more difficult to predict the onset of yielding. Many empirical relationships have been developed but only the most widely accepted ones will be considered here.

2.2.1. The maximum shear stress criterion.

Tresca, as a result of experimental studies on the extrusion process in 1864, proposed that the onset of yielding of a ductile material under a complex state of stress does not depend on the individual values of the component stresses but occurs when the maximum shear stress attains a critical value. That is, for instance, in a triaxial state of stress consisting of principal stresses σ_1, σ_2, σ_3 where $\sigma_1 > \sigma_2 > \sigma_3$ yielding will occur when

$$\sigma_1 - \sigma_3 = Y_0 \qquad (2.1)$$

where Y_0 is the yield stress of the material under a uniaxial state of stress.

Equation (2.1) can be modified appropriately for a non-principal stress state. It can also be expressed in terms of the yield stress in shear of the material:

$$\sigma_1 - \sigma_3 = 2k \qquad (2.2)$$

In effect,

$$k = \frac{Y_0}{2} \qquad (2.3)$$

2.2.2. The maximum shear strain energy criterion.

Tresca's yield criterion is unsatisfactory because it ignores the influence of the intermediate stress of a triaxial state of stress on yielding. The results of experiments by Lode[2] and Taylor and Quinney[3] strongly indicate that the effect of the intermediate shear stress is significant. Moreover, in some problems of plasticity, it may not be possible to assess which stress is the largest or smallest. The maximum shear strain energy criterion, often attributed to Maxwell, von Mises, Hencky, or Huber, takes the intermediate stress into account and it is not necessary to know the relative magnitude of the stresses. It states that yielding will occur when:

$$[\sigma_1 - \sigma_2]^2 + [\sigma_2 - \sigma_3]^2 + [\sigma_3 - \sigma_1]^2 = 2 Y_0^2 \qquad (2.4)$$

or in terms of the yield stress in shear of the material:

$$[\sigma_1 - \sigma_2]^2 + [\sigma_2 - \sigma_3]^2 + [\sigma_3 - \sigma_1]^2 = 6K^2 \qquad (2.5)$$

That is,

$$K = \frac{\sqrt{3}}{3} Y_0 \qquad (2.6)$$

Although the maximum shear ~~strain~~ energy criterion has been developed largely from the results of experimental observations, it can be derived by consideration of the potential energy of elastic distortion, that is, the difference between the total elastic strain energy and the strain energy tending to produce volume change. When the potential energy of distortion attains a critical value, yielding will occur.

2.2.3. The validity of the yield criteria.

The results of numerous experimental investigations notably by Lode[2] Taylor and Quinney[3] and Siebel[4] show that the maximum shear strain energy criterion is more accurate than the maximum shear stress criterion. However, the latter is often preferred because of its simplicity and because of the safety factor resulting from its use in design calculations, since it underestimates the stress at which yielding (or failure) will occur.

2.3. Yielding in plane strain.

When a body is deforming plastically under a complex state of stress, for instance, the principal stresses σ_1, σ_2, σ_3, the principal stresses and strains are related as follows:

$$\begin{aligned} \varepsilon_1 &= \frac{1}{E_p}\left[\sigma_1 - 0.5(\sigma_2+\sigma_3)\right] \\ \varepsilon_2 &= \frac{1}{E_p}\left[\sigma_2 - 0.5(\sigma_1+\sigma_3)\right] \\ \varepsilon_3 &= \frac{1}{E_p}\left[\sigma_3 - 0.5(\sigma_1+\sigma_2)\right] \end{aligned} \qquad (2.7)$$

where E_p is the plastic strain modulus. When plastic flow is restricted to a single plane so that the strain in one direction is equal to zero, deformation is taking place under plane strain conditions.

It follows from equation (2.7) that:

$$\sigma_2 = \frac{\sigma_1 + \sigma_3}{2} \qquad (2.8)$$

Hence, from equation (2.4),

$$\sigma_1 - \sigma_3 = \frac{2}{\sqrt{3}} Y_0 \qquad (2.9)$$

and from equation (2.6),

$$\sigma_1 - \sigma_3 = 2k \qquad (2.10)$$

It will be noted that equations (2.2) and (2.10) are identical for plane strain conditions. In plane strain deformation, it is more appropriate to express the yield criterion in terms of the yield stress in shear of the material, since deformation occurs in pure shear.

Whereas the maximum shear stress criterion implies that the yield stress in uniaxial strain and in plane strain are identical, the maximum shear strain energy criterion shows that they differ by a factor of 1.15. The latter is found to be more correct in practice.

3. A REVIEW OF THE PUBLISHED WORK ON FLAT ROLLING.

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3.1. Introduction.

A considerable proportion of metal sections, tubes, plates and sheets used in engineering either as finished products or as raw materials for other metalworking processes, are produced by rolling. It is not surprising therefore, that rolling has occupied a dominant position in industry for several hundred years. Despite this. a fundamental understanding of the process was lacking until the last sixty years or so. However, in this period, a considerable effort has been made to develop theories for predicting the rolling parameters which are important from the point of view of the design and operation of a rolling mill. Furthermore, the causes of such rolling defects as edge cracking, bad shape, thickness variation, and poor surface finish are now known fairly well. In the review of the literature on flat rolling which follows, emphasis will be placed on the development of hot and cold flat rolling theories, but recent developments in the practice of flat rolling will also be discussed briefly.

3.2. The calculation of the roll separating force.

The methods which have been adopted for the analysis of the rolling process and the determination of the roll separating force can be classified into seven broad categories:

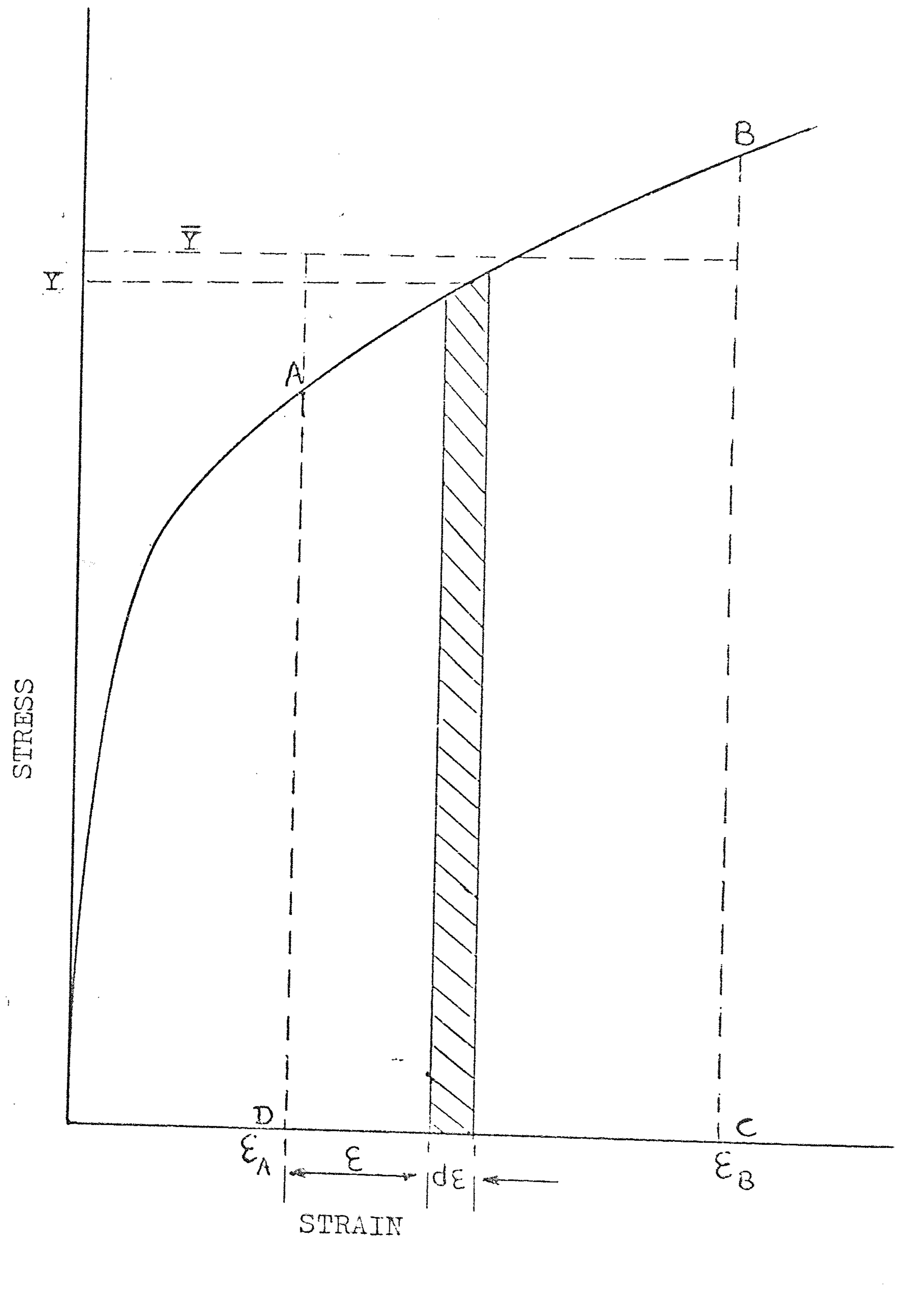


FIGURE 1 THE STRESS-STRAIN CURVE FOR THE DETERMINATION OF THE ROLL FORCE FROM THE WORK OF DEFORMATION.

3.2.1. The determination of the roll force from the work of deformation.

When a work-hardening material is compressed from an initial strain ε_a to a final strain ε_b, the work of deformation is equivalent to the area under the stress-strain curve within the appropriate strain limits. The area is represented by ABCD in figure 1 and is equal to:

$$W = \int_{\varepsilon_a}^{\varepsilon_b} Y \, d\varepsilon \qquad (3.1)$$

for unit Volume

By equating this work to the work done by a force P in compressing the material from strain ε_a to ε_b, it can be shown that:

$$P = w.L.\bar{Y} \qquad (3.2)$$

where $\bar{Y}$ is the yield stress of the material,

w is the width,

and L is the length of the deformation zone.

The deformation in well lubricated cold rolling is similar to that which occurs in plane strain compression and equation (3.2) is commonly used to estimate the roll separating force, by replacing $\bar{Y}$ with $\bar{Y}_p$, the mean yield stress of the material in plane strain. That is,

$$P = w.L.\bar{Y}_p \qquad (3.3)$$

Equation (3.3) often underestimates the roll separating force because it ignores the contribution of friction.

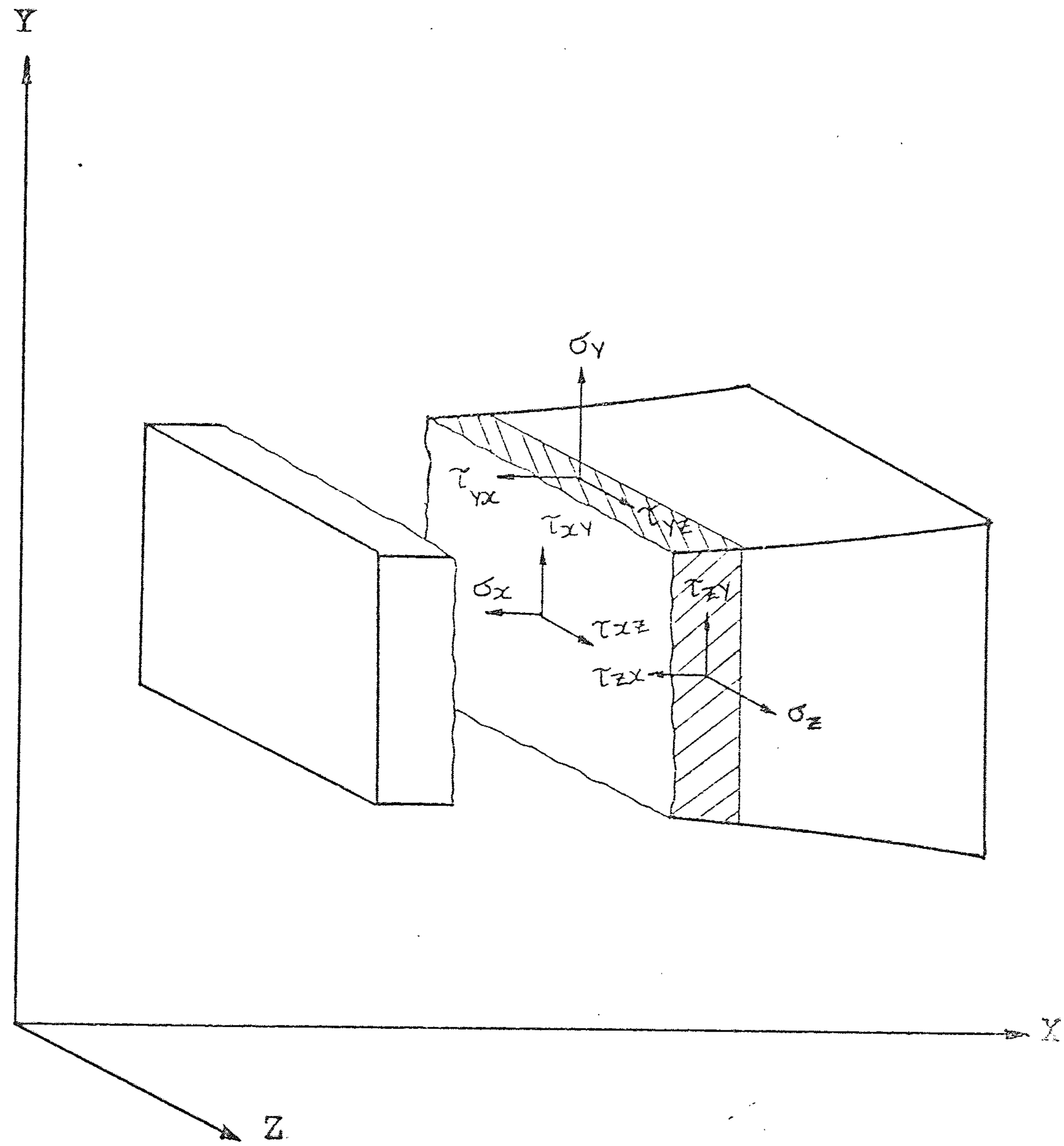


FIGURE 2   A THREE - DIMENSIONAL REPRESENTATION OF THE STATE OF STRESS IN THE ROLL GAP.

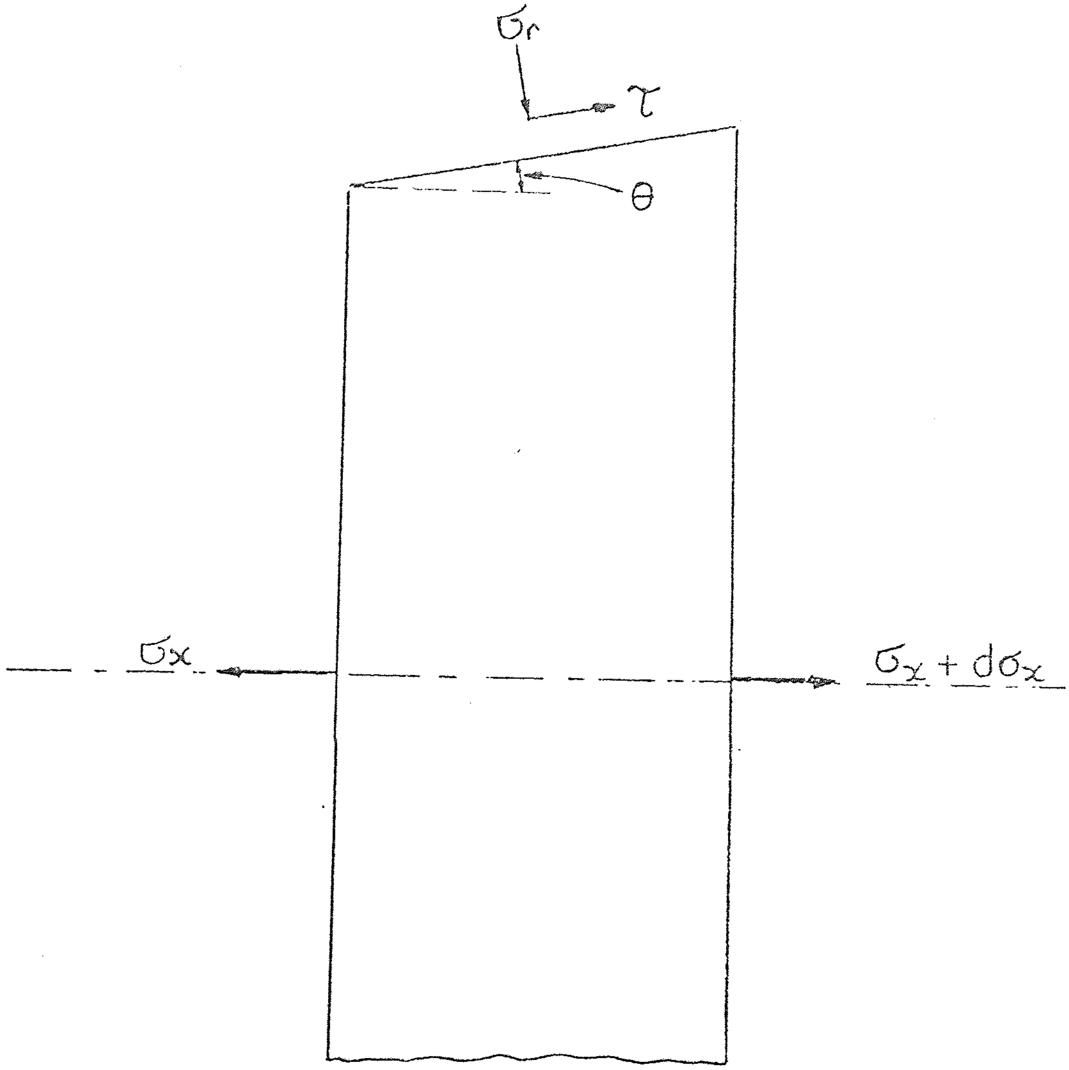


FIGURE 3 THE STRESSES ACTING ON AN ELEMENT IN THE ROLL GAP. (EXIT ZONE)

In practice, a correction factor of roughly 20 percent is often introduced so that,

$$P = 1{\cdot}2\,wL\,\bar{Y}_p \qquad (3.4)$$

3.2.2. The determination of the roll force by the by the equilibrium approach.

A considerable proportion of the published work on flat rolling theory, and indeed many other metalworking processes, has been based on the consideration of the equilibrium of forces acting on an element of the material in the deformation zone.

From the consideration of the three mutually perpendicular directions shown in figure 2, the equilibrium of the forces acting on the shaded element can be written in the general form:

$$\begin{aligned} &\text{X-direction} \quad \frac{d\sigma_x}{dx} + \frac{d\tau_{xy}}{dy} + \frac{d\tau_{xz}}{dz} = 0 \\ &\text{Y-direction} \quad \frac{d\tau_{xy}}{dx} + \frac{d\sigma_y}{dy} + \frac{d\tau_{yz}}{dz} = 0 \qquad (3.5) \\ &\text{Z-direction} \quad \frac{d\tau_{xz}}{dx} + \frac{d\tau_{yz}}{dy} + \frac{d\sigma_z}{dz} = 0 \end{aligned}$$

noting that $\tau_{xy} = \tau_{yx}$ etc. .

Equations (3.5) can be simplified considerably by making certain assumptions:

(i) The directions X,Y,Z coincide with the directions of the principal stresses.

(ii) The material does not spread in the lateral direction. That is $\varepsilon_z = 0$.

(iii) The stresses are evenly distributed across any vertical cross-section, so that each element is identical to any other element in the cross-section.

(iv) τxy is small compared with σx and σy.

Equations (3.5) then reduce to

$$\frac{d\sigma_x}{dx} + \frac{d\tau_{xy}}{dy} = 0; \quad \frac{d\tau_{xy}}{dx} + \frac{d\sigma_y}{dy} = 0 \qquad (3.6)$$

By consideration of the equilibrium of the forces in the roll gap, see Figure 3 it can be shown that equation (3.6) is equivalent to

$$\frac{d}{d\theta}\left[h\sigma_x\right] = D\cos\theta\left[(\sigma_y \pm \tau\tan\theta)\tan\theta \pm \tau\right] \qquad (3.7)$$

The top sign in equation (3.7) refers to the exit zone and the bottom sign refers to the entry zone of the arc of contact, in accordance with the usual rolling convention.

It is usual to assume that slipping friction operates between the rolls and the workpiece. Then,

$$\frac{d}{d\theta}\left[h\sigma_x\right] = \frac{D\cos\theta\,\sigma_y\left[\tan\theta \pm \tau\right]}{\left[1 \mp \mu\tan\theta\right]} \qquad (3.8)$$

Equation (3.8) is combined with the maximum shear strain energy criterion to obtain

$$\frac{d}{d\theta}\left[h\sigma_x\right] = \frac{D\cos\theta\left[\sigma_x + Y_p\right]\left[\tan\theta \pm \mu\right]}{\left[1 \mp \mu\tan\theta\right]} \qquad (3.9)$$

An exact solution of equation (3.9) is difficult and many authors have made additional assumptions in order to obtain approximate solutions. The method of solution and the assumptions made are the major points of difference between the many solutions which have been proposed.

One of the earliest solutions was obtained by Siebel[5]. He assumes that

(a) the pressure distribution along the arc of contact is constant and equal to the mean yield stress in plane strain. That is,

$$\tau = \mu \bar{q}_p \tag{3.10}$$

(b) the angle of bite is small, so that,

$$\begin{aligned} \cos\theta &\approx 1 \\ \sin\theta &\approx \theta \\ \tan\theta &\approx \theta \end{aligned} \tag{3.11}$$

(c) the arc of contact is circular.

(d) the vertical pressure is approximately equal to the roll pressure.

(e) the deformation is homogeneous and plane sections remain plane throughout deformation.

Following these assumptions, it is now possible to integrate equation (3.9) to obtain the pressure distribution. The roll separating force is obtained by integrating the pressure distribution over the arc of contact.

It is not surprising that Siebel's solution is often found to underestimate both the pressure distribution and the roll force. The pressure distribution at any point along the arc of contact is always higher than the yield stress in plane strain, except, possibly at the planes of entry and exit of the zone of deformation. In the rolling of thin, hard materials the peak pressure may be considerably higher than the yield stress, as a result of roll flattening.

von-Karman[6] makes the same assumptions as Siebel except that the pressure distribution along the arc of contact is constant. He develops an equation similar to (3.9) which he solves by step integration along the arc of contact. The solution is simplified considerably by using graphs prepared by Trinks[7] for a wide range of rolling parameters.

Smith[8] solves equation (3.9) by assuming that the arc of contact is not circular but parabolic and can be represented by the equation

$$h = h_0 + R\theta^2$$

This assumption also follows from equation (3.11). Smith's equation is similar to von-Karman's equation and can be solved only graphically by Trinks' method or by step integration. Underwood[9] has shown that the error introduced by the assumption of a parabolic arc of contact is small.

Tselikov[10] replaces the arc of contact with:

(a) a single chordal plane.

(b) a chordal plane each for the entry and exit zones.

Equation (3.9) is simplified considerably as a result and can be integrated without difficulty. The assumption of a planar arc of contact may lead to errors unless the radius of the roll is large compared with the length of the arc of contact.

Orowan[11] discards most of the assumptions made by the previous authors and integrates equation (3.20) step-by-step along the arc of contact.

Bland and Ford[12] make the same assumptions as von-Karman and further mathematical simplifications. The simple equations which they develop have been found in practice to predict the roll force and torque within acceptable limits of accuracy, except for the rolling of annealed strip when high back tension is applied. A method of correction for this rolling condition has been proposed by Bland and Sims[13]. Graphical solutions of the Bland and Ford equations have been developed by Ford, Ellis and Bland[14] and Lianis and Ford[15].

Other solutions of equation (3.9) have been developed by many authors[16 - 21] and a modified solution has been developed by Hoffman and Sachs[108] for steckel rolling in which the material is pulled through idle rolls. Most of the theories discussed so far predict the roll separating force to within 5 - 15 percent of measured values for a wide range of cold rolling parameters, but may grossly overestimate the roll force when applied to hot rolling. The errors are due to the assumptions made in deriving equation (3.9), particularly that,

(a) slipping friction operates between the rolls and the workpiece. This is not valid for certain cases of cold rolling and is certainly not valid for most cases of hot rolling. The frictional shear stress at the tool- workpiece interface may attain the limiting value - the yield stress in shear of the material. The material then sticks to the rolls and deformation continues by internal shearing.

(b) Most authors assume that deformation is homogeneous, that is, the layers of the material across its thickness deform at the same rate and plane sections remain plane throughout deformation. This is not valid for hot rolling, particularly of thick stock, when considerable internal distortion may occur.

Orowan[22] discards both assumptions and develops comprehensive equations based on the solution by Prandtl[26] for the deformation of a material between rough parallel dies and Nadai's extension[27] of the solution to rough inclined dies. Nadai's solution is for the flow of the material towards the apex of the dies. This is analogous to the exit zone of the arc of contact in flat rolling and is therefore applicable. Orowan assumes that the solution is valid also for the entry zone where the direction of flow of the material is away from the apex. This has been shown to be valid by Lee[28]. The most common objections to Orowan's "exact" theory are:

(a) The assumption that the material does not spread in the lateral direction. This is valid when the width of the material is more than about eight times its thickness. In hot rolling, considerable spread may occur. Approximate methods of taking it into account in the formulation of rolling theory have been developed by many authors[23-25, 29-33].

(b) Nadai's equations on which Orowan's analysis was based, are applicable only to cases where the angle between the plates is small. Orowan's equations, therefore, are applicable only to cases where the angle of bite is small. Most cases of cold rolling fall into this category, but in the hot rolling of thick stock, large reductions per pass are often achieved and the assumption of a small angle of bite may lead to considerable errors.

(c) Orowan's equations are unwieldy and unsuitable for use in cold rolling practice. The equations have been re-written by Cook and Larke[34] in a form suitable for solution on a computer. The simplified theories of Bland and Ford[12] and Sims[18] for cold rolling and Orowan and Pascoe[29] and Sims[18] for hot rolling are often preferred unless very accurate results are required.

Most roll force equations can be written in the form:

$$P = w.L.\bar{Y}_p.f_p \qquad (3.12)$$

where w is the width of the material,

L is the length of the arc of contact,

and f_p is a function which takes into account friction and ~~the inhomogeneity of~~ redundant deformation.

This form is convenient because it enables the relative accuracies of the various theories to be assessed by comparing the values of f_p [37].

3.2.3. <u>Energy method of determination of the roll force.</u>

The total power required for rolling is given by the sum of

(a) The power required for homogeneous rolling.

(b) The power supplied to the coiler and decoiler.

(c) The power losses due to friction in the bearings and between the rolls and the material.

(d) The power losses due to redundant shearing in the material.

(e) The power losses in the drives.

By equating the sum of the above components to the total power supplied to the drives, it is possible to derive the roll force, torque, the coefficient of friction, and the maximum bite angle. However, the method is very involved and often leads to considerable errors due to the numerous assumptions which are usually made in deriving the various components of the energy balance equation[38,39].

3.2.4. Semi-empirical methods of the determination of the roll force.

One of the earliest rolling theories was developed by Ekelund[40]. Based on many assumptions, he derives an equation of the form:

$$P = w \times L \times \bar{Y}_p \times f_E \qquad (3.13)$$

where

$$f_E = 1 + \frac{1.6\mu L - 1.2(h_i - h_o)}{h_i + h_o}$$

and

$$\mu = 0.8[1.05 - 0.005T]$$

T is the rolling temperature in degrees centigrade. The numerical factors in equation (3.13) are chosen to give the best correlation with experimental measurements. Although Ekelund's equations were derived originally for hot rolling, they can be modified without difficulty for cold rolling when no tension is applied. The equations have been tested by Ford[41] and Cook and Larke[34] for a wide range of rolling parameters and found to be accurate within acceptable limits. For this reason, and because of the simplicity of the equations, Ekelund's theory is still widely used in industry, despite the more accurate theories which have been developed more recently.

The practical application of most rolling theories requires the knowledge of the yield stress of the material and the coefficient of friction, the extent of roll flattening, and so on. None of these factors can be determined easily and a considerable effort has been made by many authors to develop rolling theories which do not require the knowledge of these factors. One such theory developed by Cook and Larke[34] and Cook and Parker[43] is based on the assumption that the magnitude of the pure work of rolling is independent of the number of passes required to achieve a given reduction. Initial rolling experiments are necessary in order to establish first-pass curves from which the roll force can be predicted for subsequent passes. The method is particularly useful in the planning of rolling schedules[43,44]. Initially, the practical application of the method was restricted because of the necessity for an access to a fully instrumented rolling mill for the measurement of the roll force. Most modern mills are now fitted with load measuring devices and the method is now applied more widely in industry.

3.2.5. Shear line field method of determination of the roll force.

The plastic deformation of a material takes place by slip along the closest packed atom planes nearest to the directions of the maximum shear stresses. In metalworking operations, the metal consists of a large number of atoms and the behaviour of an individual atom or a small group of atoms is of secondary interest.

In general, it is assumed that the material is isotropic and no particular group of atoms is more favourably oriented for slip than others. It is also assumed that the directions of slip and the maximum shear stresses coincide. When deformation takes place by pure shear, for example, in plane strain deformation, it is possible, by consideration of the flow of the material along shear lines, to derive the stress system and hence the force causing deformation. In the rolling of wide sheet, deformation occurs approximately in plane strain. The shear line field method is therefore applicable. The solution is relatively easy when one

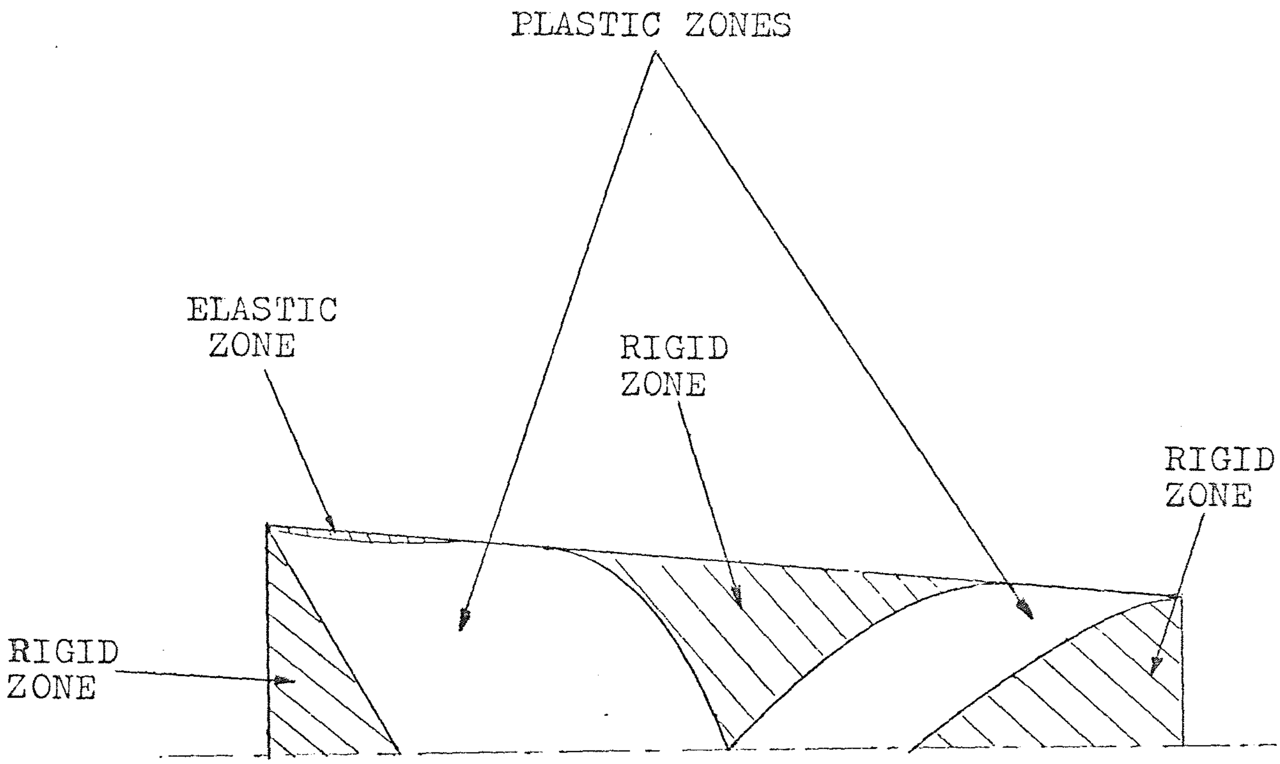


FIGURE 4 ALEXANDER'S SHEAR LINE FIELD SOLUTION FOR HOT ROLLING SHOWING THE RIGID AND PLASTIC ZONES OF THE ARC OF CONTACT.

or more of the following frictional conditions exists at the tool-workpiece interface

(a) Friction is absent at the tool-workpiece interface. This cannot occur in flat rolling.

(b) Friction at the tool-workpiece interface is negligible. This is reasonably valid for well lubricated cold rolling.

(c) The friction at the tool-workpiece interface is sufficiently high to cause sticking between the tool and the workpiece. This occurs often in hot rolling.

In developing the shear line field theory for hot rolling, Alexander[46], and more recently, Crane and Alexander[47] assume that the frictional stress at the tool boundary is limiting and equal to the yield stress in shear of the material. The result of the analysis is shown in Figure 4 and confirms the suggestion by Orowan[48] that rigid zones may exist at the entry and exit zones and in the region of the neutral plane. The boundary frictional condition in cold rolling is either one of complete slip or a mixture of slipping and sticking. The application of the shear line field approach is difficult therefore and has been made only for one or two geometrical configurations[49-51].

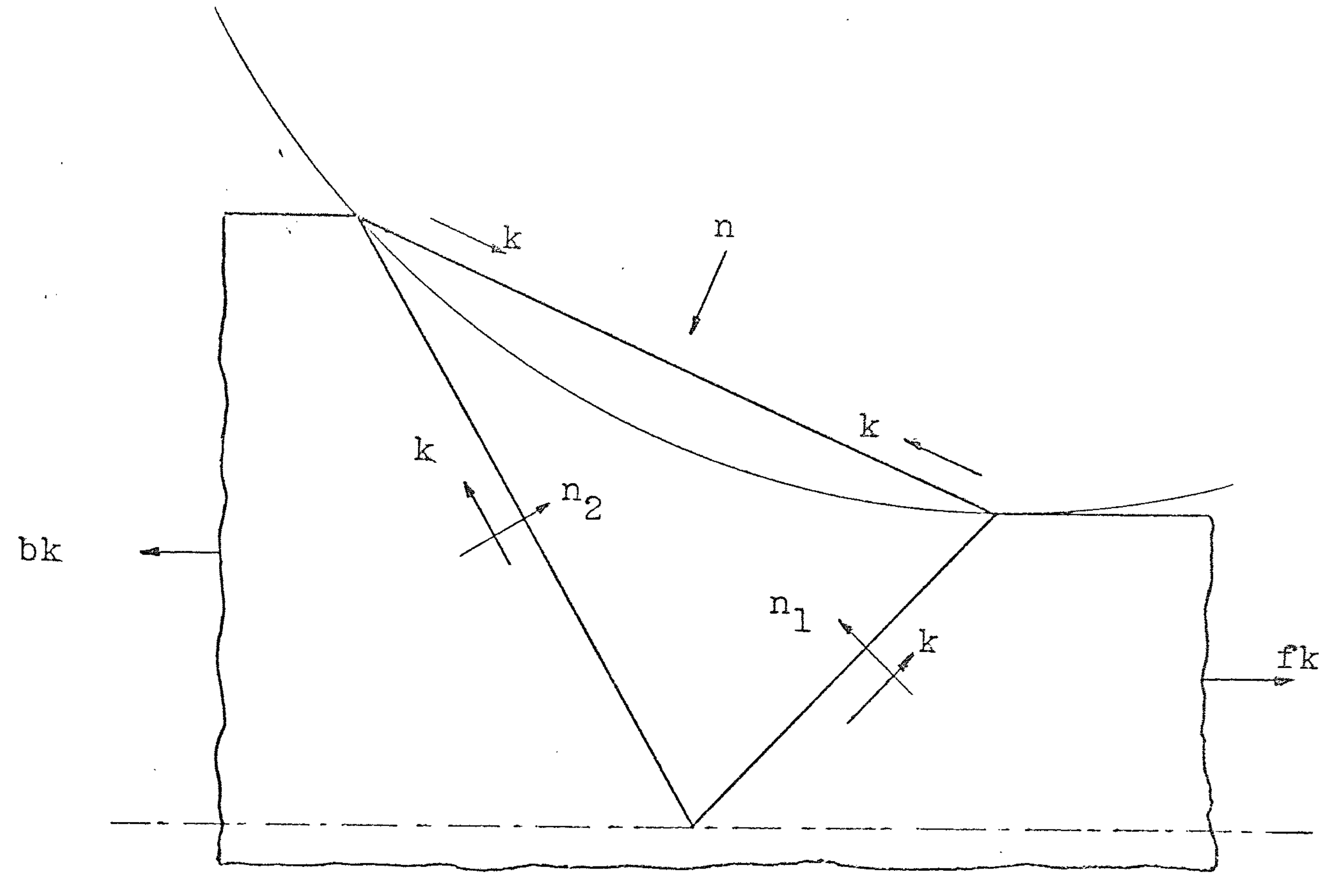


FIGURE 5 UPPER BOUND SOLUTION FOR HOT ROLLING SHOWING THE SHEAR PLANES IN THE ARC OF CONTACT. (GREEN and WALLACE[55])

3.2.6. Load bounding method and limit analysis.

In section 3.2.2, the equation of the roll force was derived by consideration of a statically admissible stress field for the zone of deformation. No account was taken of the flow of the material in the roll gap. It can be shown[52] that the roll force derived by this method is lower, or at best just equal to the actual roll force developed. The solution constitutes a lower limit or lower bound for the roll force. An upper bound can be obtained from the analysis of a kinematically admissible strain field from which a compatible stress field is derived. It is assumed that an element of the material in the roll gap deforms in such a way as to offer a maximum resistance. The roll force obtained from an admissible strain field therefore, is definitely an overestimate, or, in the limit, just equal to the actual roll force.

The upper bound method of estimating the load required to effect deformation was developed mainly by Johnson and Kudo[54] for the extrusion process, but has been adapted by Green and Wallace[55] for hot rolling. The arc of contact is replaced by a chordal plane. By consideration of the equilibrium of a perfectly rigid plastic material in the roll gap, on the boundaries of which the shear stress assumes a maximum value - the yield stress in shear of the material, the roll force is derived by a geometrical method. The stress configuration assumed by Green and Wallace is shown in Figure 5. The solution is simplified considerably by a modification suggested by Shipp and Smith[56]. The analysis has been extended by Green, Sparling and Wallace[57] to the cases of slipping friction and combined slipping and sticking friction, both of which can occur in cold rolling. The single triangle in Figure 5 is replaced by an arbitrary number of triangles, the acceptable solution being the configuration which gives the minimum load. An upper bound solution for cold rolling has been developed also by Avitzur[58].

If the lower bound solution underestimates the roll force and the upper bound solution is almost definitely an overestimate, then the correct value must be between these solutions.

The shear line field solution proposed by Alexander[46] and discussed in section 3.2.5 constitutes an upper bound since the flow of the material in the roll gap is considered. However, since it is not shown that plastic deformation does not take place in the rigid zones, the solution is only a partial upper bound. If it can be shown that an equilibrium stress distribution satisfying the rigid zone-plastic zone boundary conditions is insufficient to cause yielding in the rigid zones, then the solution is not only a complete upper bound but also satisfies the requirements for a lower bound solution as well, and it is the exact solution. Alexander and Ford[59], by adapting Hill's[60] solution of the yielding of a wedge shaped vertex, have extended Alexander's shear line field solution to include the rigid zones. They show that no yielding occurs in the rigid zones and combine[61] the exact solution with Orowan and Pascoe's[29] equations for hot rolling. They derive simple equations for the roll force and torque.

3.2.7. <u>The hydrodynamic method of determination of roll force.</u>

The hydrodynamic theory of rolling is based on the assumption that a deforming metal can be treated as a viscous fluid. Work in this direction has been pioneered mainly by Kneschke and others[62-65]. Equations of roll force and torque are derived for both slipping and sticking boundary frictional conditions, using the Navier-Stokes equations of fluid flow. It is doubtful whether a deforming metal can be treated as a Newtonian fluid. Whereas, for a Newtonian fluid, the relationship between the applied stress and the strain rate is independent of time, the contrary is true for a metal.

3.3. The calculation of the roll torque.

The roll torque T, required for deformation is given by

$$T = 2 \times P \times a \qquad (3.14)$$

where P is the resultant roll force and a is the distance of its line of action from the plane or exit. In hot rolling,

$$a \simeq 0.5 \times L \qquad (3.15.a)$$

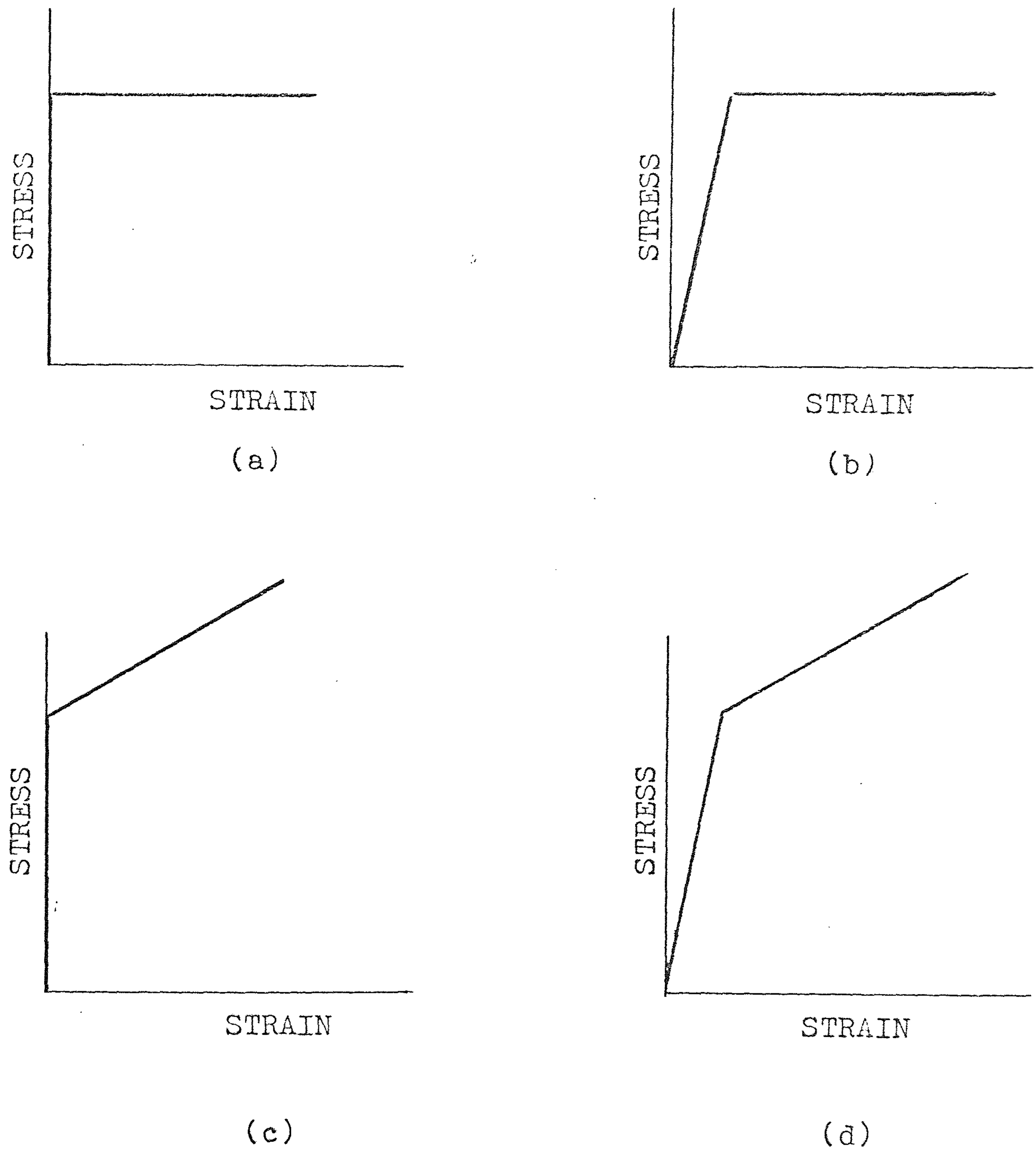
and in cold rolling,

$$a \simeq 0.3 \times L \qquad (3.15.b)$$

where L is the length of the arc of contact. The lever arm, a, can be obtained more accurately from the friction hill by a method proposed by Larke[66].

3.4. Measurement of the roll force, torque and pressure distribution.

It is desirable to check the validity of rolling theory by comparison with measured data. A considerable amount of measured data is available for hot and cold rolling [67-82] and also for the pressure distribution in the roll gap[83-87, 200]. Very little work has been done on the independent assessment of the relative validities and merits of rolling theories. A few attempts have been made by Ford[41], Gupta and Ford[68], and Le May and Nair[89], but more work is necessary in this direction, particularly with regards to the more



<u>FIGURE 6</u> TYPICAL STRESS-STRAIN CURVES COMMONLY ASSUMED IN THE DEVELOPMENT OF FLAT ROLLING THEORY.

recent theories.

3.5. Factors which affect the roll force and torque.

3.5.1 The yield stress.

The theory of plasticity is based on the assumption that the material is rigid-plastic, (figure 6(a)). However, most metals are not rigid-plastic and it is necessary to modify plasticity equations to take into account the elastic deformation and plastic work-hardening. The resulting equations are usually too complicated to be of practical use, but can be simplified considerably if the actual stress-strain curve is replaced by one of the curves shown in figure 6. The basic yield stress curve for a material is affected by a number of factors:

(a) The amount of previous deformation of the material from the annealed state.

(b) The temperature of deformation.

(c) The rate of deformation.

Work-hardening may be accompanied by partial or complete recrystallisation, depending on the temperature at which straining is taking place. At low temperatures, for instance room temperature recrystallisation is non-existent or minimal in most metals. As the temperature increases, some recrystallisation may occur, and the rate of work-hardening is reduced. Since recrystallisation is time dependent, the rate is reduced as the rate of deformation increases, and the rate of work-hardening is increased.

The effect of the rate of deformation on the stress-strain curve is negligible for most metals at room temperature, super-pure aluminium and copper being possible exceptions since they recrystallise at temperatures only slightly higher than room temperature. The rate of deformation may be significant also in some high speed metalworking operations, even at room temperature, for instance, in high energy rate forging. The effect of the rate of deformation on the yield stress curve has been investigated by many authors[45, 91,92]. The results of an experimental investigation of the hot rolling process carried out by Nikitin[93] show that, by increasing the rolling speed from 1000 ft/min. to 8000 ft/min., the roll separating force is increased by 20 percent.

It is difficult to take into account the effect of the rate of deformation in the formulation of rolling theories because it varies along the arc of contact. However, it is usually sufficiently accurate to assume a mean value for the whole of the arc of contact[21,94,95].

3.5.2. Determination of the yield stress.

The application of rolling theory often depends on the knowledge of the yielding characteristics of the material. The tensile test offers a convenient method of determination, but the stresses in rolling are predominantly compressive. Another drawback of the tensile test is the limitation on the amount of plastic deformation achievable before the onset of necking. The plane compression test developed for cold rolling by Ford and his colleagues[67,96-98] overcomes these limitations. Also, an approximate stress-strain curve can be obtained from the measurement of the hardness distribution over the arc of contact for a part-rolled specimen[99]. Because the arc of contact is usually small, considerable errors may arise from the measurement of the hardness and the corresponding strain distribution.

The plane strain compression test is unsuitable for hot rolling for the following reasons:

(a) The friction at the roll-workpiece interface is high.

(b) Considerable spread may occur.

The cam plastometer designed by Orowan[100] for testing materials in homogeneous compression at various temperatures partly overcomes these difficulties. A plane strain cam plastometer has been developed also[103]. Considerable data is available from investigations involving the use of the cam plastometer[45,90,101-103,186].

3.5.3. The coefficient of friction.

Unlike most other metalworking processes, friction is essential in rolling, since without it, the rolls cannot grip the workpiece. However, excessive friction may cause a substantial increase in the roll separating force and torque. In the rolling of thin, hard strip, it may account for up to 70 percent of the roll force[104]. The phenomenon of friction in rolling, particularly in cold rolling, is not well understood. For instance, it is not certain whether the friction is of the coulomb or the viscous type, nor is it known whether the coefficient associated with coulomb friction remains constant or varies along the arc of contact, although the former is usually assumed. Many types of friction have been assumed in the development of rolling theories:

(i) Constant friction stress.

Siebel[5] was perhaps the first to assume a constant frictional stress between the rolls and the workpiece. That is :

$$\tau = \mu \bar{Y} \qquad (3.16)$$

where $\bar{Y}$ is the yield stress of the material and its value depends on the criterion of yielding assumed. This is tantamount to assuming that the pressure ditribution along the arc of contact is constant and equal to the yield stress of the workpiece. It is likely that this assumption will lead to an underestimation of the roll separating force particularly when friction is substantial. However, Siebel's equation is sometimes found to be of the same order of accuracy as the more comprehensive theories probably because many of the errors introduced due to the assumptions made by Siebel cancel out.

(ii) Viscous (hydrodynamic) friction.

In lubricated, high speed rolling with highly polished rolls, it is possible that a thin film of lubricant may remain trapped in the arc of contact in spite of the high pressure. If this occurs, (and there is considerable doubt about it) then the frictional shear stress at the tool-work-piece interface is a function of the viscosity and the thickness of the lubricant film, and also the speed of rolling. Thus:

$$\tau = \mu \frac{dv}{dy} \qquad (3.17)$$

where τ is the frictional shear stress,

μ is the viscosity of the lubricant,

and $\frac{dv}{dy}$ is the velocity gradient across the thickness of the lubricant film.

The case of viscous friction has been considered by Nadai[16] and more recently by Tselikov[105] and Bedi and Hillier[106]. The poor agreement between the analysis by Bodi and Hillier and experimental results is probably due to the assumption that the film thickness is constant over the entire arc of contact, and the difficulty of defining the conditions under which full or partial hydrodynamic friction may occur.

(iii) Coulomb (Slipping) friction.

Most of the rolling theories developed prior to 1943 were based on the assumption of coulomb friction, that is, it is assumed that the frictional shear stress is proportional to the normal roll pressure:

$$\tau = \mu \sigma_r \qquad (3.18)$$

The assumption of slipping friction is reasonably valid for cold rolling but not for hot rolling when substantial sticking may occur.

(iv) Sticking friction.

The results of experimental investigations by Orowan[48] and Tarnovskii et.al. show that sticking may occur in hot or cold rolling when the frictional shear stress attains the value of the yield stress in shear of the workpiece. That is:

$$\tau = k \qquad (3.19)$$

The extent of sticking or slipping in rolling depends on many factors, including the coefficient of friction, the rolling temperature, the reduction, the angle of bite, and the ratio $\frac{L}{hm}$ of the length of the arc of

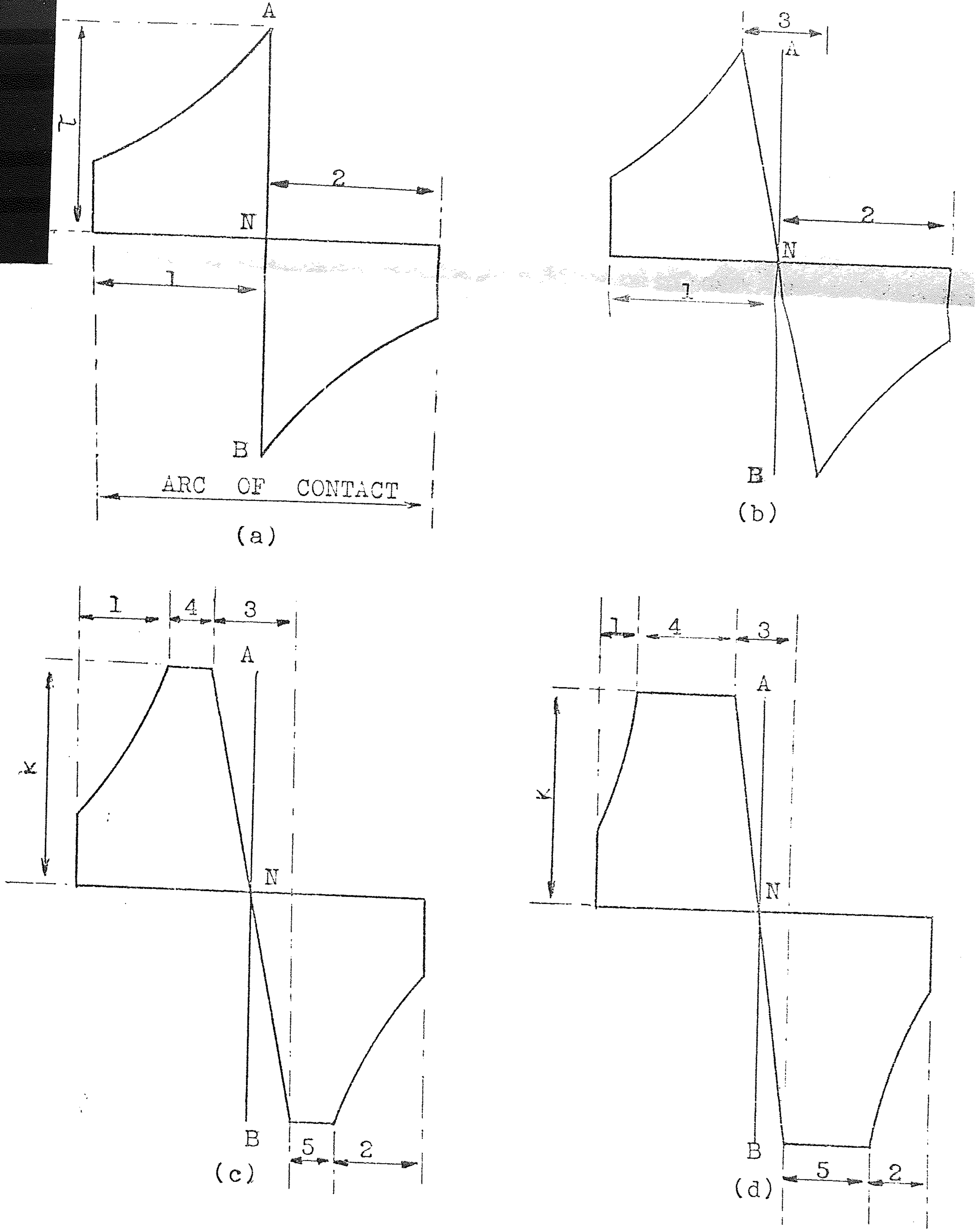
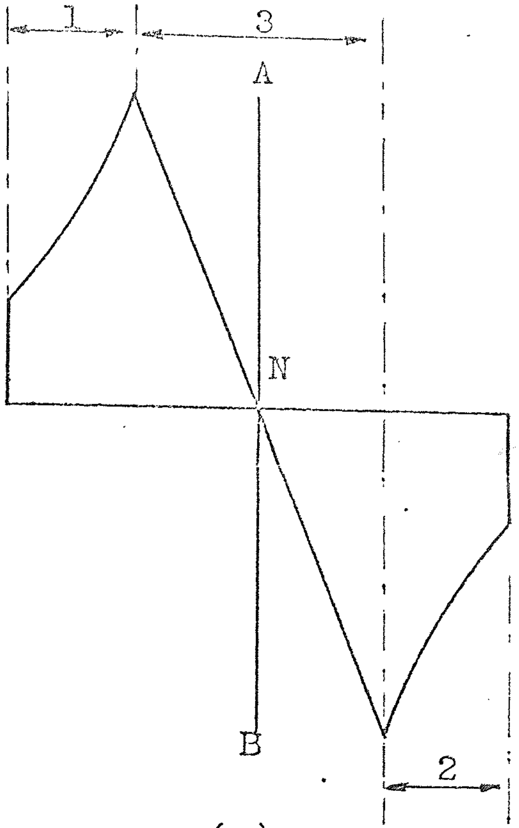
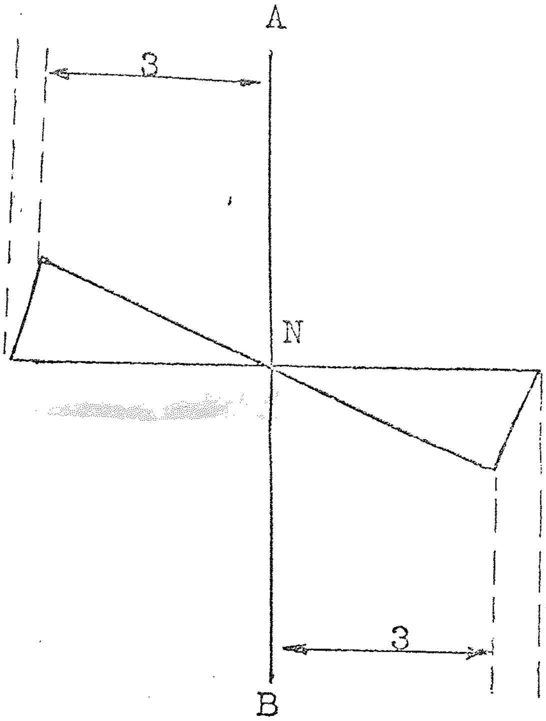


FIGURE 7 POSSIBLE TYPES OF THE DISTRIBUTION OF THE FRICTIONAL SHEAR STRESS IN THE ROLL GAP.



(e)



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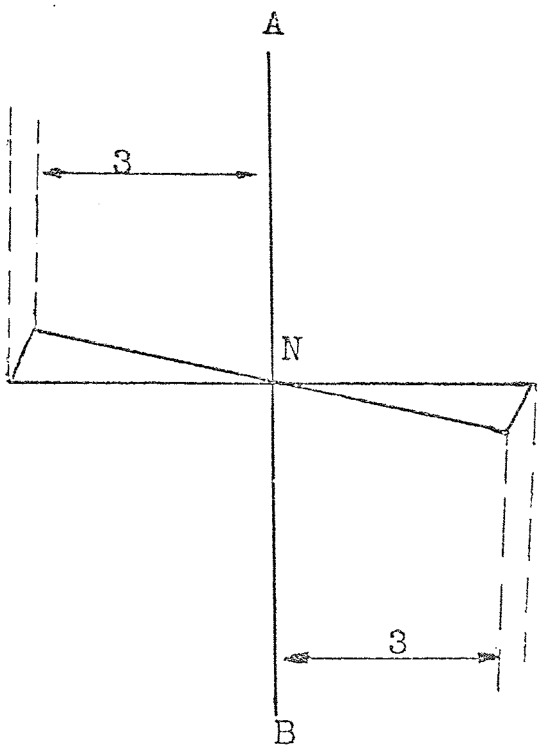


(g)

FIGURE 7 CONTD. POSSIBLE TYPES OF THE DISTRIBUTION OF THE FRICTIONAL SHEAR STRESS IN THE ROLL GAP.

contact to the mean thickness of the workpiece in the deformation zone. The possible types of the frictional shear stress distribution over the arc of contact are shown in figure 7.

Figure 7(a). Slipping friction operates over the entire arc of contact except in the neutral plane ANB which constitutes the boundary between forward and backward slip. At this plane, the rolls and the workpiece move at the same speed. This type of frictional stress distribution is likely to occur in well lubricated cold rolling when $\frac{L}{hm}$ is greater than about 5[187].

Figure 7 (b). In cold rolling, even with good lubrication, the neutral zone may extend over a small but finite area (zone 3) in which the transition between the forward and backward slip occurs.

Figure 7 (c). Some sticking may occur even in cold rolling. However, the extent may not be significant compared with the zones of slipping and can be ignored.

Figure 7 (d). In hot rolling, sticking may occur over most of the arc of contact. Some slipping may occur in the zones of entry and exit.

Figure 7 (e). When the arc of contact is small compared with the mean thickness of the material in the deformation zone, ($\frac{L}{hm}$ between 2 and 5), the frictional stress cannot increase to the value of the yield stress in shear of the material before the neutral zone is reached, hence the absence of sticking zones. This may occur in hot bar rolling.

Figure 7 (f). When $\frac{L}{hm}$ is less than 2, as in billet rolling the sticking zone may be absent and the slipping zone negligible. Hence the neutral zone extends over a considerable proportion of the arc of contact.

Figure 7 (g). When $\frac{L}{hm}$ is less than about 0.5, the frictional stress contributes only a very small proportion of the total roll force and may be ignored.

3.5.4. Determination of the coefficient of friction.

(i) Coefficient of friction derived from the measurement of slip.

This method is based on two equations relating the coefficient of friction μ to the forward slip S :

$$S = \theta_n^2 \frac{R}{h_o} \qquad (3.20)$$

$$\frac{\theta_n}{\theta_m} = 0.5\left[1 - \frac{\theta_m}{\tan^{-1}\mu}\right] \qquad (3.21)$$

where θ_n is the neutral angle, θ_m is the angle of bite, ho is the final thickness of the material, and R is the radius of the rolls. The second equation is based on the assumption that the pressure distribution along the arc of contact is constant. Similar equations have been developed by many authors[109-112]. The forward slip is obtained from the measurement of the distances between two marked points on one of the rolls and their impressions on the workpiece. The validity of this

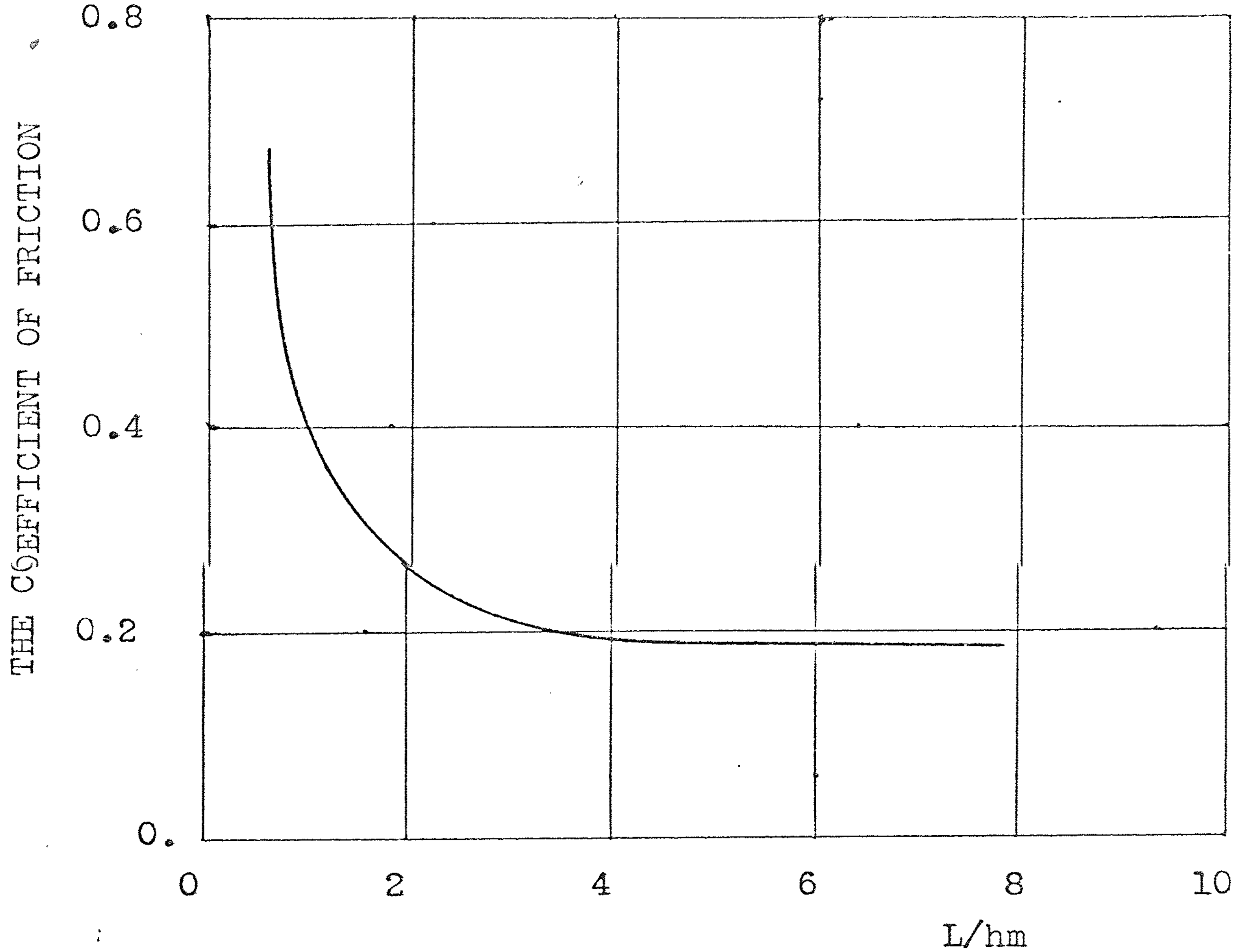


FIGURE 8 THE VARIATION OF THE COEFFICIENT OF FRICTION (OBTAINED FROM THE MEASUREMENT OF SLIP) WITH THE SHAPE FACTOR. (TARNOVSKII et.al.[113])

method can be assessed from the results of calculations by Tarnovskii et.al.[113] shown in figure 8. Similar results have been obtained by Golovin[114] and Chizhikov.[115] For $\frac{L}{hm}$ greater than unity, the calculated value of the coefficient of friction is admissible, but it is unlikely that the infinite value predicted for $\frac{L}{hm}$ less than unity can occur in practice.

(ii) Determination of the coefficient of friction from the angle of bite.

It is well known in practice that the rolls will not grip the workpiece unless the friction is sufficiently high. The maximum bite angle θm at which the rolls will just not grip the workpiece is given by the equation

$$\theta_m = \tan^{-1}\mu \qquad (3.22)$$

This maximum bite angle θm is determined by first setting the roll gap too small so that the rolls skid on the workpiece, and then increasing the gap until the rolls just grip the workpiece. θm is obtained from the geometry of the rolls and the workpiece. The validity of equation (3.22) is in doubt as a result of experiments by Presnyakov[116] and Perlin and Goderzian[117]. Bakhtinov and Shternov[118] have suggested that the angle of bite is not only a function of the coefficient of friction but also the width of the workpiece.

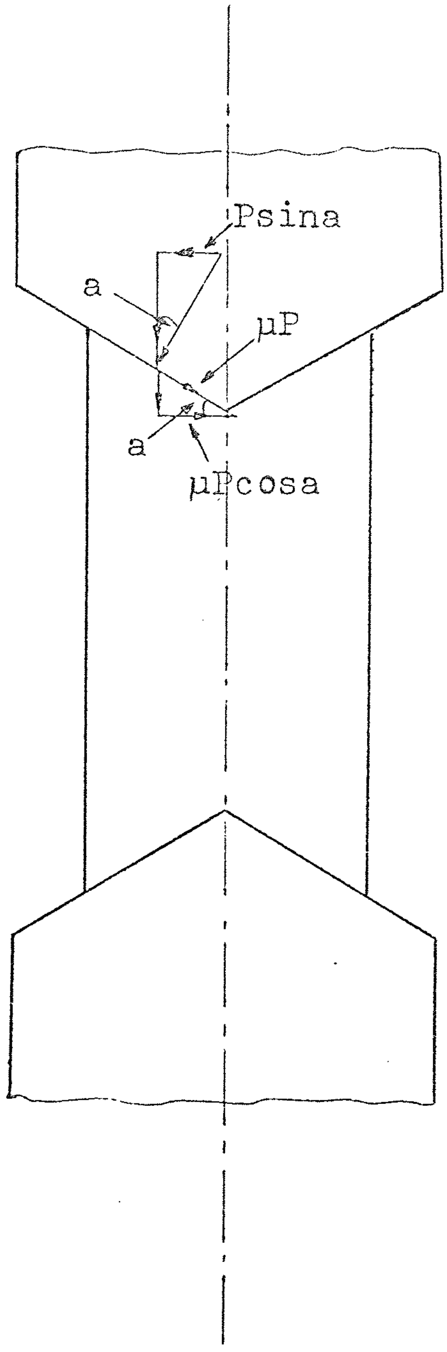


FIGURE 9 THE CONED COMPRESSION METHOD OF DETERMINATION OF THE COEFFICIENT OF FRICTION.

(iii) Determination of the coefficient of friction from coned compression tests.

A method of determination of the coefficient of friction developed by Siebel[120] involves the compression of cylindrical specimens between tapered dies (figure 9). If the angle a can be chosen so that the horizontal components of the normal and tangential forces cancel out, a linear state of stress is created in the specimen and the sides should remain parallel. The coefficient of friction is given by

$$\mu = \tan a \qquad (3.23)$$

The roughness of the tools and workpiece can be altered to simulate surface conditions in rolling. As there is no net horizontal force, yielding occurs under stresses equal to the yield stress of the material in homogeneous compression. The common objection to this method is the assumption of a linear state of stress. Zaleskii and Puz[119] have shown that a volumetric state of stress in the specimen is possible.

(iv) Determination of the coefficient of friction from measured rolling parameters.

A method devised by Pavlov[121] consists of rolling a specimen and applying an increasing back tension until the rolls start to skid on the specimen. The relationship between the coefficient of friction μ and the measured roll force P, the back tension Q, and the angle of bite at skidding θ_m is given by

$$\mu = \frac{Q}{2P} + \tan\frac{\theta_m}{2} \qquad (3.24)$$

A similar method devised by Bland[91] and applied by Whitton and Ford[92] consists of the application of an increasing back tension until skidding occurs and the measurement of the roll force and torque. The coefficient of friction is given by

$$\mu = \frac{T}{PR} \qquad (3.25)$$

where T is the measured roll torque and R is the radius of the rolls.

Data obtained from the experiments by Pavlov and Whitton and Ford, particularly the latter, are perhaps the most reliable so far. However, the conditions under which the coefficient of friction is measured are not truly representative of rolling practice for the following reasons:

(a) When the rolls start to skid on the workpiece, the neutral plane coincides with the plane of exit and the frictional stress acts in one direction only. There can be no plastic deformation under this condition. In effect, the coefficient of friction applies to two elastic bodies in contact and may not be valid for rolling, in which one member is in a plastic state.

(b) The method is based on the assumption of slipping friction over the entire arc of contact and precludes the possibility of sticking friction.

The distribution of the roll pressure σ_r and the tangential frictional shear stress τ can be measured by inserting normal and oblique pin load cells in one of the rolls. The coefficient of friction is given given by

$$\mu = \frac{\tau}{\sigma_r} \qquad (3.26)$$

The results of investigations in which this method is applied[86,87,124,125] suggest that the coefficient of friction varies along the arc of contact. The reliability of the method depends on the accuracy with which the normal and tangential stresses can be measured. A small error in either may lead to large errors in the value of the coefficient of friction.

Another method of obtaining the coefficient of friction from measured rolling parameters involves the substitution of the parameters into a roll force equation, so that the coefficient of friction is the only unknown in the equation[126]. This method is clearly unsatisfactory, since it is based on the assumption that the equation is initially correct.

3.5.5. The roll diameter.

The effect of the roll diameter on the roll separating force is threefold:

(a) The roll pressure increases with increasing roll radius.

(b) The area of contact and hence the roll force increases with increasing roll radius.

(c) The extent of roll flattening increases with increasing roll radius. The effective roll radius in turn increases with increasing roll flattening.

The results of an investigation by Cook and Larke Larke[34] suggest that the relationship between the roll separating force and the roll radius is approximately linear.

3.5.6. Spread.

The assumption that spread is negligible in flat rolling is only valid when the width of the workpiece is at least eight times its thickness. In hot rolling, the thickness may be of the same order as the width or may even be greater. In this case, spread is not negligible. Many attempts have been made to develop rolling theories which take into account the effect of spread[23-25,29-33]. Because of the numerous assumptions made, the theories can only be regarded as approximate.

3.5.7. Rolling speed.

The effect of speed on the yield stress has been

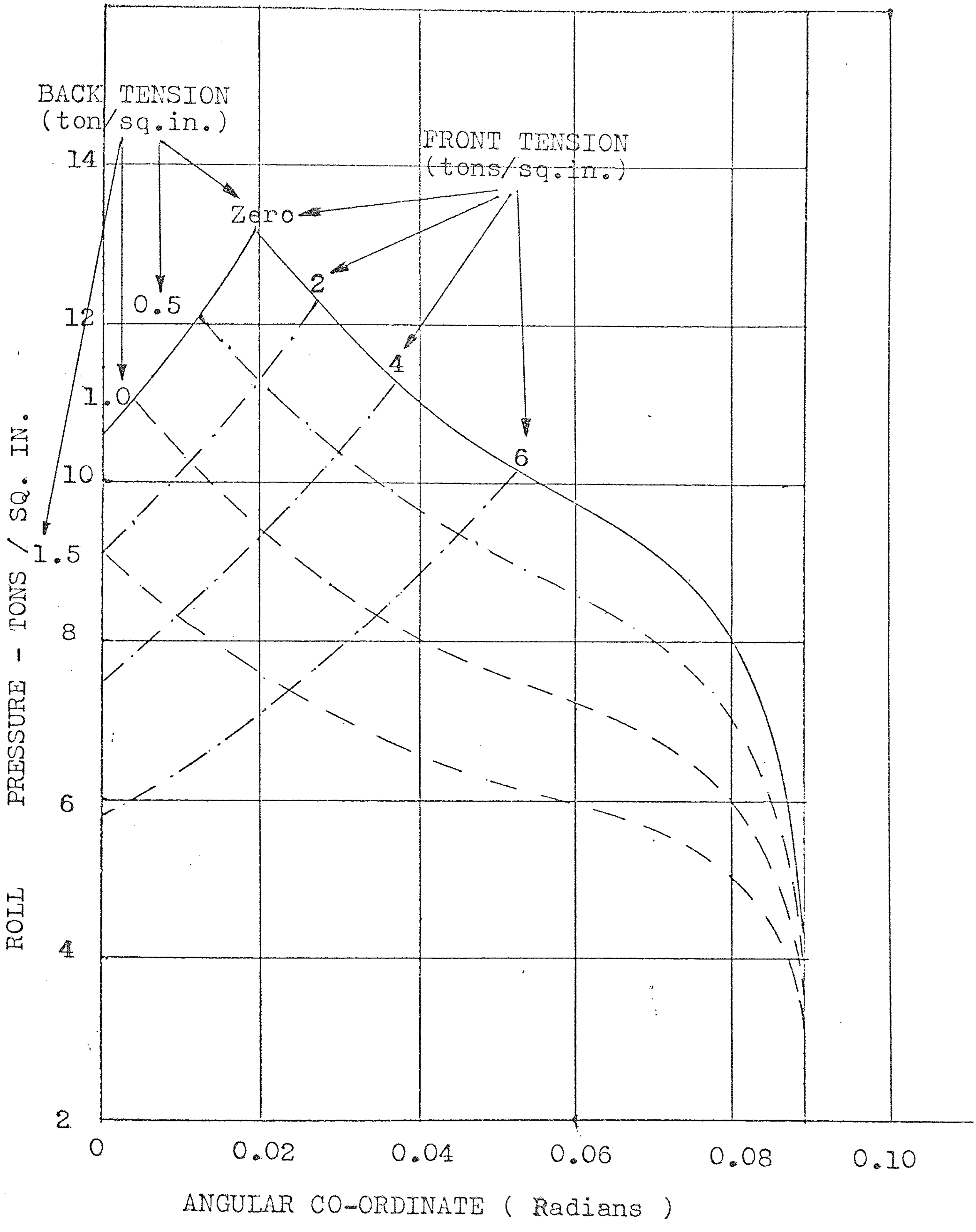


FIGURE 10 DIAGRAM SHOWING THE EFFECT OF THE FRONT AND BACK TENSIONS ON THE PRESSURE DISTRIBUTION IN THE ROLL GAP. (LARKE[30])

discussed in section 3.5.1. The increase in the yield stress due to an increase in the rate of deformation will cause a corresponding increase in the roll force. However, in lubricated cold rolling, the roll force and gauge may decrease with increasing rolling speed probably because more lubricant is drawn into and trapped in the roll gap by hydrodynamic action[97,98].

3.5.8. Applied tensions.

The effect of applied tensions on the roll force is shown in figure 10, taken from the theoretical analysis by Larke[130]. Similar results have been obtained experimentally by Hayes and Burns[131] and Hessenberg and Sims[68]. It is clear from figure 10 that the back tension is much more effective in reducing the roll separating force than the front tension. This is not surprising since most of the deformation of the workpiece takes place in the entry zone of the arc of contact.

3.5.9. Inhomogeneity of deformation.

Deformation is not always homogeneous in flat rolling especially when the friction is high and sticking occurs between the rolls and the workpiece. Initially plane sections do not remain plane after rolling but become distorted, usually concave to the direction of rolling. The conditions under which inhomogeneity of deformation may occur have been studied extensively both theoretically and experimentally by many authors[46,48,132,133]. The most important factors which determine the degree of inhomogeneity are:

(a) The coefficient of friction.

(b) The ratio of the length of the arc of contact to the mean thickness of the workpiece in the deformation zone.

(c) The ratio of the initial thickness of the workpiece to the roll diameter.

(d) The ratio of the draft to the roll diameter.

Tarnovskii et.al.[132] have shown that distortion is not confined to the thickness of the workpiece alone but can occur accross the width as well. They show also that deformation can extend beyond the geometrical limits of the arc of contact, particularly in the entry zone.

3.5.10. <u>Temperature rise due to the work of deformation.</u>

The effect of the rise in temperature of the workpiece due to the work of deformation is usually ignored in the calculation of roll force and torque, though the problem has been considered by many investigators[127,134-138]. A temperature rise of up to 450°F has been encountered in cold rolling, even when the rolls were water cooled[134]. Taylor and Quinney[137] have shown that most of the work of deformation re-appears as heat in the workpiece. When the reduction per pass is high, as in planetary or pendulum rolling, or high speed tandem rolling, the temperature rise may be very substantial. Only a few attempts have been made, notably by Ford[127] and Inhaber[138] to modify rolling theory to take its effect into account.

3.5.11. Elastic deformation of the rolls and the workpiece.

The effect of the elastic deformation of the rolls and the workpiece and the initial thickness of the workpiece on the roll force is more significant in the rolling of thin hard strip than in normal rolling and will be discussed in the appropriate section.

4. THE ROLLING OF THIN HARD STRIP.

4. THE ROLLING OF THIN HARD STRIP.

4.1 Introduction.

Conventional rolling theory is often not applicable to the rolling of thin, hard strip when it neglects the effect of roll flattening and the elastic compression of the strip. The latter is often negligible compared with the plastic compression. However, in the rolling of thin, hard strip, or in temper rolling, the elastic strain may be of the same order as the plastic strain and should be taken into account in the formulation of rolling theory.

4.2. The elastic flattening of the rolls.

The elastic compression of the rolls under load can be calculated without difficulty if the pressure distribution along the arc of contact is known. However, the pressure distribution can be calculated only when the precise shape of the deformed arc of contact is known. This interdependence of the roll pressure and the deformed shape of the arc of contact makes the determination of either of them difficult. A method commonly attributed to Hitchcock[139] and based on the work of Prescott[140] involves the replacement of the original arc of contact of radius R with a larger arc of radius R' where

$$\frac{R'}{R} = \left[1 + \frac{cP}{w\delta}\right] \qquad (4.1)$$

where P is the roll separating force.

w is the width of the workpiece.

δ is the draft.

c is the elastic constant for the roll material.

For steel rolls $c = 3.34 \times 10^{-4}$

For cast-iron rolls $c = 6.57 \times 10^{-4}$.

For chilled-iron rolls $c = 3.82 \times 10^{-4}$.

The derivation of equation (4.1) is based on many assumptions including

(a). The angle of bite is small, so that $\cos\theta = 1$.

(b) The elastic compression of the strip is negligible.

(c) The deformation of the rolls is symmetrical about the mid-point of its length and the greatest deformation occurs at the mid-point.

(d) The actual pressure distribution is replaced by an elliptical one giving the same total load. This enables the analysis by Prescott to be used.

(e) The arc of contact remains circular. It is known from the theory of elastic bodies in contact by Hertz[141], that the roll surface under an elliptical pressure distribution, is deformed into a circular arc of larger radius.

A more comprehensive analysis of roll flattening by Bland[142] has shown that, despite the numerous assumptions on which Hitchcock's equation is based, it is reliable for $\frac{R'}{R}$ less than 2. However, it is difficult to apply without the aid of a computer, since equation (4.1) can be solved only by successive iteration. A graphical solution has been developed by Winton[143] and methods of reducing the amount of necessary calculations have been proposed by Sims[18] and Troost and Hollman[144].

Jortner et.al.[53,145] have developed a method for the calculation of the elastic deformation of the rolls and the workpiece. Starting from the earlier work by Mitchell[146], they derive an influence function for a model cylinder deforming in plane strain under the action of two diametrically oppisite loads. The influence function can be solved to give the radial deformation at any point on the surface of the cylinder. It is assumed that the pressure distribution between the chuck or back-up roll and the workpiece is the same as between the work roll and the workpiece, and that the contribution of the frictional shear stress to roll flattening is negligible. The latter assumption is reasonable for most cases of cold rolling, but the pressure distribution between the chucks and the rolls is different from that between the roll and the workpiece. However, Zorowski and Weinstein[147] have shown that this assumption has little effect on the ultimate result of the analysis.

4.3. Measurement of roll flattening.

The distribution of roll flattening along the arc of contact can be measured by half rolling a specimen and measuring the distribution of deformation along the arc of contact, the roll pressure being released as quickly as possible to avoid creep. This method, which ignores the elastic compression of the strip, has been used by Orowan[99] and more recently by Fazan and Albert[143]. Orowan identifies a distinctive "bump" in the neutral zone of the arc of contact. In the extreme case, the arc divides into three - the entry and exit zones where plastic deformation is taking place, and a dead metal zone in the middle where no deformation occurs. This result invalidates the common assumption that the arc of contact remains circular. However, the roll flattening would have been excessive in Orowans's experiments. Using his parameters in equation (4.1), the deformed radius is approximately four times the undeformed radius. This is not typical of rolling practice. Moreover, the height of the "bump" is so small that it may not significantly affect the results of roll flattening analysis. Nevertheless, such a phenomenon has been shown by Bland[142] to be possible from the theoretical point of view.

4.4. THE SIGNIFICANCE OF ROLL FLATTENING IN ROLLING PRACTICE.

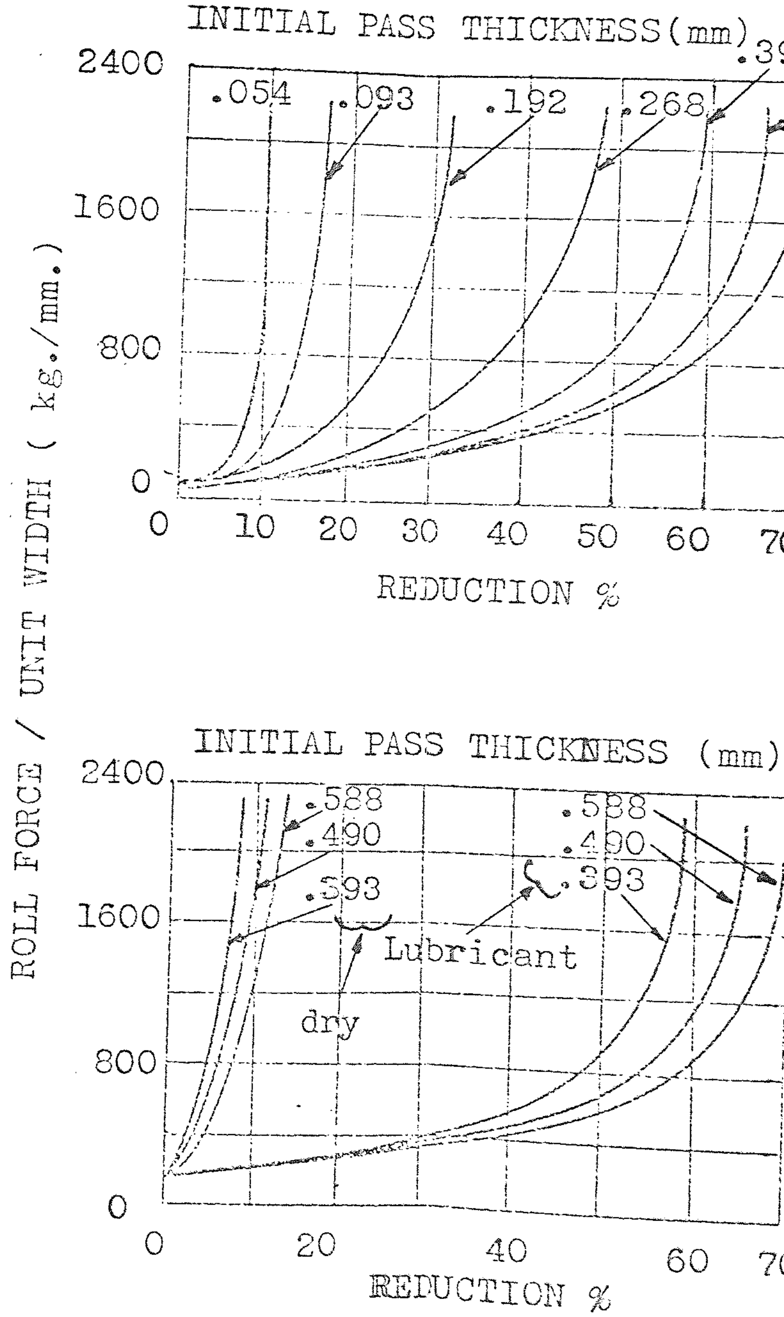
4.4.1. Limiting thickness.

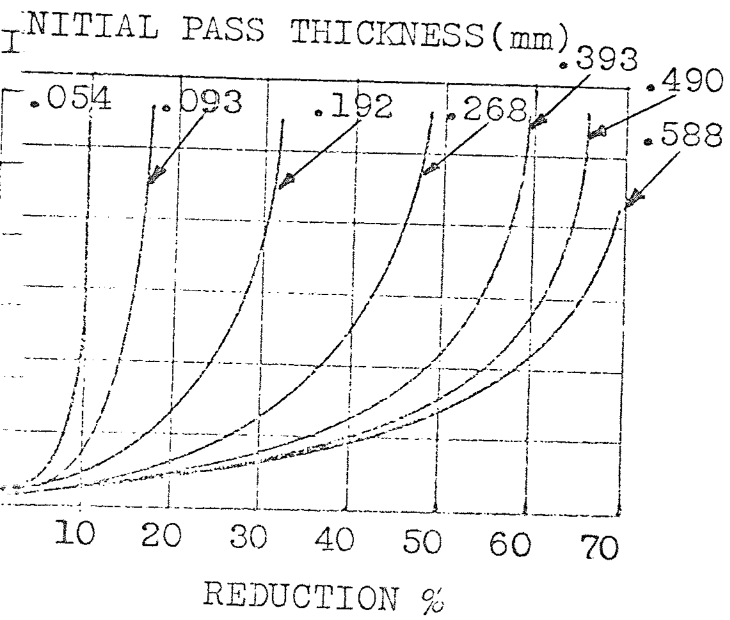
It can be seen from equation (4.1) that the deformed radius increases as the draft or the initial thickness of the workpiece decreases. In the limit, the workpiece emerges from the roll gap undeformed. The limiting thickness is defined as the initial thickness at which plastic deformation is just impossible. It is often confused with the maximum thickness at which the rolls start to skid and cannot drag the workpiece into the roll gap. Numerous attempts[18, 149-158] have been made to develop theories which enable the limiting thickness to be predicted from a particular set of rolling parameters. Huggins[159] has investigated the validity of some of the theories with respect to experimental measurements and concludes that none of them predicts a true limiting thickness. He suggests that the discrepancy may be due to the fact that the theories ignore the additional lateral pressure which is imposed on the workpiece when the rolls flatten to the extent that the workpiece is "boxed in". A more probable reason is that the rolls touch before the limiting thickness is reached, thereby falsifying the measured values. The limiting thickness depends also on many other factors including

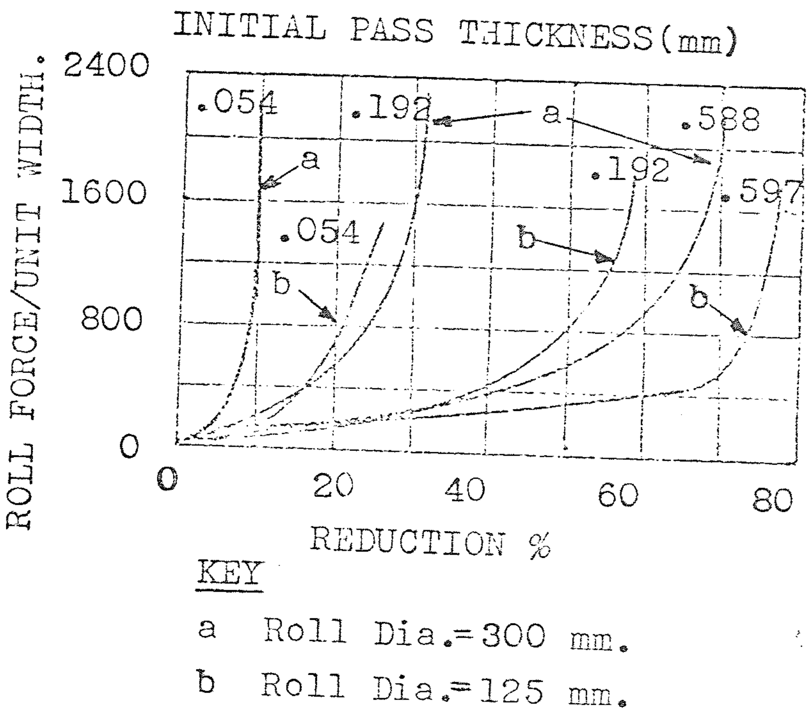
(a) Roll radius.

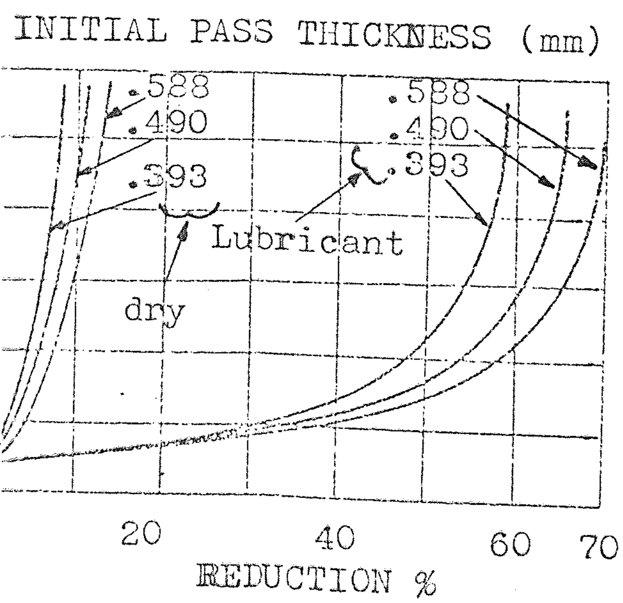
FIGURE 11

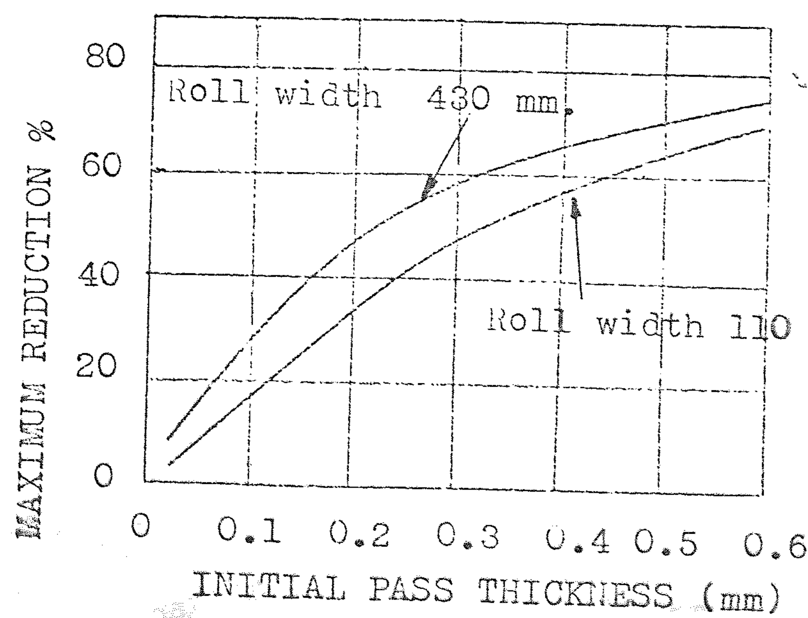
THE EFFECT OF THE INITIAL PASS THICKNESS, ROLL WIDTH AND DIAMETER, AND FRICTION ON THE LIMITING REDUCTION.
(PAWELSKI AND KUDING 161)




INITIAL PASS THICKNESS(mm)
.054
.093
.192
.268
.393
.490
.588
10 20 30 40 50 60 70
REDUCTION %


INITIAL PASS THICKNESS(mm)
ROLL FORCE/UNIT WIDTH.
2400
1600
800
0
.054
.192
a
.588
.192
.597
.054
b
b
b
0 20 40 60 80
REDUCTION %
KEY
a Roll Dia.= 300 mm.
b Roll Dia.= 125 mm.


INITIAL PASS THICKNESS (mm)
.588
.490
.393
.588
.490
.393
Lubricant
dry
20 40 60 70
REDUCTION %


MAXIMUM REDUCTION %
80
60
40
20
0
Roll width 430 mm.
Roll width 110
0 0.1 0.2 0.3 0.4 0.5 0.6
INITIAL PASS THICKNESS (mm)

(b) The coefficient of friction.

(c) The yield stress of the workpiece.

(d) The elastic properties of the rolls and workpiece.

(e) Roll bending.

(f) The elastic straining of the mill housing.

Pawelski and Kuding[161] have investigated the effect of varying the initial thickness, roll radius, the coefficient of friction, and the width of the roll on the limiting thickness. Figure 11 is taken from their results. It can be seen that the coefficient of friction has the most significant effect. This is supported by the results of an experimental investigation by Thorp[161], and also by Rudback and Severdenko[162].

4.4.2. Minimum thickness.

As a result of roll flattening, there is a value of the initial thickness below which it is impossible to achieve a given final thickness. This minimum thickness is difficult to determine, since it is influenced by all the factors which affect roll flattening and the limiting thickness.

4.4.3. Limiting reduction.

For a given set of rolling parameters, there is a limiting reduction which can be achieved in one pass before it becomes easier to deform the rolls than the workpiece. Again, the limiting reduction is often confused with the maximum reduction possible in one pass before the rolls start to skid on the workpiece.

4.5. The elastic compression of the strip.

The elastic compression of the strip is usually small compared with the plastic strain when thick strip is rolled. However, for thin strip, the elastic strain may be of the same order as the plastic strain. An approximate method of taking its effect into account in the formulation of rolling theories has been proposed by Bland and Ford[163] and more recently by Jortner et.al.[145]. The elastic strain comprises of the elastic compression at the entry and the elastic recovery at the exit zone of the arc of contact, the latter being usually more significant. The elastic straining of the strip contributes to the roll separating force in three ways:

(a) There is a direct increase due to the force required for the elastic compression.

(b) Additional compressive stresses imposed on the plastic zones contribute to the total roll force.

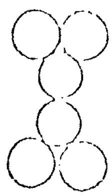
(c) The roll force is augmented by the increase in the radius of the deformed arc of contact as a result of the elastic zones.

5. THE TREND OF DEVELOPMENTS IN FLAT ROLLING.

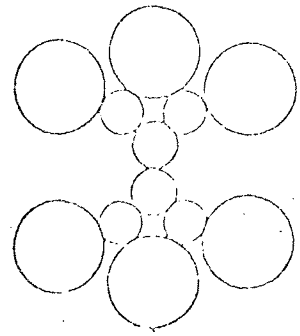
5.1 Small diameter rolls.

5.1.1. The Sendzimir mills.

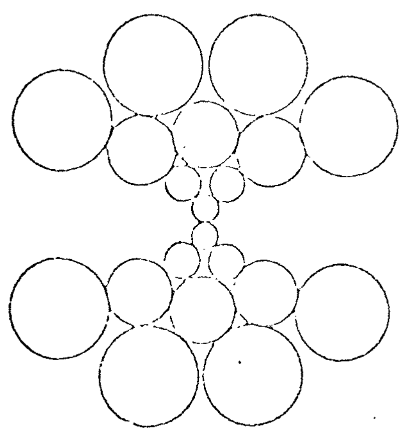
Since the roll separating force and the extent of roll flattening decrease with decreasing roll diameter, it is desirable that the latter should be as small as possible. However, the necessity to support the rolls to prevent them from bending often results in intricate arrangements of the back-up rolls. Some examples are shown in figure 12. The Sendzimir cold rolling mill is basically similar to the conventional rolling mill except that it is capable of rolling thin hard strip down to very small thicknesses which cannot be achieved on a conventional mill. Conventional rolling theory is applicable provided an account is taken of the elastic compression of the rolls and the workpiece. However, the Sendzimir planetary hot mill is different. Deformation is achieved incrementally by small rolls arranged in a ~~planet~~ cage round a back-up roll (figure 12(b) and very large reductions can be achieved in one pass. The initial problems were concerned with the efficient operation of the planetary mill and the elimination of scallops from the surface of the rolled product. Recently, considerable efforts have been made notably by Tovini[164], Sparling [165] and Muller and Bellenberg[167-170] to develop theories for the process.



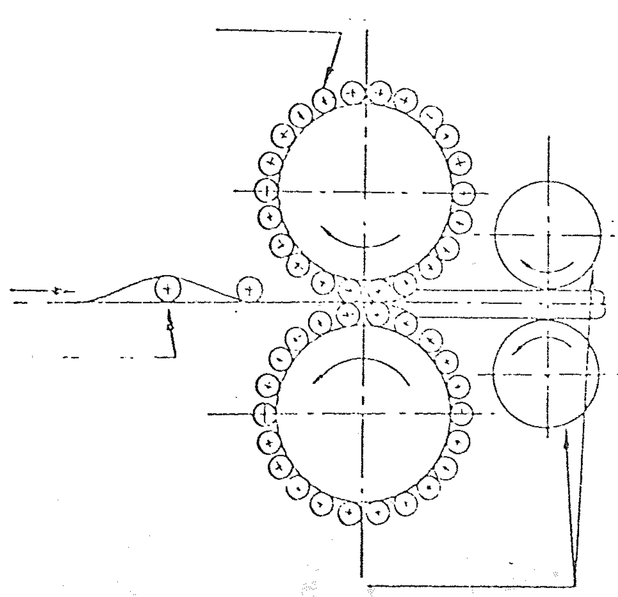
The six-high mill.



The 12-high mill.



(a) The 20-high mill.



(b) The Planetary mill.

Figure 12. <u>The Sendzimir small diameter roll mills</u>.

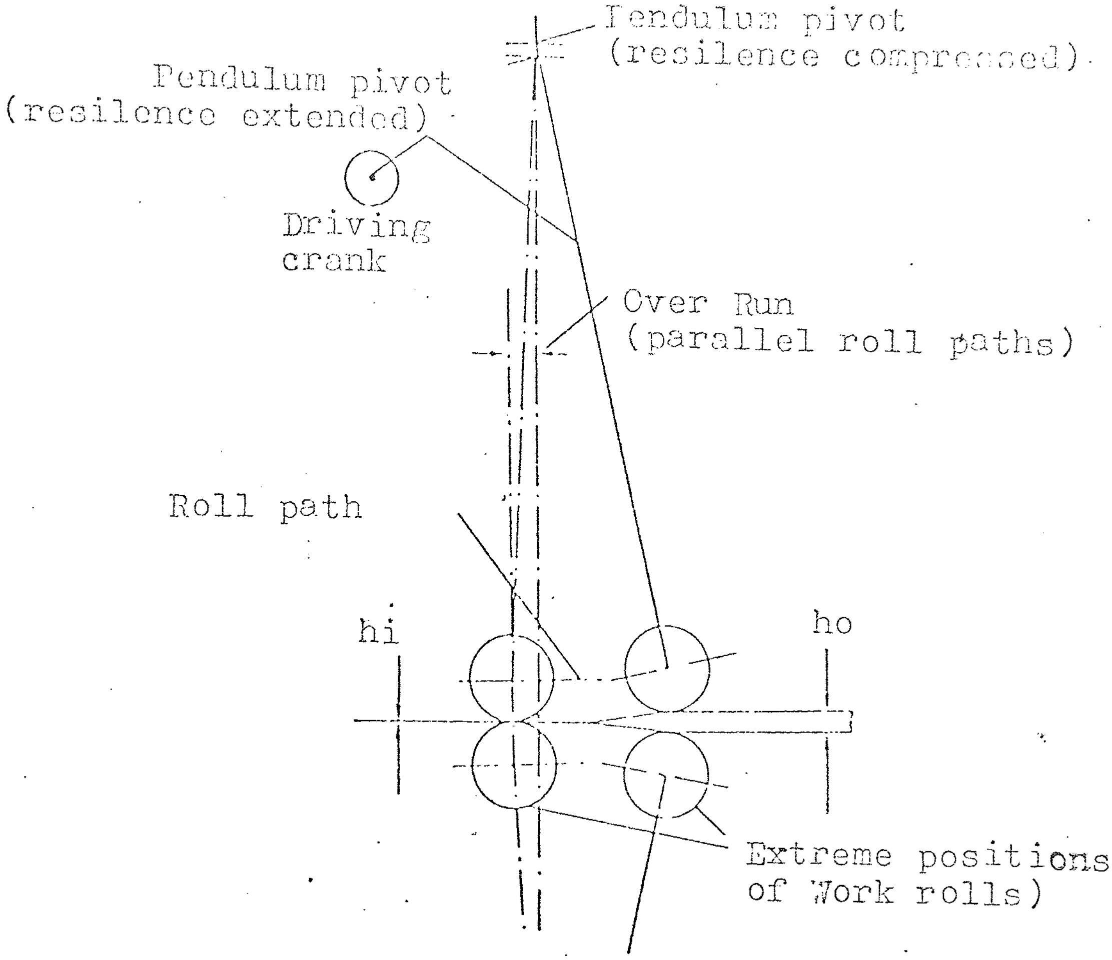


Figure 13. The Saxl Pendulum mill.

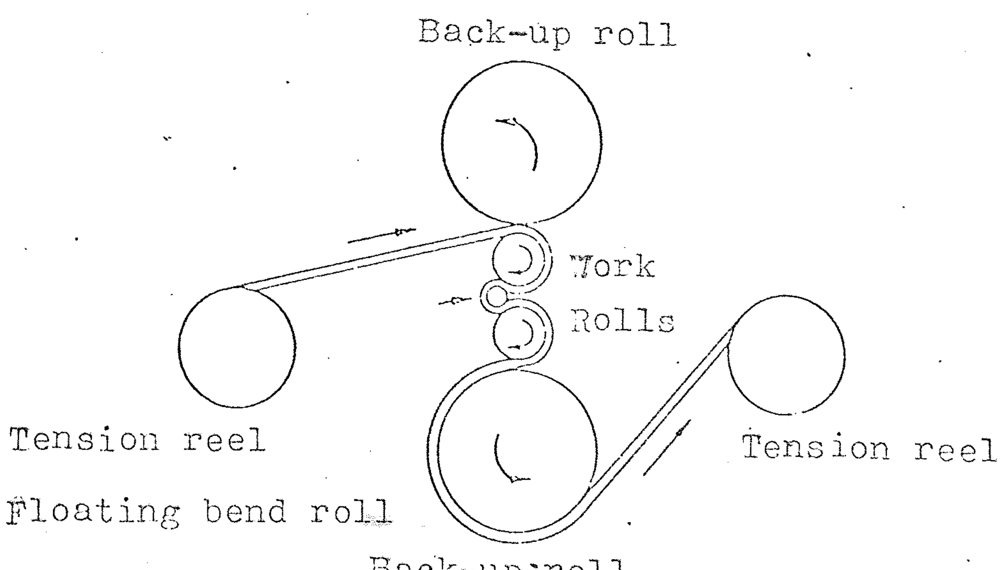


Figure 14. The C-B-S mill.

5.1.2. The Pendulum mill.

The method of incremental reduction similar to the planetary rolling process is applied in the pendulum rolling process developed by Saxl[171]. A pair of small tungsten carbide work rolls is mounted on two pivoted pendulum arms (figure 13). Each work roll is backed up by a pair of steel rolls. The pendulums swing backwards and forwards so that the work rolls traverse the workpiece, effecting a reduction in both directions. The mill is capable of rolling hard strips from 0.25 in. to 0.025in. in one pass. The same reduction can be achieved on a conventional mill in about eight passes and four or five anneals. Since the reduction in pendulum rolling is incremental, the roll separating force developed is small. A prototype 10-in. mill is operating commercially already, but considerable development is necessary to enable wider sheets to be rolled and also to exploit the potentiality of the mill as a link between a continuous casting machine and a cold finishing mill.

5.1.3. The C-B-S mill.

The contact-bend-stretch mill was developed by Coffin[172,173] and the General Electric Company of the U.S.A. . The strip is wrapped round a pair of small work rolls and a floating roll (figure 14). Gauge is controlled entirely by adjusting the applied tensions which determine the position of the floating roll. In addition to the advantage of using small diameter work rolls and applying tensions, the inventors claim that the additional bending stresses imposed on the strip enable the strip to be rolled to very thin gauges. A typical rolling schedule quoted for stainless steel is from 0.05 in. to 0.004 in. in 8 passes without intermediate anneals and up to 55 percent reduction in one pass. Strips are also said to have been rolled down to 0.0002 in. on this mill[172]. Despite the advantages of this mill and its potentiality as a finishing mill, considerable design and operational difficulties have delayed the development of a commercially viable mill. However, considerable interest is growing in this direction..

5.2. <u>The application of oscillatory energy to rolling.</u>

Oscillatory energy has been applied to many metalworking processes including wire drawing, tube rolling, and flat rolling with a view to reducing the deformation load or to improve the surface finish of the product. A comprehensive review of the literature on oscillatory metalworking has been published recently by Winsper and Sansome[173]. Two mechanisms of load reduction have been proposed by many authors:

(a) A reduction in load as a result of the reduction in the yield stress.

(b) A reduction in the load as a result of the reduction in friction.

The results of experimental investigations[174-177] indicate that the second mechanism is more likely to be true. In the rolling of thin, hard strip, friction may account for up to 70 percent[104] of the total rolling load and the application of oscillatory energy may be of value in this respect. The oscillations may be applied to the rolls radially or longitudinally, or to the workpiece. When the oscillations are applied to the rolls, it is desirable that the rolls should be as small as possible to avoid wasting a substantial proportion of the oscillatory energy in overcoming the inertia of the rolls. McKaig[178] and Cunningham and Lanyi[179] have reported on rolling trials in which the oscillatory energy was applied to the rolls or to the workpiece. A reduction in the rolling load of between 3 and 13 percent is claimed by Cunningham and Lanyi. However, since they were rolling thick bars of copper and aluminium, the reduction in load may be higher for thin hard material.

More recently, Westinghouse Electric Corporation of the U.S.A. have reported a reduction of up to 65 percent for aluminium and similar reduction in load for copper, lead and steel. They also claim that edge cracking is reduced or prevented when oscillatory energy is applied to rolling, and report on the commercial production of nickel base alloys for the manufacture of the secondary burners of jet engines.

5.3. Powder rolling.

The production of metal sheets from powder by roll compaction is well established. However, the possibility of producing thin sheets of difficult metals by this method in preference to conventional rolling is only just beginning to arouse interest. Considerable work is being done on the fundamental and production aspects of the process[181-185].

6. A DISCUSSION OF THE PUBLISHED WORK ON FLAT ROLLING.

6. A DISCUSSION OF THE PUBLISHED WORK ON FLAT ROLLING.

Despite the extensiveness of the published work on flat rolling, comparatively little work has been done to test the validity of the various theories over a wide range of rolling parameters. The major difficulties have been the determination of the coefficient of friction and the measurement of other rolling parameters under production conditions, particularly in hot rolling. It is difficult therefore to assess the relative merits of the theories which have been developed. Often, the coefficient of friction is used as a correlation factor, its value being that which gives the best correlation between theoretical results and experimental measurements. This is clearly unsatisfactory, since it is assumed that the rolling theory is initially correct.

Orowan's analysis is perhaps the most comprehensive so far, but the equations are inherently difficult to apply without the aid of a computer, particularly in industry. However, the analysis is valuable as a standard for the assessment of the accuracies of the simplified theories.

In most cases of cold rolling, the simplified theories of Sims, Tselikov, von-Karman, Bland and Ford, and others give results which agree closely with results obtained when Orowan's equations are applied.

This is probably because such factors as sticking friction and the inhomogeneity of deformation which Orowan took into account but which the other authors ignored are not very significant in cold rolling practice. In hot rolling, Orowan's analysis is significantly more accurate than the simplified theories by Orowan and Pascoe, Sims, Ekelund and others, but it is often not necessary to determine the roll force and torque precisely in rolling practice and the simplified theories, particularly those of Sims and Orowan and Pascoe are often sufficiently accurate.

The determination of the radius of the deformed arc of contact by the method due to Hitchcock appears to be the most acceptable to date, from the point of view of simplicity and accuracy. The more complicated and relatively new analysis by Jortner et.al. has not yet been tested to the same extent as Hitchcock's equation.

The effect of roll hardness on roll flattening is usually ignored. Heat treatment may cause a change of over 5 percent in the Young's modulus of some steels[201] and it may be necessary to take this into account if accurate results are required.

The results of experimental investigations by Huggins, Pawelski and Kuding, and Thorp suggest that the theoretical prediction of the limiting thickness may be seriously in error, probably because the rolls flatten to the extent that they touch on the sides of the workpiece thus preventing any further deformation of the workpiece. When this occurs, the theoretical thickness will be lower than the value obtained in practice. Further work is necessary to clarify the conditions under which the rolls touch and to develop a method of taking its effect into account in rolling theories.

In the last decade or so, major efforts have been directed towards the development of more efficient rolling mills and ancillary equipment. With the proliferation of computers, fully automated plants are being installed and rolling theories are being applied in the planning of rolling schedules, in preference to the common practice of depending on trial and error or past experience. Further development of the Planetary mill has resulted in the Krupp-Platzer type mill which is capable of rolling sheets free from surface scallops. Interest is growing in the Pendulum mill, the C-B-S. mill, Powder rolling and Oscillatory rolling and it is likely that future development will be along these lines.

7. A REVIEW OF THE PUBLISHED WORK ON SANDWICH ROLLING.

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7.1. Introduction.

The fact that the roll separating force may be reduced when a metal is rolled sandwiched between layers of softer metal has been known for many years. Pomp and Lueg (1942)[188] reported a reduction in the roll separating force of up to 44 percent when mild steel was hot rolled between layers of copper. The copper content of the sandwich was varied from 5 to 40 percent. The possibility of adopting the method for the rolling of difficult metals was proposed by Shofman[189] in 1952. However, only a few attempts have been made to study the process in detail and to identify the parameters which determine the amount of reduction in the roll separating force which can be achieved. Nevertheless, a considerable amount of literature has been published on the practical aspects of the formation of composite metals by rolling. In this process, the primary object is to produce a bond between the layers of the composite metals by rolling, and any reduction in the roll separating force is of secondary interest. In the review which follows, emphasis will be placed on the theoretical and experimental investigations of sandwich rolling, in which the primary object is to achieve a reduction in the roll separating force; work on roll bonding will be mentioned only when it is relevant .

7.2. THE THEORY OF SANDWICH ROLLING.

The effect on the roll force of rolling thin, hard metals between sheets of softer metal is threefold:

(i) When the sandwich is rolled, the softer metal will tend to deform more rapidly than the hard matrix. If the friction at the clad-matrix interface is sufficiently high, the movement of of the softer metal will be restricted. As a result, tensile and compressive stresses are induced in the matrix and clad respectively. Consequently, because of the superimposed stresses, the clad will be more difficult to deform and the matrix will deform more readily.

(ii) Because of the overall increase in the initial thickness of the workpiece, the extent of roll flattening and hence the roll separating force is reduced.

(iii) Usually, the friction at the tool-workpiece interface is lower when the hard metal is cladded with softer metal than when rolled without clad. Theory and practice show that the roll separating force is further reduced.

A mathematical analysis of the sandwich rolling process taking into account the above factors is complex. It is difficult to determine, for instance, the proportion in which the total strain is sh ared between the matrix and the clad, or the condition under which joint plastic deformation occurs between the layers of the sandwich. However, the analysis may be simplified considerably by postulating one of the following hypotheses, to enable an equivalent yield stress to be determined:

(i) <u>The equal stress hypothesis.</u>

It may be assumed that the layers of the sandwich are subjected to equal stresses, but different strains. The equivalent strain is given by

$$\varepsilon_e = B\,\varepsilon_c + (1-B)\,\varepsilon_m \qquad (7.1)$$

where ε_e is the equivalent strain.

ε_c is the strain in the clad.

ε_m is the strain in the matrix.

B is the proportion of clad in the sandwich.

(ii) <u>The equal strain hypothesis.</u>

It may be assumed that the strain in each layer of the sandwich is the same, that is, joint plastic deformation of the layers occurs. The equivalent yield stress is given by

$$\bar{Y}_{pe} = B\bar{Y}_{pc} + (1-B)\bar{Y}_{pm} \qquad (7.2)$$

where $\bar{Y}_{pe}$ is the equivalent yield stress.

$\bar{Y}_{pc}$ is the yield stress of the clad.

$\bar{Y}_{pm}$ is the yield stress of the matrix.

Both hypotheses were applied by Dorn and Starr[190] in their analysis of the yielding characteristics of a two-phase alloy. Davies[191] carried out an analysis of the plane strain compression of sandwich metals in which he tested both hypotheses and found that the equivalent yield stress obtained by assuming equal strains in the sandwich layers agreed more closely with measured values.

In the analysis of the formation of composite metals by rolling carried out by Holmes[192] and more recently, the analysis of sandwich rolling by Arnold and Whitton[1], the equivalent yield stress was derived in the form:

$$\bar{Y}_{pe} = \frac{h_c\bar{Y}_{pc} + h_m\bar{Y}_{pm}}{h_c + h_m} \qquad (7.3)$$

where h_m is half the thickness of the matrix.

h_c is the thickness of the clad.

A similar equation has been derived by Arkulis[193] for the deformation of composite metals, and also by Gulyaev and Rakov[194] for the rolling of bimetals. The individual thicknesses of the sandwich layers may be expressed as proportions of the total thickness of the sandwich as follows:

$$h_c = Bh \qquad (7.4)$$

Since $$h_c + h_m = h$$

Then $$h_m = (1-B)h \qquad (7.5)$$

By combining equations (7.3) to (7.5), we obtain:

$$\bar{Y}_{pe} = \bar{Y}_{pm} - B(\bar{Y}_{pm} - \bar{Y}_{pc}) \qquad (7.6)$$

It will be seen that equations (7.2) and (7.6) are the same.

Having obtained an equivalent value of the yield stress, the sandwich is treated as an uncladded sheet and any deformation theory may be applied.

Arnold and Whitton[1] have applied the equal strain hypothesis to sandwich rolling and concluded that the results of the theoretical calculations were sufficiently accurate for practical purposes. They found a considerable discrepancy between the measured and calculated values of the roll separating force for copper-titanium sandwiches for which they suggested two reasons:

(i) The greater dependence of the yield stress of copper on strain rate at room temperature.

(ii) The equal strain hypothesis was not valid, since the copper strained considerably more than the titanium.

It is unlikely that the first reason was valid, since the effect of strain rate was taken into account in the determination of the yield stress curves. If the discrepancy was caused by unequal straining in the layers, then the former should decrease with increasing reduction, since the authors showed that differential straining reduced with increasing reduction. However, this was not the case. A more probable reason for the discrepancy was the increasing difference in the work-hardeming rates of copper and titanium with increasing reduction. By using the equivalent yield stress method, it was implied that ($\bar{Y}pm - \bar{Y}pc$) remained constant. Any substantial variation of this factor with reduction will cause considerable errors in the calculation of the equivalent yield stress.

A different approach to the analysis of the rolling of composite metals has been developed by Tarnovskii[195]. By applying variational principles, equations were derived for calculating the strain in the individual layers of the composite and the roll separating force. The equations were extremely complex and the symbols used in the derivation were not well defined. However, Korshchikov et. al.[196] have claimed that the layer strains and mean specific pressure calculated by this method agree closely with experimental measurements. The validity of this claim is difficult to assess, since the details of the experimental investigation were not given and the symbols were again not well defined.

7.3. EXPERIMENTAL INVESTIGATION OF SANDWICH ROLLING.

One of the earliest experimental investigations of sandwich rolling was carried out by the United Steel Corporation of the U.S.A. and a report on the work was published by Orr and Romeo[197]. The method was applied to the production of special steel sheets for the aircraft and missile industries. Several sheets of the alloy steels up to 140 inches wide were hot rolled between two relatively thick plates of carbon steel. Final thicknesses of the alloy steels of 0.02 inch were reported to have been achieved. It was reported also that gauge tolerances were much better than could be achieved in conventional rolling, the power requirement was reduced considerably, and edge cracking was reduced or completely eliminated.

Arnold and Whitton[1] have published the results of an experimental investigation in which titanium alloy sheet was rolled between layers of copper, or brass, or mild steel. They reported a reduction in the roll separating force of up to 60 percent, the greatest

TABLE 1

COMPOSITE MATERIALS	CHANGE IN THICKNESS COMPOSITION % INTERFACE		
	SMOOTH	LUBRI-CATED	ROUGH
aluminium-lead-aluminium	4.0	4.5	33.25
aluminium-copper-aluminium	1.25	1.75	4.75
aluminium-steel-aluminium	4.25	4.75	23.0
copper-lead-copper	11.25	12.25	33.0
copper-aluminium-copper	2.0	3.34	-
copper-steel-copper	1.0	2.25	4.75
steel-aluminium-steel	5.5	10.25	-
steel-copper-steel	1.25	3.0	6.0

Table 1. The effect of the clad:matrix interface friction on the relative reduction of the layers. (Holmes. Ref 192)

TABLE 2

INTERFACE CONDITION	REDUCTION %		RELATIVE REDUCTION RATIO(a/b)
	CLAD (a)	MATRIX(b)	
copper-steel-copper			
Hatched	32.4	27.8	1.17
Smooth dry	32.2	26.7	1.21
Smooth lubricated	32.0	25.8	1.24
Polished dry	32.2	29.8	1.08
Polished lubricated	32.0	28.2	1.14
aluminium-steel-aluminium			
Hatched	32.8	28.8	1.14
Smooth dry	33.7	26.2	1.29
Smooth lubricated	34.5	20.2	1.71
aluminium-copper-aluminium			
Hatched	32.8	31.9	1.03
Smooth dry	32.4	31.8	1.02
Smooth lubricated	33.6	30.6	1.10
lead-aluminium-lead			
Hatched	31.0	27.0	1.15
Smooth dry	31.5	26.0	1.21
Smooth lubricated	33.0	22.0	1.5
lead-copper-lead			
Hatched	27.8	19.5	1.43
Smooth dry	30.1	18.6	1.62
Smooth lubricated	32.0	5.6	5.7

Table 2. The effect of the clad:matrix interface friction on the relative reduction of the layers. (Boyarshinov. Ref 199)

reduction having been achieved when the softest clad was used. Clearly, the difference between the hardnesses (or yield stresses) of the clad and matrix materials cannot be increased indefinitely, the limit being when all the deformation occurs in the clad and the matrix is undeformed. Furthermore, the softer the clad with respect to the matrix, the greater the tendency of the latter to edge-crack, since excessive relative movement may occur at the clad-matrix interface.

Alexander[198] showed from the results of Arnold and Whitton[1] that there is an optimum value of the clad thickness which gives the lowest roll separating force. This is supported by the results obtained by Davies[191] for the plane strain compression of copper-aluminium sandwiches.

The effect of the clad-matrix interface friction on the differential reduction of the layers of a composite has been studied by Holmes[192] and more recently by Boyarshinov[199]. The results of the investigations are summarised in Tables 1 and 2. It is interesting to note that, in Table 2, there is less differential reduction between the layers of the copper-steel sandwich when the clad-matrix interface is polished and dry than when it is smooth and dry. This probably because the tendency for the layers to weld will be greater in the former case.

8. A DISCUSSION OF THE PUBLISHED WORK ON SANDWICH ROLLING.

8. A DISCUSSION OF THE PUBLISHED WORK ON SANDWICH ROLLING.

Arnold and Whitton[1] have shown that the calculation of the roll separating force by the equivalent yield stress method is sufficiently accurate for practical purposes, provided that the yield stress of the hard metal is not more than about three times that of the soft metal. They have shown that the proportion of the clad in the sandwich affects the roll force. Alexander[198] has shown by re-plotting Arnold and Whitton's results, that there is an optimum value of the clad thickness which gives the lowest roll separating force. However, there is a need for a more comprehensive theoretical analysis of the process. It is desirable to be able to predict the optimum conditions for the lowest roll separating force and to identify the critical parameters on which the success of the process depends, from the point of view of the quality of the product.

Pomp and Lueg[188] have shown that a reduction in the roll separating force occurs whether the harder metal constitutes the matrix or the clad in hot rolling, but to a lesser extent in the latter case. It would be expected that the same would apply to cold rolling, but it is unlikely that any major advantage can be derived when the harder metal constitutes the ~~matrix.~~ clad

The effect of cladding on the roll torque has not been studied as far as the author is aware. Orr and Romeo[197] have claimed that the net power requirement per net ton of the product is lower for the sandwich than for the components rolled separately. The information given in the publication was insufficient to enable the claim to be checked. It is considered that the torque would be a more appropriate criterion than the power requirement, since the former may increase with the thickness of the cladding to the extent that the strength of the drive shaft of the mill may become the limiting factor.

The results of the work by Davies[191] are particularly interesting. He concluded that the matrix of the sandwich may undergo considerable necking in the same way as a tensile specimen. This is quite possible particularly when the matrix is much thinner than the clad. More work is necessary in order to clarify the conditions under which such a phenomenon may occur.

9. A DISCUSSION TO ESTABLISH THE SCOPE OF INVESTIGATION.

9. A DISCUSSION TO ESTABLISH THE SCOPE OF INVESTIGATION.

Composites are used in engineering in order to combine certain physical, chemical or mechanical properties of one material with those of another, or to overcome their respective deficiencies. In general, they can be classified into three broad categories:

(i) Composites in which the thickness of the coating (or clad) is only a few microns and is negligible compared with the thickness of the base metal, or one metal is distributed evenly in another. Galvanised and chrome plated sheets, and multi-phase alloys come under this category.

(ii) Composites in which the clad constitutes a significant proportion of the total thickness, and is bonded permanently by rolling, explosive forming, or adhesives. This category includes bimetals used in electrical circuitry, aluminium cladded with stainless steel used for cooking utensils, high carbon steels cladded with stainless steel used for chemical storage vessels, carbon steel cladded with titanium or tantalum used in the aerospace industry, and duralumin cladded with aluminium for many applications requiring high strength, lightness and high resistance to corrosion.

(iii) Composites in which layers of the same metal or of different metals are deformed jointly, specifically to alter the deformation characteristics. The layers are separated afterwards. Examples include the rolling of difficult metals sandwiched between sheets of softer metal, ply rolling in which several layers of the same metal are rolled together, extrusion of stainless steel coated with copper.

The present investigation was concerned primarily with the third category which will be referred to henceforth as sandwiches. However, the results are applicable to composites of the second category as well, since they are rolled, deep drawn, or spinned at some stage in the process of manufacture. The most important parameters selected for investigation were:

(a) The roll force.

(b) The roll torque.

(c) The clad-matrix interface friction.

(d) The position of the harder metal in the sandwich.

(e) The proportion of clad in the sandwich.

(f) The disparity in the strengths of the component materials.

(g) The effect of applied tensions.

The programme of experiments was designed to cover as wide a range of metals and thicknesses as possible and the possibility of using non-metals as clad, with a view to reducing costs was briefly investigated.

9.1. THE SELECTION OF MATERIALS.

The materials of primary interest in this investigation were the high carbon steels of the type used in the manufacture of saw blades. However, it was considered necessary to extend the programme to include non-ferrous metals and to interpret the terms "hard" and "soft" as describing one component of the sandwich with respect to the other, so that mild steel, copper and aluminium could be used in either capacity.

An attempt was made to obtain each material in a wide range of thicknesses and uniform mechanical properties. However, this proved difficult and a slight variation in the mechanical properties of the copper and mild steel had to be accepted.

In order to enable as wide a range of metal combinations and reductions as possible to be investigated without exceeding the maximum safe load of the mill, it was decided to use specimens approximately one inch wide. Consequently, the materials which were supplied in sheet form, were sheared to this width.

TABLE 3

MATERIAL	THICKNESSES (in)	AVERAGE HARDNESS (VPN)	SURFACE ROUGHNESS (microns)
1.25% C. STEEL	0.036	280	0.06
0.71% C. STEEL	0.026	156	0.06
AUSTENITIC STAINLESS STEEL	0.047	135	0.25
NIMONIC 105	0.012	275	
NIMONIC 90	0.031	214	
NIMONIC 80	0.031	165	
STABILISED MILD STEEL	0.018, 0.029, 0.033, 0.039, 0.048	95	1.6 – 2.2
HIGH CONDUCTIVITY COPPER	0.01, 0.02, 0.032, 0.04, 0.064.	60	0.065 – 0.30
COMMERCIAL PURITY ALUMINIUM	0.049, 0.028.	18	0.08

Table 3. Details of materials.

9.2. DETAILS OF MATERIALS.

This programme of research originated from discussions with manufacturers who were confronted with the problem of producing thin hard strip on conventional rolling mills. Most of the materials used in the investigation were kindly supplied by them. The details of the materials are shown in Table 3.

9.3. SELECTION OF ROLLING CONDITIONS.

9.3.1. The rolling mill.

The original plan was to modify for the investigation, an existing steckel mill designed by Quaiser[124]. However, preliminary rolling tests indicated that the mill was not sufficiently rigid to enable thin, hard materials to be rolled. It was decided therefore, to design a new mill, incorporating suitable parts of the steckel mill. The design is described fully in Appendix 20.1.

9.3.2. The roll diameter.

A pair of 4-inch diameter rolls was salvaged from the steckel mill and reground to a finish of approximately 15 micro-inches. A second pair of rolls was made from chrome vanadium steel, the specification of which is given in Appendix 20.2. . The diameter was 4.5 inches. This value was chosen in order to leave enough travel clearance for the screwdown and at the same time to enable the rolls to be re-ground many times if necessary.

9.3.3. The rolling speed.

It was realised from the start that the effect of rolling speed on the roll force and torque in sandwich rolling could not be included conveniently in the programme of investigation, since it would have been difficult to design a mill capable of operating in the speed range in which the rolling speed is normally significant in flat rolling,in view of the limited resources available. The speed of 10 ft/min. was selected for the programme of experiments except those in which tension was applied. The choice of a low speed enabled a higher torque to be developed for rolling. Also, at this speed, it was possible to obtain reasonably long load and torque records without having to use excessively long specimens.

9.3.4. Lubrication.

It was stated in section 7.2. that the reduction in the roll separating force in sandwich rolling was partly due to the frictional force at the clad-matrix interface. It was considered necessary therefore, that this interface should be free from any form of lubricant. However, it was expected that the capacity of the mill could be increased by applying a lubricant to the roll-clad interface, since the roll separating force would be further reduced. Rolling tests were carried out on sandwich specimens consisting of 0.033 in. mild steel matrix and a pair of 0.032 in. copper clads. Shell M.24 lubricant was applied to the roll-clad interface. It was found that some of the lubricant got into the clad-matrix interface despite precautions to prevent this. Furthermore, since the extent of the programme of experiments necessitated the preparation of a large number of specimens, it would have been difficult to lubricate each specimen carefully. It was decided therefore not to use a lubricant at all. The rolls and the feed platform were cleaned with trichloroethylene at intervals throughout the programme of experiments.

10. INSTRUMENTATION.

10. INSTRUMENTATION.

10.1. Design of measuring apparatus.

10.1.1. The roll force meters.

Two roll force meters were designed as shown in figures 15 and 16. The material used was Vibrac 45 alloy steel, the analysis of which is given in Appendix 20.2. . The roll force meters were heat-treated at 850°C. for 30 minutes and quenched in oil. This was followed by a temper for one hour at 150°C. giving 540 VPN. hardness. The top and bottom faces and the central part of the roll force meters were finish ground to the dimensions shown in figure 16.

The centre cylinder of each meter on which strain gauges were to be bonded, was roughened and subsequently cleaned with trichloroethylene. Eight foil gauges, each having 75 ohms resistance and dimensions 1/4 x 1/4 in., were bonded on the centre cylinder, using Araldite AY. 105 and hardener HY. 951. The gauges and bonding materials were supplied by Saunders Roe Ltd. The arrangement of the gauges on each meter is shown in figure 17. After bonding, each gauge was tested for continuity and resistance to earth.

The strain gauges were cured in an oven at 60°C. for 24 hours, and were then checked for continuity and resistance to earth. The latter was found to be in

Figure 15. The roll force meter.

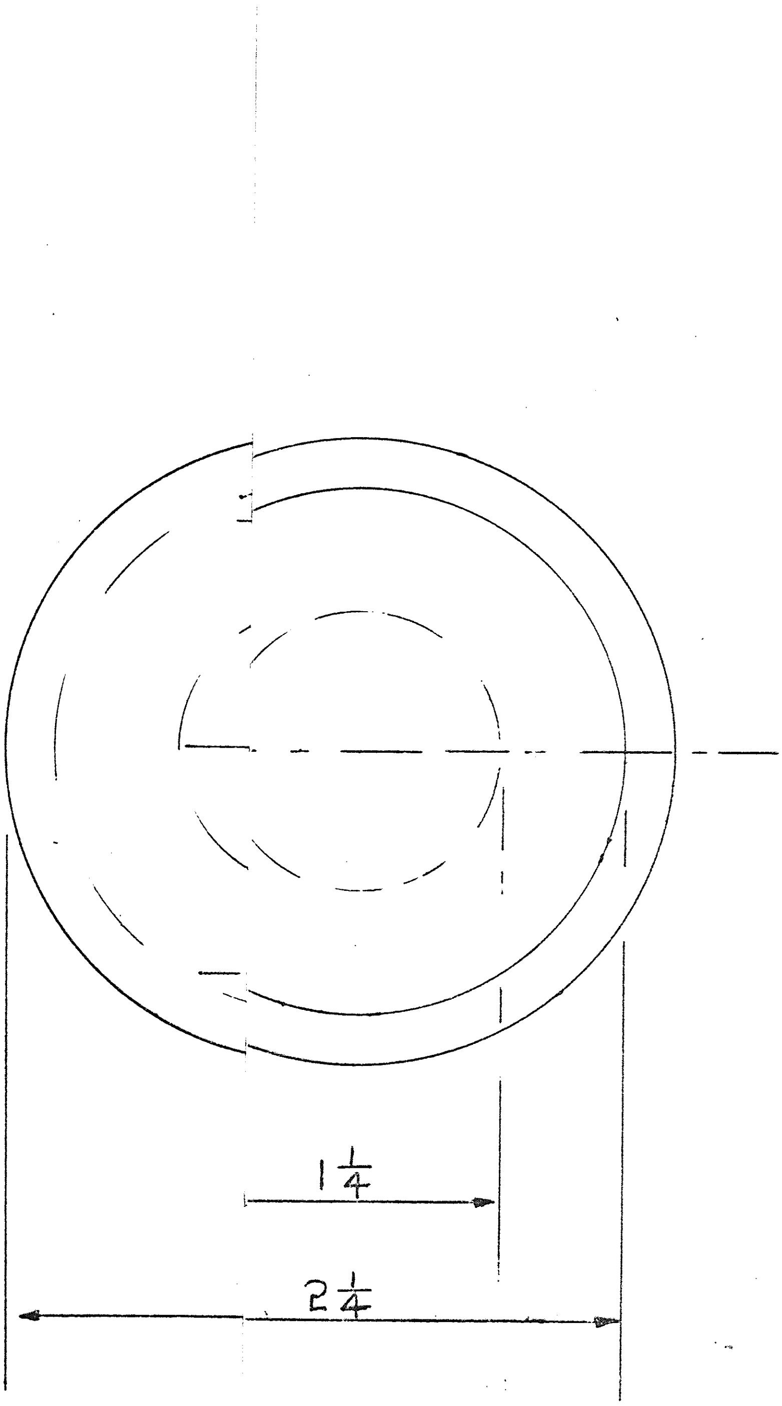
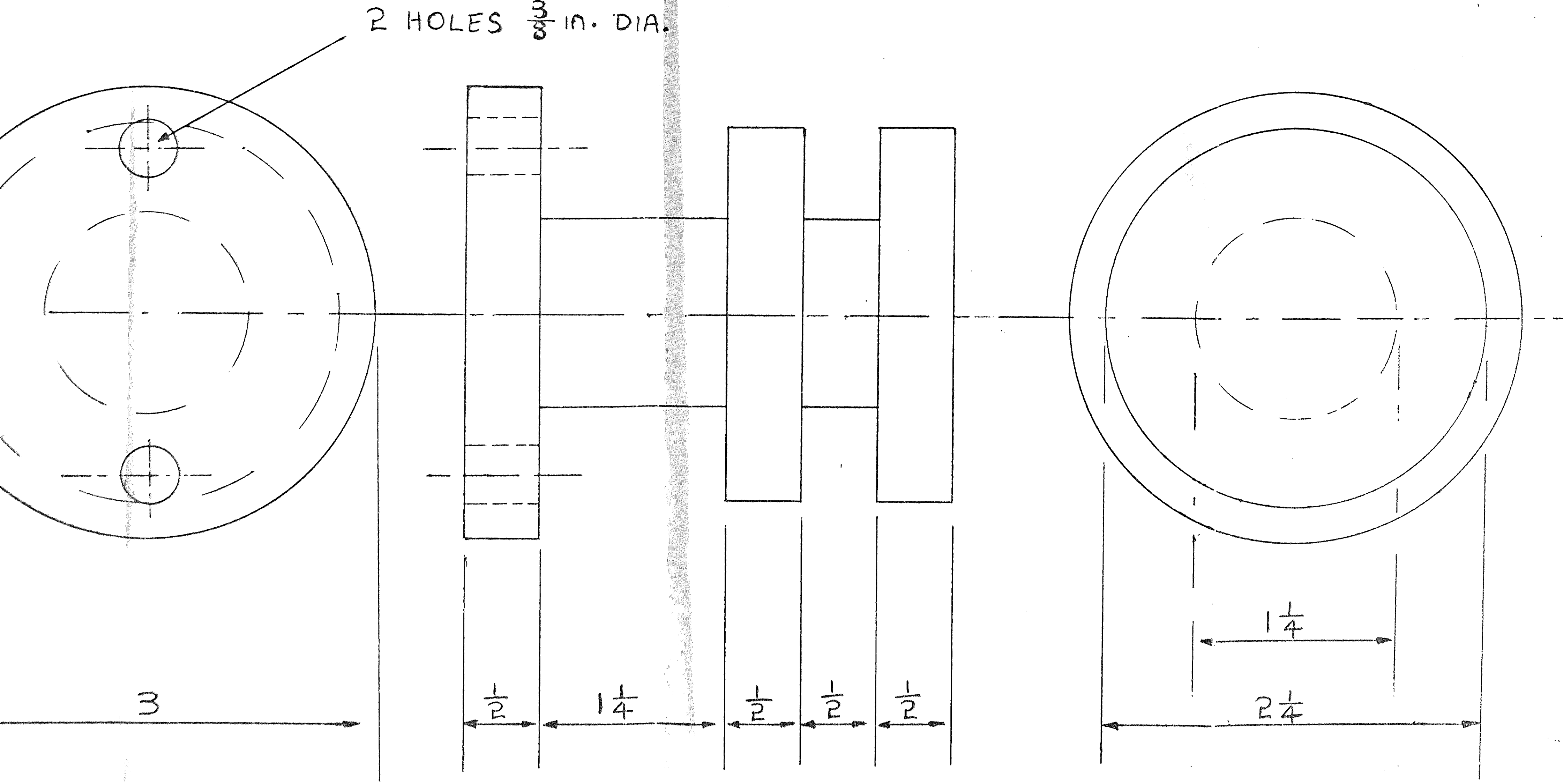
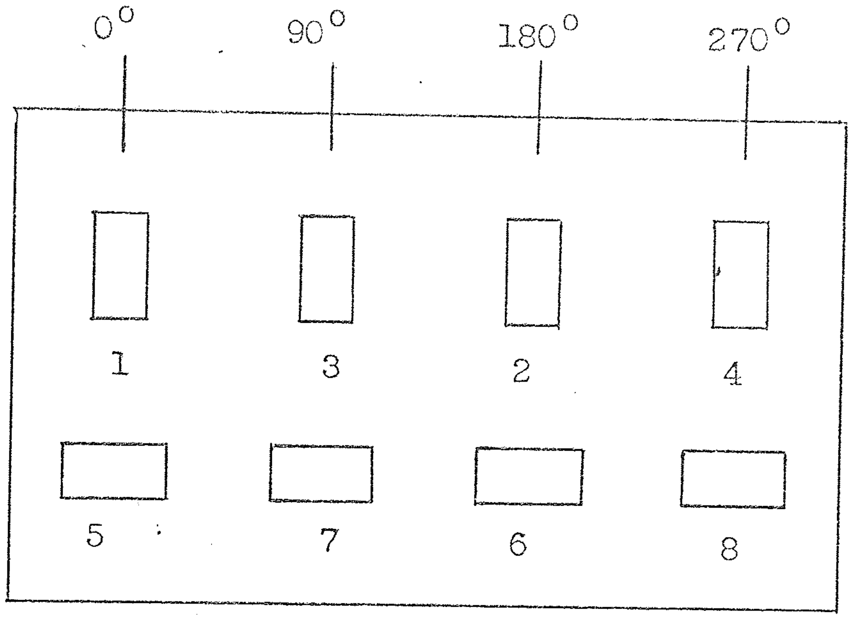


FIGURE 16. ROLL



ROLL FORCE METER DESIGN DETAILS.



ARRANGEMENT OF THE STRAIN GAUGES ON THE ROLL FORCE METER.

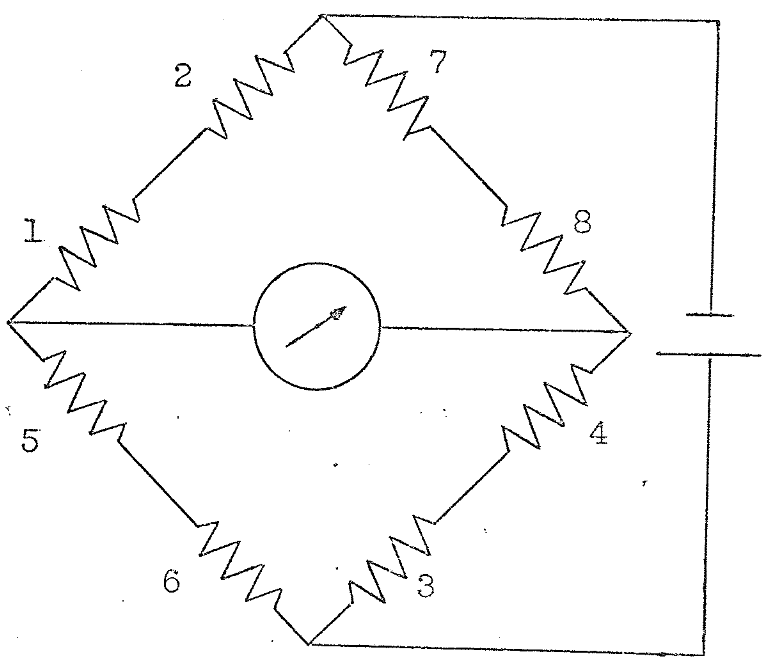


Figure 17.

THE WHEATSTONE BRIDGE FOR THE ROLL FORCE METER.

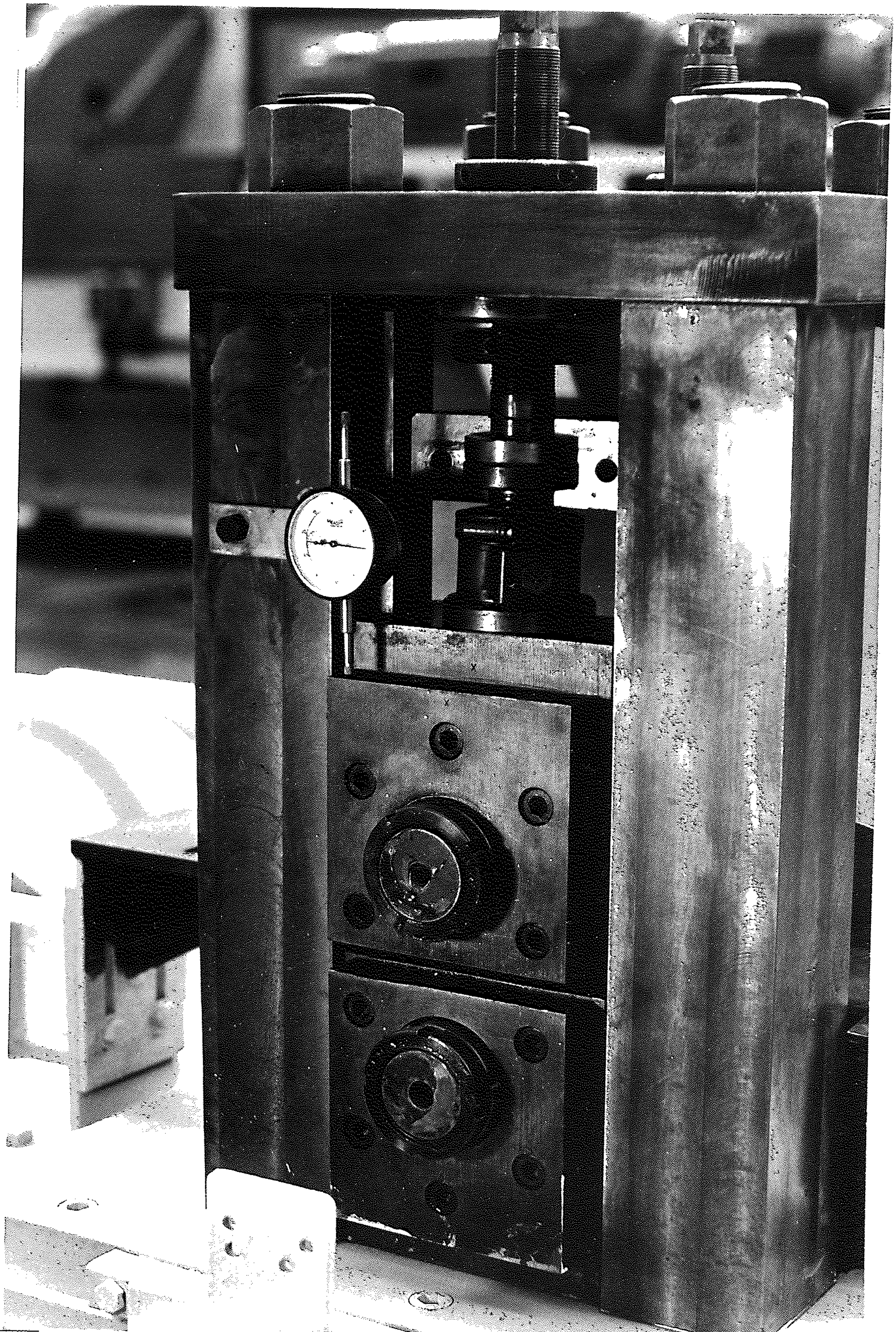


Figure 18. The roll force meter in position.

excess of 200 megohms. The gauges were connected into a Wheatstone bridge as shown in figure 17. The arrangement of the gauges on the meters and the wiring technique were designed to eliminate stresses due to temperature changes and bending caused by eccentric loading.

The gauges were cleaned with trichloroethylene and the meters were left to dry in an oven for 24 hours at 60°C. Then the gauge connections were checked finally for continuity and resistance to earth, and protected with mild steel covers made in two halves and held together by clips. Figure 18 shows the position of one of the roll force meters on the mill.

10.1.2. <u>The torque meters.</u>

The torque meters were machined from Vibrac 45 alloy steel, of the same specification as for the roll force meters. The heat-treatment was also the same. The centre cylinder of each torque meter was finish ground to the dimensions shown in figure 19, roughened and cleaned. Sixteen foil torque gauges were bonded to each cylinder as shown in figure 20, and, after curing, the gauges were connected into a Wheatstone bridge, also shown in figure 20. The procedure for bonding and connecting up the gauges was the same as that adopted for the roll force meters. Each gauge was checked for

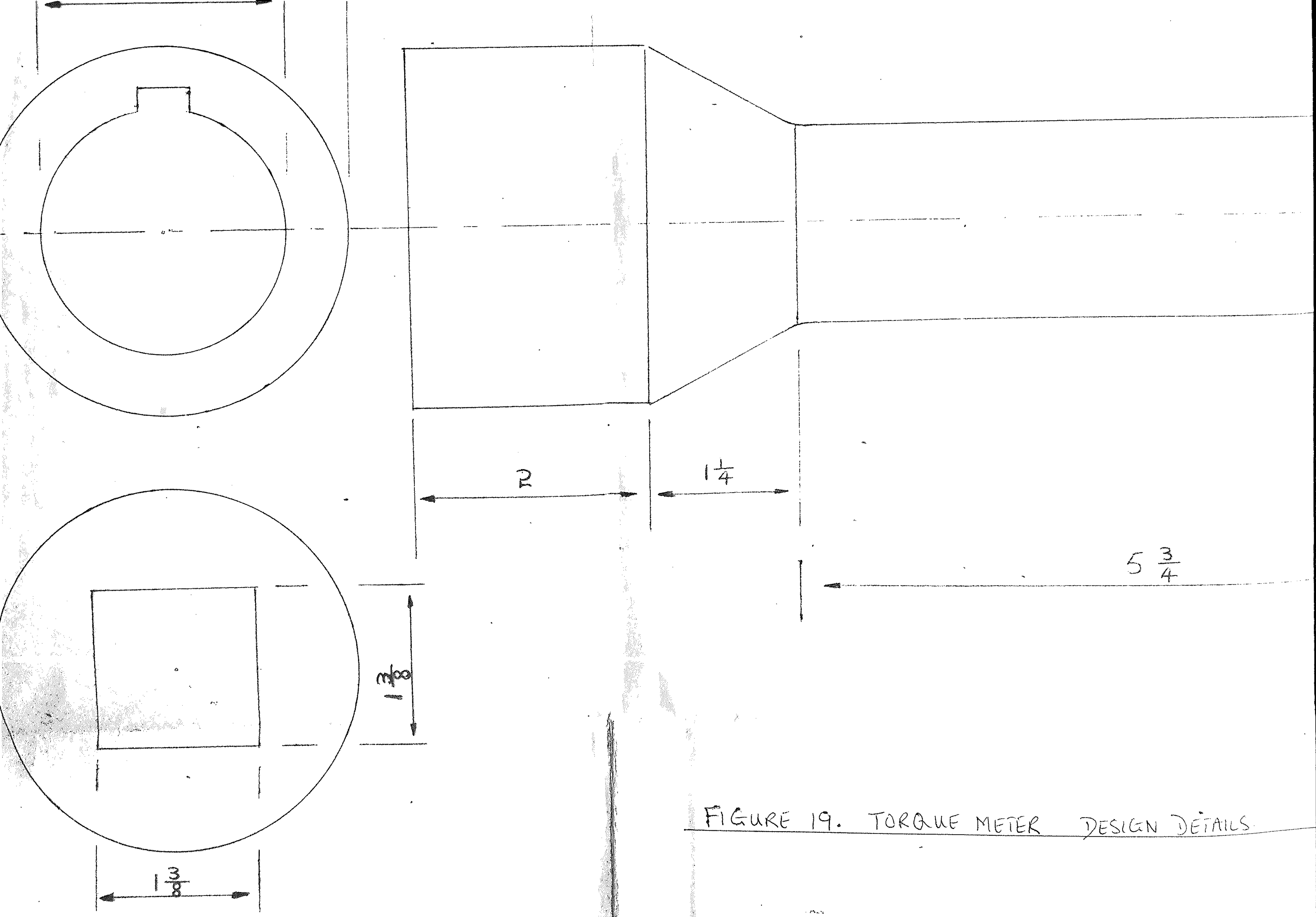
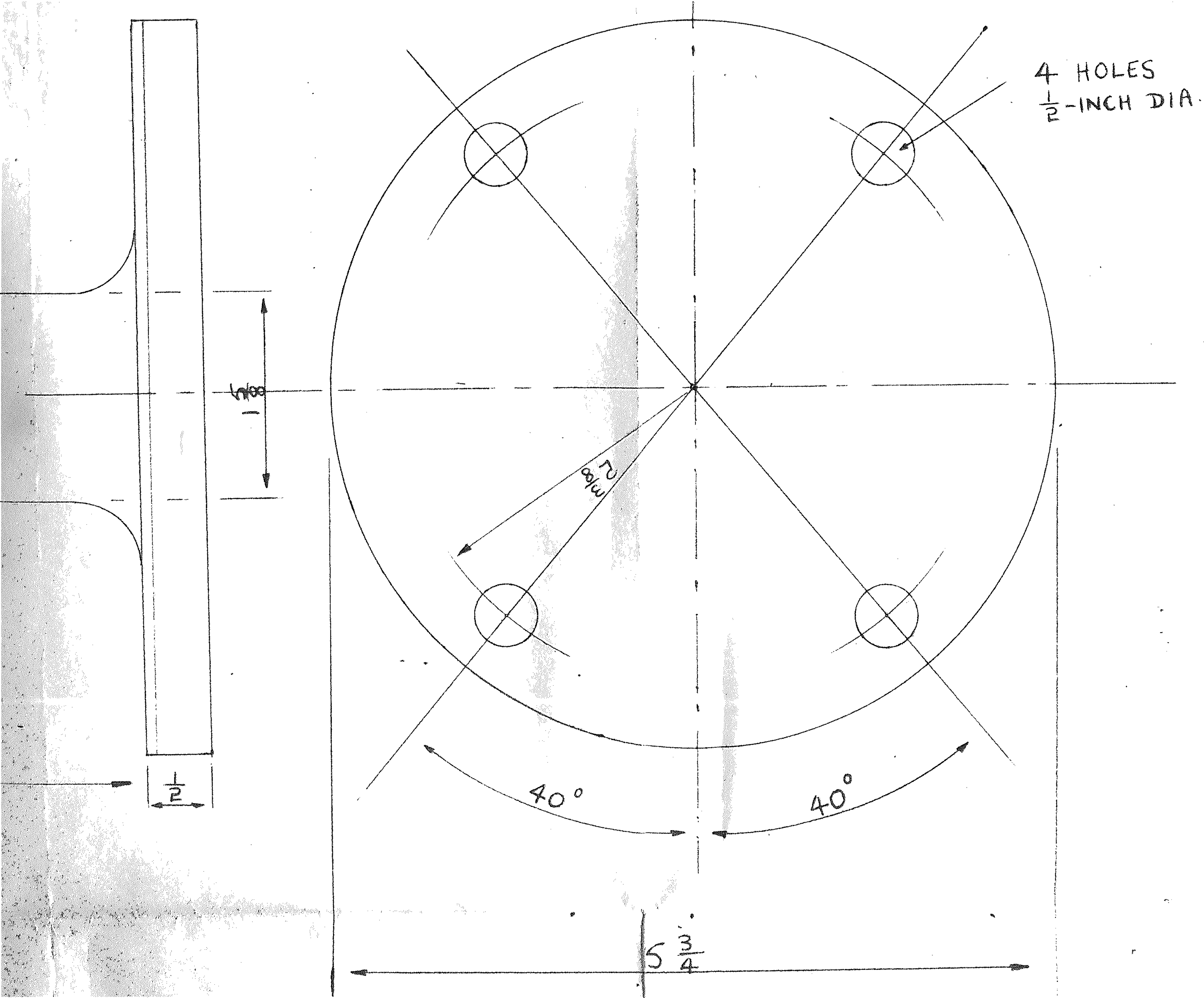


FIGURE 19. TORQUE METER DESIGN DETAILS


4 HOLES
1/2-INCH DIA.
R 2 3/8
40°
40°
5 3/4
1 5/8
1/2

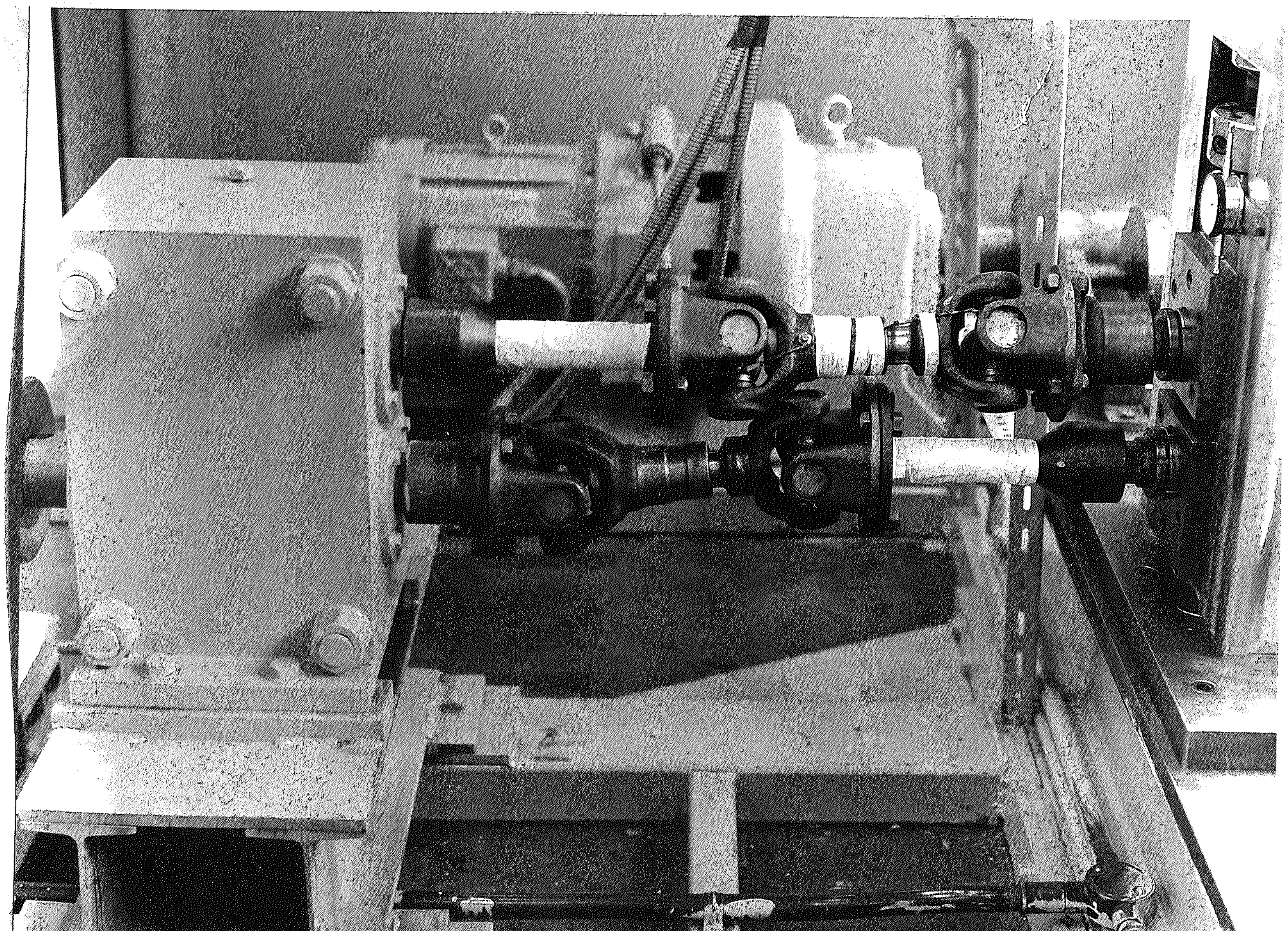


Figure 21. Torque meters in the main drive.

continuity and resistance to earth. Figure 21 shows the torque meters in position in the main drive. The wires from the meters were passed through small holes in the rolls to the opposite end of the chocks where they were connected to slip rings. The specification of the slip rings is given in Appendix 19.2.

10.1.3. The tension meters.

A torsion bar arrangement shown in figures 22 and 23 and designed by Quaiser[124] was used for the measurement of the front tension. A second torsion bar was made from the same material (Vibrac 45) and to the same dimensions and used for the measurement of the back tension. The heat-treatment was the same as described for the roll force meters. An extension shaft was bolted to each end of the bar. Each extension shaft was passed through a mild steel block bolted to the base plate of the mill. One end of the extension shafts was fixed in the steel block while the other was free to rotate in the other steel block which contained roller bearings.

The two ends of the torsion shafts were connected by two torsion arms to a cross arm which carried a freely rotating drum. The torsion arm at the fixed end of the torsion bar was free to rotate on roller bearings mounted on the end of the torsion bar. The other end of the torsion bar was fixed to the second arm.

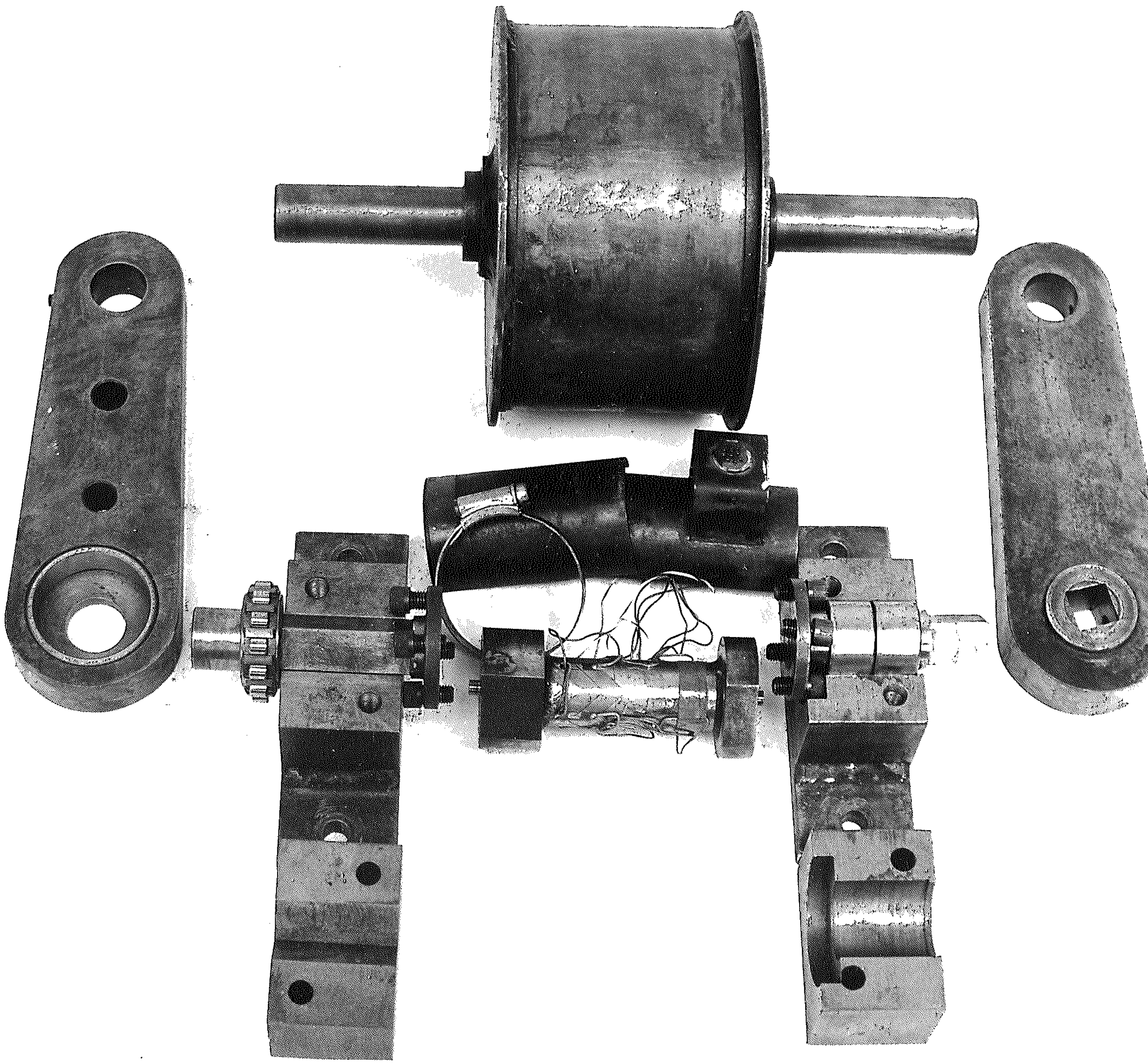


Figure 22. The tension meter.

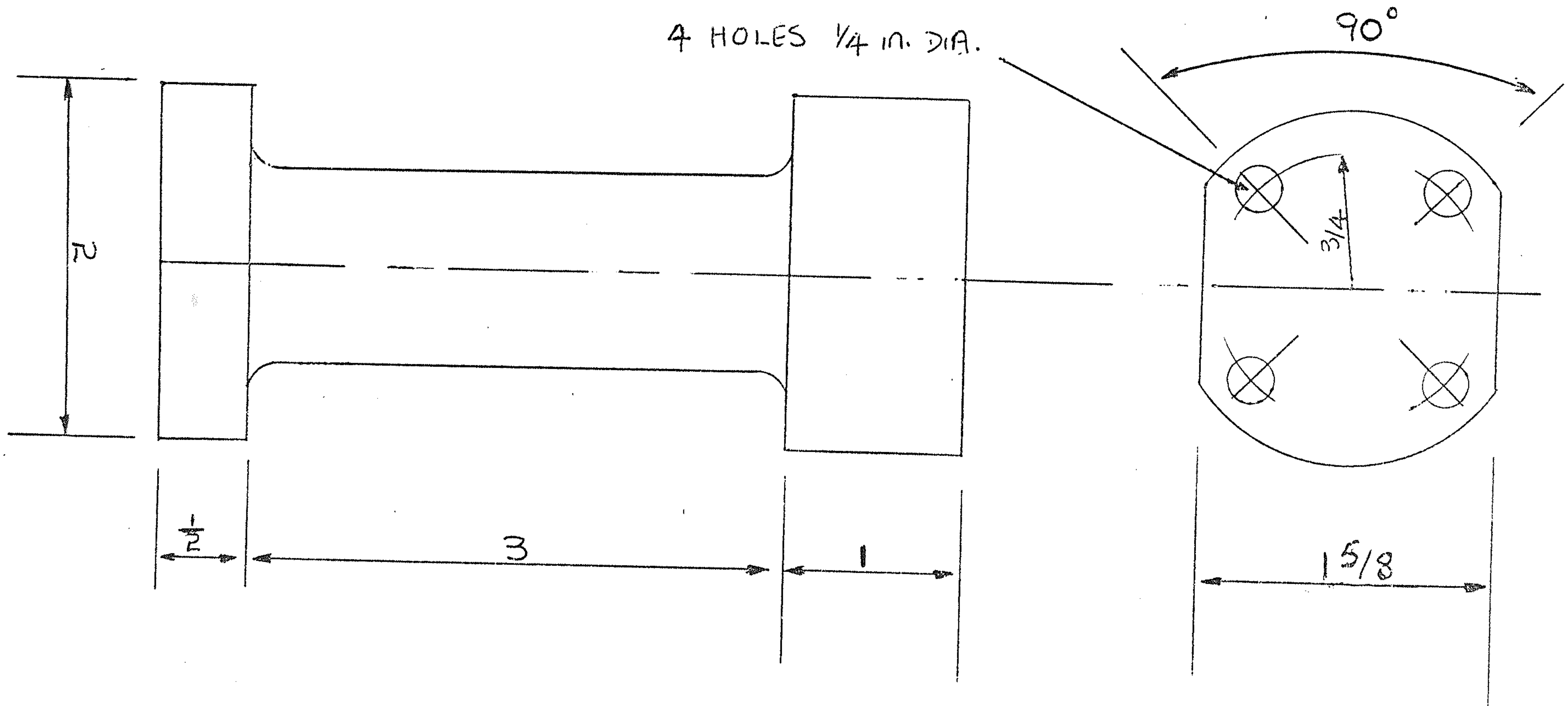


FIGURE 23. TENSION METER DESIGN DETAILS.

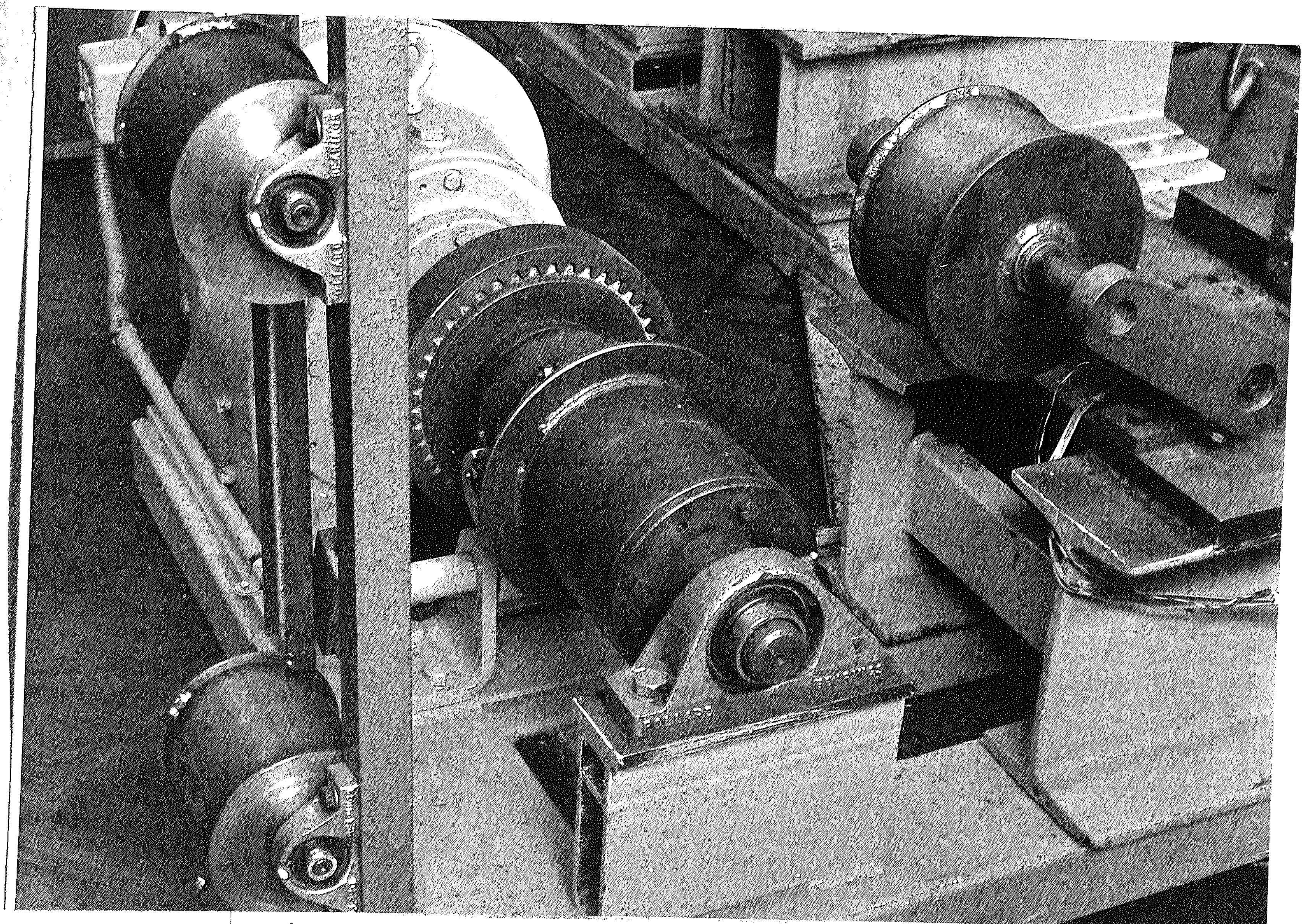
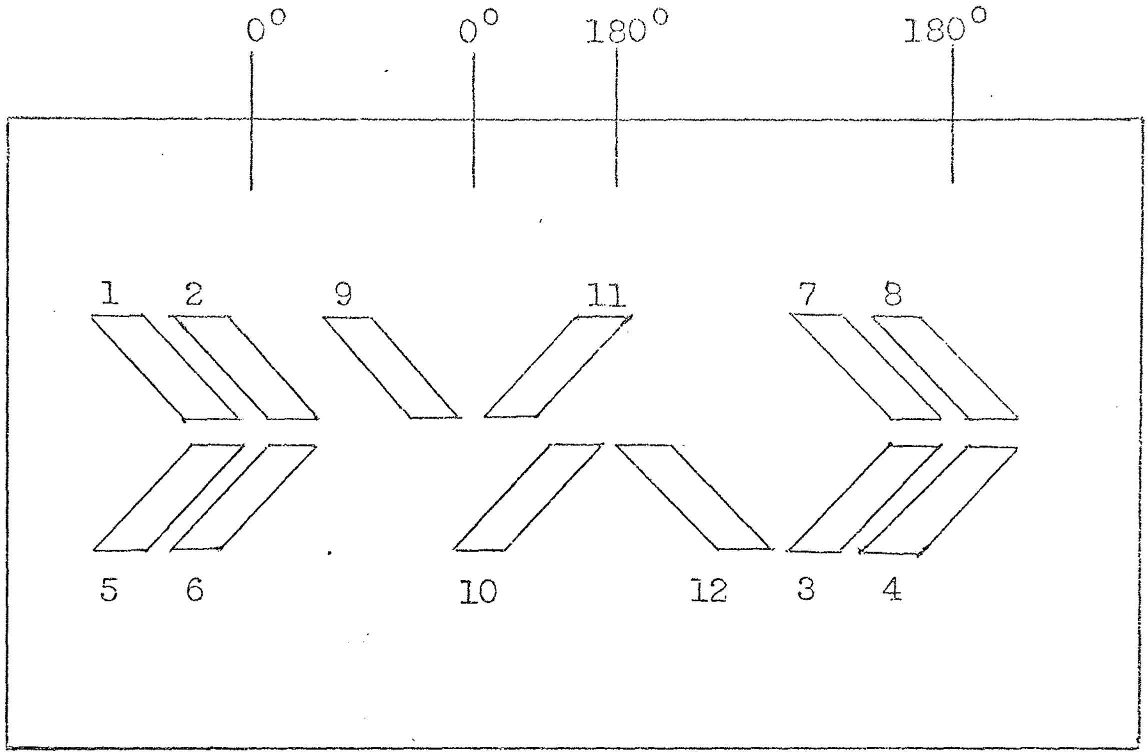
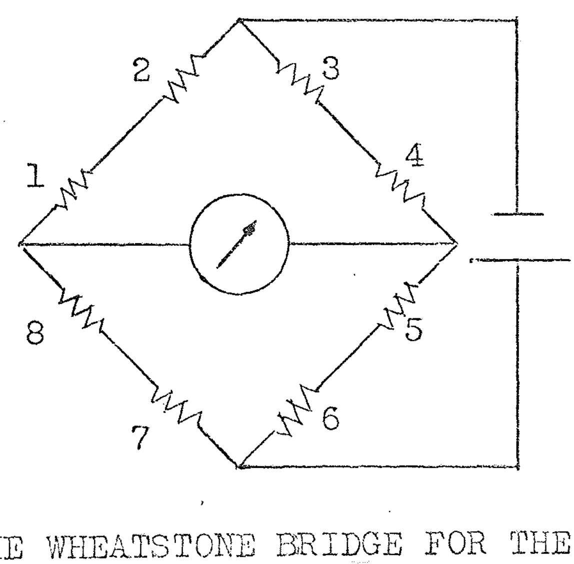


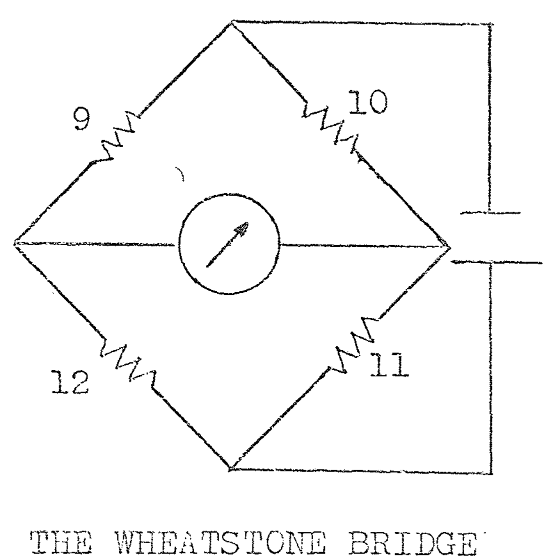
Figure 24. The back tension meter in position.



ARRANGEMENT OF THE STRAIN GAUGES ON THE TORSION BARS.



THE WHEATSTONE BRIDGE FOR THE TORSION BAR.



THE WHEATSTONE BRIDGE FOR THE TENSION INDICATOR.

Figure 25.

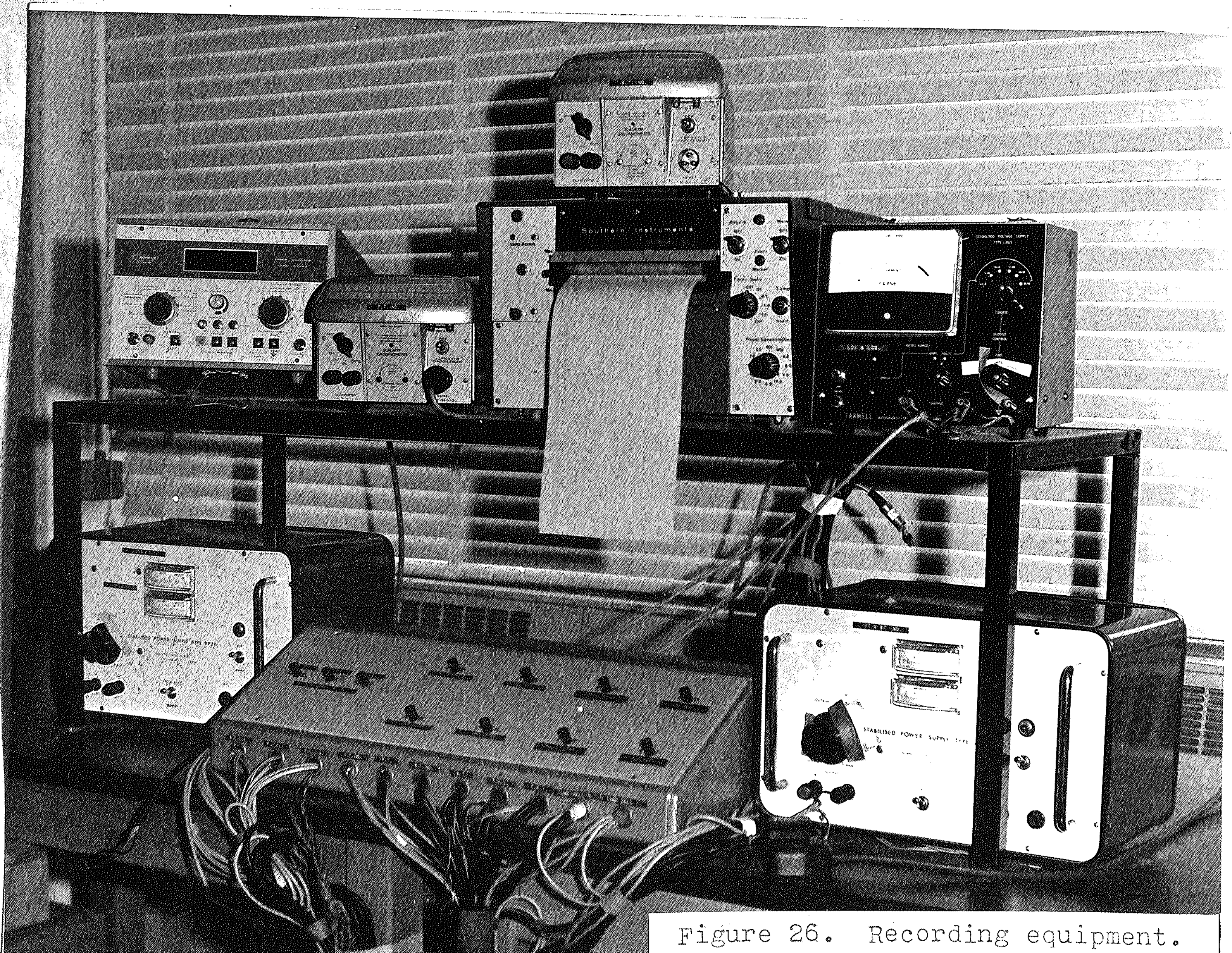


Figure 26. Recording equipment.

Figure 24 shows the torsion bar in position on the mill. Twelve foil torque gauges, each having 91 ohms resistance were bonded in two groups of four and two respectively, on each torsion bar as shown in figure 25 using the bonding technique described already for the previous meters. Each group was connected into a separate Wheatstone bridge, so that two separate signals were obtained from each bar. The signal from one bridge was fed into a Scalamp galvanometer which was calibrated for tension, and the other was fed into the recording apparatus. The former was necessary in order to enable the tension in the strip to be set at approximately the desired values and also to avoid overloading the torsion bar and the tension drives.

10.1.4. <u>The power supply.</u>

The bridge input currents for the meters were supplied by two stabilised direct current supplies with variable voltage output of 0 to 30 volts and a maximum current output of 1 ampere. A complete specification of the power supplies is given in Appendix 20.2.

10.2. <u>The recording equipment.</u>

The signals from the roll force, torque, and tensile meters were fed into a 10-channel ultra-violet recorder utilising mirror galvanometers of variable sensitivities. The recorder is shown together with the other recording equipment in figure 26. The galvanometer sensitivity for each meter was selected to give a maximum deflection of approximately 10 cm. at the highest bridge signal output. Details of the specifications for the recorder are given in Appendix 20.2. .

11. CALIBRATION OF MEASURING APPARATUS.

11. CALIBRATION OF MEASURING APPARATUS.

11.1. The roll force meters.

Each roll force meter was calibrated separately in a 50-ton Denison universal testing machine. A compressive load was applied slowly, and in steps of 0.5 ton, the corresponding galvanometer deflection being recorded for each load. The calibration was repeated for the load decreasing from the maximum value to zero and final records were made only when consistent results were obtained. The calibration curves are shown in Appendix 20.3. The maximum calibration load was 10 tons.

11.2. The torque meters.

The calibration of the torque meters was carried out on a 60,000-lbf.in. torsion testing machine. Special adaptors were made from the same material as the torque meters and are shown in figure 27. The torque was applied at increments of 1000 lbf.in. up to 10,000lbf.in. by turning manually a large wheel on the testing machine and the signal from the torque meter was recorded for each increment. The calibration was repeated many times for increasing and decreasing torque until consistent results were obtained. The calibration curves are given in Appendix 20.3. .

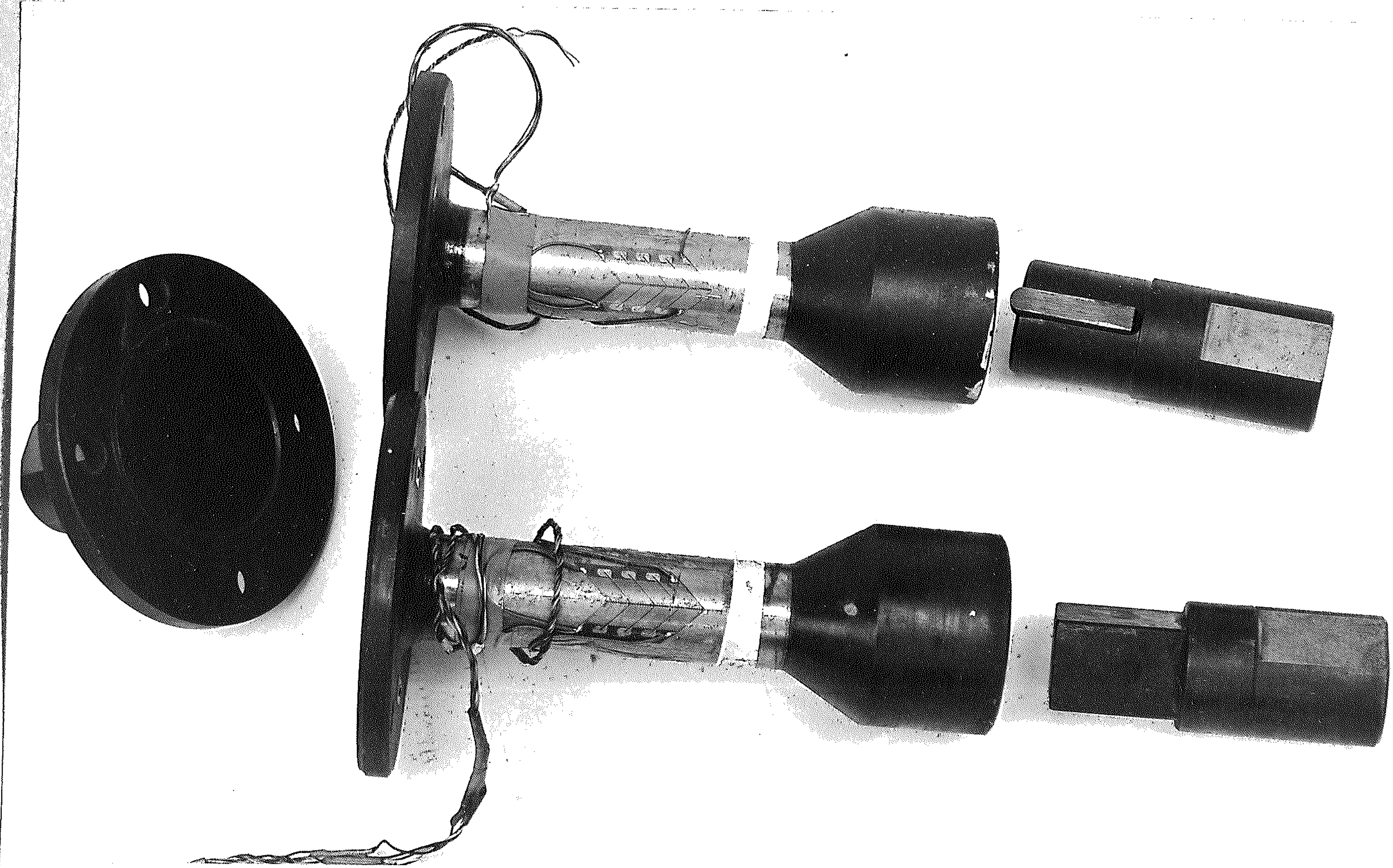


Figure 27. Torque meters with adaptors for calibration.

11.3. The tension meters.

The tension meters were designed originally for calibration on a torsion testing machine. The torque was related to the tension in the strip passing over the drum by consideration of the geometry of the tension meter assembly, based on the assumption that the strip was tangential to the drum. This was tantamount to assuming that the drum was level with the lower roll irrespective of the tension in the strip. Preliminary rolling tests in which tension was applied showed that the drum deflected considerably particularly when high tension was applied. It was decided therefore to adopt a different method for the calibration. The apparatus shown in figure 28 was designed for this purpose.

A mild steel strip 2 feet long and 0.04 inch thick was cut from the coil and two strain gauges each having 75 ohms resistance were bonded on each side of the two broad sides of the strip by the same technique that was adopted previously. The gauges were connected into a Wheatstone bridge as shown in figure 29. The strip was calibrated on the Denison universal testing machine by applying slowly a tensile load in increments of 0.05 ton and recording the signal from the strain gauge bridge on the strip. The maximum load applied was 0.4 ton, equivalent to a stress of 10 tonsf/sq.in.

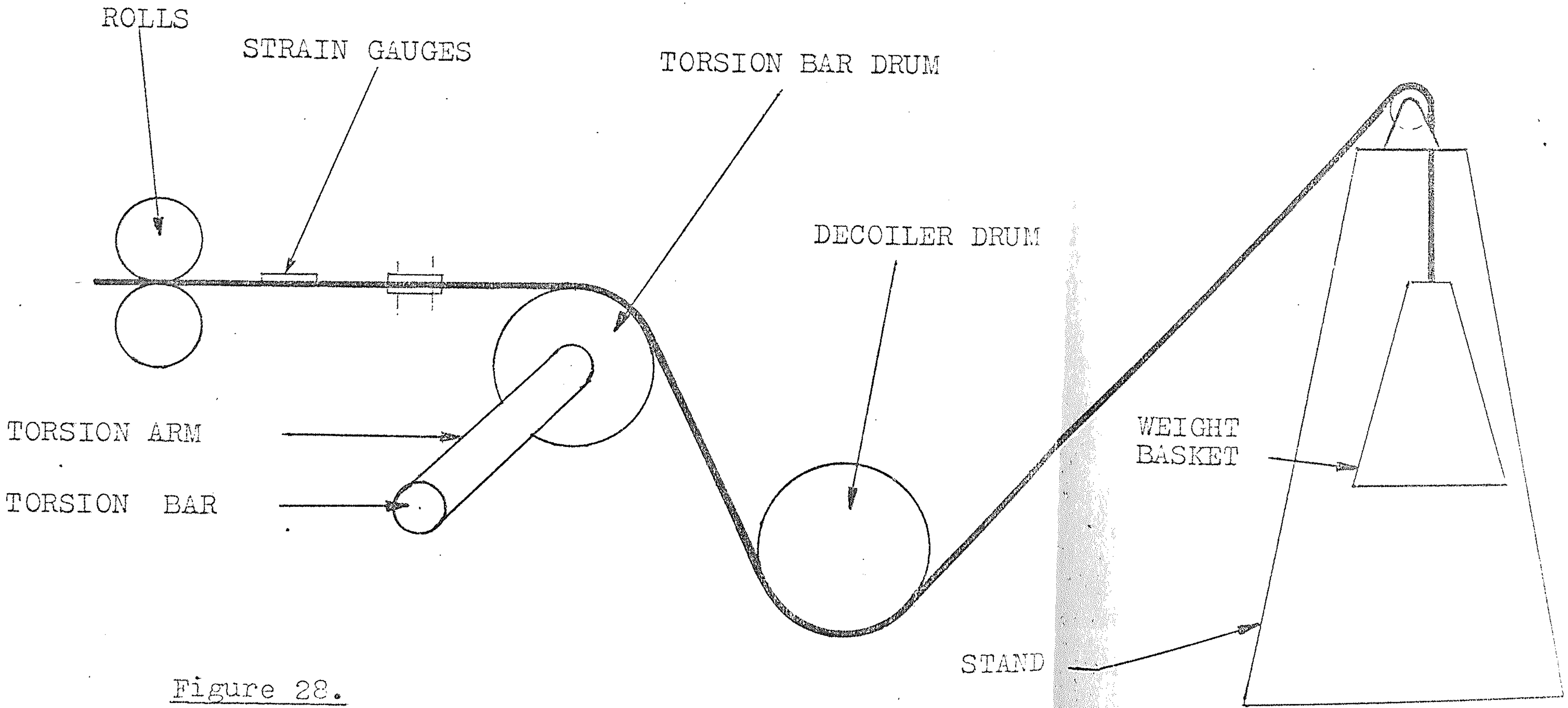
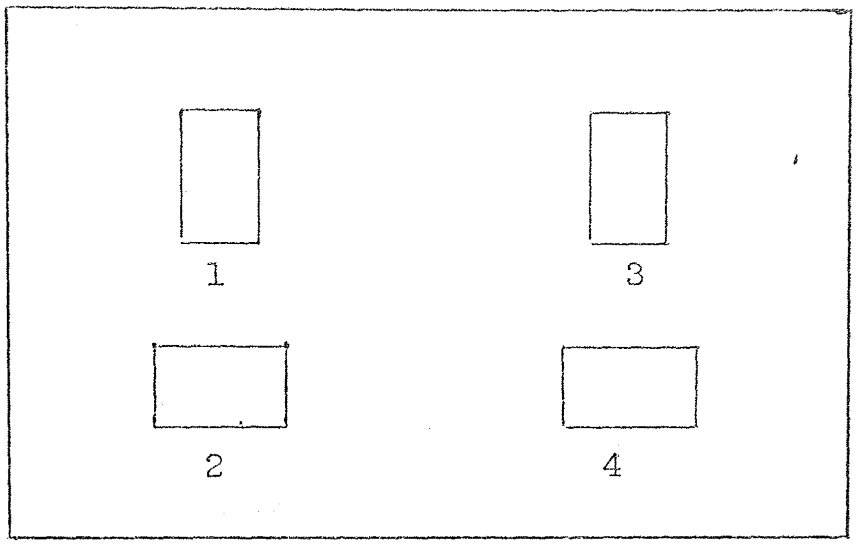


Figure 28.

CALIBRATION OF THE TORSION BAR.



ARRANGEMENT OF THE STRAIN GAUGES ON THE TENSION STRIP.

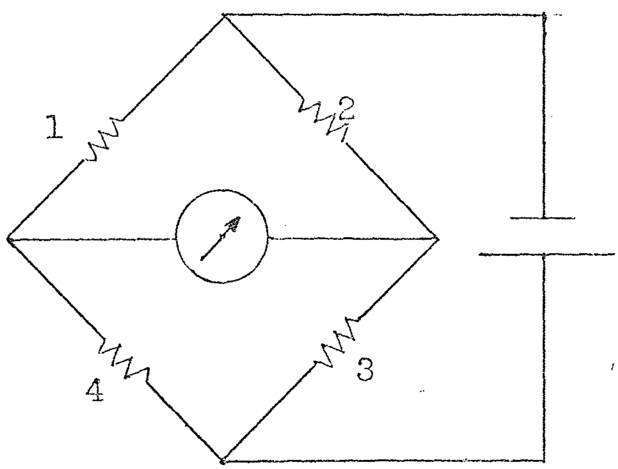


Figure 29.

THE WHEATSTONE BRIDGE FOR THE TENSION STRIP.

in the strip. The calibration curve is given in Appendix 20.3..

After calibration, the tension strip was connected at one end to a long mild steel strip of the same width and thickness. The free end of the tension strip was held securely in the roll gap. The extended strip was taken over the tension drum and passed under the de-coiler drum as it would be in actual rolling, but instead of winding it onto the drum, the strip was taken over a cylindrical drum mounted on a high stand. The drum was supported at each end by a housing consisting of roller bearings to enable it to rotate freely. The end of the strip was connected to a weight basket. A diagrammatic sketch of the calibration technique is shown in figure 28. Tension was applied to the strip at increments of 50 lb. by placing weights in the basket. The strain in the torsion bar was recorded for each load. The calibration curves are given in Appendix 20.3. . Through the calibration curves for the tension strip and the torsion bar, it was possible to relate the tension in the strip to the torque applied to the torsion bar by the strip passing over the tension drum in actual rolling.

12. EXPERIMENTAL PROCEDURES.

12. EXPERIMENTAL PROCEDURES.

12.1. Hardness tests.

Hardness tests were carried out on all materials to be rolled, except those that were too thin and also the non-metals. The tests were carried out on a Vickers hardness testing machine and the results were included in Table 3.

12.2. Determination of the stress-strain curves for the materials.

The stress-strain curves were determined for a selected number of materials, using the Watts and Ford[96,97] plane strain compression technique. The tests were carried out on the Denison universal testing machine incorporating a sub-press similar to that used by Watts and Ford. The tests were carried out on specimens which had previously been given varying pass reductions on the mill. The separate indentation technique was adopted and the specimen was lubricated with calcium stearate powder before each test. The strain rate was approximately 10^{-3} sec. . Care was taken to ensure that the tool width-strip thickness ratio remained between 2 and 4 as recommended by Watts and Ford[97], the tools being changed appropriately. The thickness and width of the specimen were measured with hand micrometers. The micrometer used for thickness measurements had a specially reduced anvil. The stress-strain curves were taken as the envelopes of the individual curves obtained for the specimens. The stress-strain curves are given in Appendix 20.4.

12.3. The preparation of specimens.

A strip each of 0.039 in. thick mild steel and 0.04 in. thick copper of lengths 5 and 12 in. respectively were cut from coils. Both sides of the mild steel strip and one side of the copper strip were roughened with grade 3 emery cloth, and both strips and the rolls were cleaned thoroughly with trichloroethylene. The copper strip was folded double with the roughened face on the inside. The mild steel strip was placed in between the copper envelope. The sandwich was flattened in the vice and rolled, with the closed end leading. The strips were separated and measured along the length and width with micrometers. The average reduction in the clad was 32 percent and in the matrix 27.9 percent. The roll force and torque were recorded. In the above test, the copper clad slid off the matrix towards the end of the pass, forming a fish tail shown in figure 30. Five more specimens were made from the same materials and by the same method as described previously. The specimens were rolled, the roll gap having been kept constant at the value for the

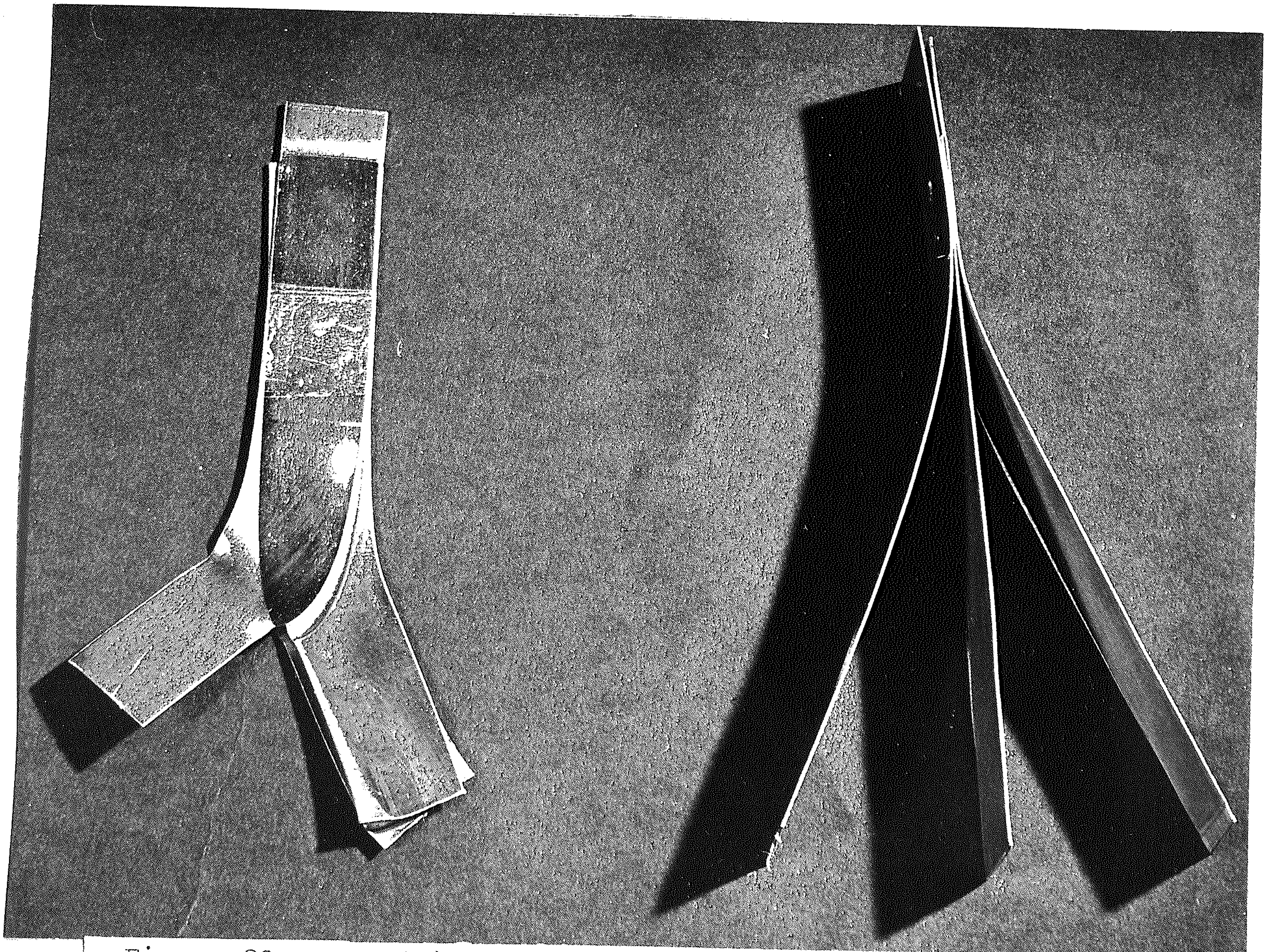


Figure 30. (a) Fish tail. (b) Rolled sandwich.

previous test. Fish tails were formed in all cases. However, the length of the fish tail was inconsistent for the specimens. It was decided therefore that a way of preventing the formation must be found. Three more specimens identical to the previous specimens were made and each was welded along the edge so that the matrix was completely boxed in. The specimens were cleaned and rolled as before. No fish tail was formed and the individual reductions in the clad and matrix respectively were 31.9 and 31.4 percent. However, it was realised that it would be impracticable to weld all specimens, considering that many hundreds of specimens would be involved. Furthermore, it was difficult to separate the layers of the sandwich for the measurement after rolling.

Three more specimens were made as described before. The layers of each specimen were rivetted together at one point near the open end of the sandwich, using nimonic alloy rivets. The specimens were cleaned and rolled. No fish tail was formed and the reductions in the clad and matrix were 32.1 and 31.2 respectively. However, the rolls were marked by the rivets. Copper rivets were found to be more satisfactory if properly hammered flat before rolling.

All sandwich specimens used in the programme of investigation were made by folding double the clad material, placing the matrix between, having roughened and cleaned the interfaces, and rivetting the layers together at the open end using copper rivets. Specimens for the conventional rolling experiments were cut in 6-inch lengths. Scales were removed from the surfaces by rubbing with fine emery cloth. The specimens were then cleaned with trichloroethylene.

12.4. Measurement of specimens.

The surface roughness of each material to be rolled was measured with the portable talysurf. The results were included in Table 3. The widths and thicknesses of the sandwich specimens were measured with micrometers before assembly. Measurements were made at several points along the length and accross the width of each layer and the average value found. The uncladded specimens were measured in the same way. After rolling, the sandwich specimens were cut open at one end and the layers were measured individually.

12.5. Fluctuations in the torque traces.

Figure 31 shows typical traces of the roll force and torque records obtained for a pass reduction of 30 percent on 0.033 mild steel. The length of the traces represents approximately one revolution of the rolls. It will be seen that, in addition to the small variations in the torque traces, there were strong

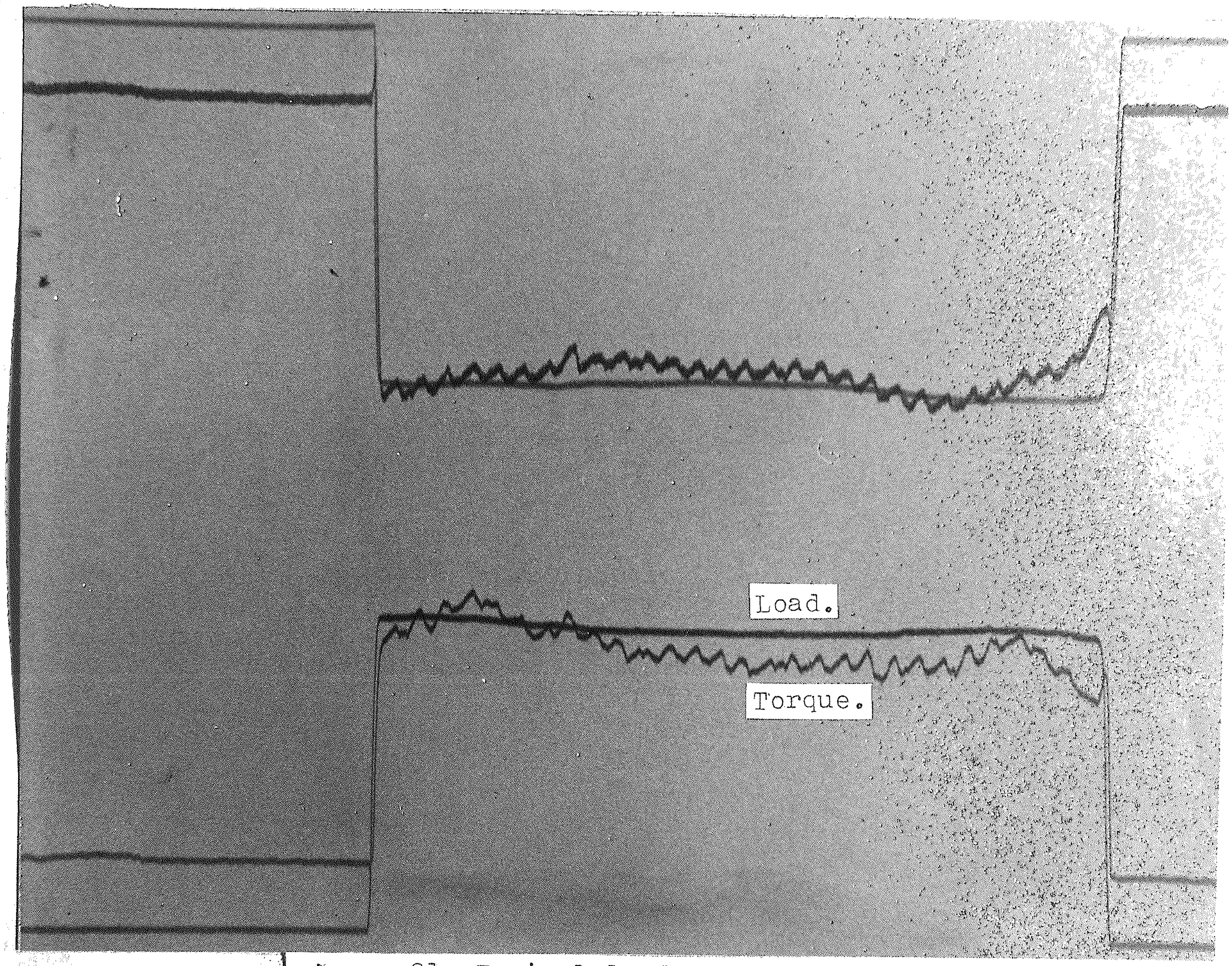


Figure 31. Typical load and torque traces.

fluctuations in both torque traces with the period of the roll revolutions. The small variations were probably due to small irregularities in the pinions. Since the corresponding variations were in opposite directions, it was expected that the total roll torque should not be affected. This was verified by feeding the signals from both torque meters into the same channel of the recorder. The total torque curve obtained was practically smooth.

The periodic fluctuations were first thought to be due to variations in the thickness of the strip, or its surface condition. However, fluctuations occured for other metals although the amplitude was approximately proportional to the torque. Furthermore, when the rolls were squeezed together without a strip between, the fluctuations still occured. Since there were no measurable corresponding fluctuations in the roll force traces or the strip thickness along its length, it was considered unlikely that the fluctuations were due to the eccentricity of one or both of the rolls. The fact that the fluctuations were out of phase strongly indicated that the universal shafts were responsible, since the out-of-line angle was different for each shaft. A mark was made on the top shaft and also on the side of the top chuck. In all subsequent rolling experiments, the specimen was pushed into the roll gap when the two marks coincided. This was to ensure that all the specimens were rolled in approximately the same period of the roll revolution. The roll torque for each shaft was taken as the average of the fluctuations.

12.6. Measurement of chart records.

The measurements of chart records were made with a pair of dividers and a foot rule graduated to 0.02 in.. Vertical lines were drawn through three points along the lengths of the traces, avoiding the entry and exit zones. By taking measurements on the vertical lines, it was ensured that the roll force, torque and tensions could be related to any point along the length of the rolled strip. For each parameter, the average of the three measurements was found.

12.7. Determination of the first pass curves.

In order to enable the effect of cladding on rolling parameters to be assessed, it was necessary to measure the parameters for the hard metals rolled without cladding. Specimens were prepared as described in section 12.3., and given varying reductions. At least eight specimens of each material were rolled at different reductions, except the very thin materials, in which case, the number of specimens rolled was

TABLE 4

MATRIX	CLAD	THICKNESS (in)		HARDNESS
		MATRIX	CLAD	RATIO
1.25%C.STEEL	MILD STEEL	0.036	0.029, 0.039, 0.048.	2.95
	COPPER		0.04.	4.65
	ALUMINIUM		0.028, 0.049.	15.5
0.71%C.STEEL	COPPER	0.026	SAME AS FOR 1.25 %C.STEEL	2.6
	ALUMINIUM			8.65
	MILD STEEL			1.64
AUSTENITIC STAINLESS STEEL	MILD STEEL	0.047	SAME AS ABOVE	1.42
	COPPER			2.25
	ALUMINIUM			7.5
STABILISED MILD STEEL	COPPER	0.039	0.04.	1.58
COPPER	ALUMINIUM	0.040	0.049.	3.34
NIMONIC 80	COPPER	0.040	0.031	2.76
	MILD STEEL	0.039	0.031	1.74
NIMONIC 90	COPPER	0.040	0.031	3.56
	MILD STEEL	0,039		2.26
NIMONIC 105	COPPER	0.020	0.012	4.6
	MILD STEEL	0.018		2.9

Table 4. Details of materials for tests on the effect of clad material.

TABLE 5

MATRIX	CLAD	THICKNESS (in.)	
		MATRIX	CLAD
1.25%C.STEEL.	MILD STEEL	0.036	0.018, 0.029, 0.039, 0.048.
	COPPER		0.01, 0.02, 0.032, 0.04.
	ALUMINIUM		0.028, 0.049.
0.71%C.STEEL.	MILD STEEL COPPER ALUMINIUM	0.026	SAME AS ABOVE.
AUSTENITIC STAINLESS STEEL.	MILD STEEL COPPER ALUMINIUM	0.047	SAME AS ABOVE.
MILD STEEL	COPPER	0.039	SAME AS ABOVE
COPPER	ALUMINIUM	0.04	SAME AS ABOVE

Table 5. The effect of the clad thickness.

determined by the limiting reduction. In these and subsequent experiments, the results were plotted into graphs immediately, so that, in the case of a discrepancy, the particular experiment was repeated.

12.8. Effect of varying the clad materials on the roll force and torque.

Sandwich specimens were made from a wide range of hard-soft metal combinations shown in Table 4. It should be mentioned here that the term "hard" or "soft" describes one component material of the sandwich with respect to the other. All specimens were cleaned thoroughly and given reductions of between 5 and 50 percent in one pass. Measurements of the dimensions of the specimens before and after rolling and the chart records were made as before.

12.9. Effect of the clad thickness.

In order to determine the effect on the roll force and torque of varying the proportion of the clad in the sandwich, specimens were made from the materials and thicknesses shown in Table 5. In all cases, the hard metal constituted the matrix. Rolling tests were carried out also on 0.048 in. thick mild steel strips soaked in copper sulphate solution for 24 hours and subsequently dried in air.

12.10. The effect of interchanging the positions of the materials in the sandwich.

So far, rolling tests had been carried out on sandwich specimens in which the hard metal constituted the matrix. In theory, a reduction in the roll force can be achieved also by interchanging the positions of the hard and soft materials in the sandwich so that the former constitutes the clad, since the stresses induced in the hard and soft metals by the interface frictional shear stress remain tensile and compressive respectively, although the magnitude may change. Sandwich specimens were made from 0.064 in. copper (matrix) and 0.018 in. mild steel (clad). In all cases the proportion of each material in the sandwich was unchanged. It was not possible to investigate a wide range of materials because of the limited range of thicknesses available.

12.11. The effect of interface friction.

The results of previous investigations reviewed in Section 7 showed that the interface friction is an important parameter in sandwich rolling. It was considered necessary therefore to investigate the effect on the roll force and relative reduction, of varying the frictional conditions at the clad-matrix interface. Sandwich specimens were prepared from 0.04 in. thick copper and 0.039 in. mild steel, the latter being the matrix. No rivets were used and the interface frictional condition was altered in four different ways:

(i) Polished and degreased.

(ii) Smooth (as received) and degreased.

(iii) Smooth and lubricated with Shell M.24 oil.

(iv) Roughened with grade 3 emery cloth and degreased.

Two reductions were carried out for each interface condition and the individual reductions in each layer of each sandwich were recorded.

12.12. The effect of the clad width.

So far in the test programme, all the three layers of the sandwich specimens had been of the same width. However, during the rolling of the 1.25 carbon steel and the nimonic 105 alloy, considerable edge-cracking in both materials at reductions above about 15 percent. It was considered that this was due to the fact that there was insufficient clad metal at the edges to induce the necessary tensile stresses in the matrix. Hence the reduction in the matrix was considerably higher at the centre than at the edges. It was decided to investigate the effect of the clad-matrix width ratio on the tendency to edge-crack. Specimens were made from the high carbon steel and the nimonic alloy (matrix) and 0.039 in. Mild steel (clad). The clad:matrix width ratio was varied between 1 and 1.5. After each specemen was rolled, the layers were separated and the matrix was inspected for edge-cracking.

12.13. Experiments with plastic clads.

From the economic point of view, it is desirable that the clad should be as cheap as possible and easily recoverable and used again. It was considered that plastic might satisfy these requirements. Preliminary rolling tests were carried out on specimens consisting of 0.049 in. aluminium and 0.083 in. Marley floor tiles, but the mild steel fractured into small bits. It was decided that the clad was too thick. Floor tiles 0.043 in. thick were obtained and were used as clads for aluminium, copper and stainless steel, 0.049, 0.032 and 0.047 inch thick respectively. The roll force, torque and reduction in the matrix were recorded. In most cases, the plastic clad was torn to pieces and the thickness was not measured.

12.14. Sandwich rolling with applied tensions.

12.14.1. Preparation of specimens.

The materials used for the rolling experiments with applied tensions were 0.032 in. thick copper and 0.033 in. thick mild steel for the clad and matrix respectively. The only reason for selecting these materials was that they were the only ones available in the required quantity, thickness and in coil form.

The copper was in two coils each approximately 50 feet long. One side of each coil was roughened by rubbing with grade 3 emery cloth. A 50 foot length of mild steel was cut and both sides were roughened by rubbing with grade 3 emery cloth. The strips were straightened and cleaned with trichloroethylene, and then assembled by placing the mild steel strip between the copper strips with the roughened wides of the copper on the inside. The layers of the sandwich were held together firmly while they were rivetted at intervals of 1 foot.

12.14.2. Application of back tension.

The sandwich specimen was cleaned and wound on the decoiler drum, the clutch having been disengaged. The roll and decoiler drives were switched on and the peripheral speeds of the rolls and the decoiler drum were set at 20ft/ minute with the aid of a digital timer and magnetic switch. The timer counter was capable of timing revolutions to 10^{-6} second. The drives were then switched off.

The roll gap was opened sufficiently so that the leading edge of the specimen could be pushed in. It was ensured that the specimen passed over the tension drum at approximately the centre of the drum. The roll gap was then set for a reduction of approximately 25 percent, with the sandwich between the rolls. The decoiler clutch was engaged and both the decoiler and roll drives were switched on at the same time. The recorder was also switched on.

Initially, there was no tension in the sandwich, since the perepheral speed of the rolls was greater than that of the workpiece at the plane of entry of the arc of contact. The roll speed was then increased gradually until a tension of approximately 5 tonf/sq.in. was indicated on the back tension indicator galvanometer. It was not possible to hold the tension at any particular value since the effective diameter of the decoiler drum decreased continuously as rolling proceeded. However, sufficient records were made before the sandwich was exhausted, to enable the roll force and torque to be obtained at 3 different tension values. The thickness of each layer of the specimen was measured between each pair of rivets.

12.14.3. Application of front tension.

The specimen was made exactly as described for the back tension experiments and, after cleaning, was wound on the decoiler drum, with the clutch disengaged. The peripheral speeds of the rolls and the coiler drum were set at 20ft./min. as described for the back tension tests. The roll and coiler drives were switched on at the same time and the speed of the latter was increased until a tension of approximately 2 tonf/sq.in. was indicated on the front tension indicator galvanometer. The tension was then allowed to build up as the effective diameter of the coiler drum increased due to the layers of strip on it. A maximum of 4 tonf/sq.in. was achieved before the strip was exhausted. The layers of the sandwich were measured as before.

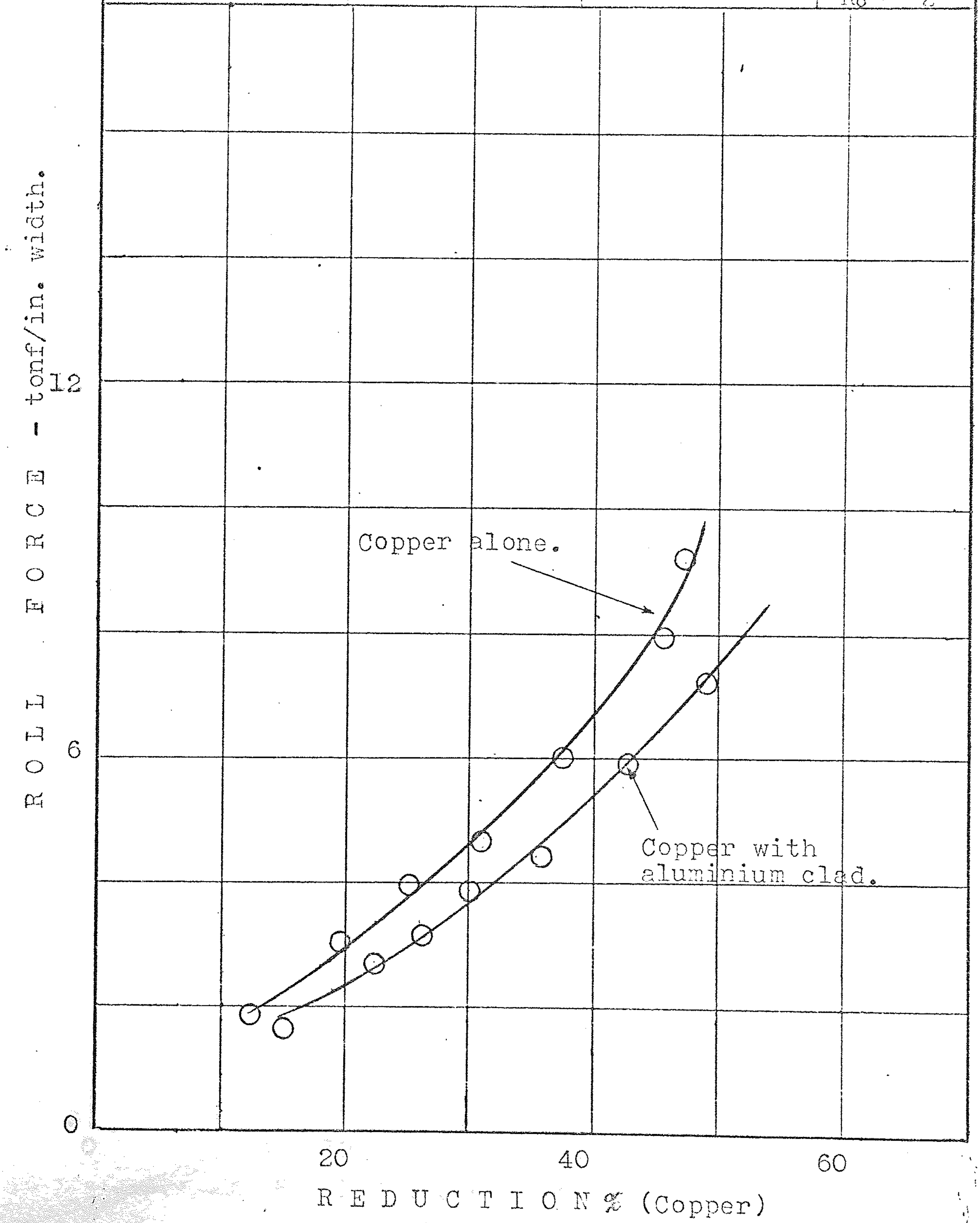
12.14.4. Measurement of chart records.

Every time a rivet on the strip passed through the roll gap, a slight "bump" occured in the roll force and torque traces. By counting the "bumps", it was possible to relate the traces to the thickness measurements along the length of the rolled strip. Measurements of the tensions and the corresponding roll force and torque were made between the "bumps" in the traces, avoiding the areas near the start of the records.

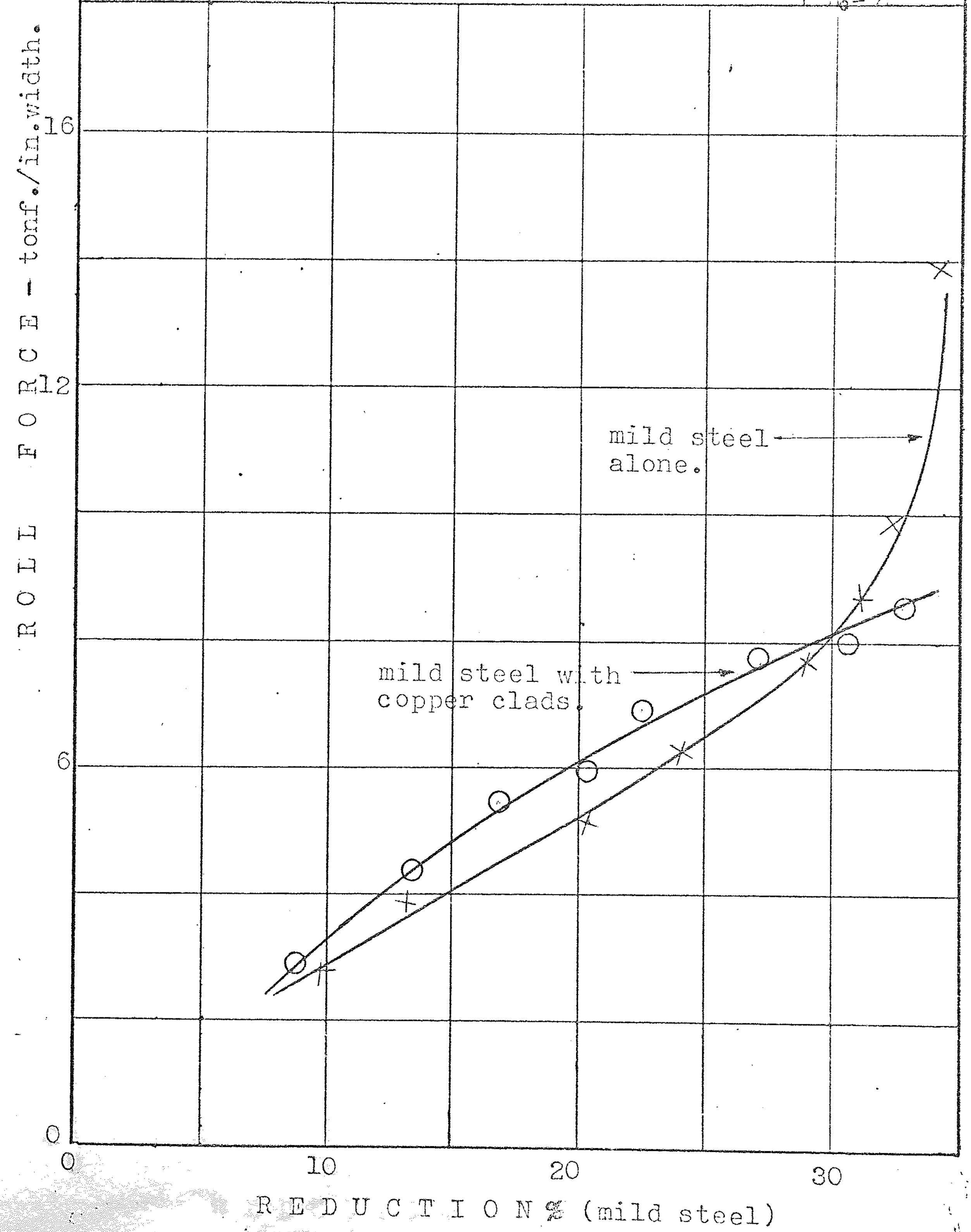
Only 3 different values of each of the front and back tensions could be obtained from the records. The tests were extremely difficult and time consuming to carry out and also required a considerable quantity of material. Furthermore, the pattern of results was the same as for conventional rolling with applied tensions. It was decided therefore, not to attempt to do anymore tests.

13. GRAPHICAL RESULTS.

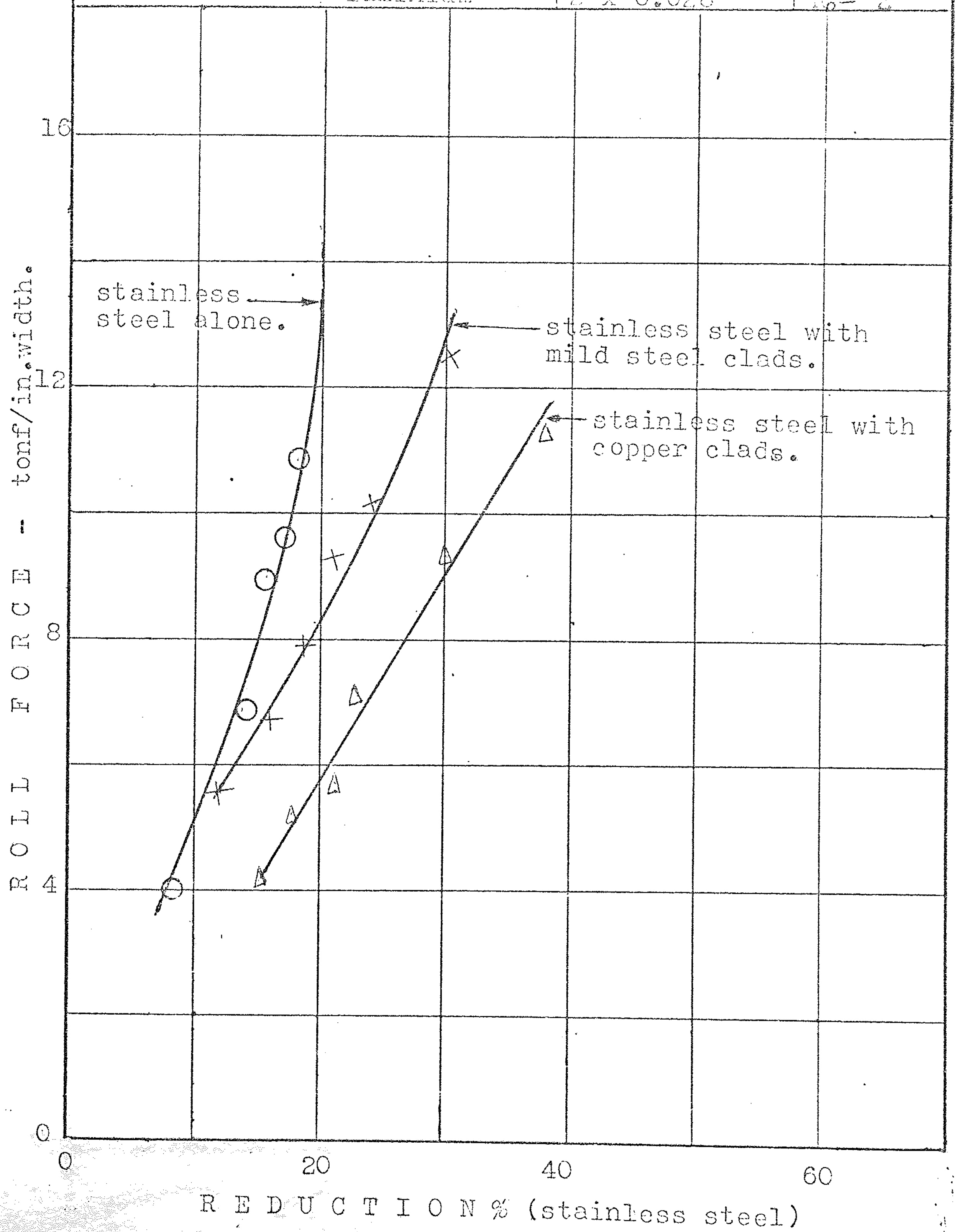
POSITION.	MATERIAL	THICKNESS (in.)	GRAPH NO 1
MATRIX :	Copper	0.04	
CLAD :(1)	aluminium	2 x 0.049	
			R_0 = 2



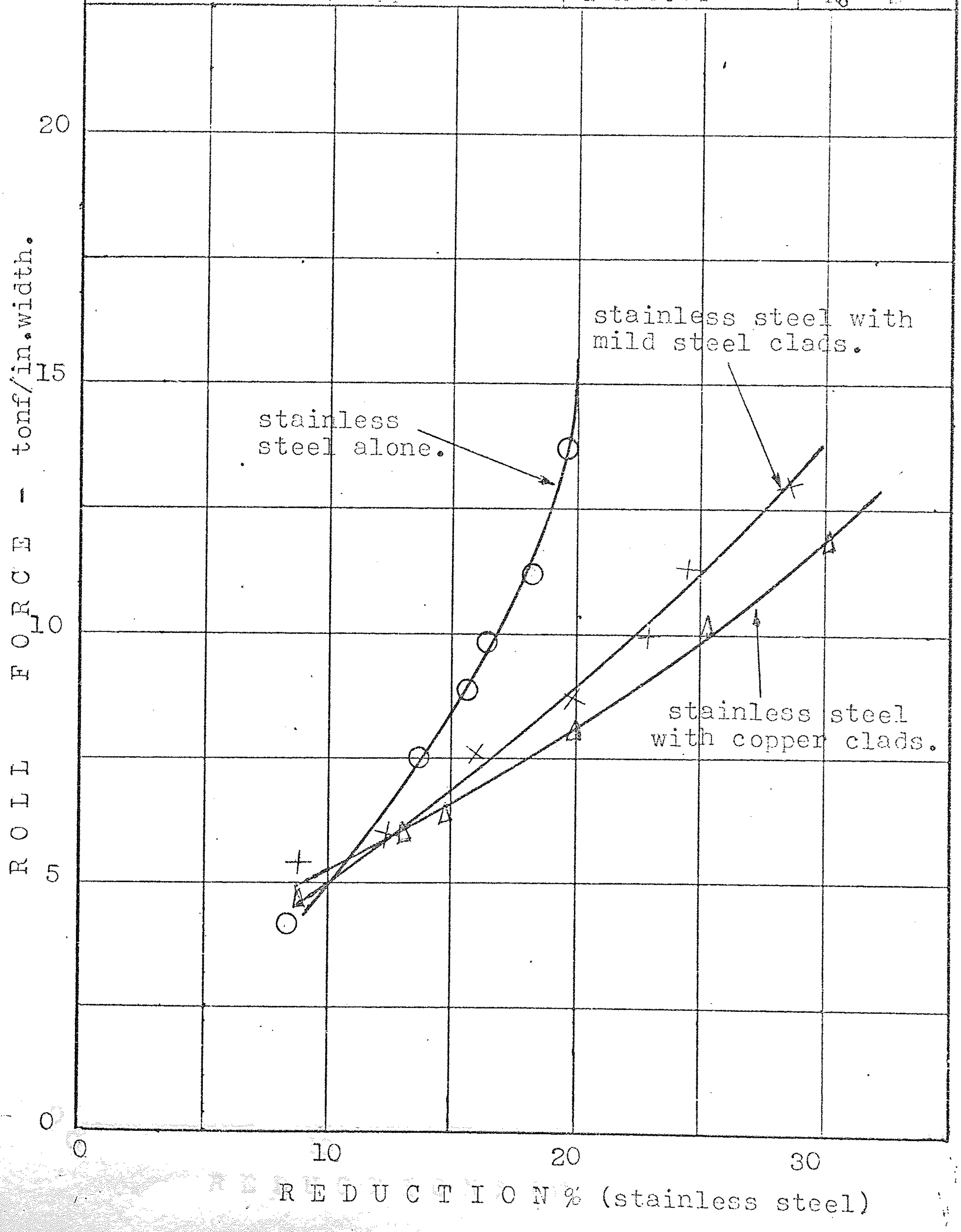
POSITION.	MATERIAL	THICKNESS(in)	GRAPH NO 2
MATRIX :	mild steel	0.039	
CLAD :	copper	2 x 0.04	
			$R_0 = 2$



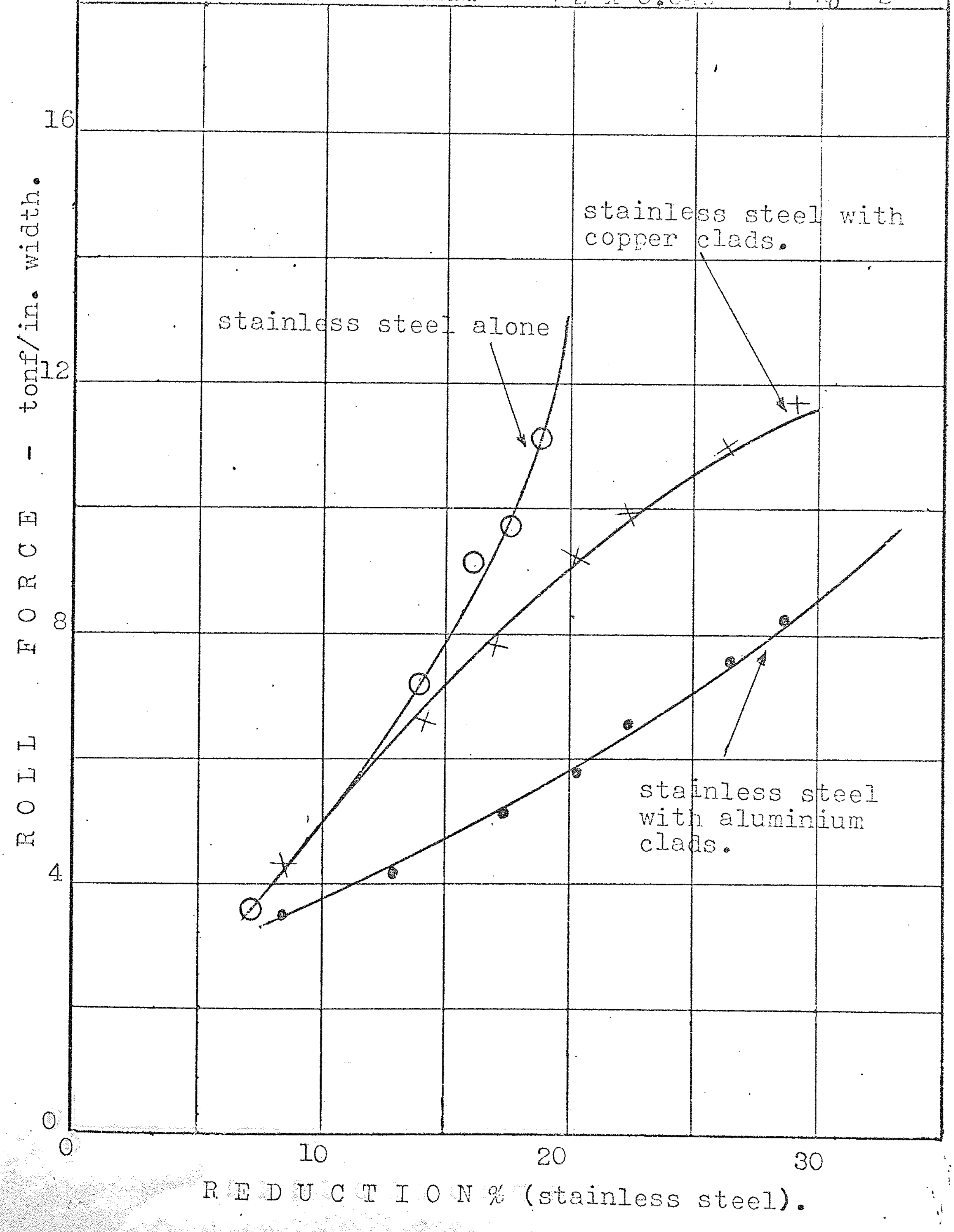
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 3
MATRIX		stainless st.	0.047	
CLAD	(1)	mild steel	2 x 0.029	
	(2)	aluminium	2 x 0.028	$R_o = 2$



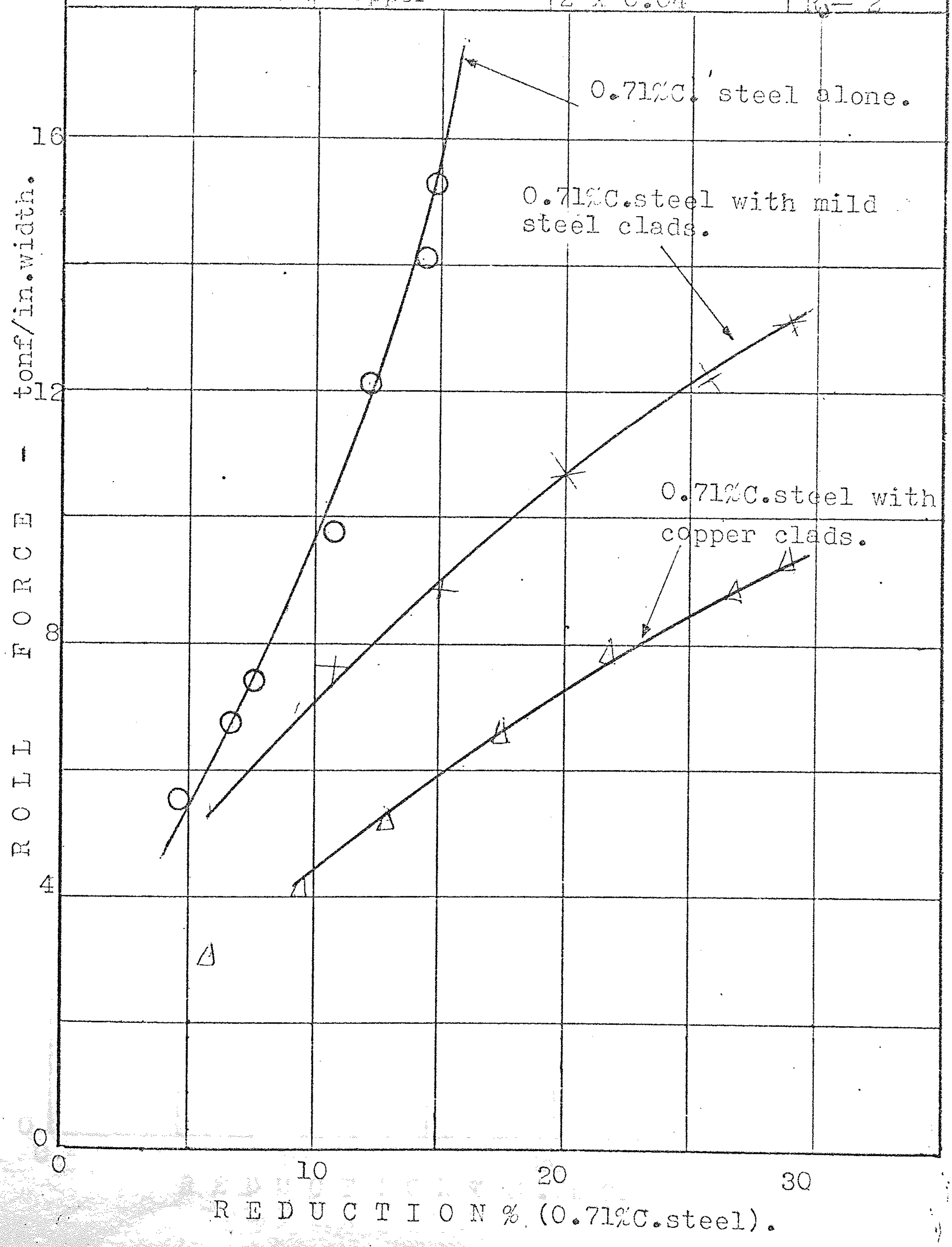
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO
MATRIX :		stainless st.	0.047	
CLAD :	(1)	mild steel	2 x 0.039	4
	(2)	copper	2 x 0.04	$R_o = 2$



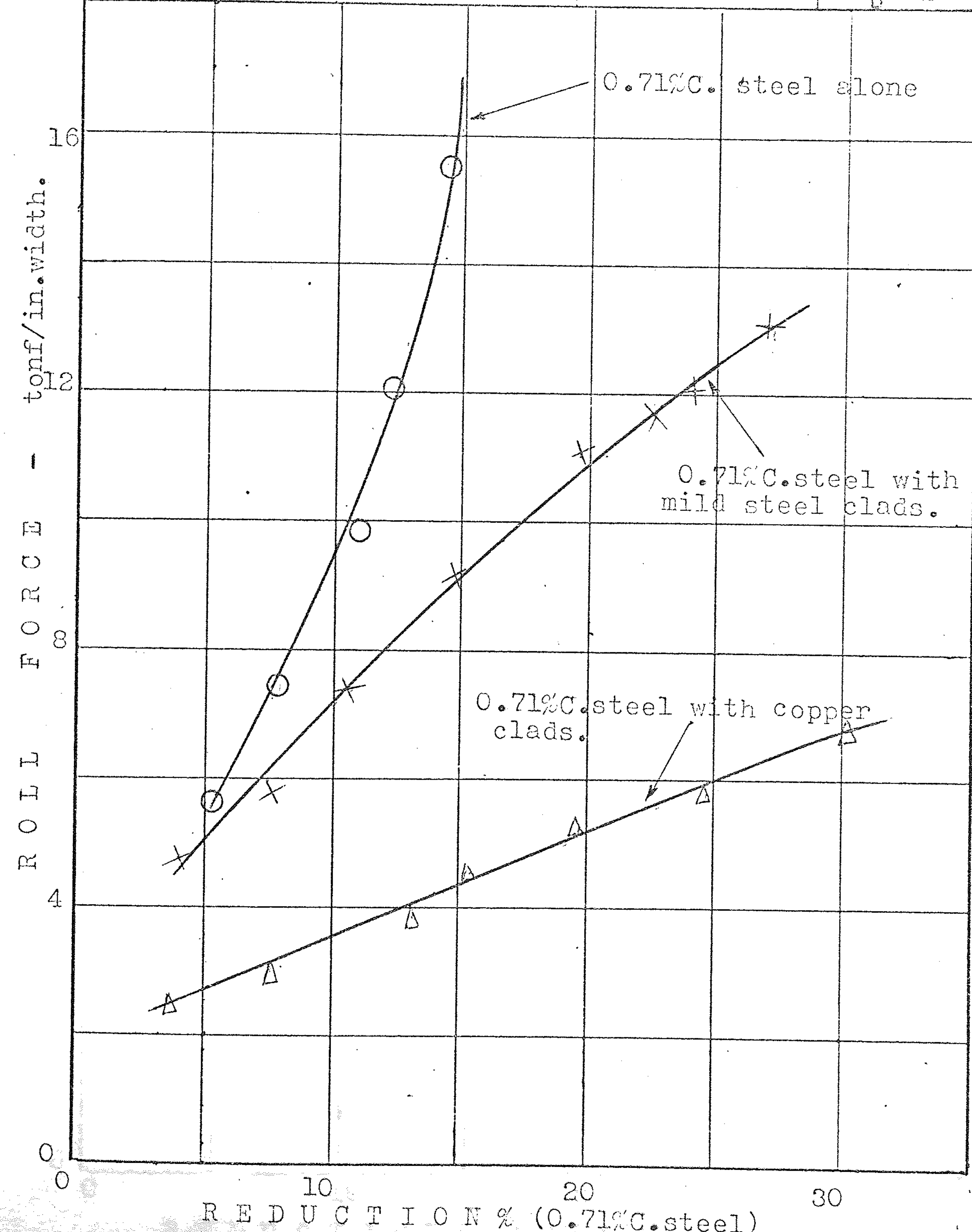
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 5
MATRIX :	stainless st.	0.047	
CLAD : (1)	mild steel	2 x 0.048	
(2)	aluminium	2 x 0.049	$R_0 = 2$



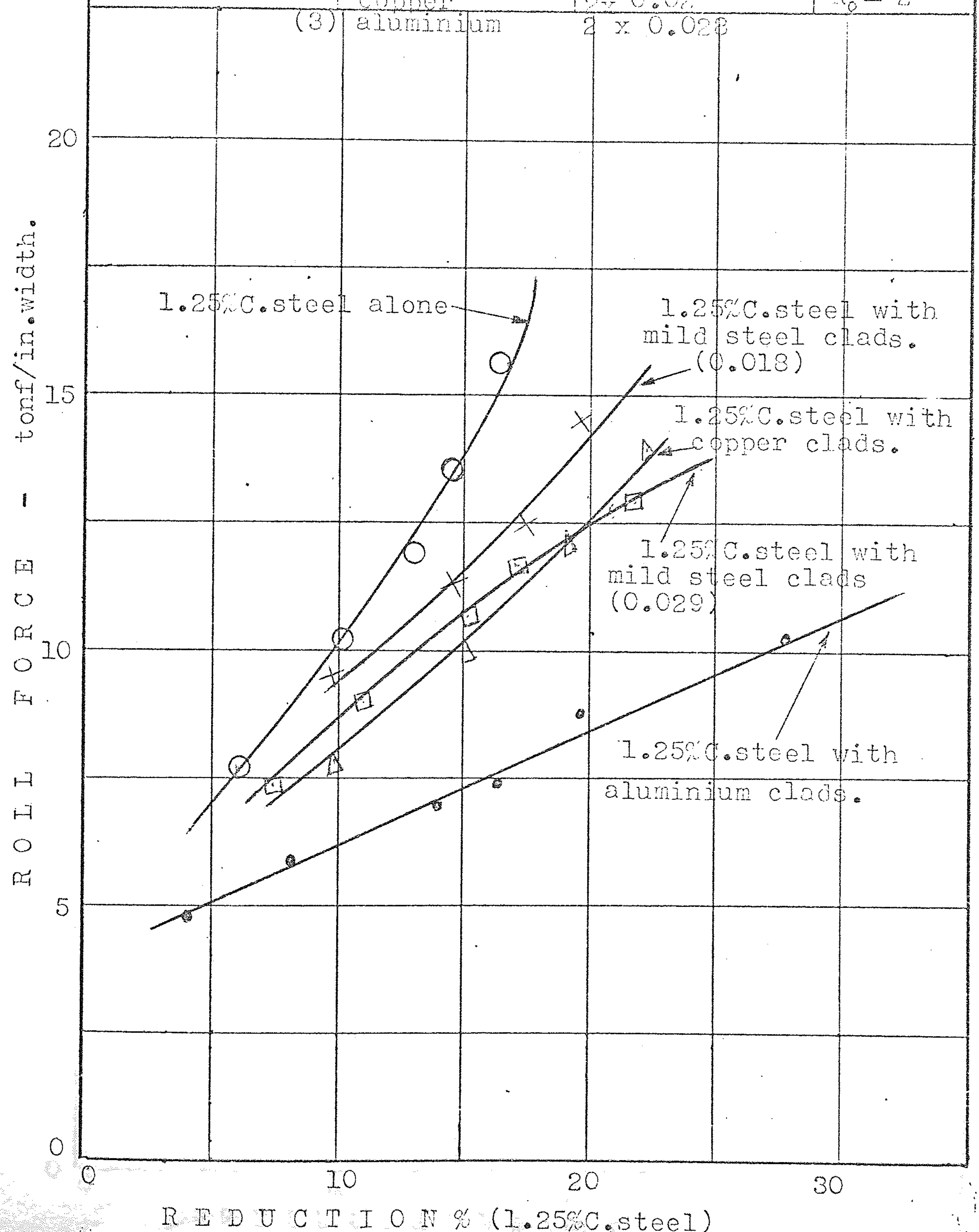
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 6
MATRIX :	0.71%C.steel	0.026	
CLAD : (1)	mild steel	2 x 0.039	
(2)	copper	2 x 0.04	$R_s = 2$



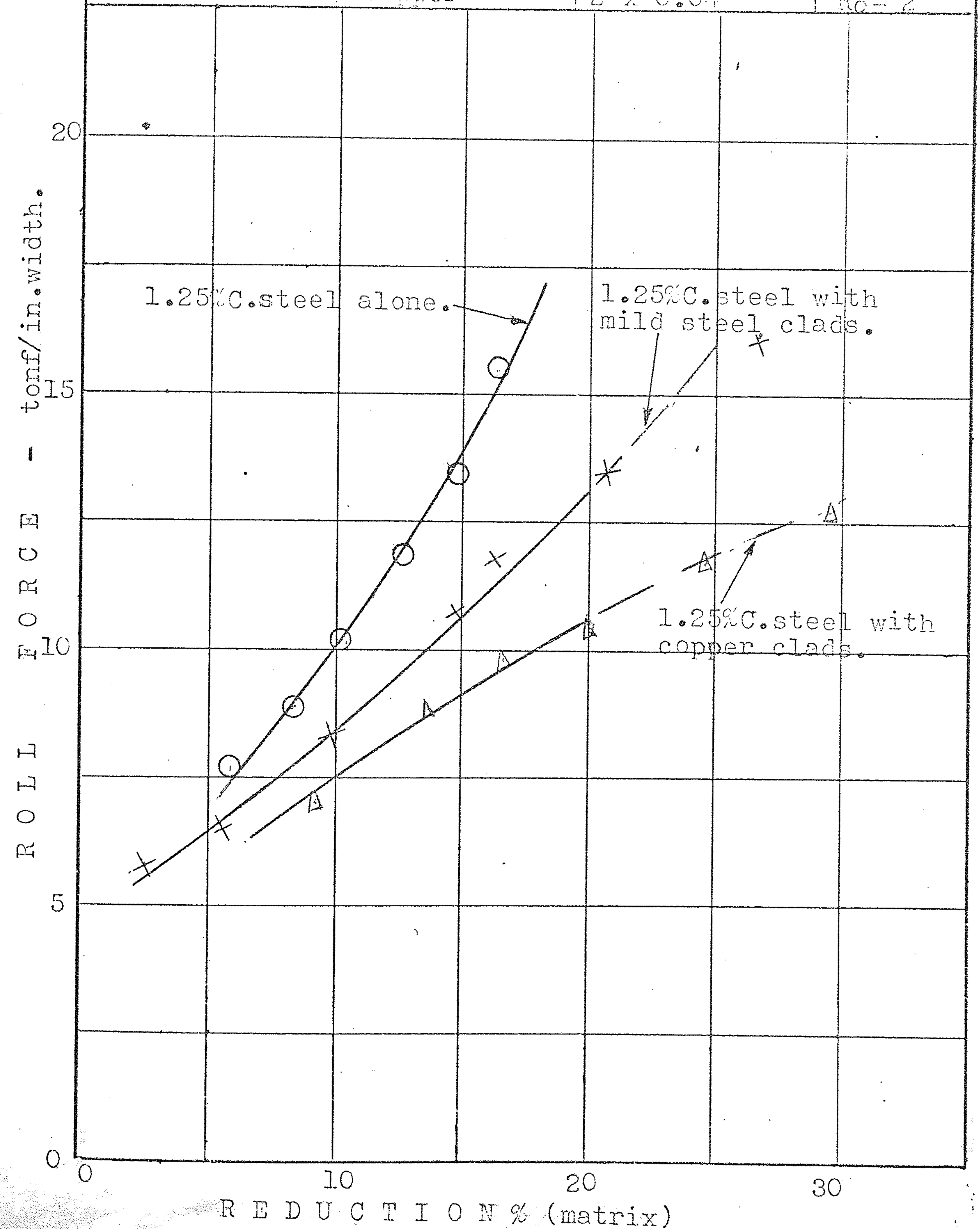
POSITION	MATERIAL	THICKNESS	GRAPH NO 7
MATRIX :	0.71%C.steel	0.026	
CLAD :	(1) mild steel	2 x 0.048	
	(2) aluminium	2 x 0.049	$R_{p} = 2$



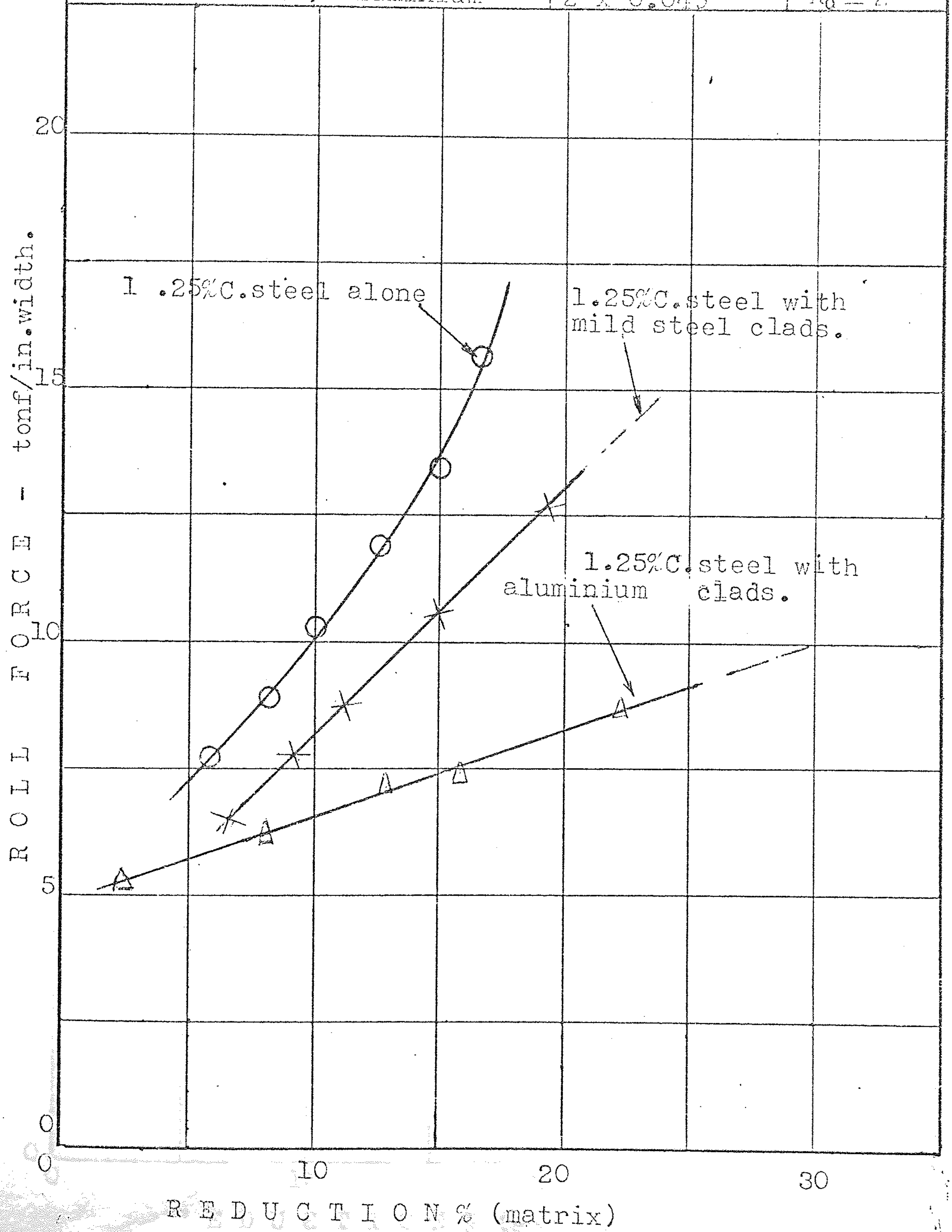
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 8 $R_o = 2$
MATRIX :	1.25%C.steel	0.036	
CLAD : (1)	mild steel	2x(0.018, 0.029)	
(2)	copper	2x 0.02	
(3)	aluminium	2 x 0.028	



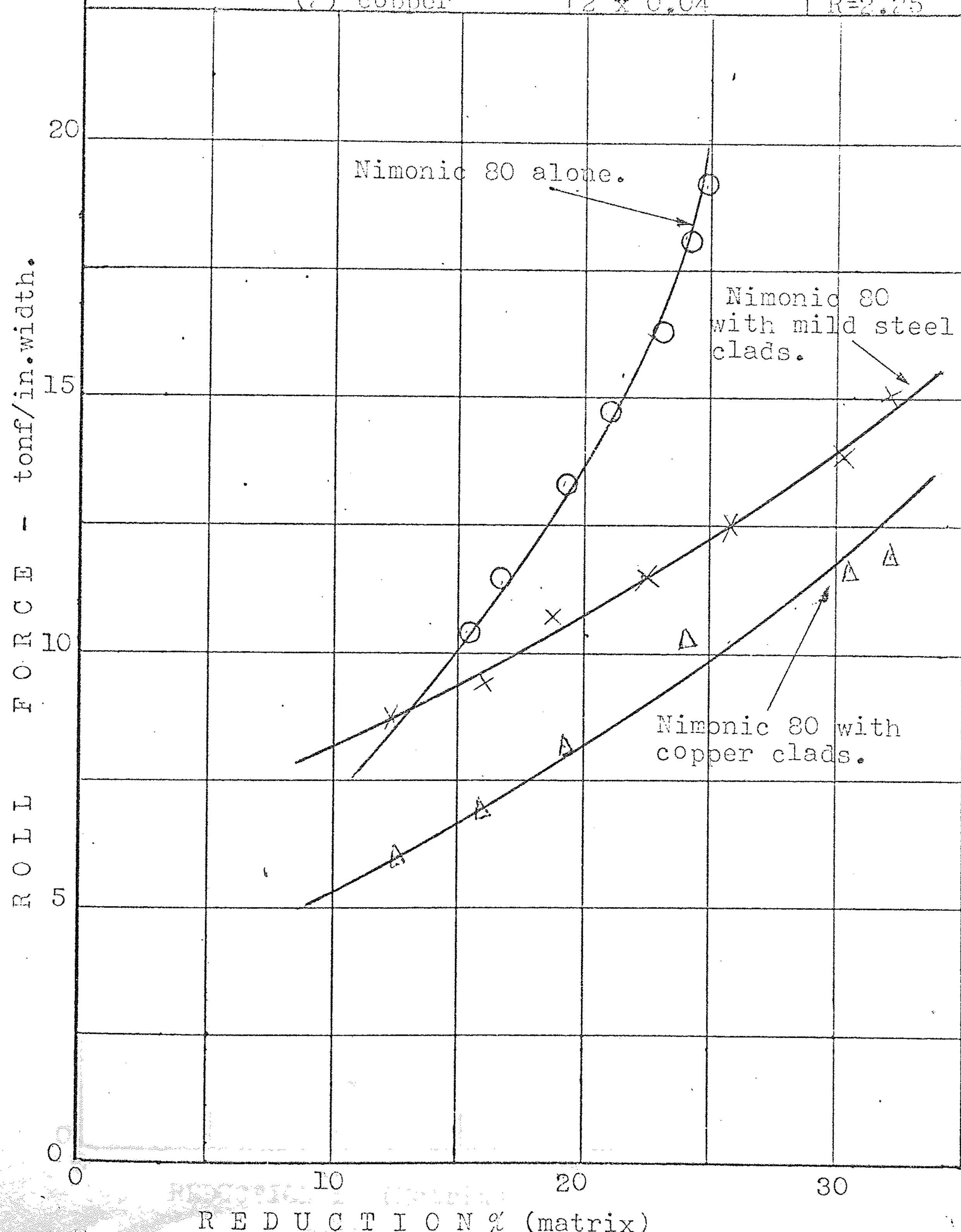
POSITION	MATERIAL	THICKNESS	GRAPH NO 9
MATRIX :	1.25%C.steel	0.036	
CLAD :	mild steel	2 x 0.039	
	copper	2 x 0.04	Rc= 2



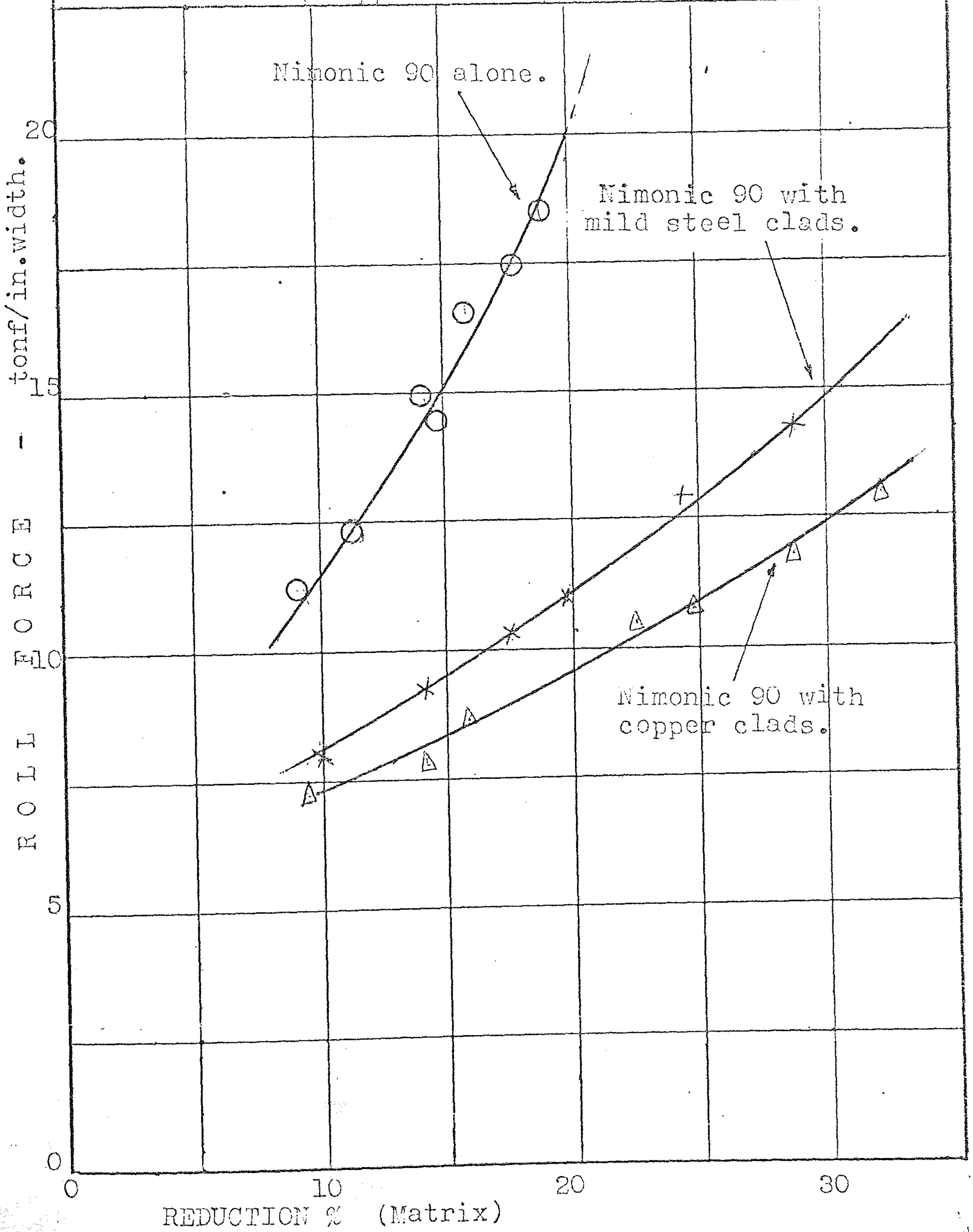
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 10
MATRIX :	1.25%C.steel	0.036	
CLAD :	(1) mild steel	2 x 0.048	
	(2) aluminium	2 x 0.040	$R_o = 2$



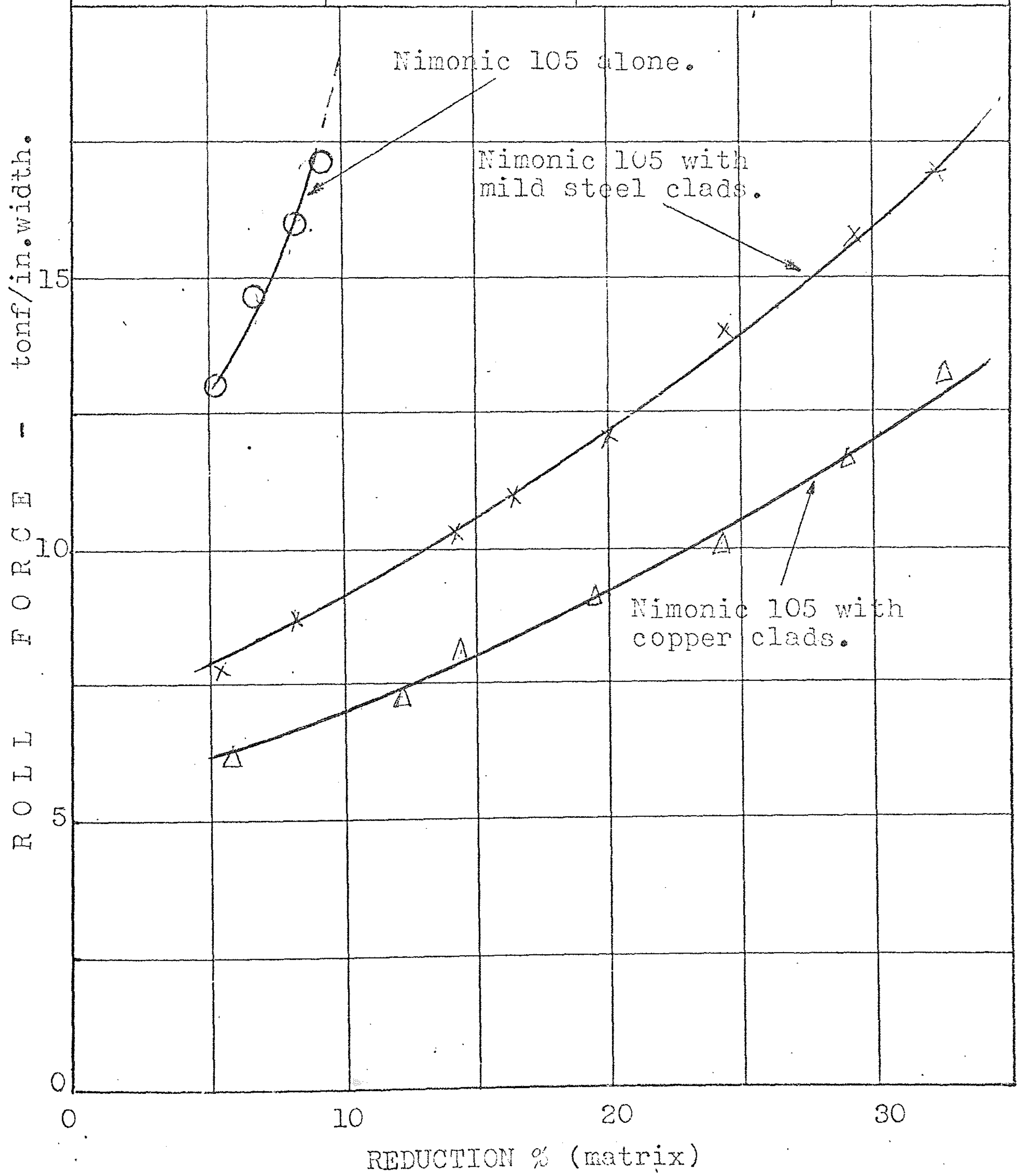
POSITION		MATERIAL	THICKNESS(in)	GRAPH NO 11
MATRIX :		Nimonic 80	0.031	
CLAD :	(1)	mild steel	2 x 0.039	
	(2)	copper	2 x 0.04	R=2.25



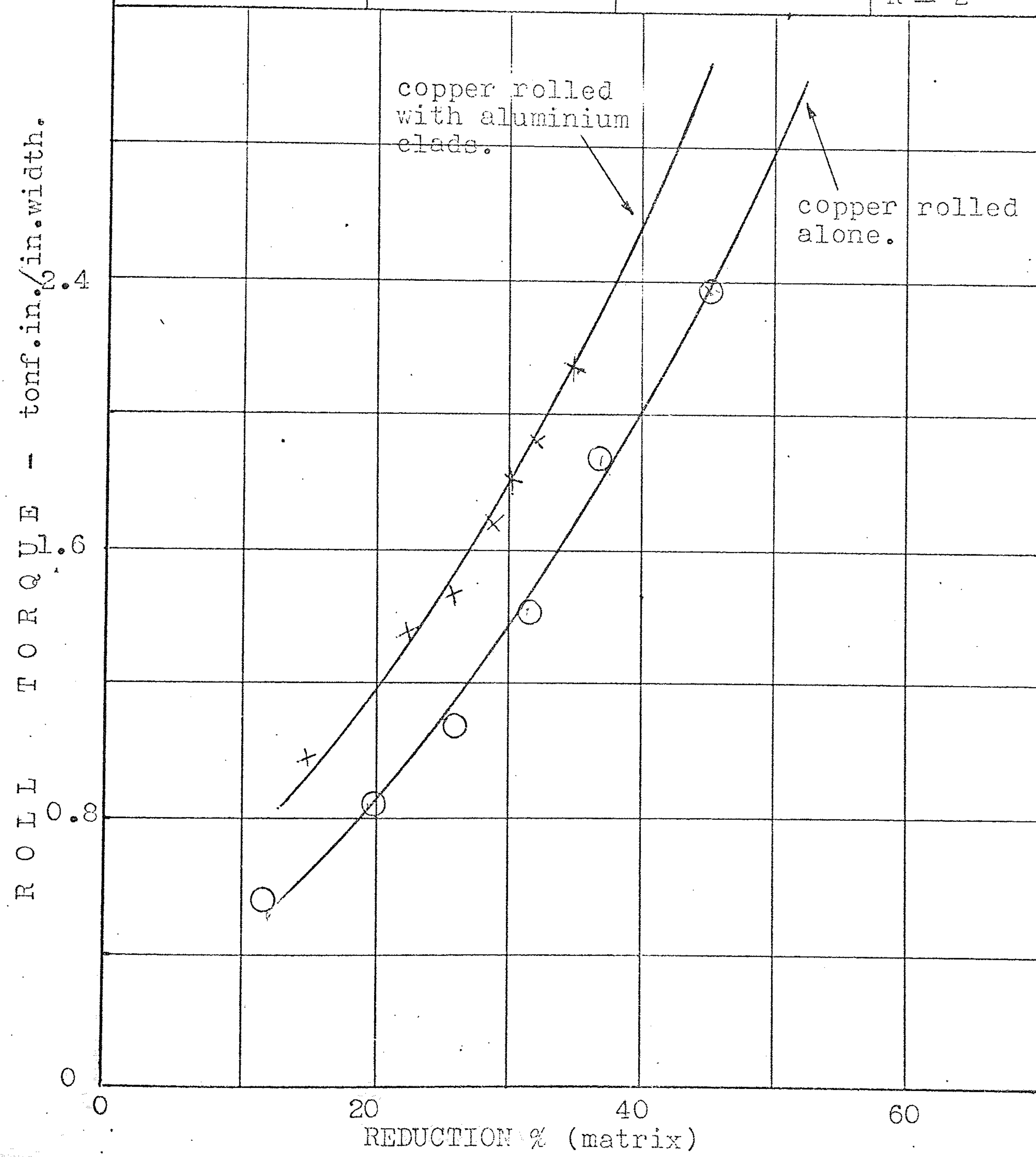
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 12
MATRIX :	Nimonic 90	0.031	
CLAD :	mild steel	2 x 0.039	
	copper	2 x 0.04	R=2.25



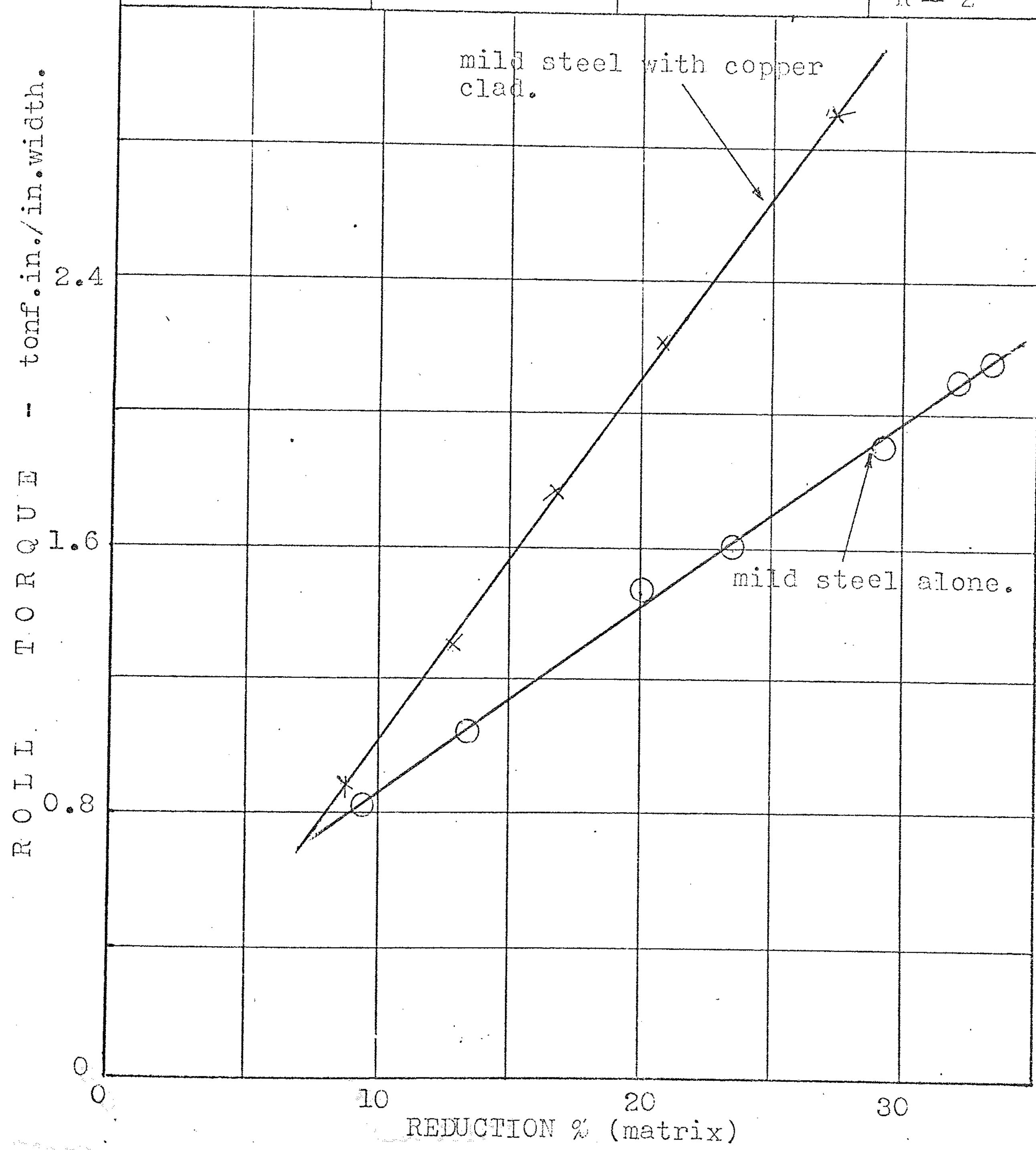
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 13
MATRIX :	Nimonic 105	0.012	
CLAD :	mild steel	2 x 0.018	
	copper	2 x 0.02	
			R=2.25



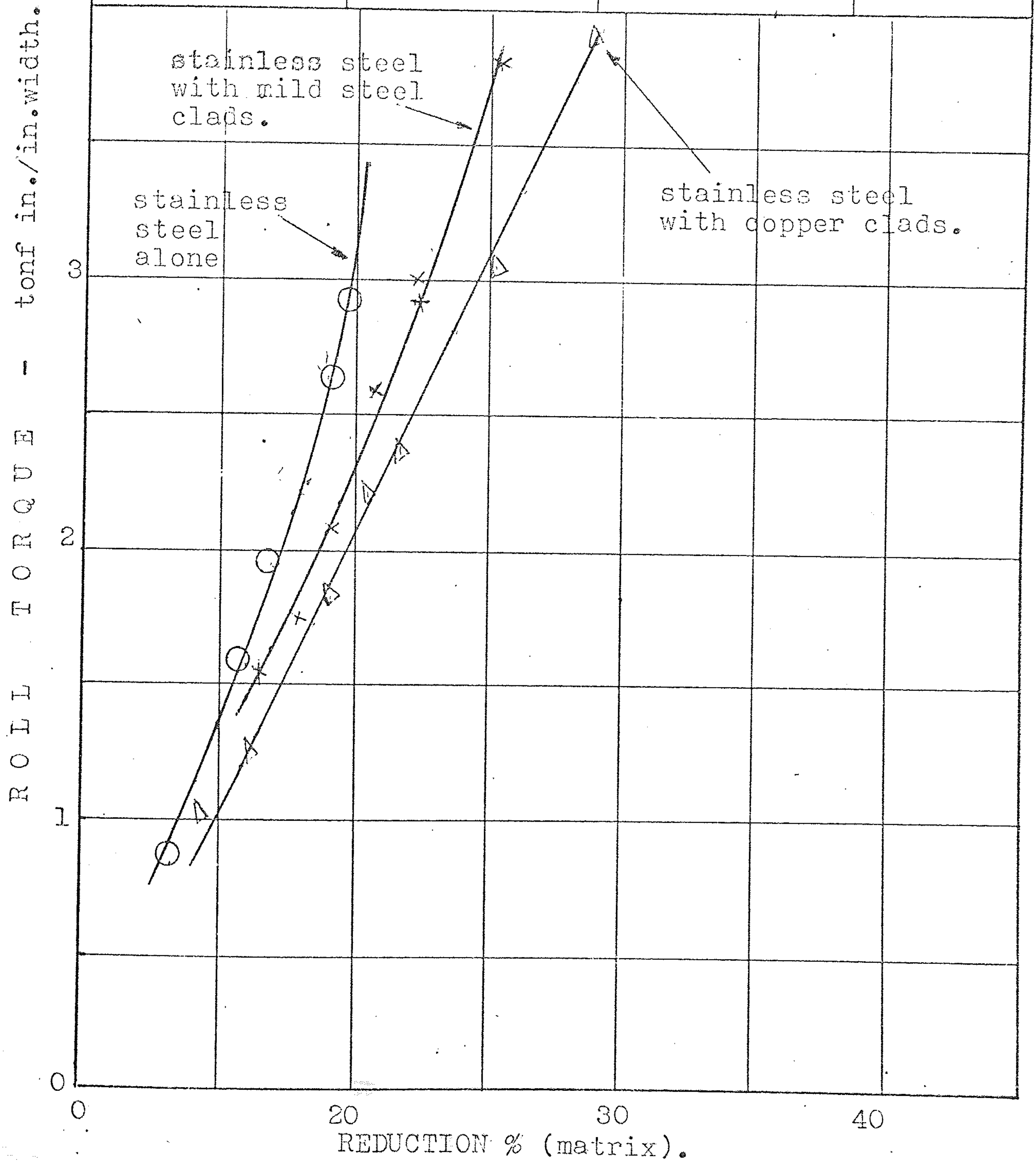
POSITION	MATERIAL	THICKNESS	GRAPH NO 14
MATRIX	COPPER	0.04	
CLAD	aluminium	2 x 0.049	
			R = 2



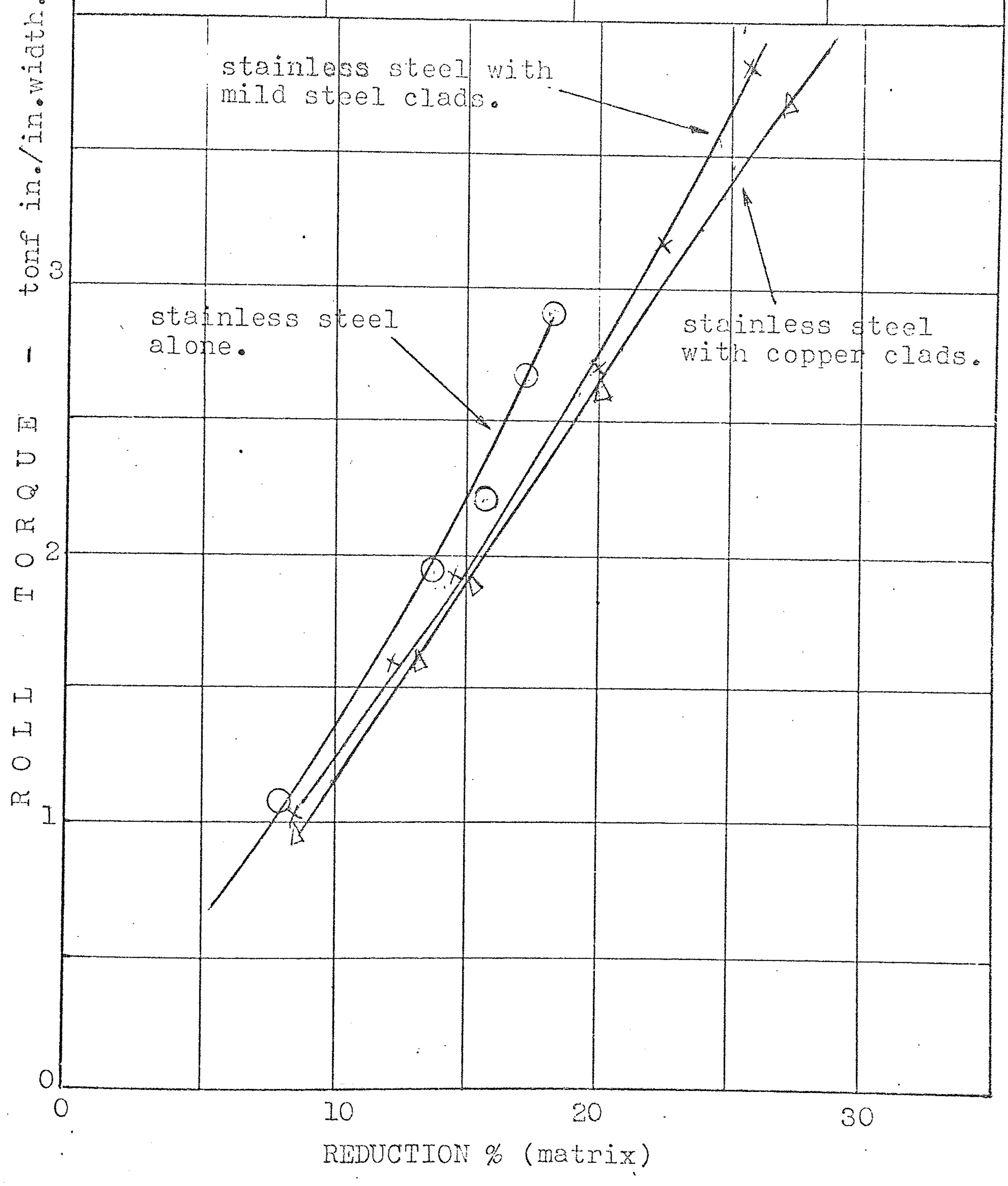
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 15
MATRIX	mild steel	0.039	
CLAD	copper	2 x 0.04	
			R = 2



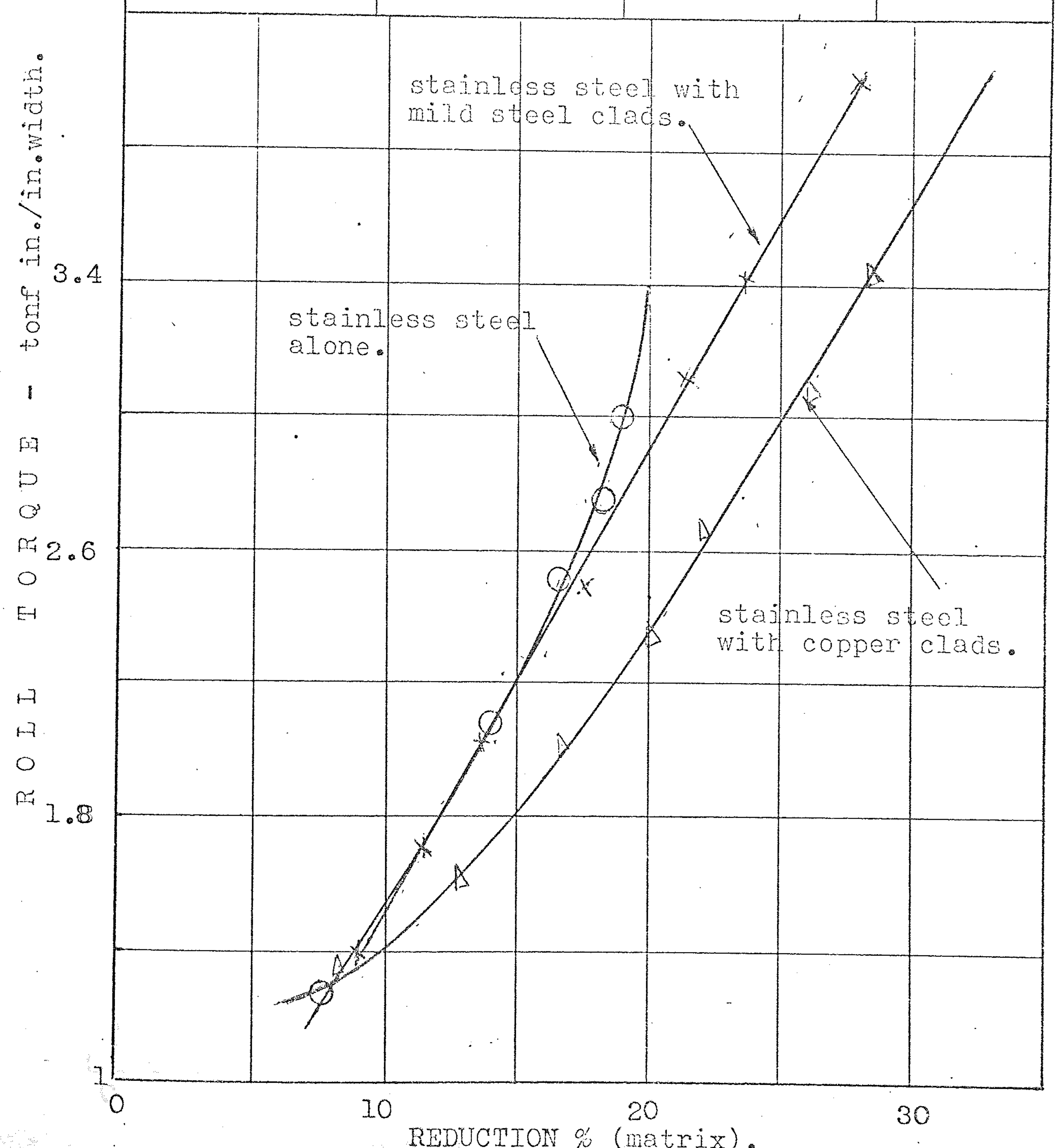
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO
MATRIX :		Stainless st.	0.047	
CLAD :	(1)	mild steel	2 x 0.029	16
	(2)	aluminium	2 x 0.028	R = 2



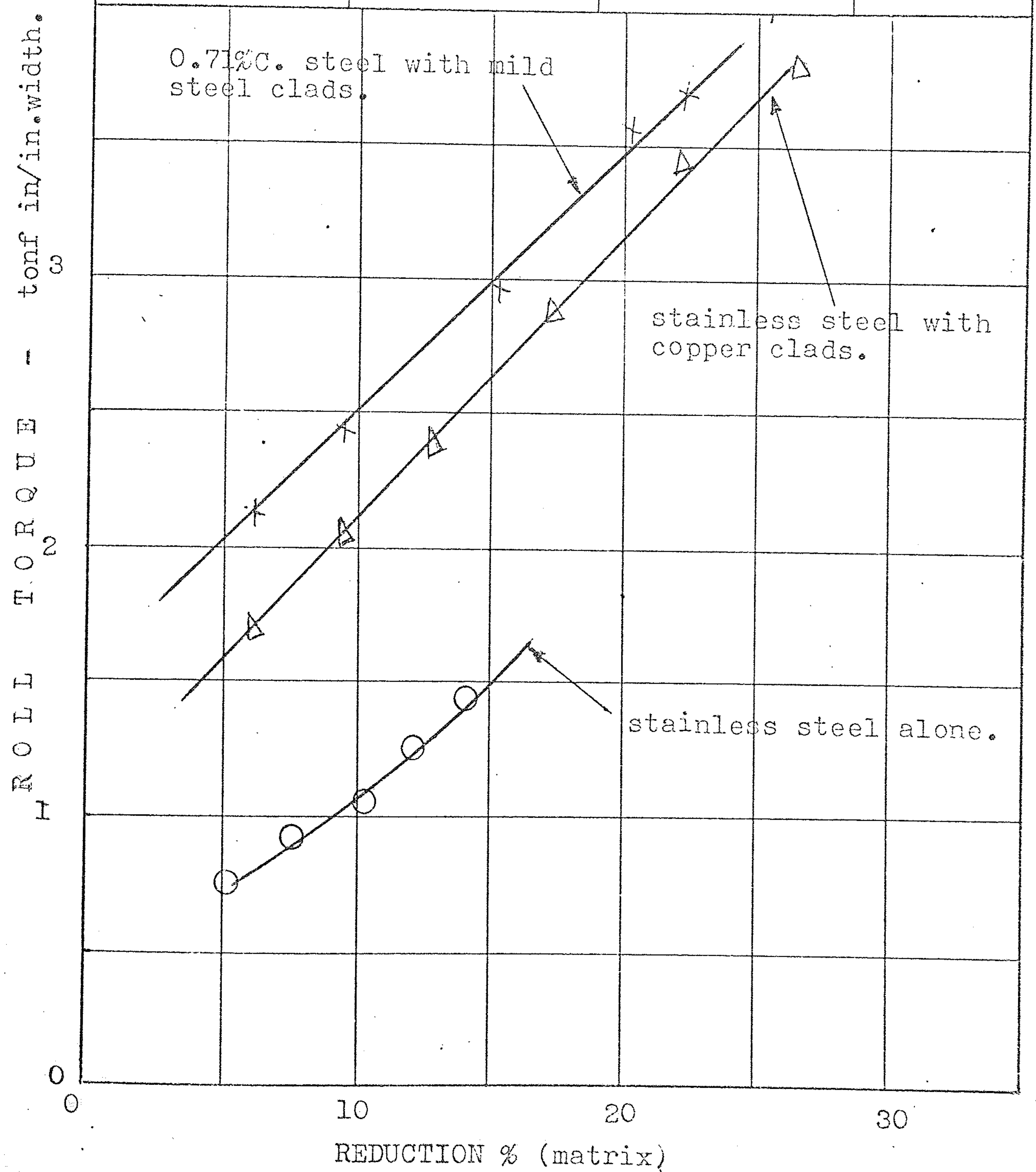
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 17
MATRIX :		stainless st.	0.047	
CLAD :	(1)	mild steel	0.039	
	(2)	copper	0.040	R = 2



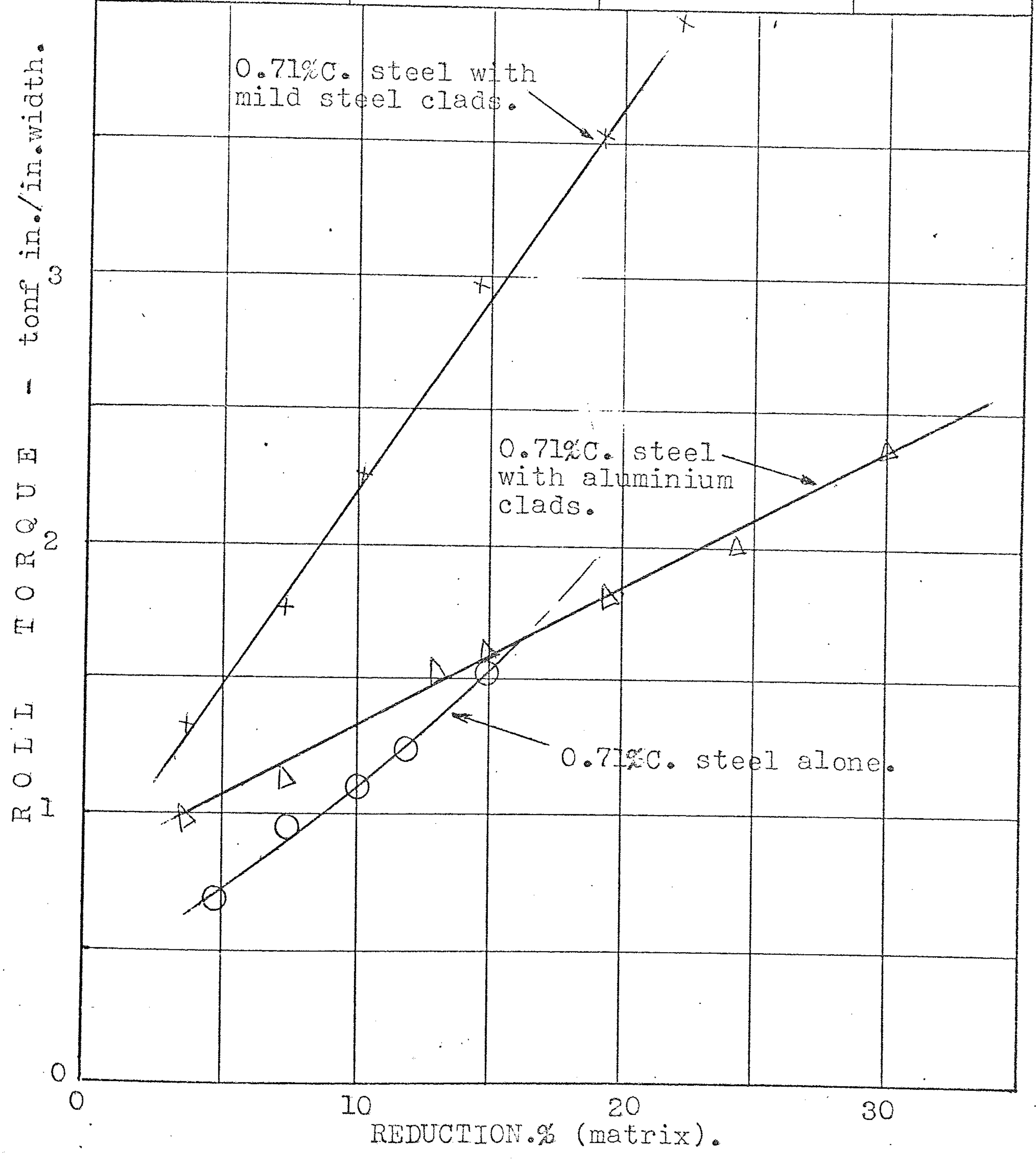
POSITION		MATERIAL	THICKNESS(in)	GRAPH NO 18
MATRIX :		stainless st.	0.047	
CLAD :	(1)	mild steel	2 x 0.048	
	(2)	aluminium	2 x 0.049	R = 2



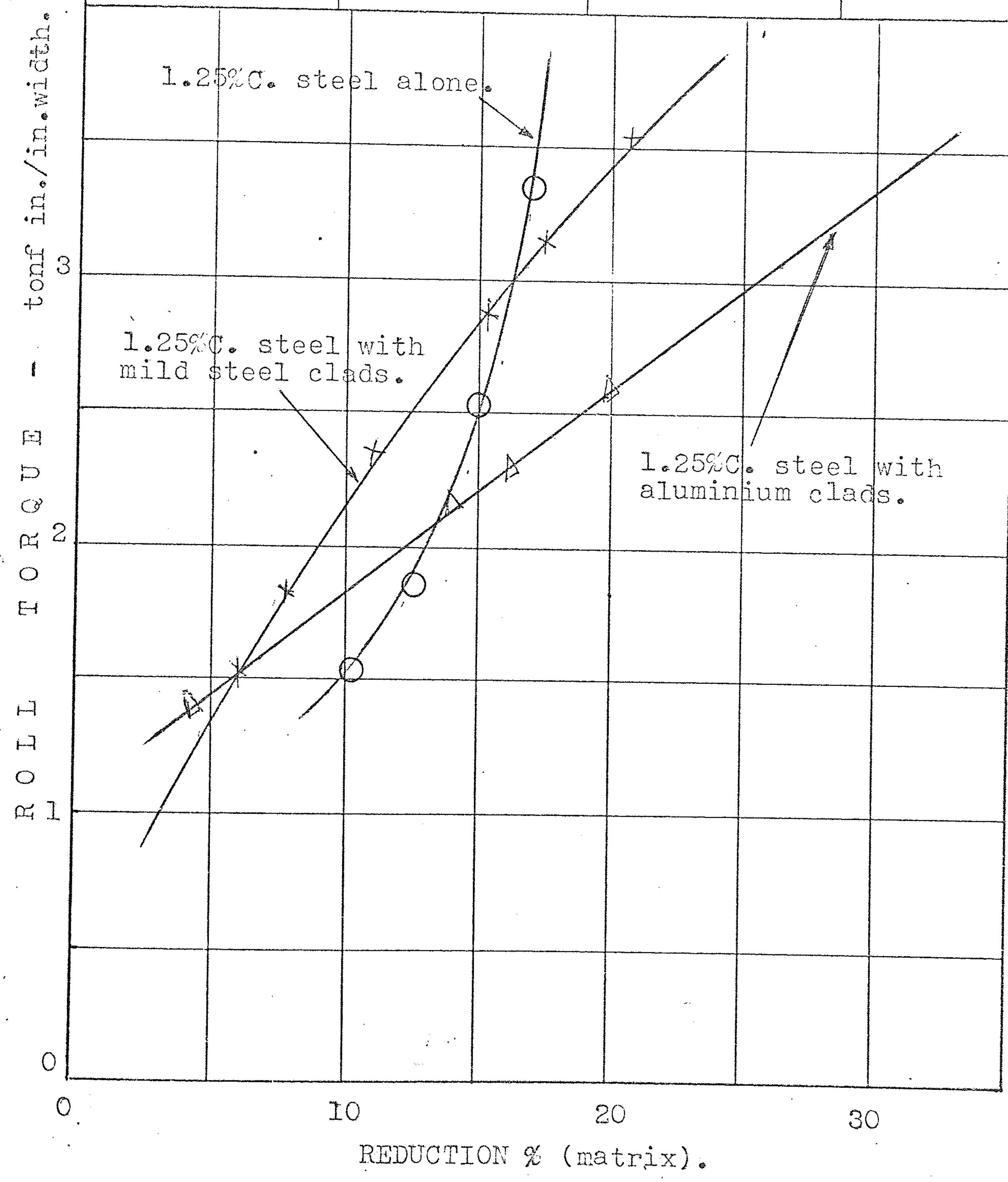
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 19
MATRIX :		0.71%C.steel	0.026	
CLAD :	(1)	mild steel	2 x 0.039	R = 2
	(2)	copper	2 x 0.04	



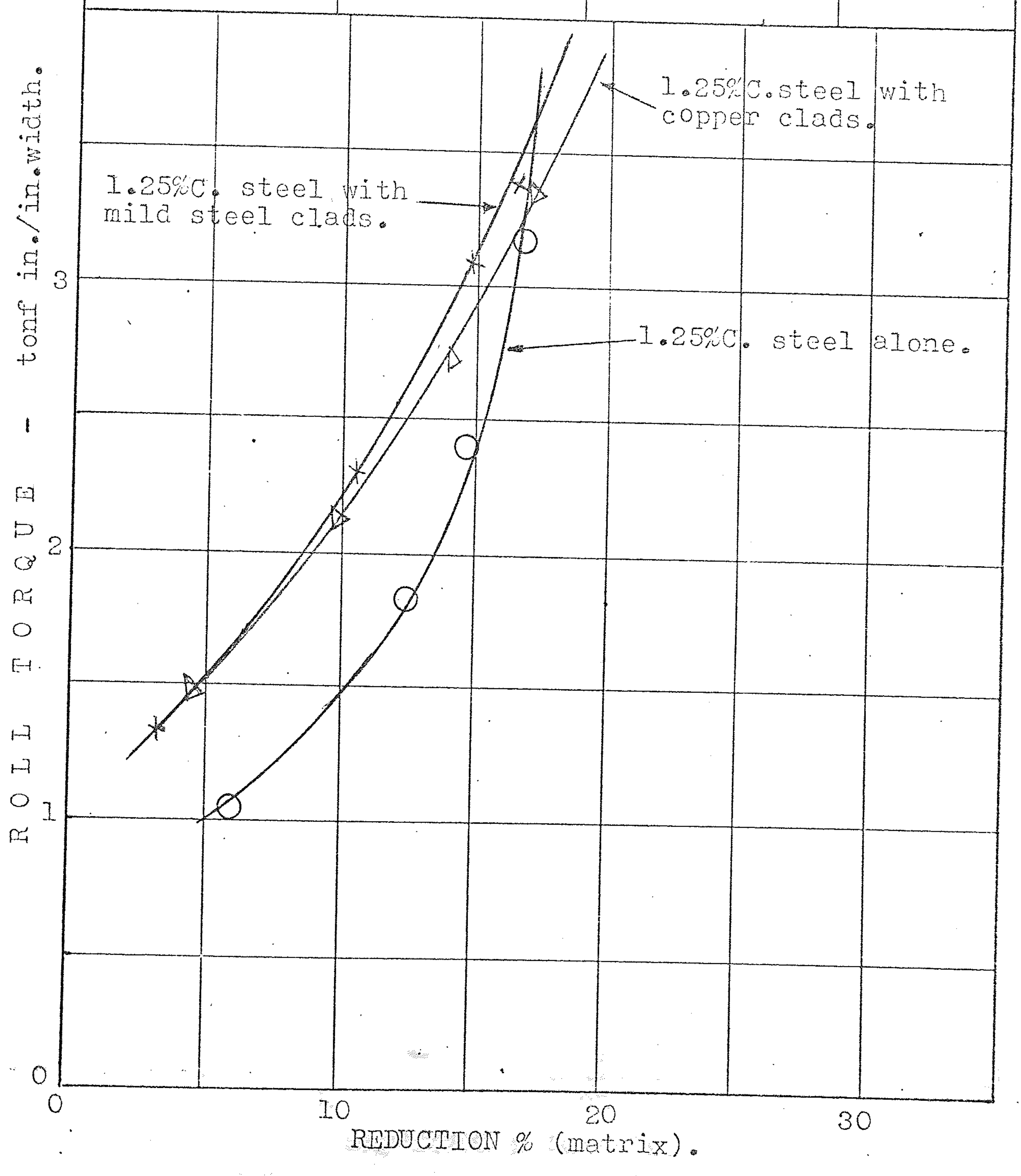
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 20
MATRIX :		0.71%C. steel	0.026	
CLAD :	(1)	mild steel	2 x 0.048	
	(2)	aluminium	2 x 0.049	R = 2



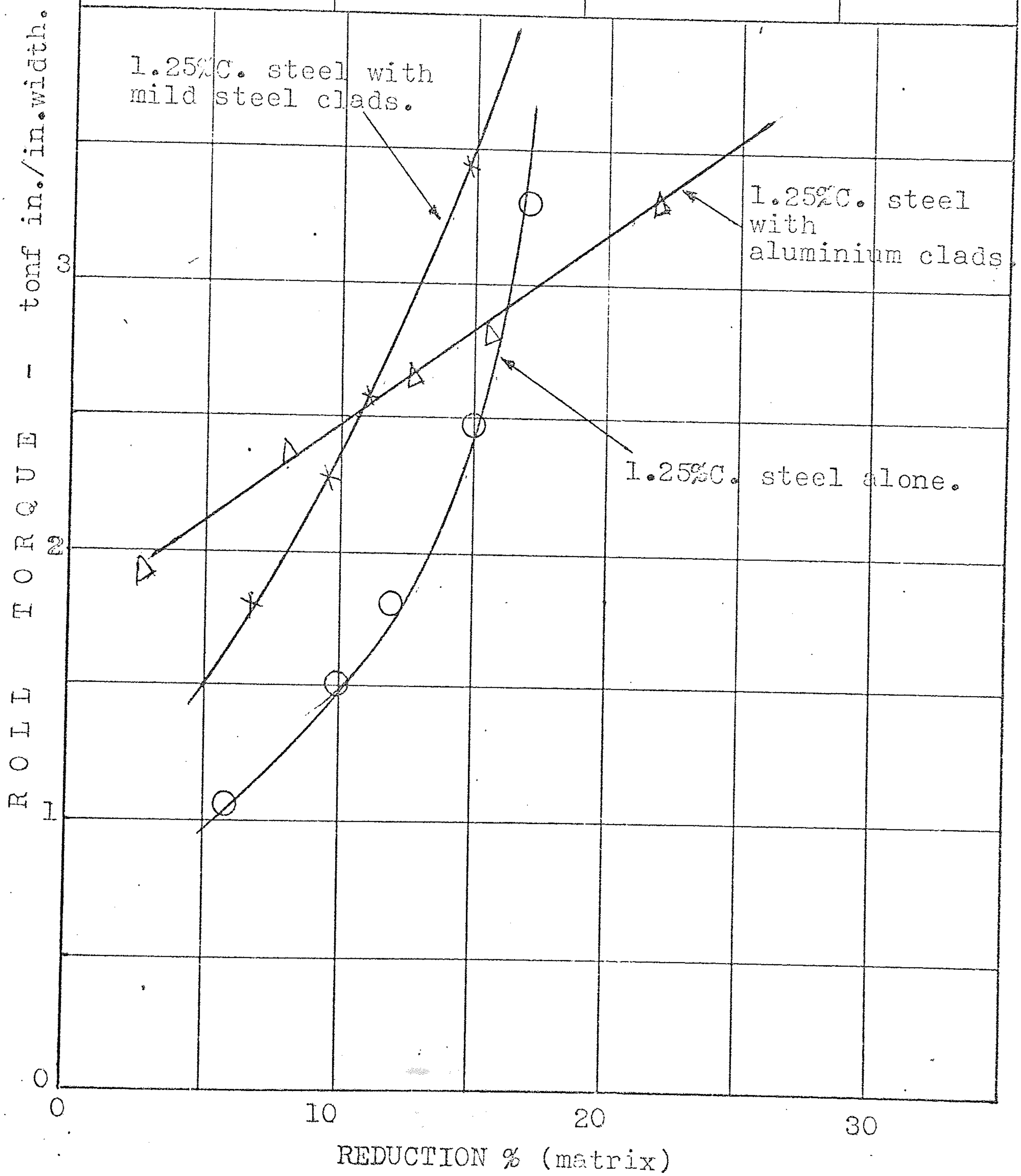
POSITION		MATERIAL	THICKNESS(in)	GRAPH NO
MATRIX :		1.25%C. steel	0.036	
CLAD :	(1)	mild steel	0.029	21
	(2)	aluminium	0.028	R = 2



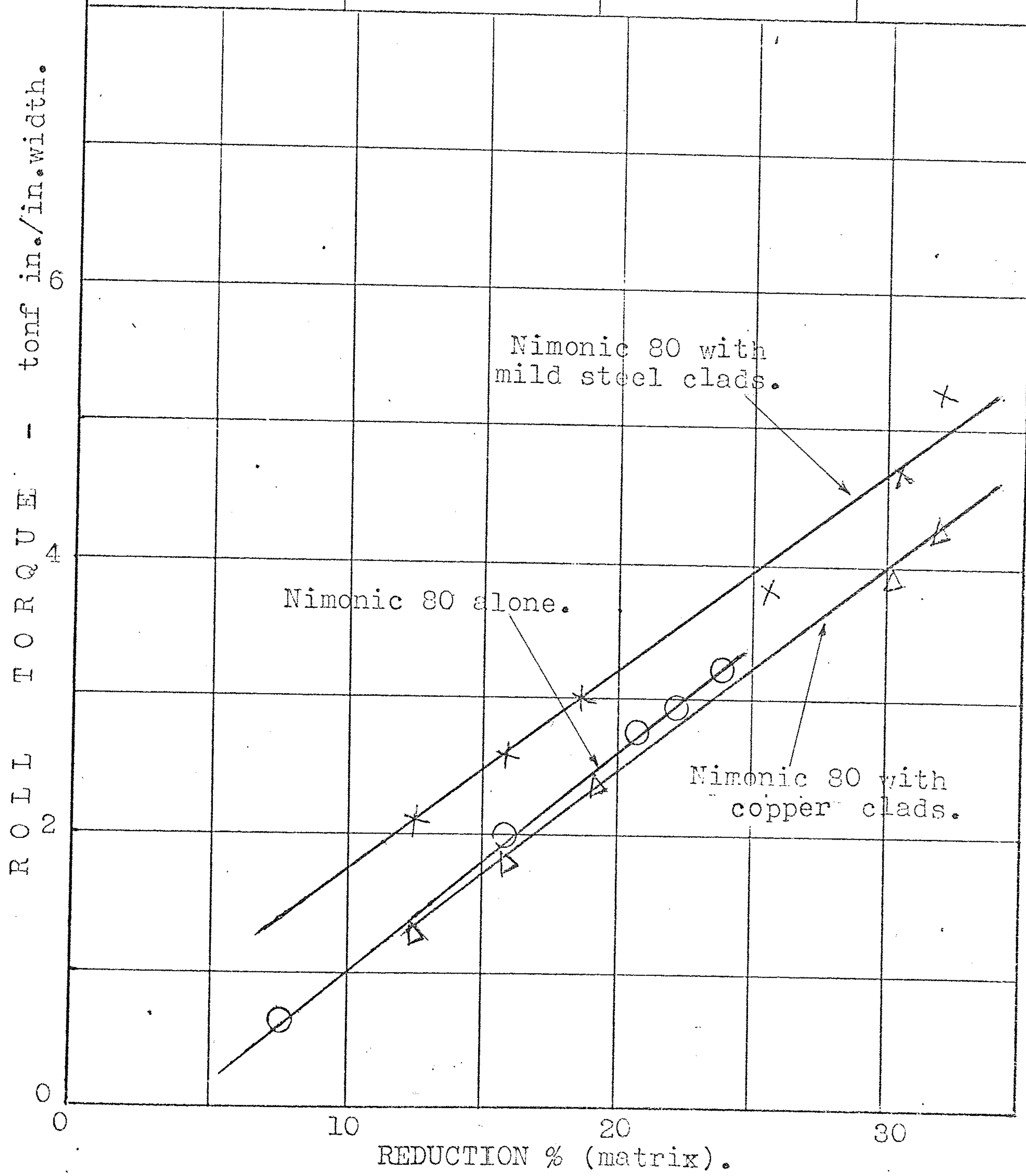
POSITION		MATERIAL	THICKNESS(in)	GRAPH NO 22
MATRIX :		1.25%C. steel	0.036	
CLAD :	(1)	mild steel	2 x 0.039	
	(2)	copper	2 x 0.04	R = 2



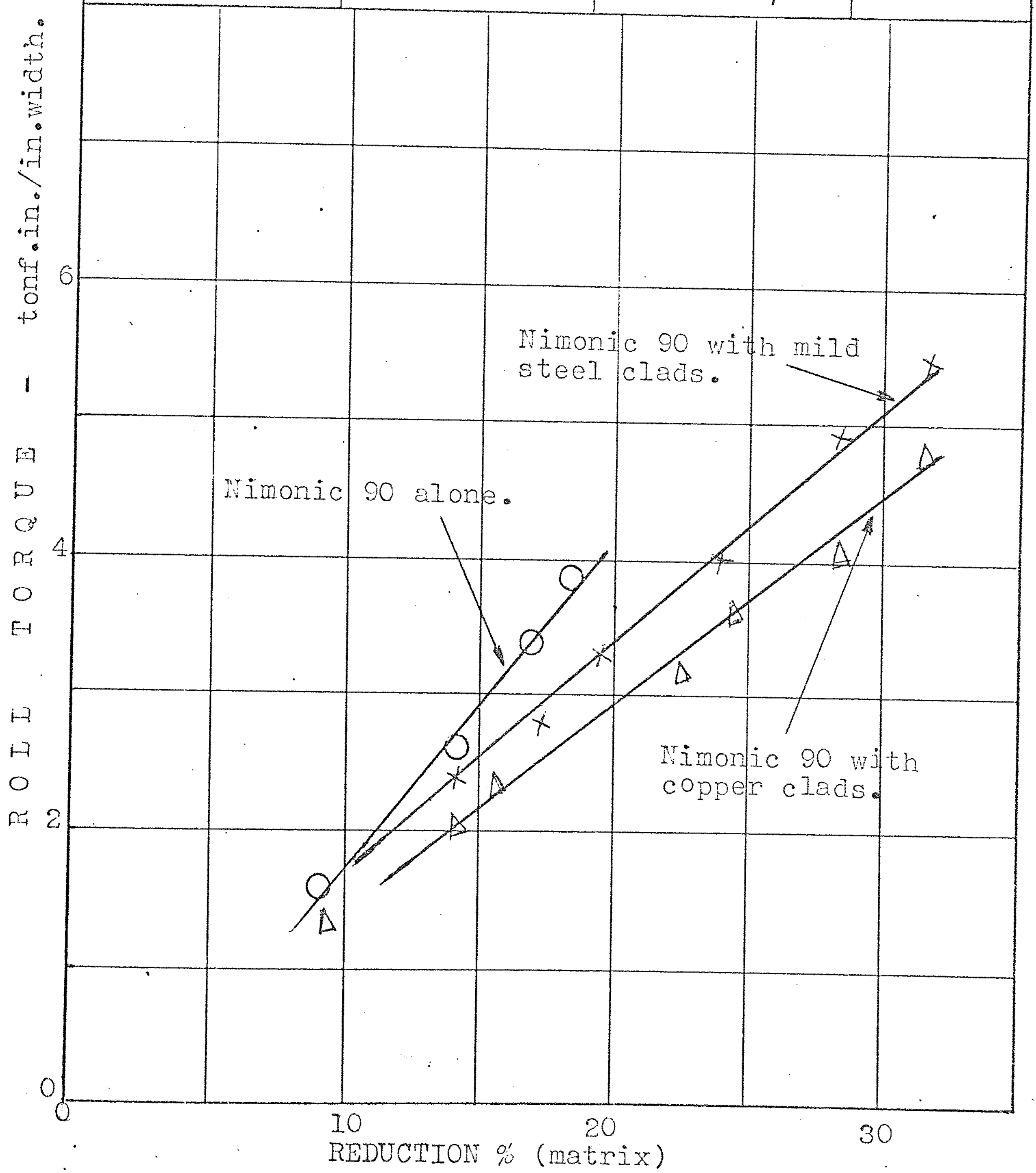
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 23
MATRIX :	1.25%C. steel	0.036	
CLAD :	mild steel	2 x 0.048	
	aluminium	2 x 0.049	R = 2



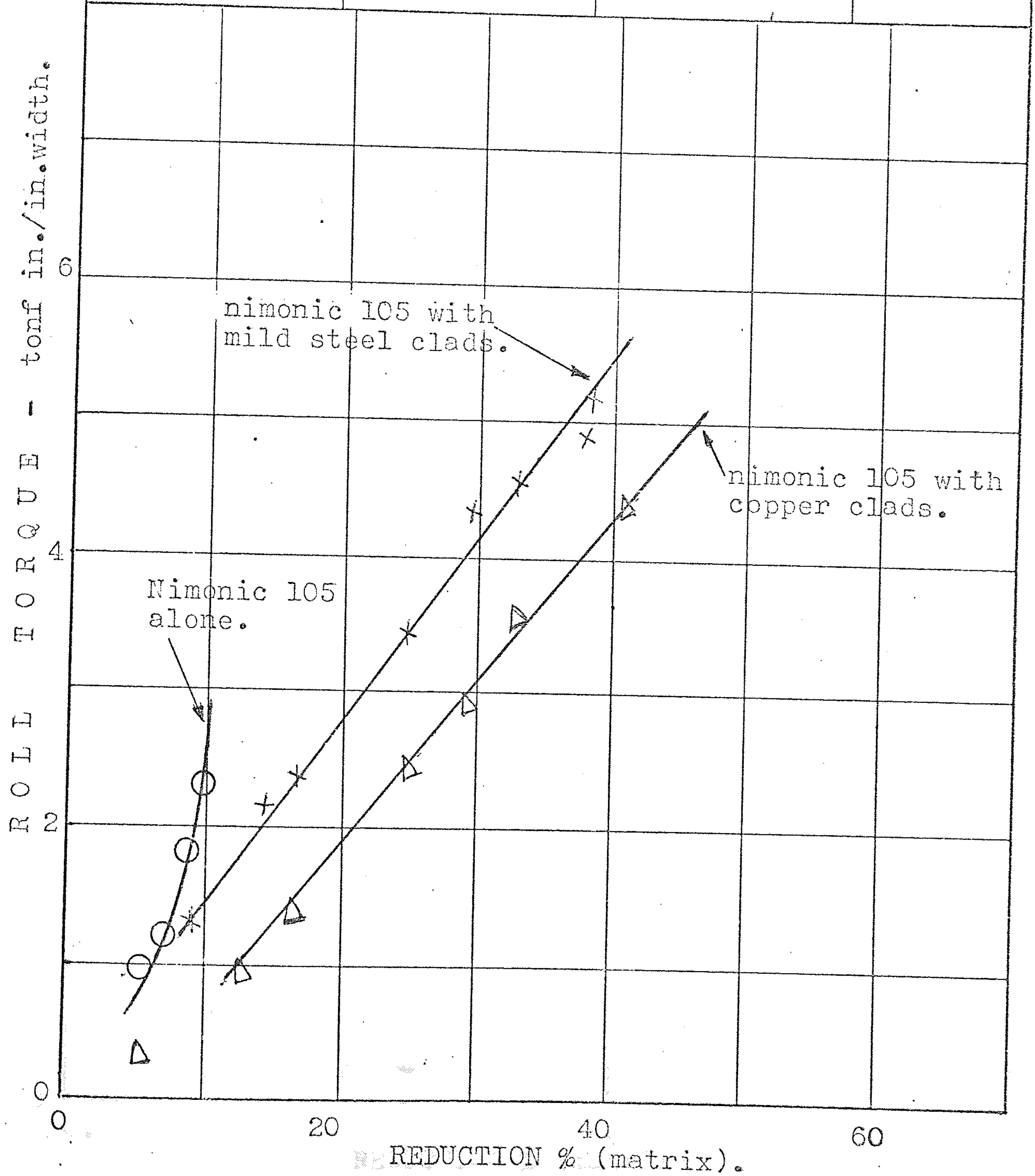
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 24
MATRIX :		Nimonic 80	0.031	
CLAD :	(1)	mild steel	2 x 0.039	
	(2)	copper	2 x 0.040	R = 2.25



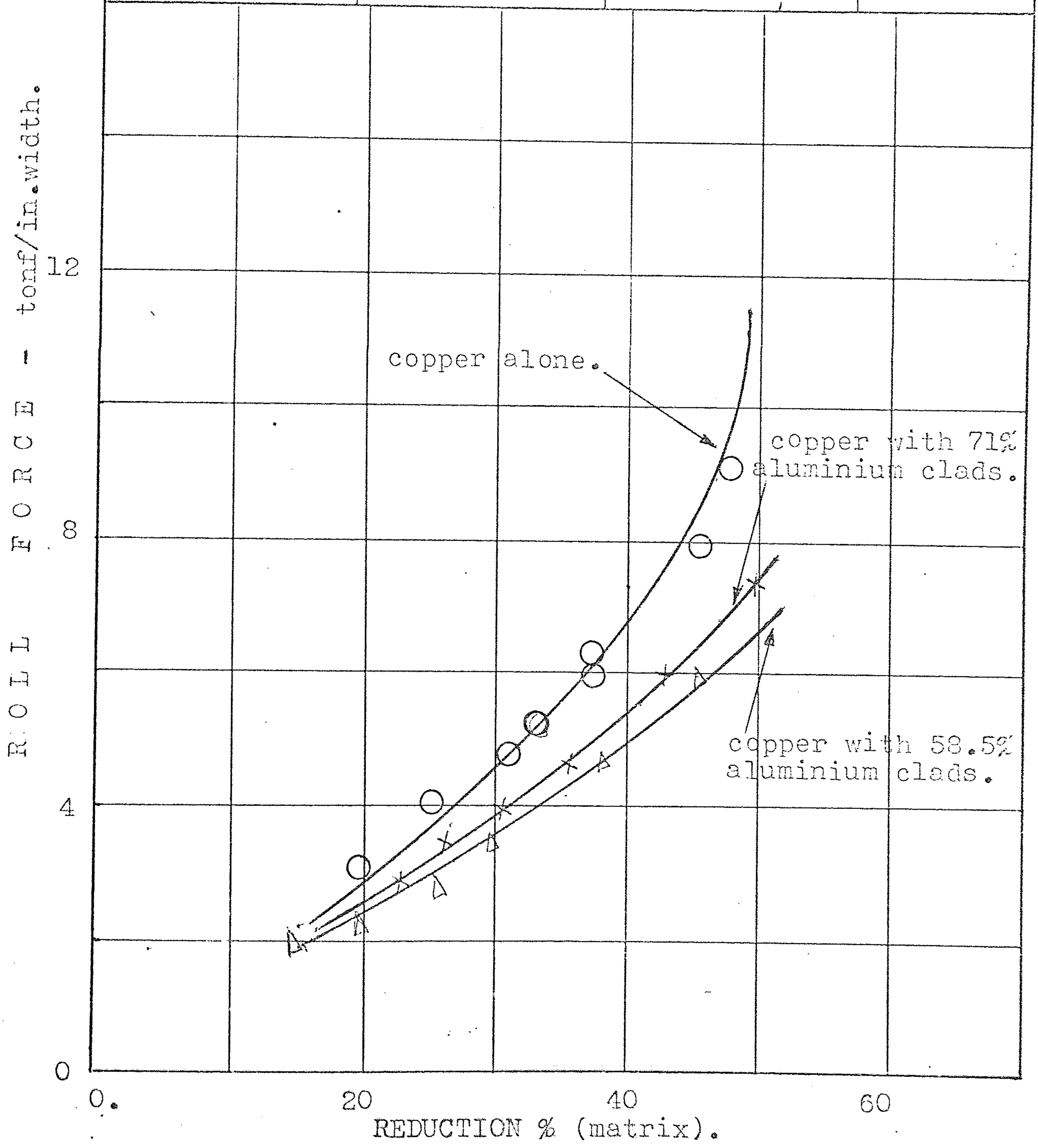
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 25
MATRIX :	Nimonic 90	0.031	
CLAD : (1)	mild steel	2 x 0.039	
(2)	copper	2 x 0.040.	R=2.25



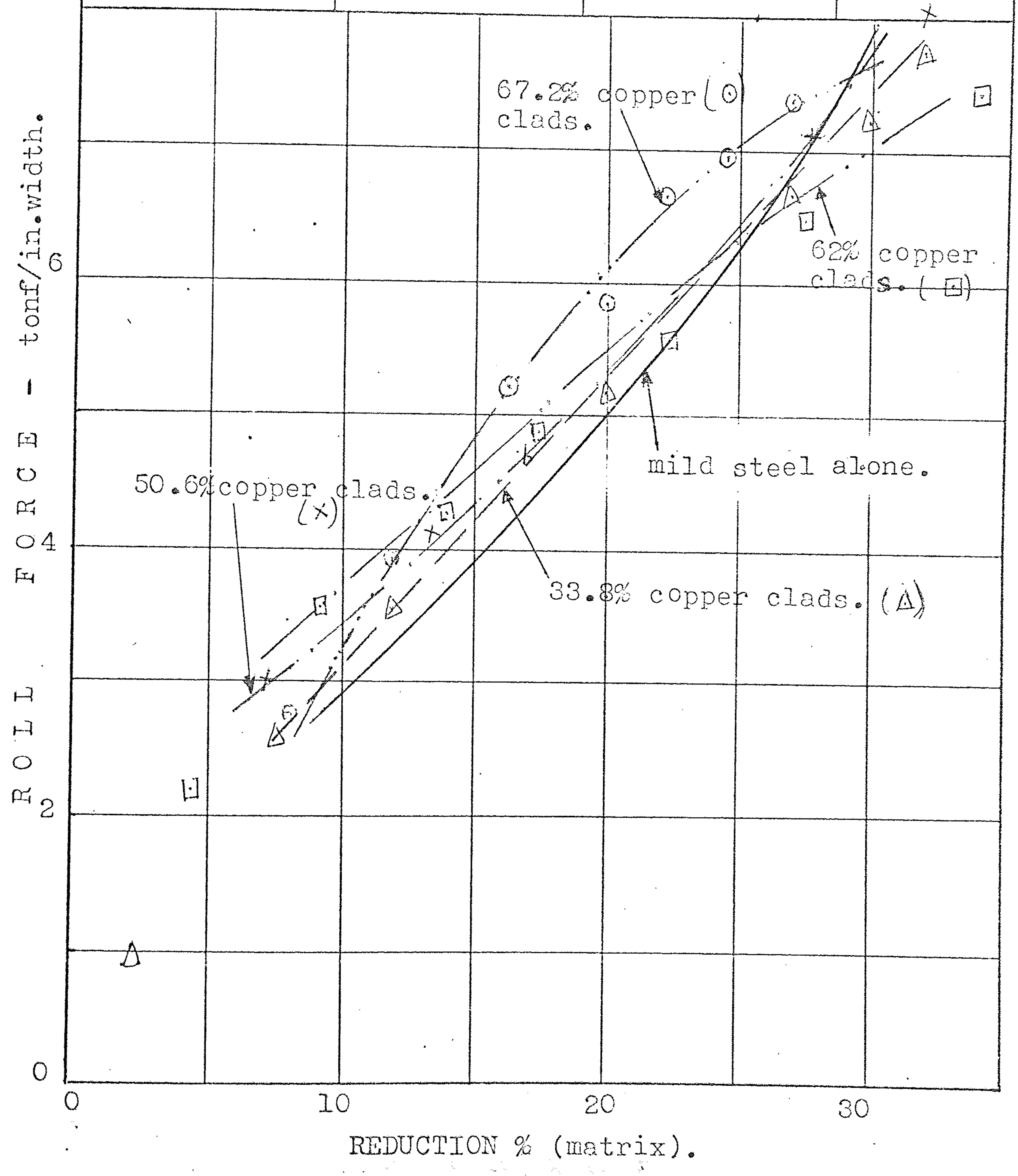
POSITION		MATERIAL	THICKNESS (in)	GRAPH NO 26
MATRIX.		Nimonic 105	0.012	
CLAD.	(1)	mild steel	2 x 0.018	
	(2)	copper	2 x 0. 02	R = 2.25



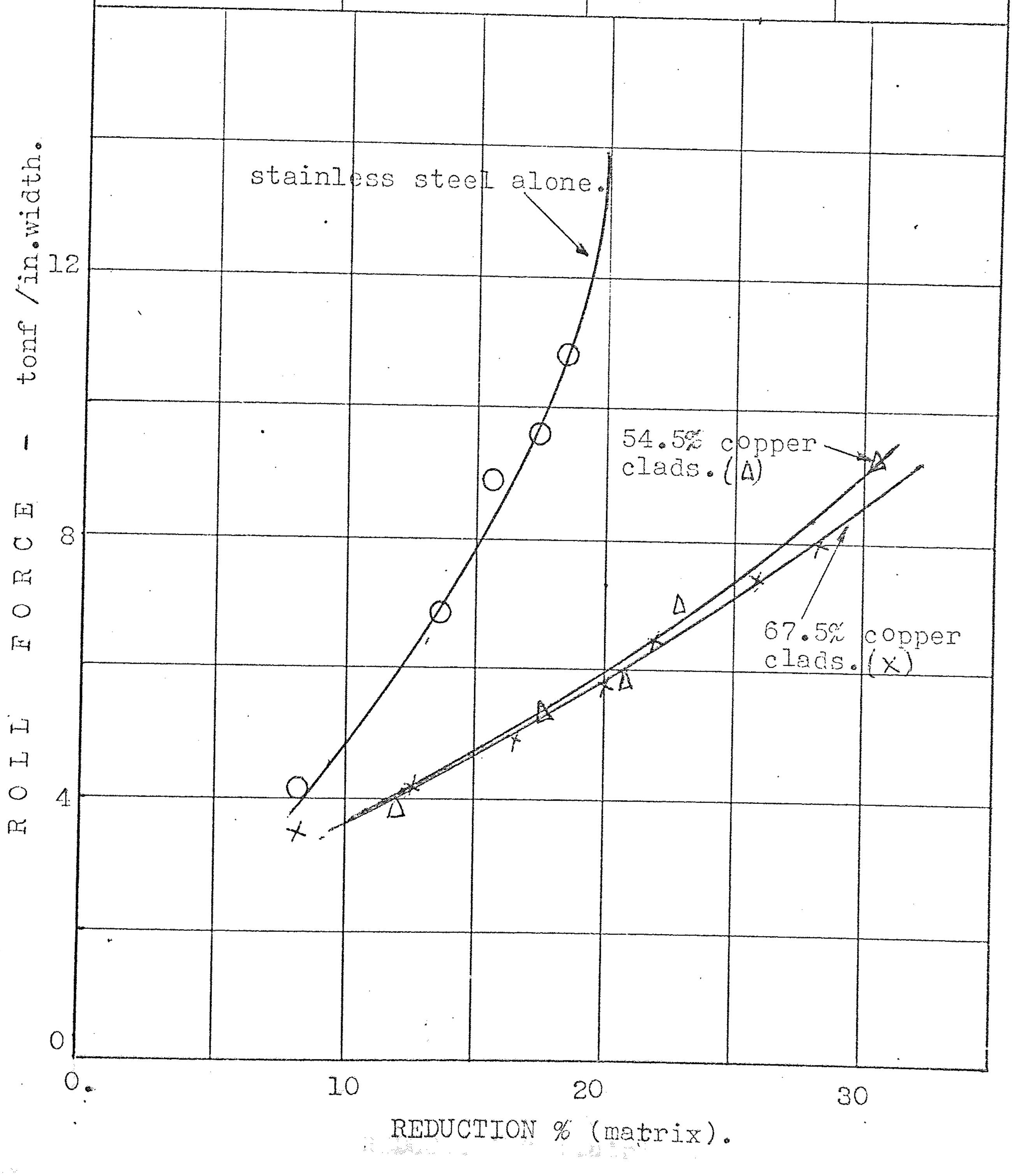
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 27
MATRIX.	copper	0.04	
CLAD.	aluminium	0.049, 0.028	R = 2



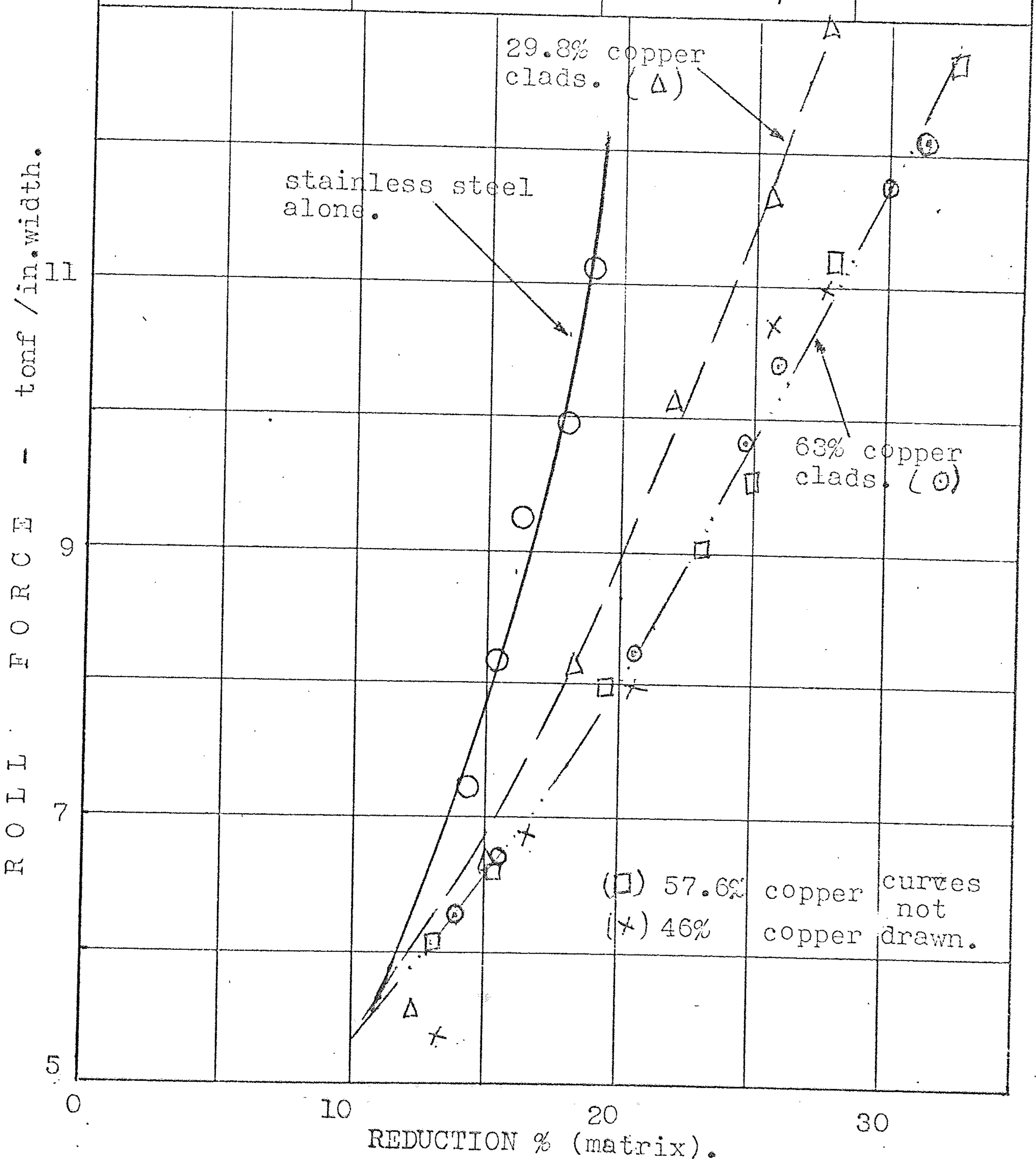
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 28
MATRIX :	mild steel	0.039	
CLAD :	copper	0.01 - 0.04	R = 2



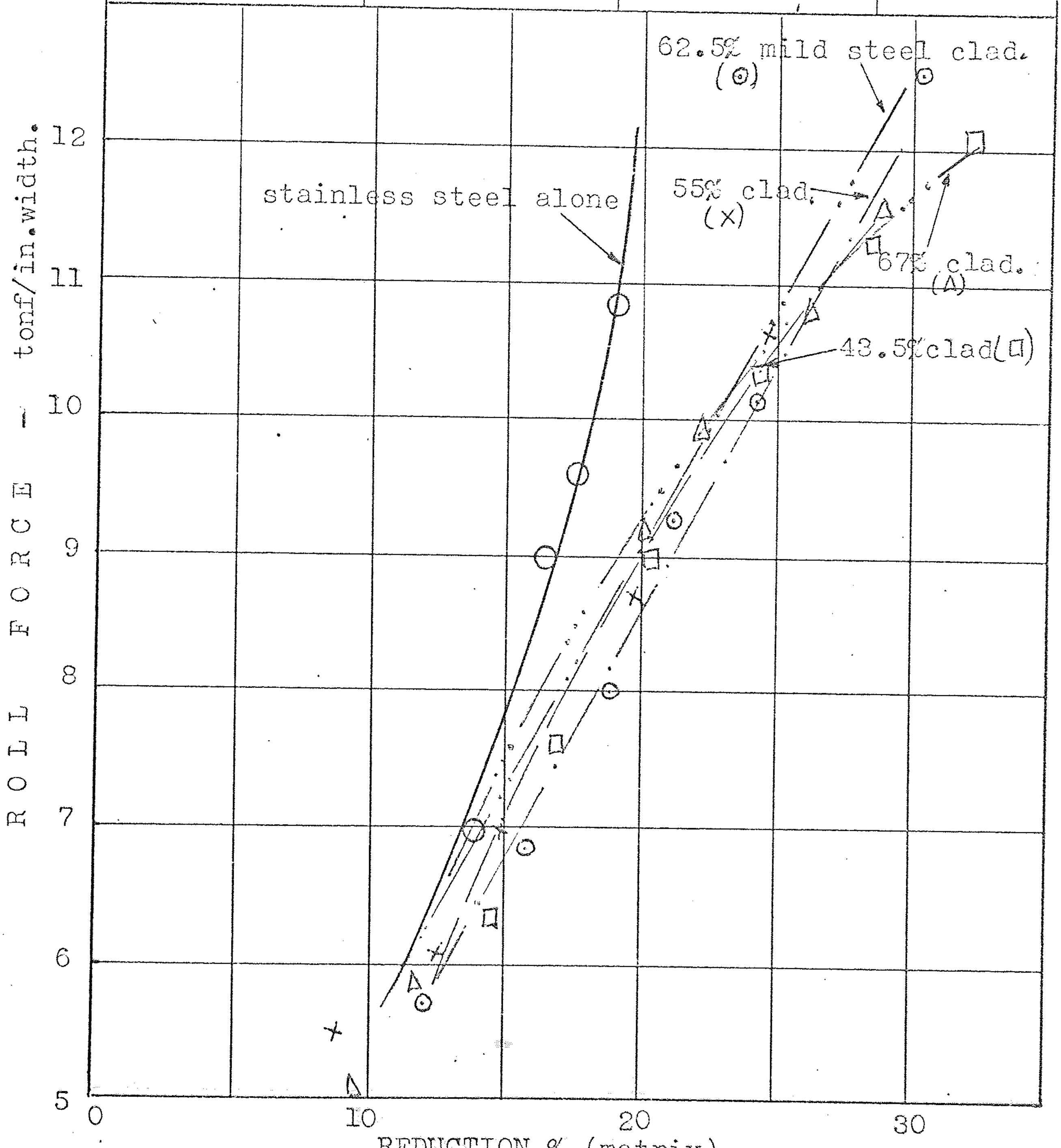
POSITION	MATERIAL	THICKNESS	GRAPH NO 29
MATRIX :	stainless st.	0.047	
CLAD :	aluminium	0.028, 0.049	R = 2



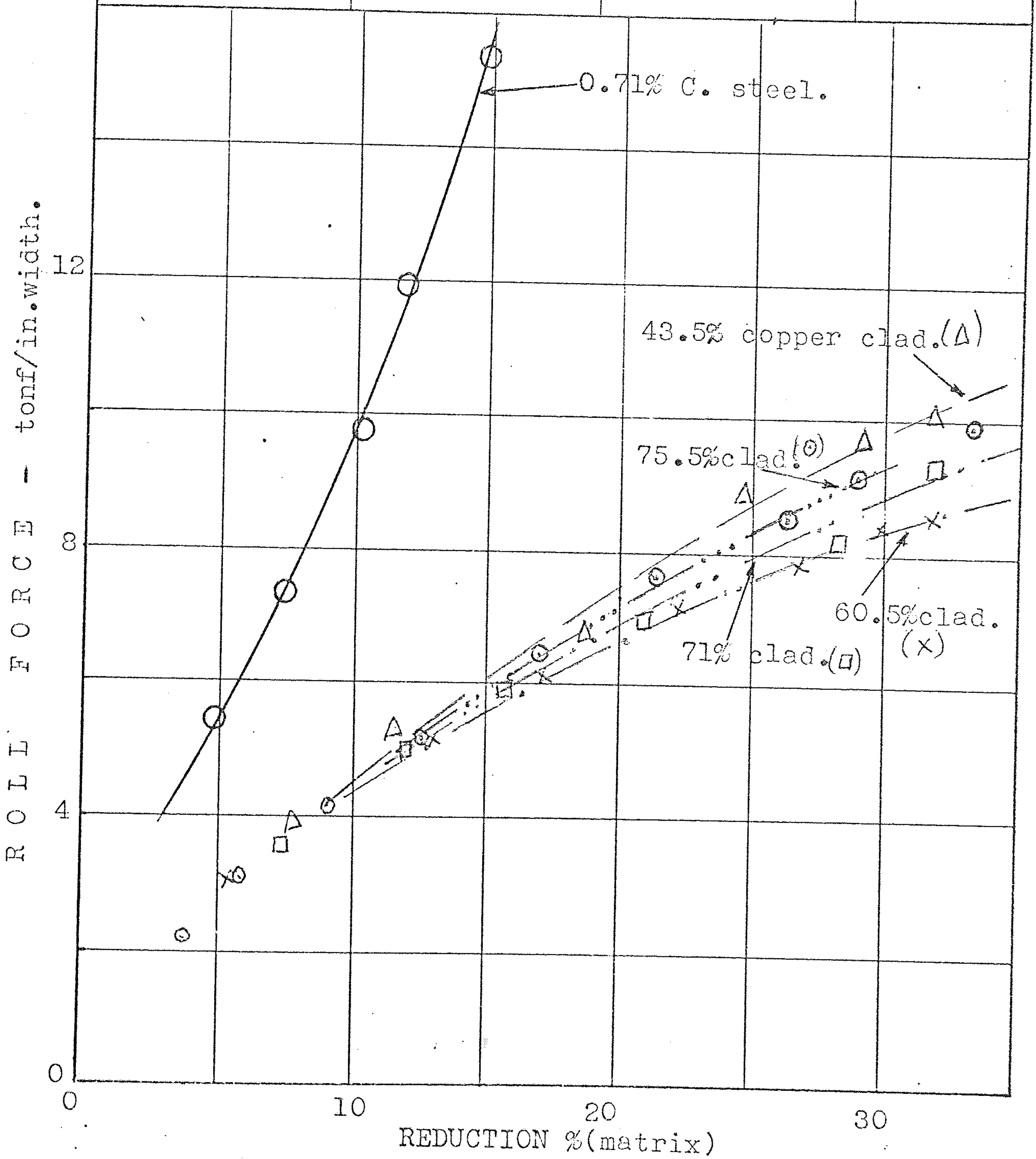
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 30
MATRIX :	stainless st.	0.047	
CLAD :	copper	0.01 - 0.04	R = 2



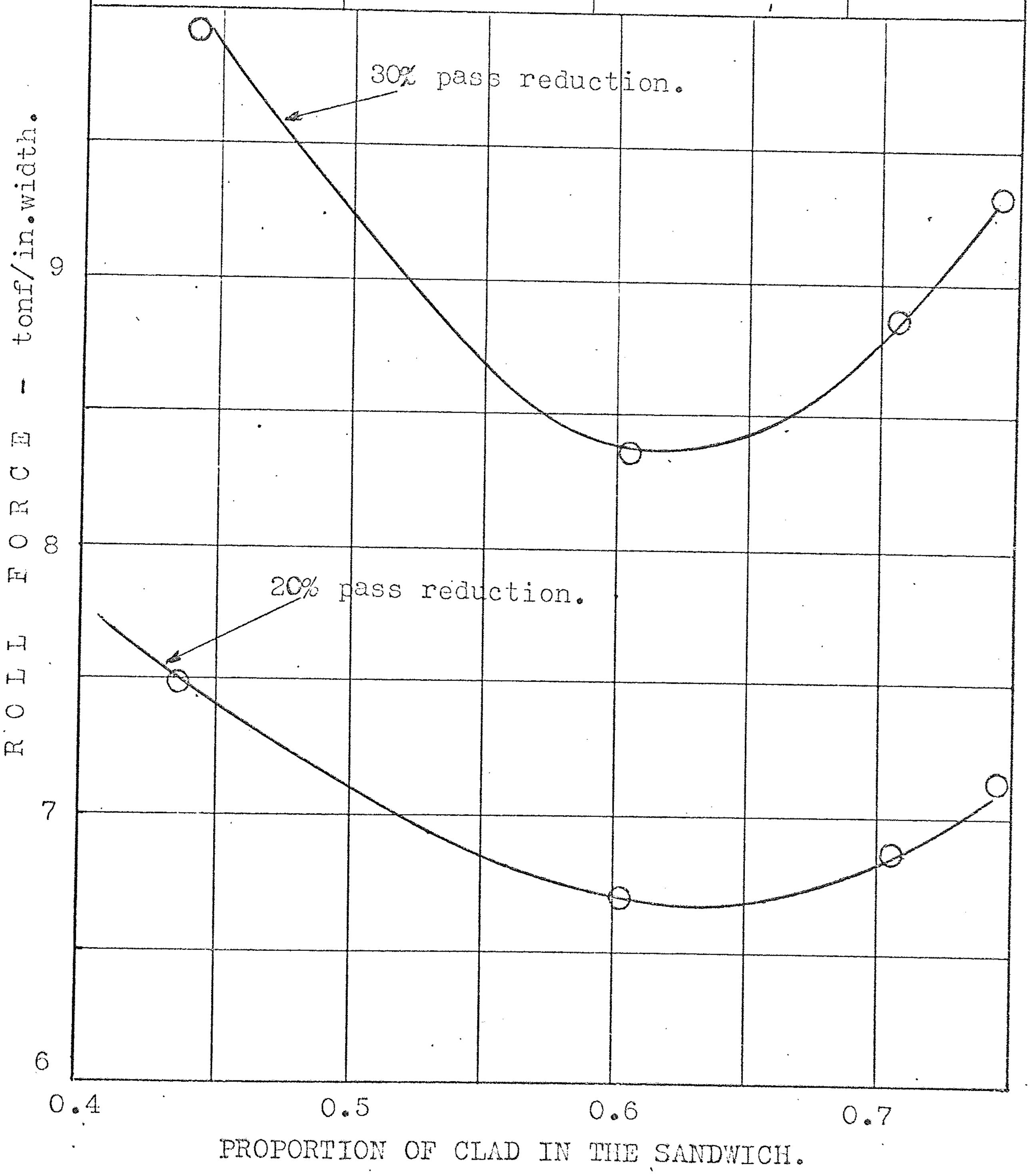
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 31
MATRIX :	stainless st.	0.047	
CLAD :	mild steel	0.018 - 0.048	
			R = 2



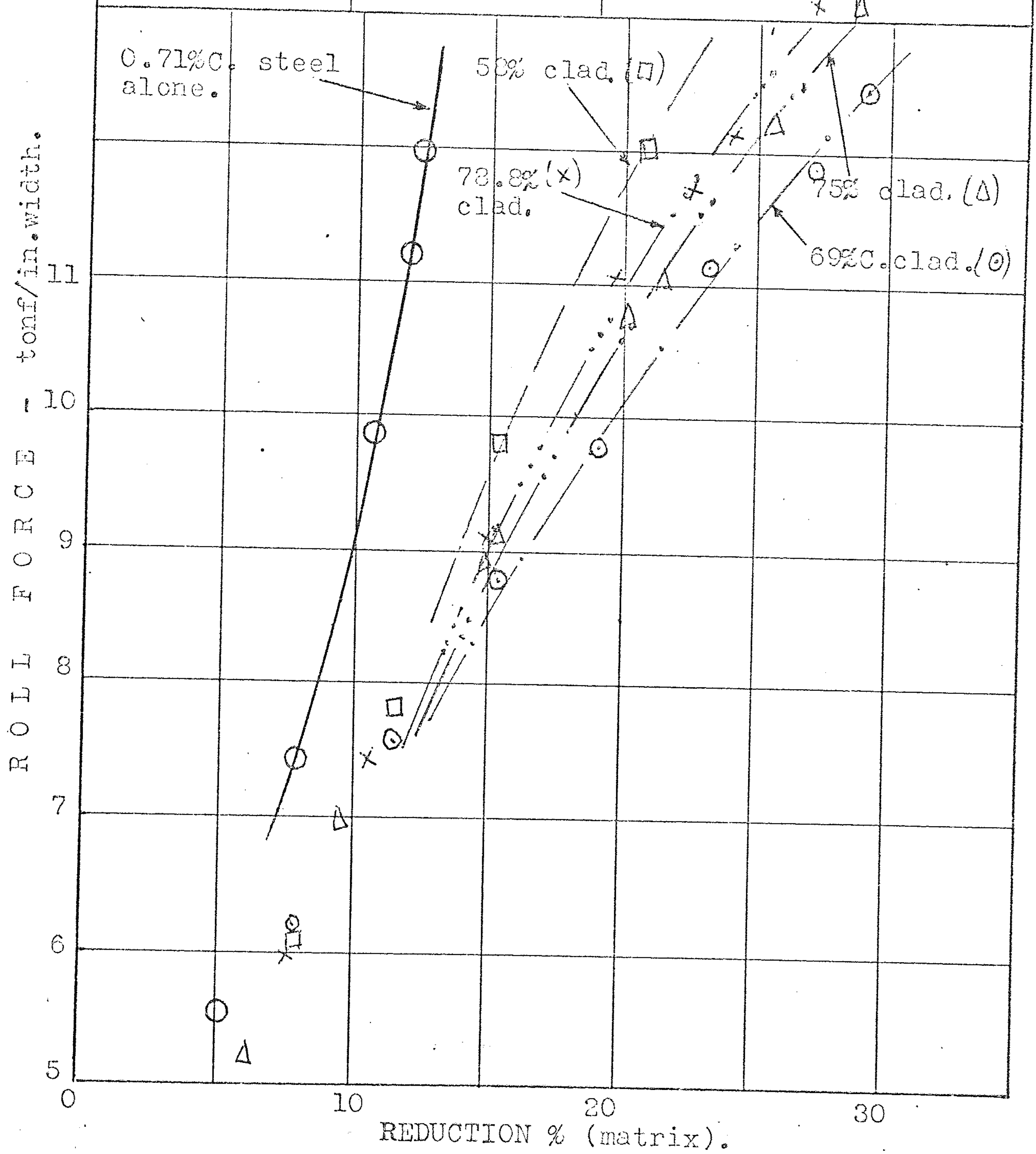
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 32
MATRIX :	0.71%C.steel	0.026	
CLAD :	copper	0.01 - 0.04	R = 2



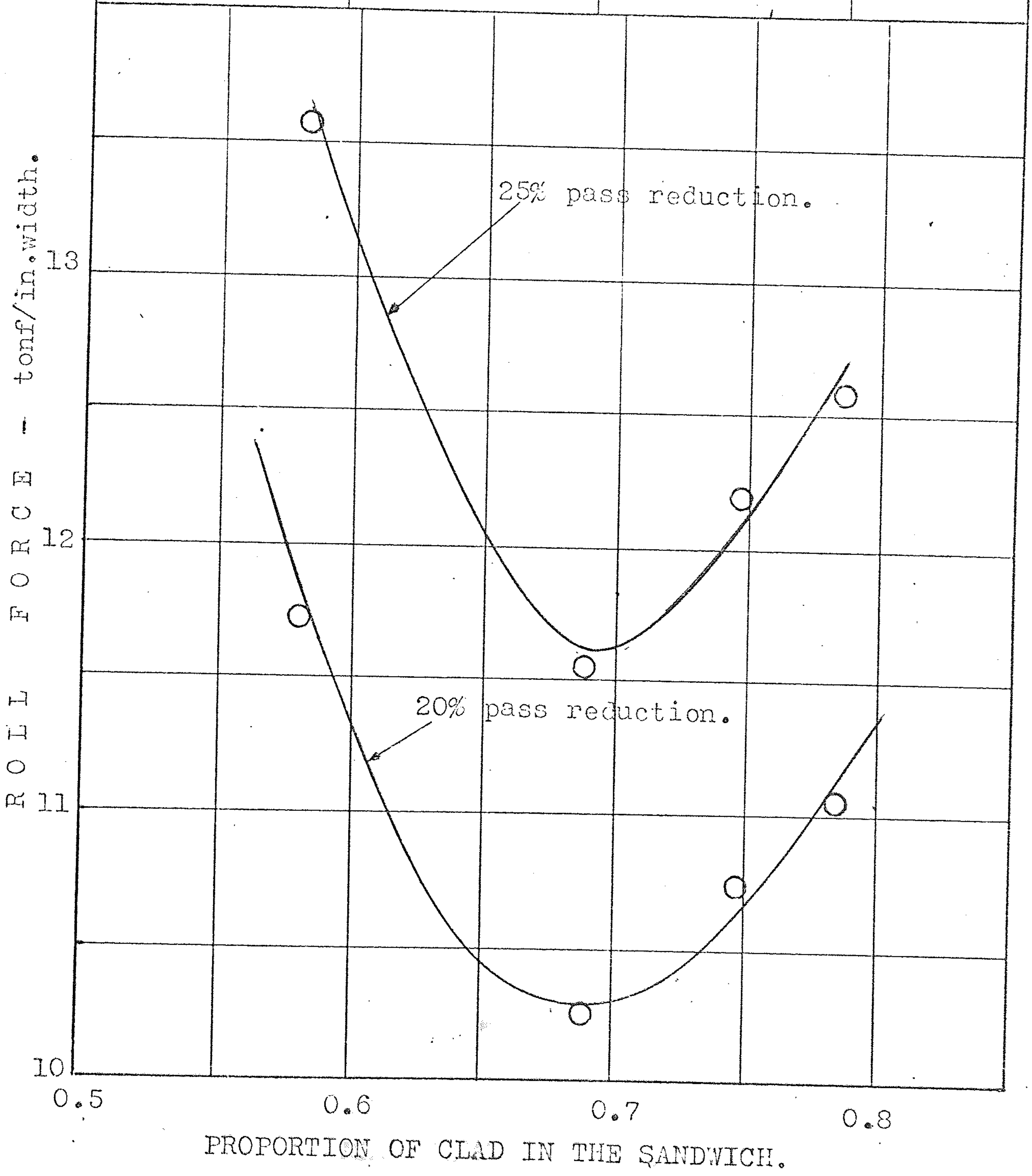
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 33
MATRIX	0.71%C.steel	0.026	
CLAD	copper	0.01 – 0.04	
			R = 2



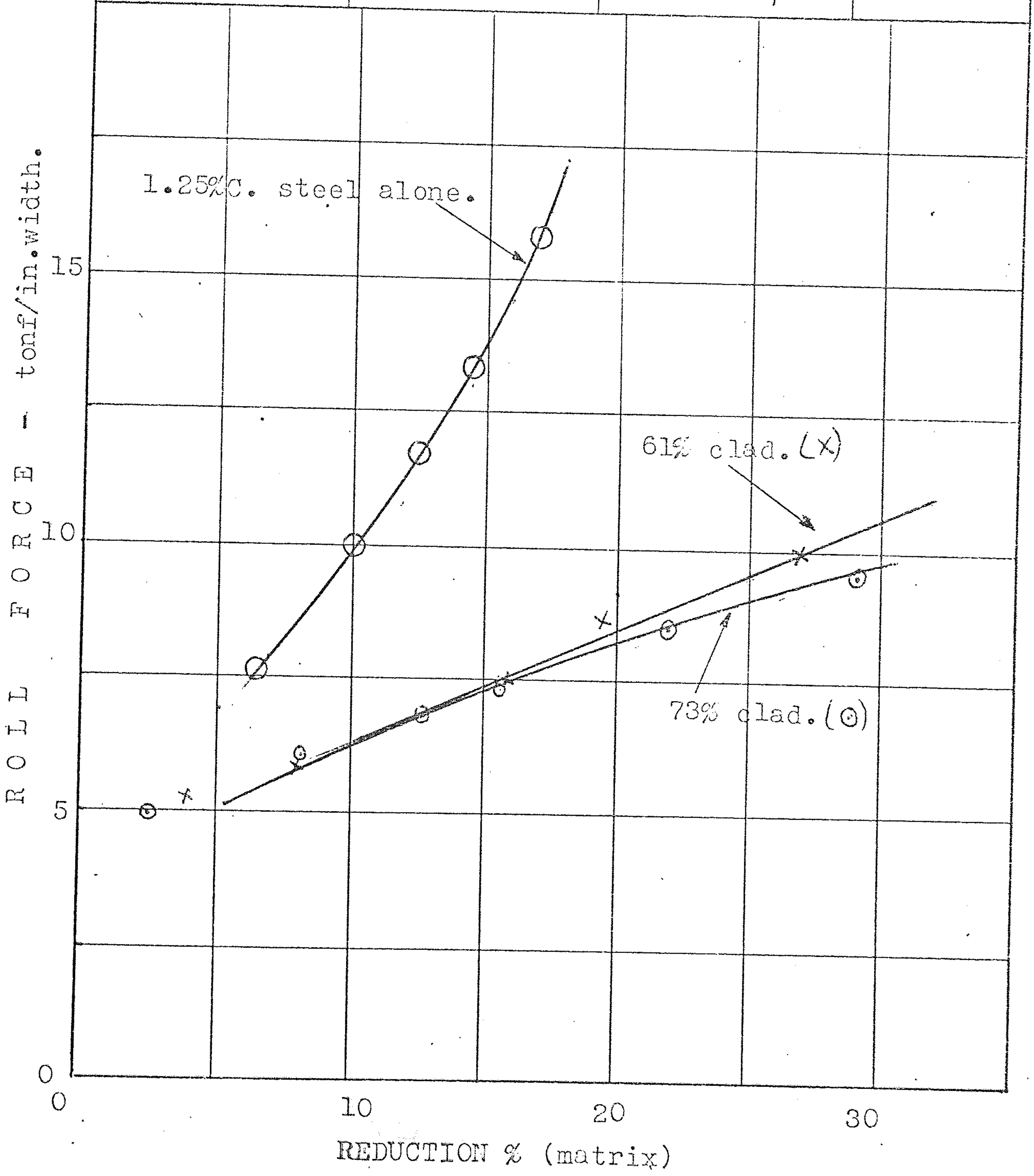
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 34
MATRIX :	0.71%C. steel	0.026	
CLAD :	mild steel	0.018 - 0.048	
			R = 2



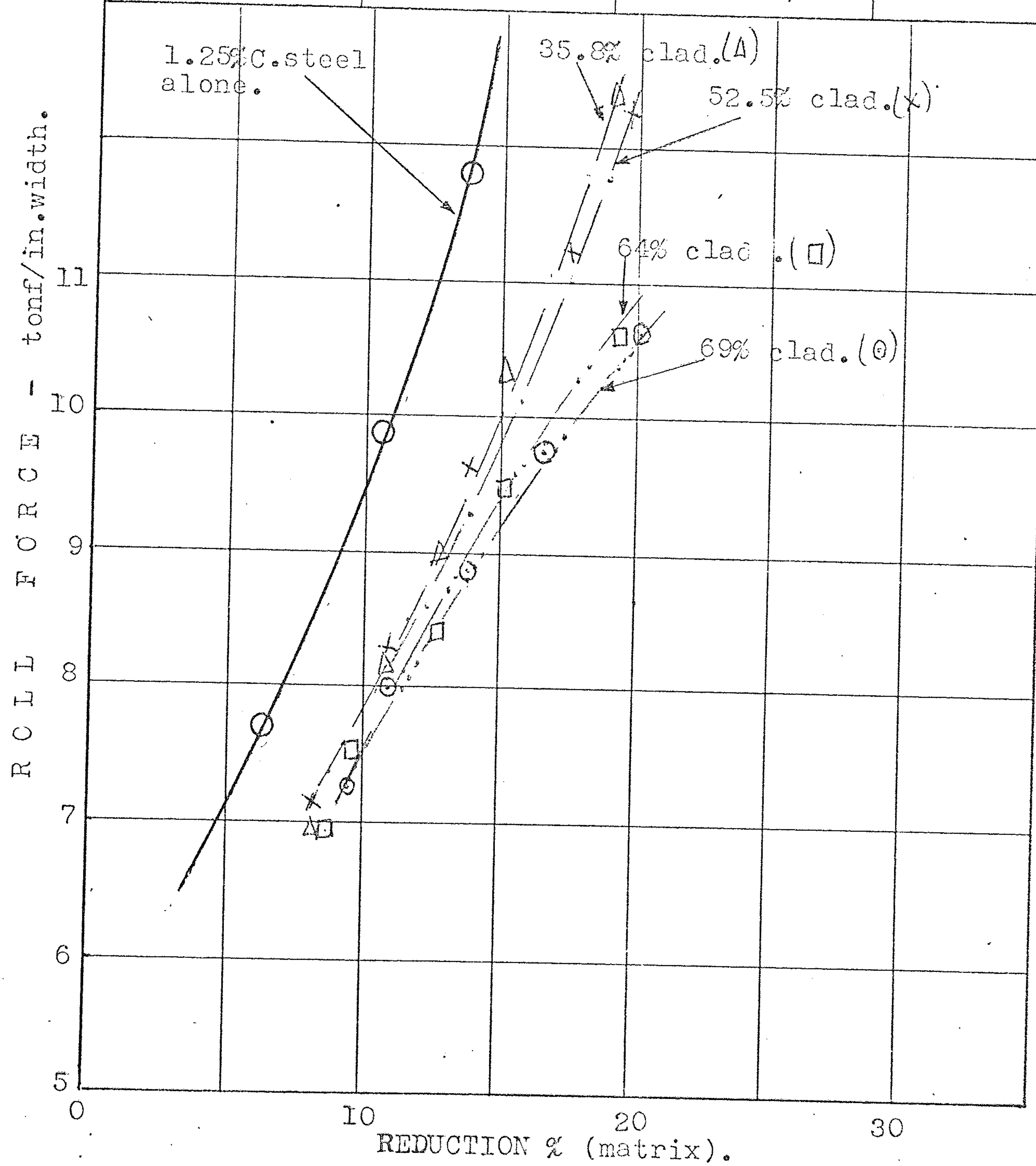
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 35
MATRIX	0.71%C.steel	0.026	
CLAD	mild steel	0.018 - 0.048	R = 2



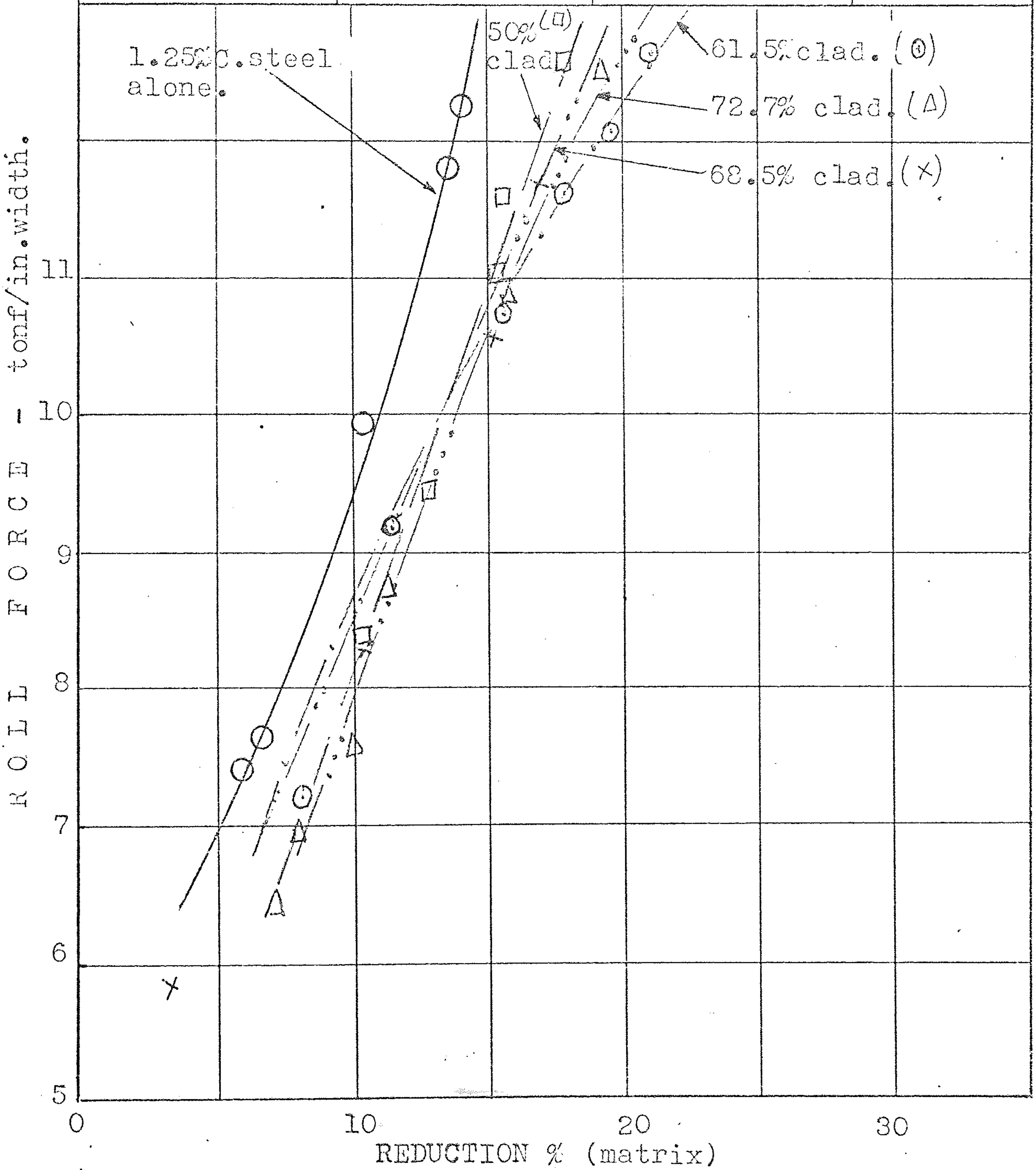
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 36
MATRIX :	1.25%C.steel	0.036	
CLAD	aluminium	0.028, 0.049	R = 2



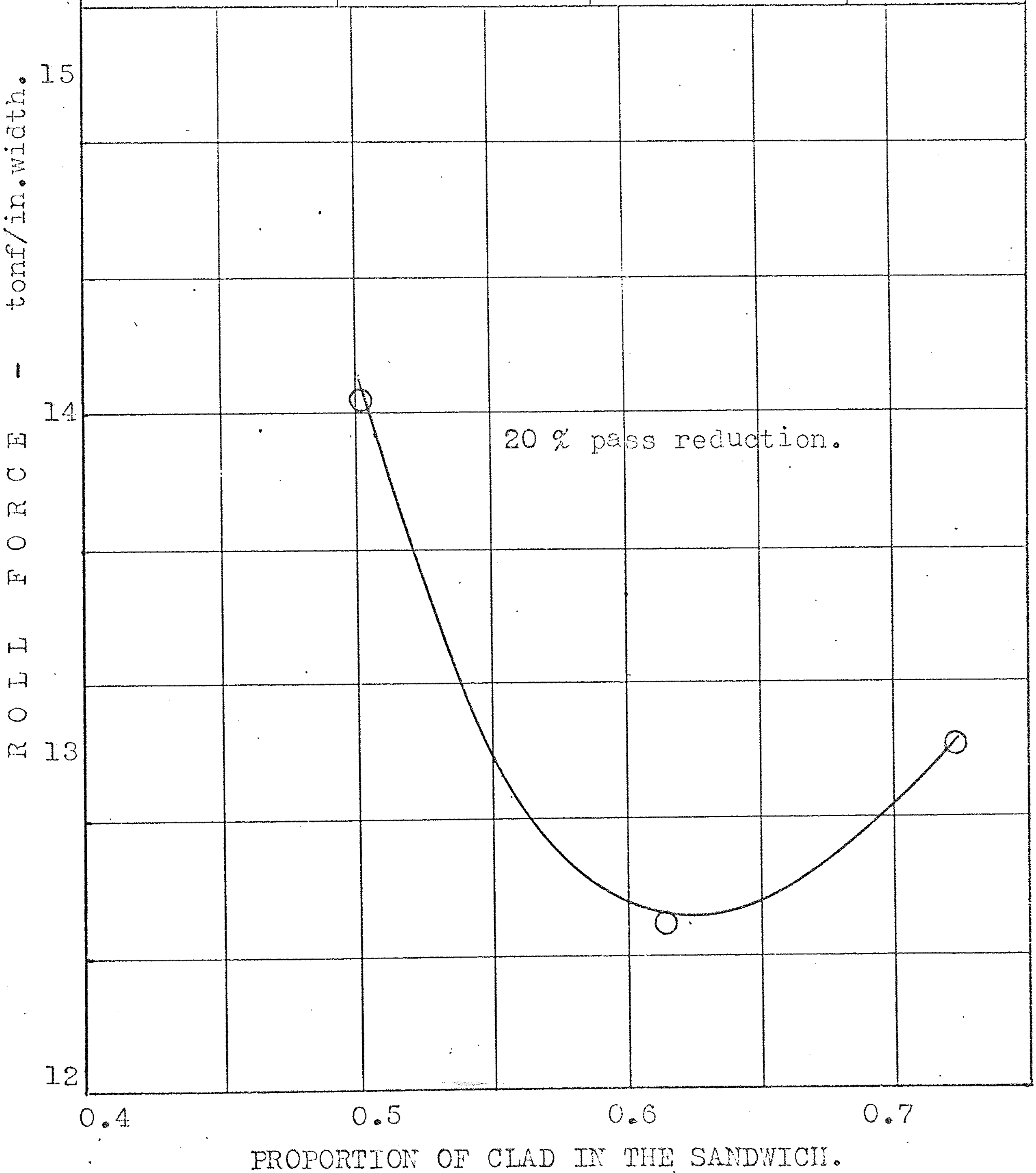
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 37
MATRIX :	1.25%C.steel	0.036	
CLAD :	copper	0.01 - 0.04	R = 2



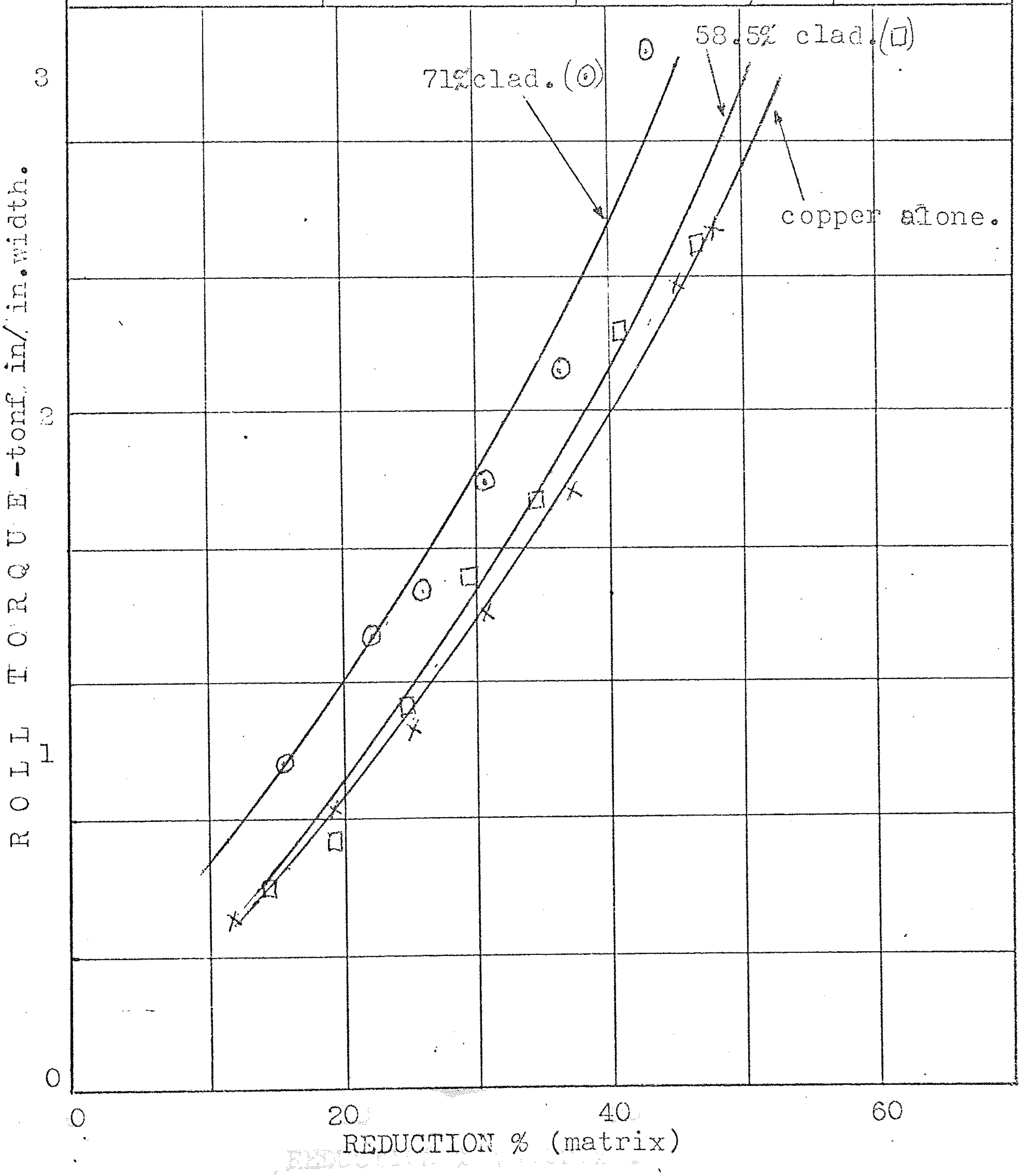
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 38
MATRIX :	1.25%C. steel	0.036	
CLAD :	mild steel	0.018 - 0.048	R = 2



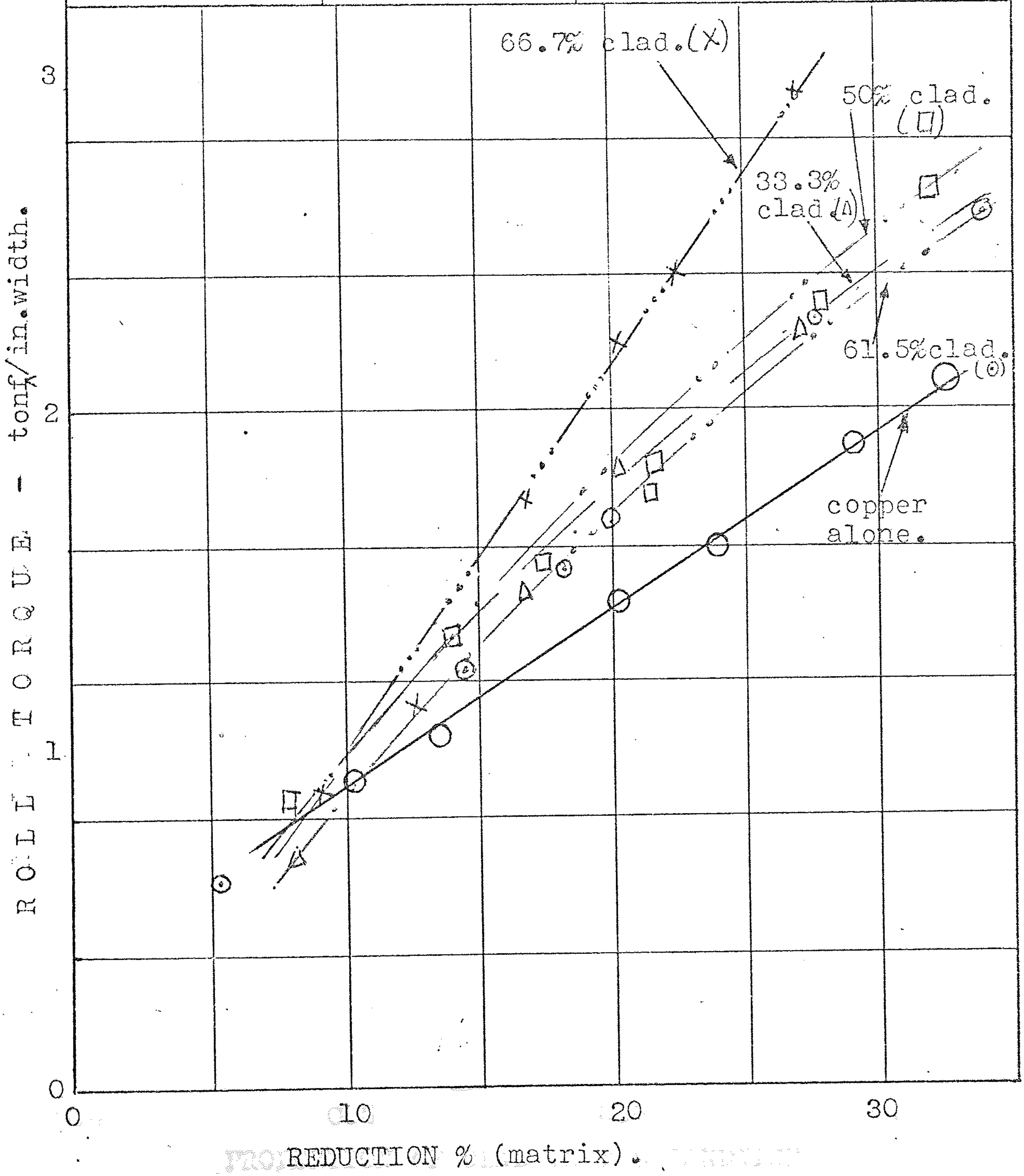
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 39
MATRIX :	1.25%C.steel	0.036	
CLAD :	mild steel	0.018 - 0.048	R = 2



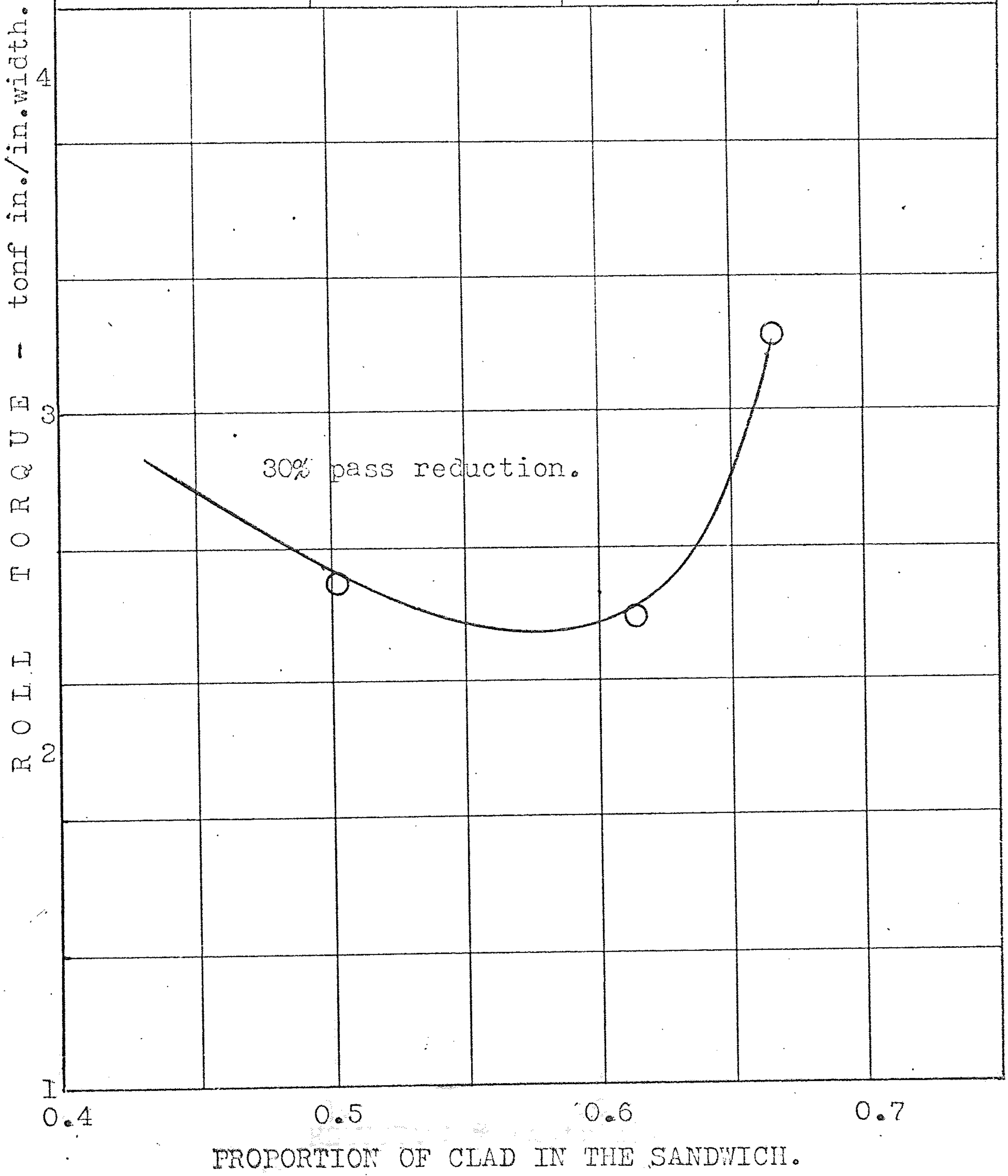
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO
MATRIX :	copper	0.04	
CLAD :	aluminium	0.028, 0.049	40
			R = 2



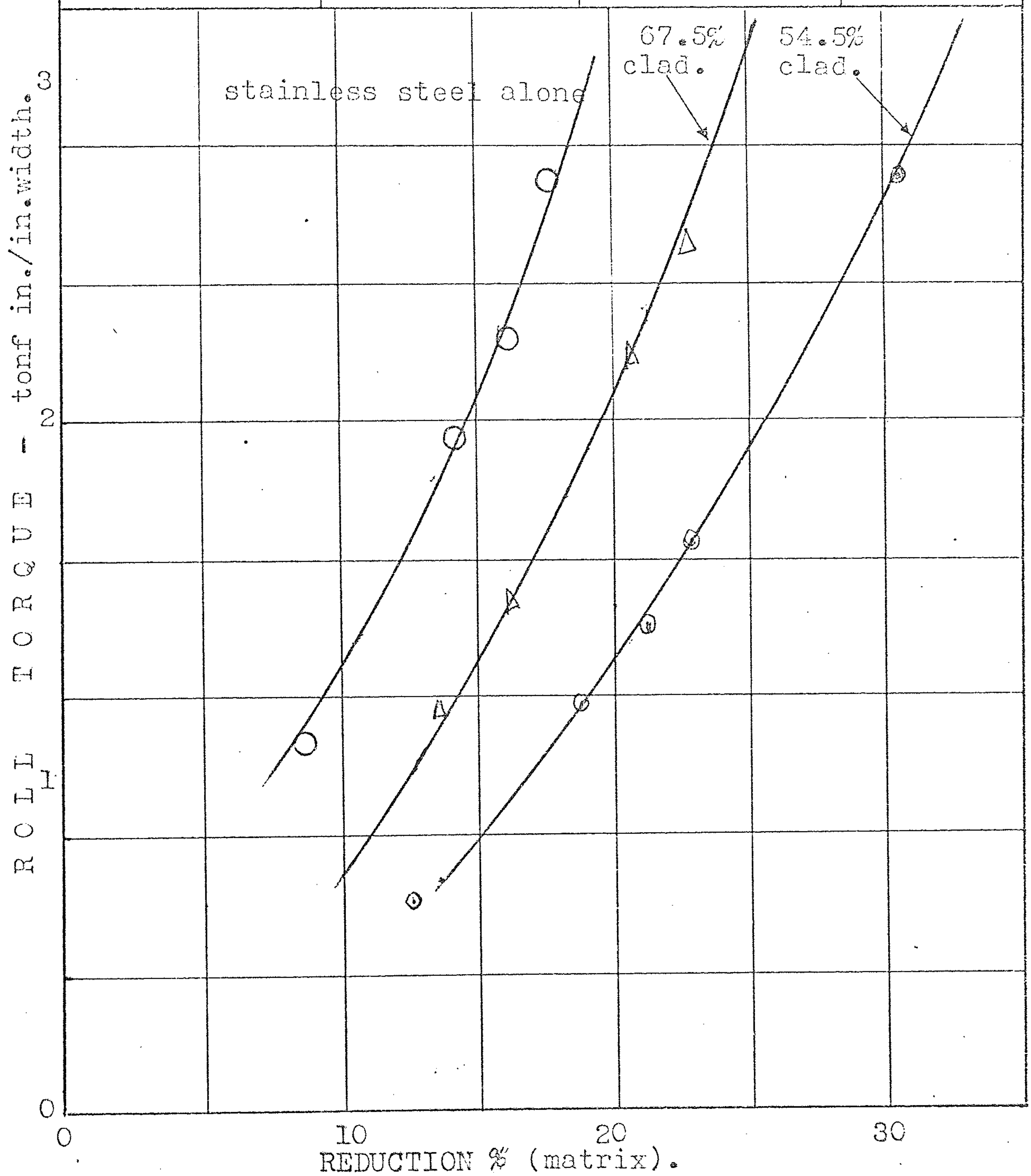
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 41
MATRIX :	mild steel	0.039	
CLAD :	copper	0.01 - 0.04	R = 2
			x



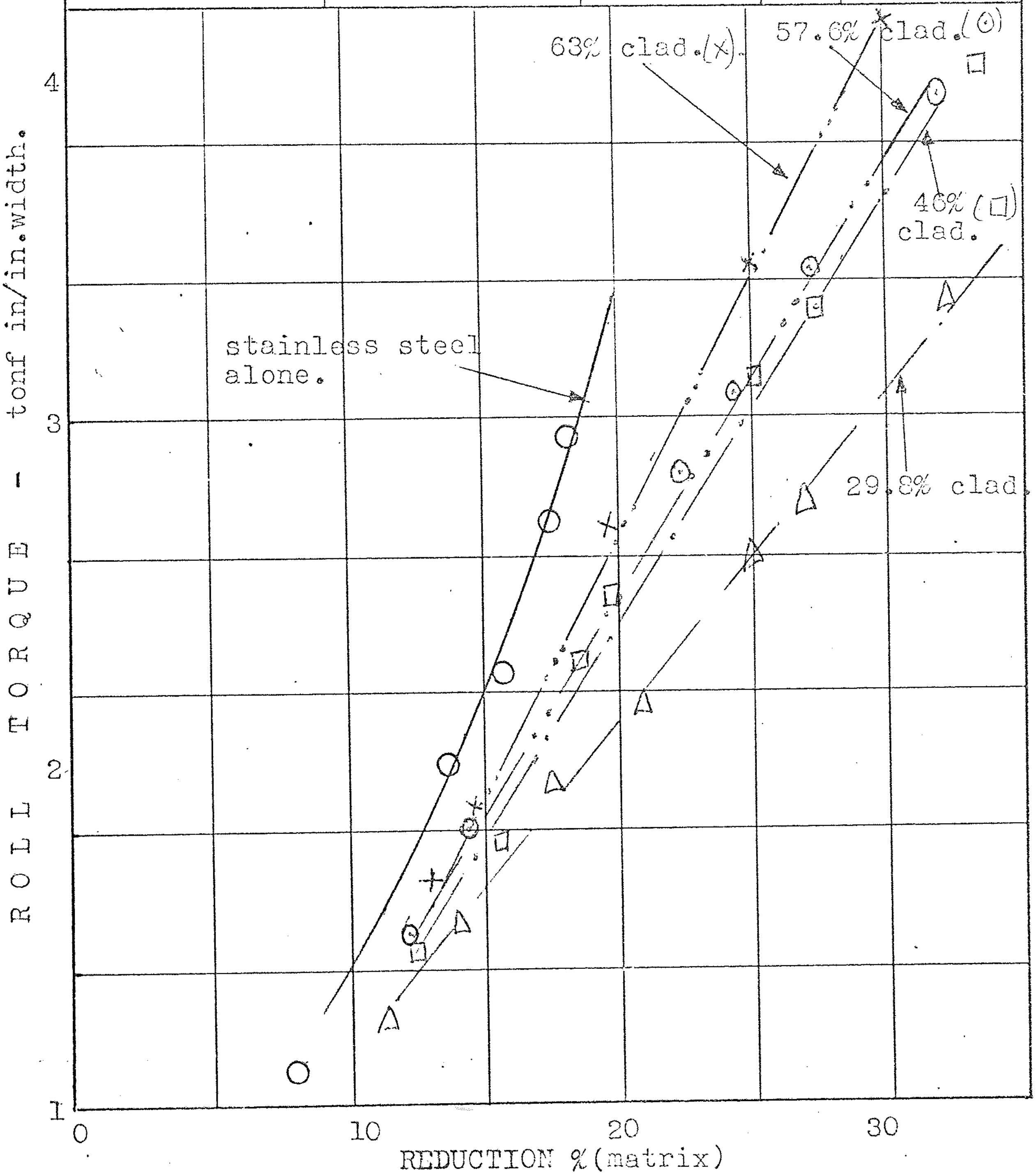
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO
MATRIX :	Mild steel	0.039	
CLAD :	copper	0.01 - 0.04	42
			R = 2



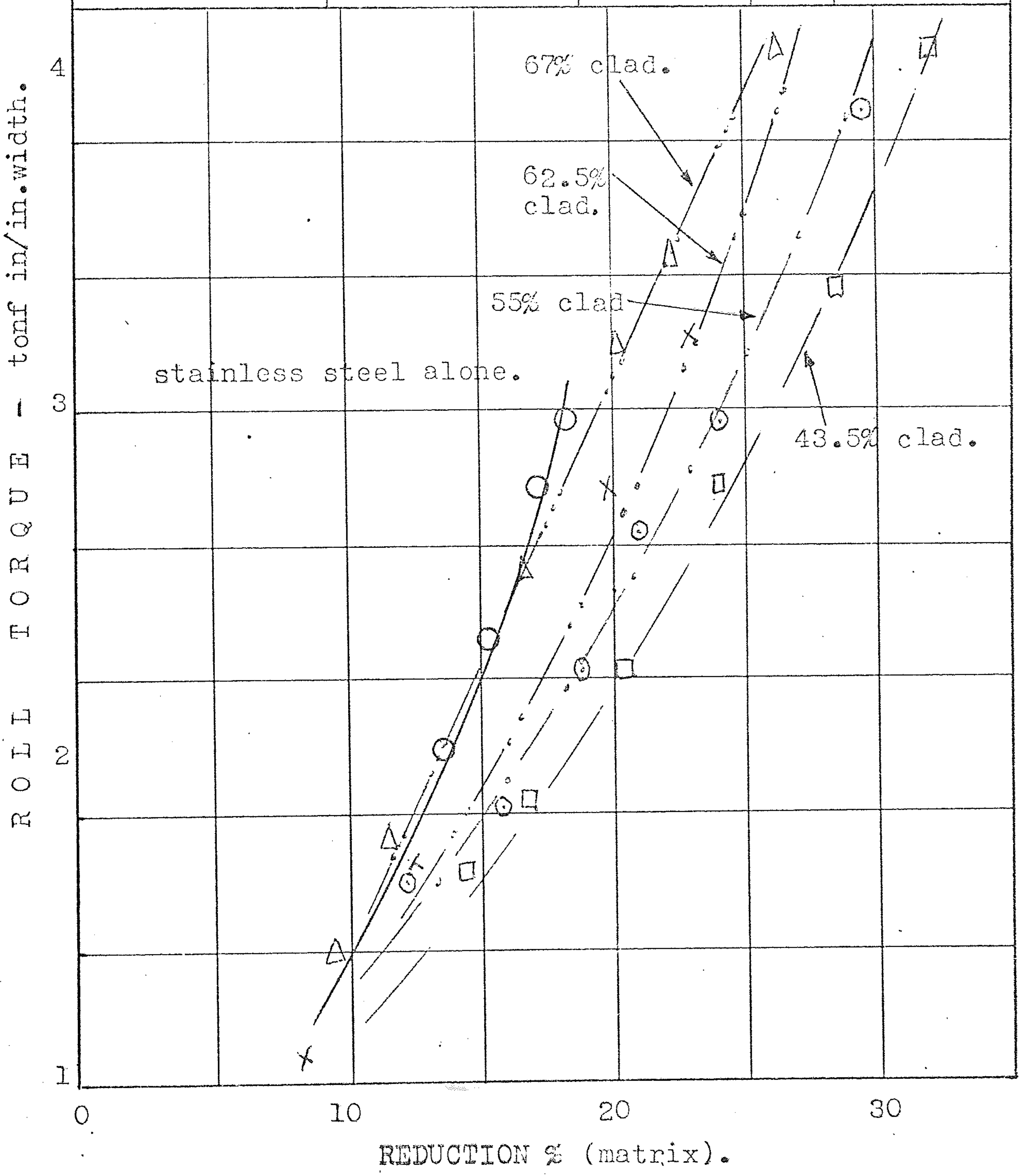
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 43
MATRIX :	stainless st.	0.047	
CLAD :	aluminium	0.028, 0.049	R = 2



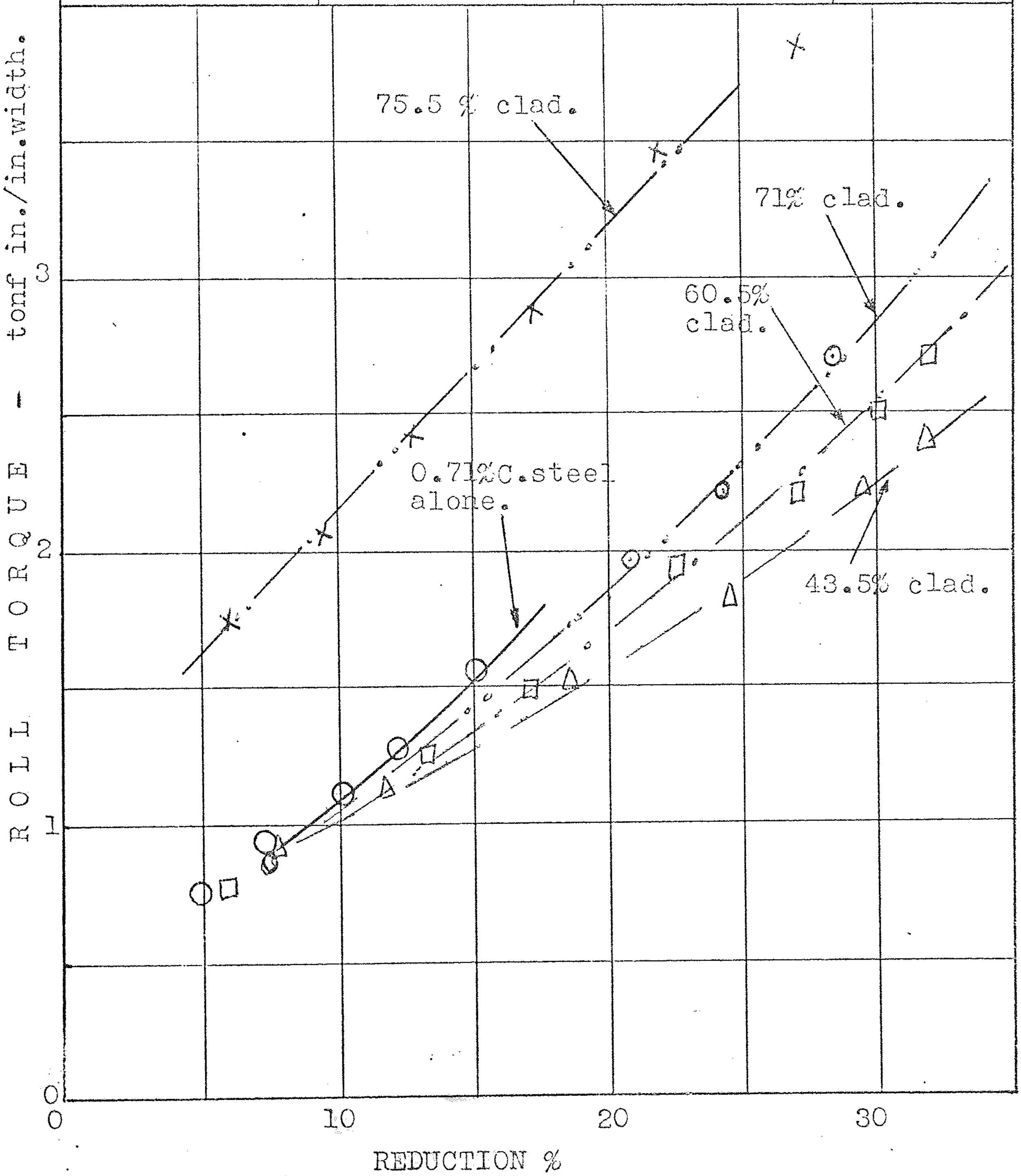
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 44
MATRIX :	stainless st.	0.047	
CLAD :	copper	0.01 - 0.04	R = 2



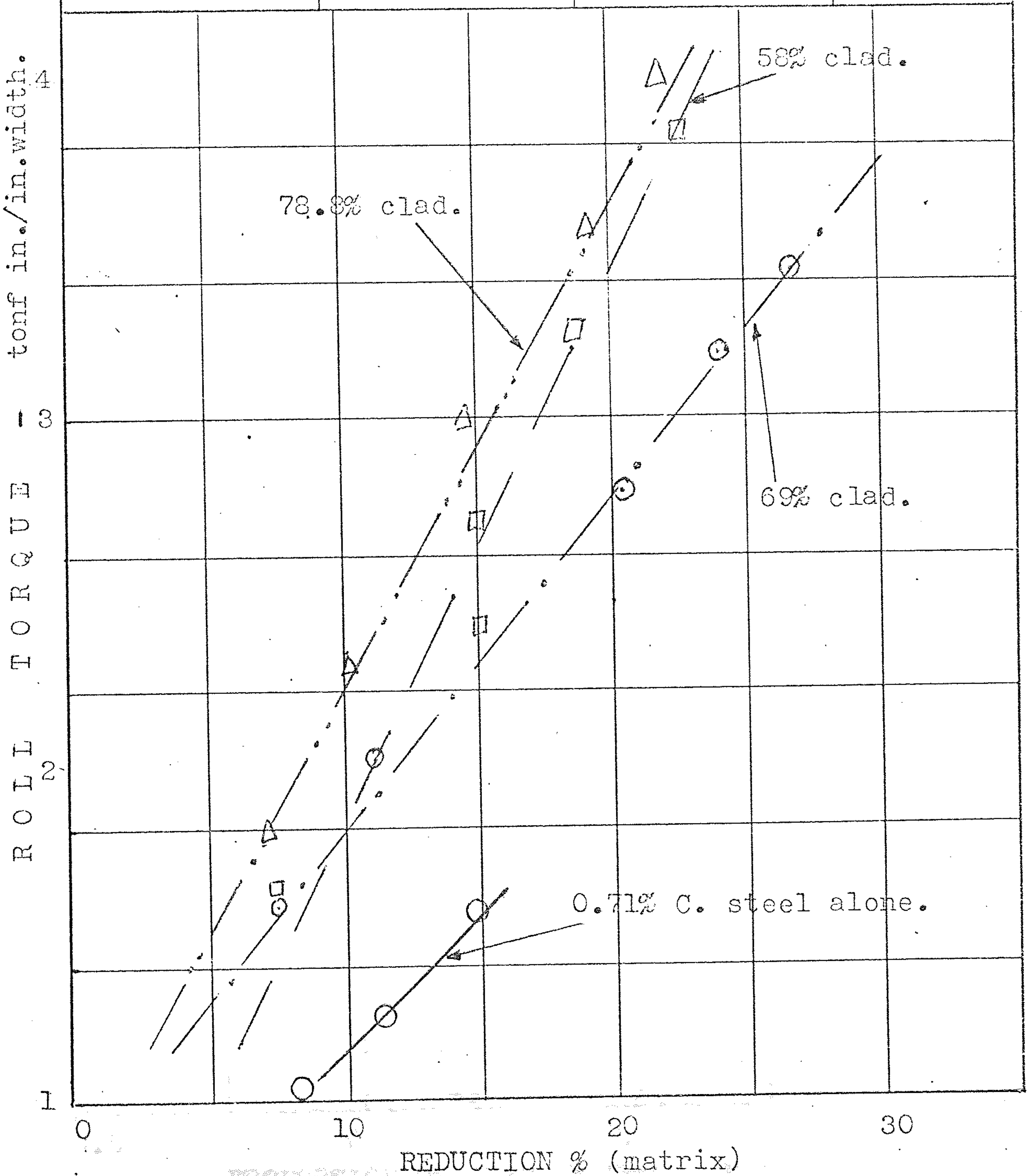
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 45
MATRIX :	stainless st.	0.047	
CLAD :	mild steel	0.018 - 0.048	R = 2



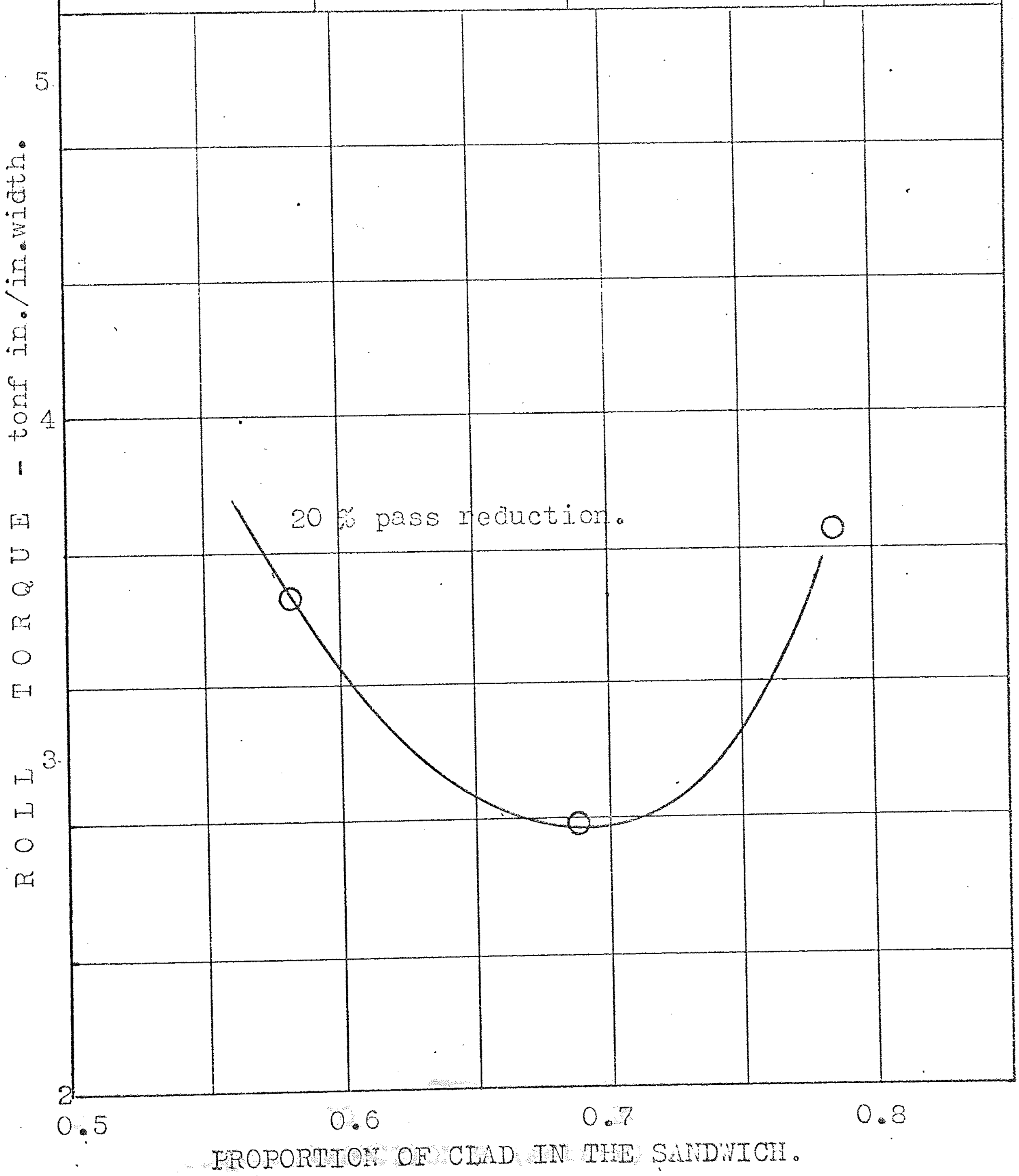
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 46
MATRIX :	0.71%C.steel	0.026	
CLAD :	copper	0.01 - 0.04	R = 2



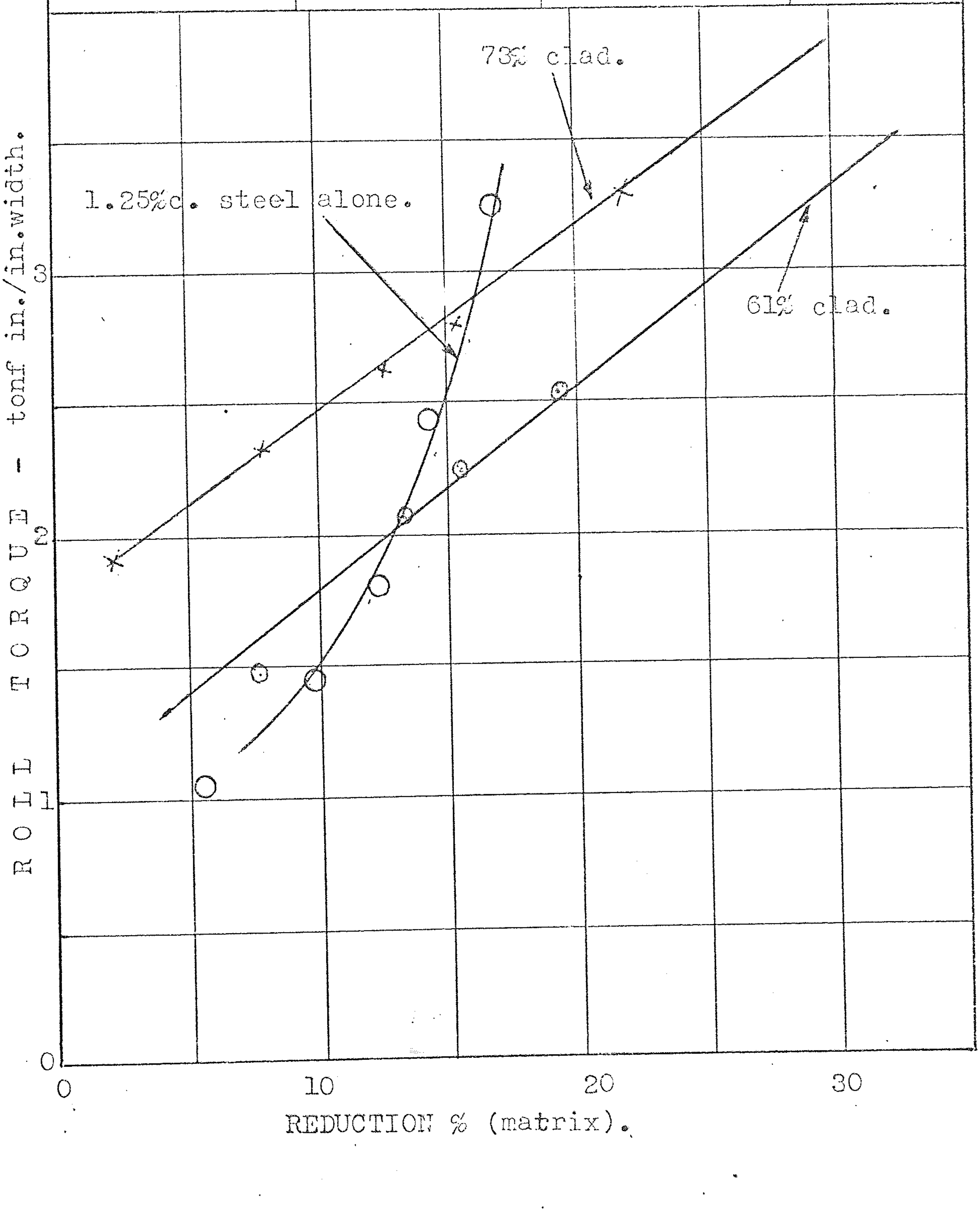
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 47
MATRIX :	0.71%C.steel	0.026	
CLAD :	mild steel	0.018 - 0.048	R = 2



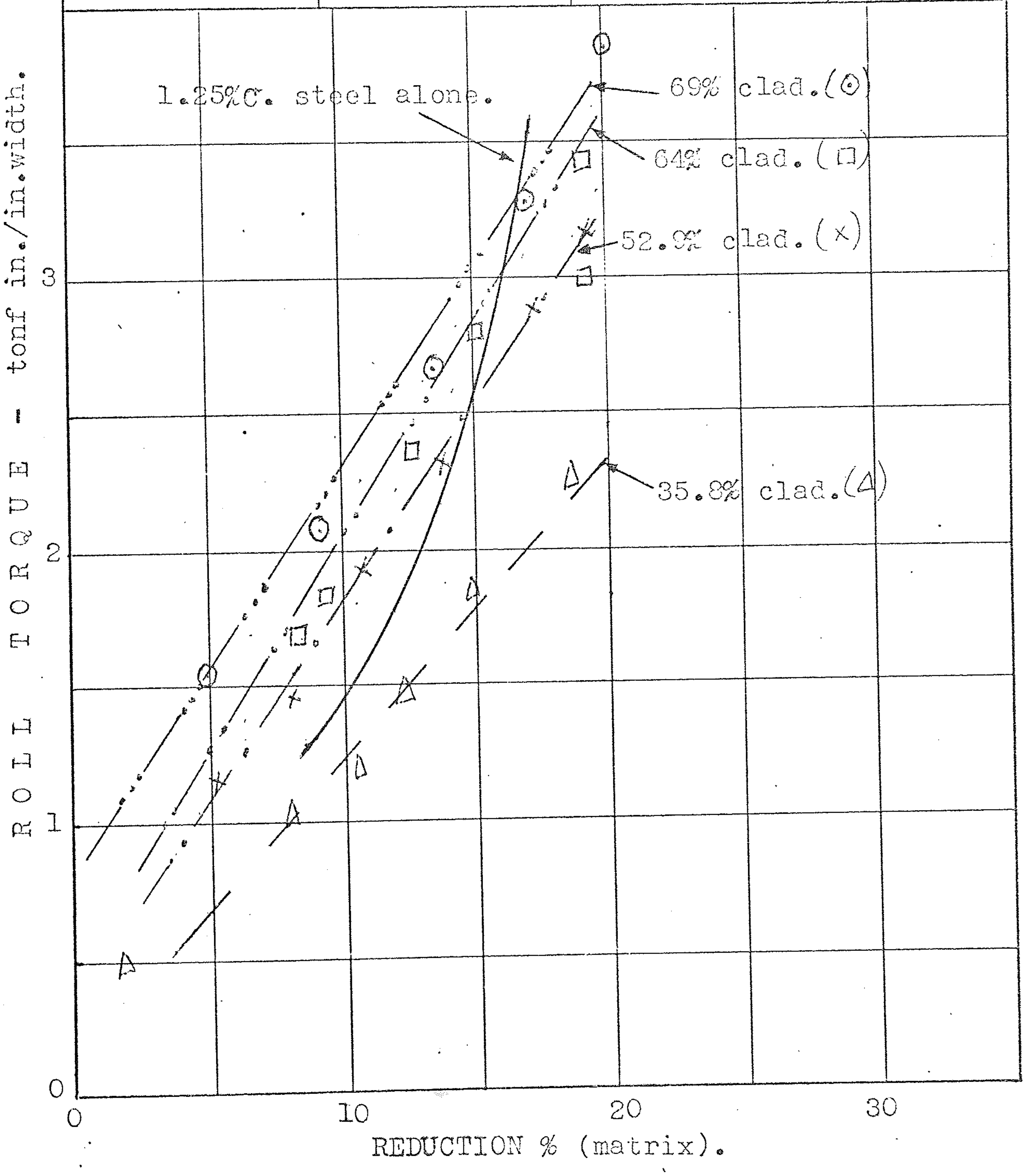
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 48
MATRIX :	0.71%C.steel	0.026	
CLAD :	mild steel	0.018 - 0.048	R = 2



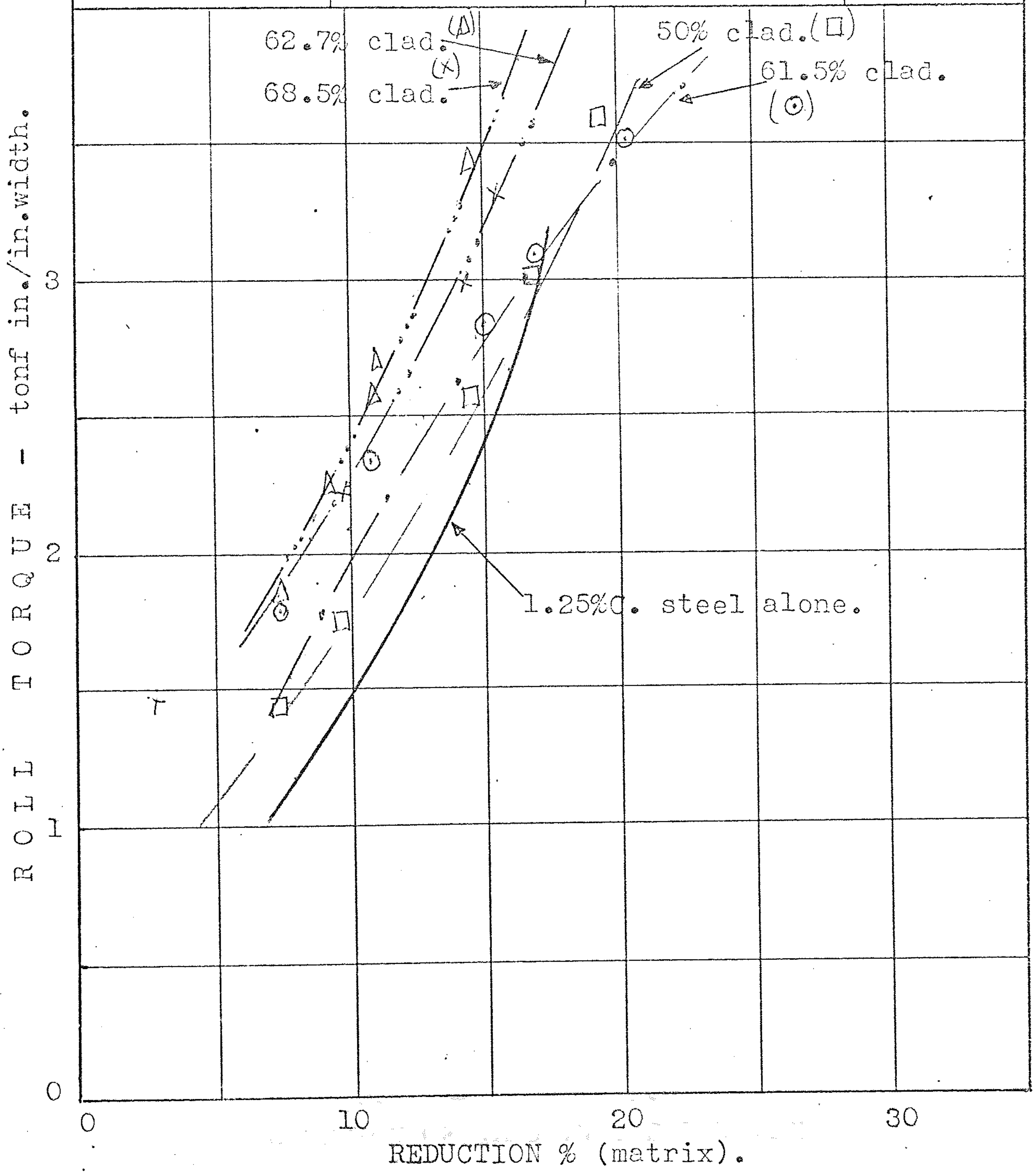
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 49
MATRIX :	1.25%C.steel.	0.036	
CLAD :	aluminium	0.028, 0.049	R = 2



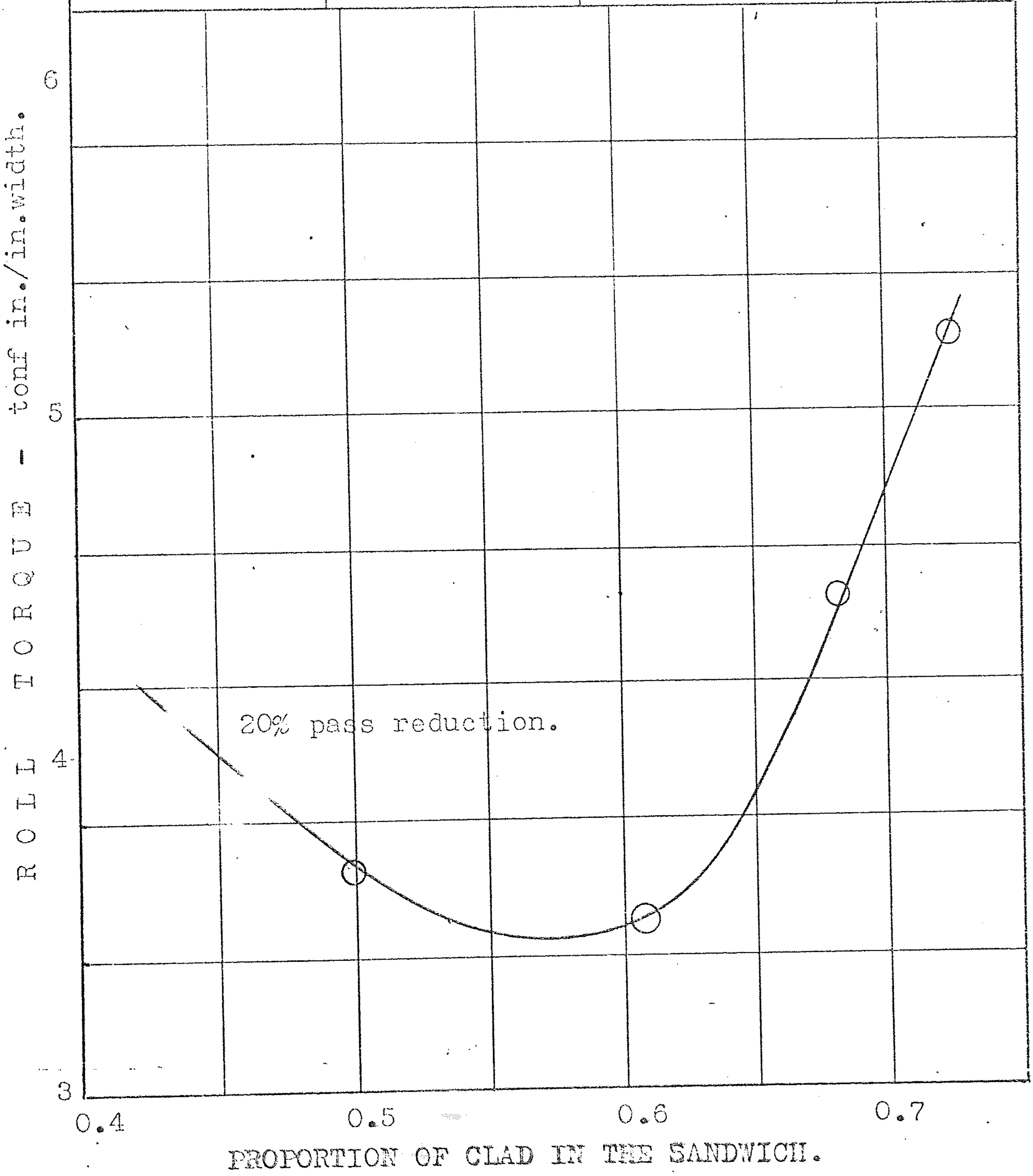
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 50
MATRIX :	1.25%C.steel	0.036	
CLAD :	copper	0.01 - 0.04	R = 2



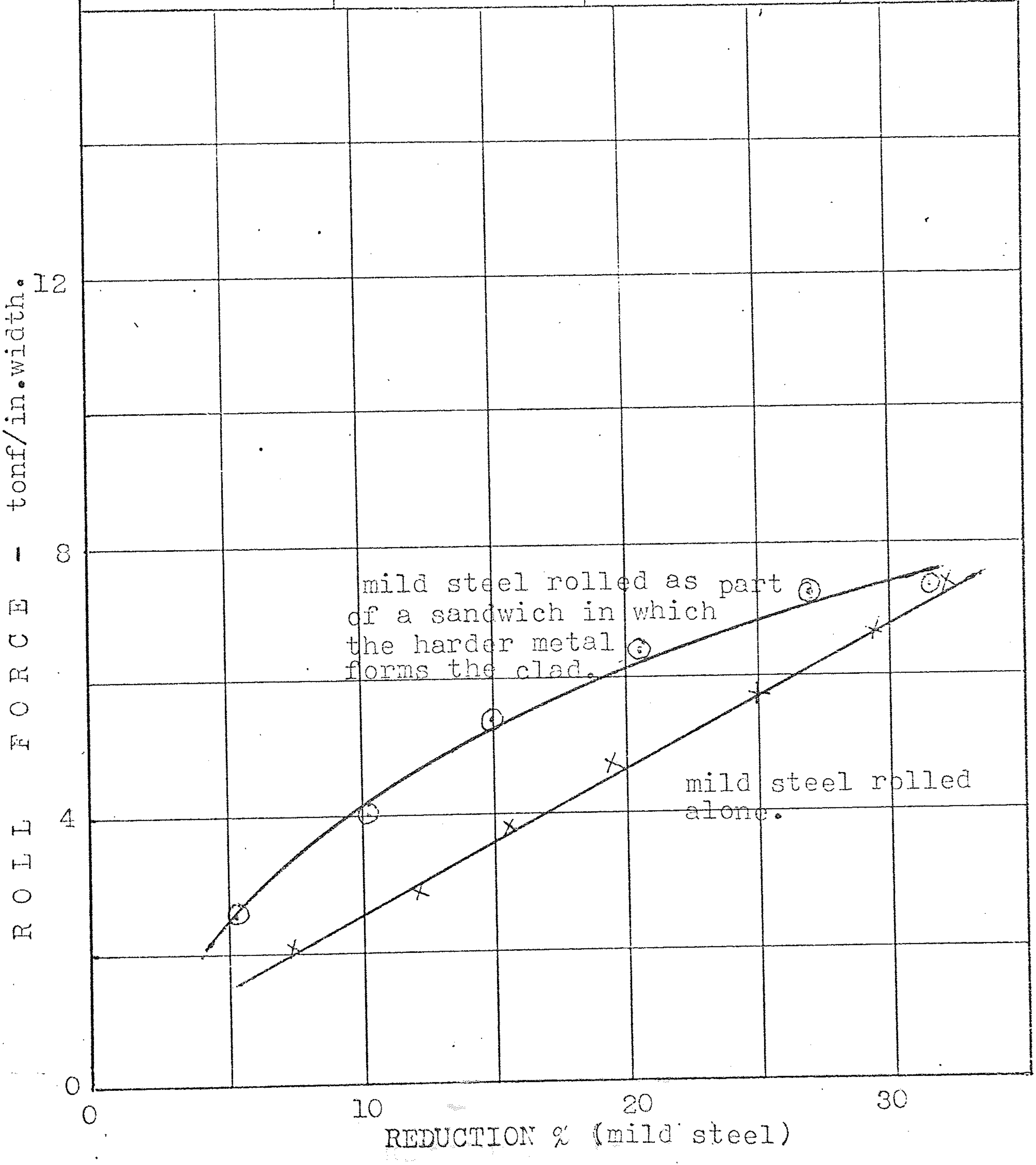
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 51
MATRIX :	1.25%C.steel	0.036	
CLAD :	mild steel	0.018 - 0.048	R.= 2



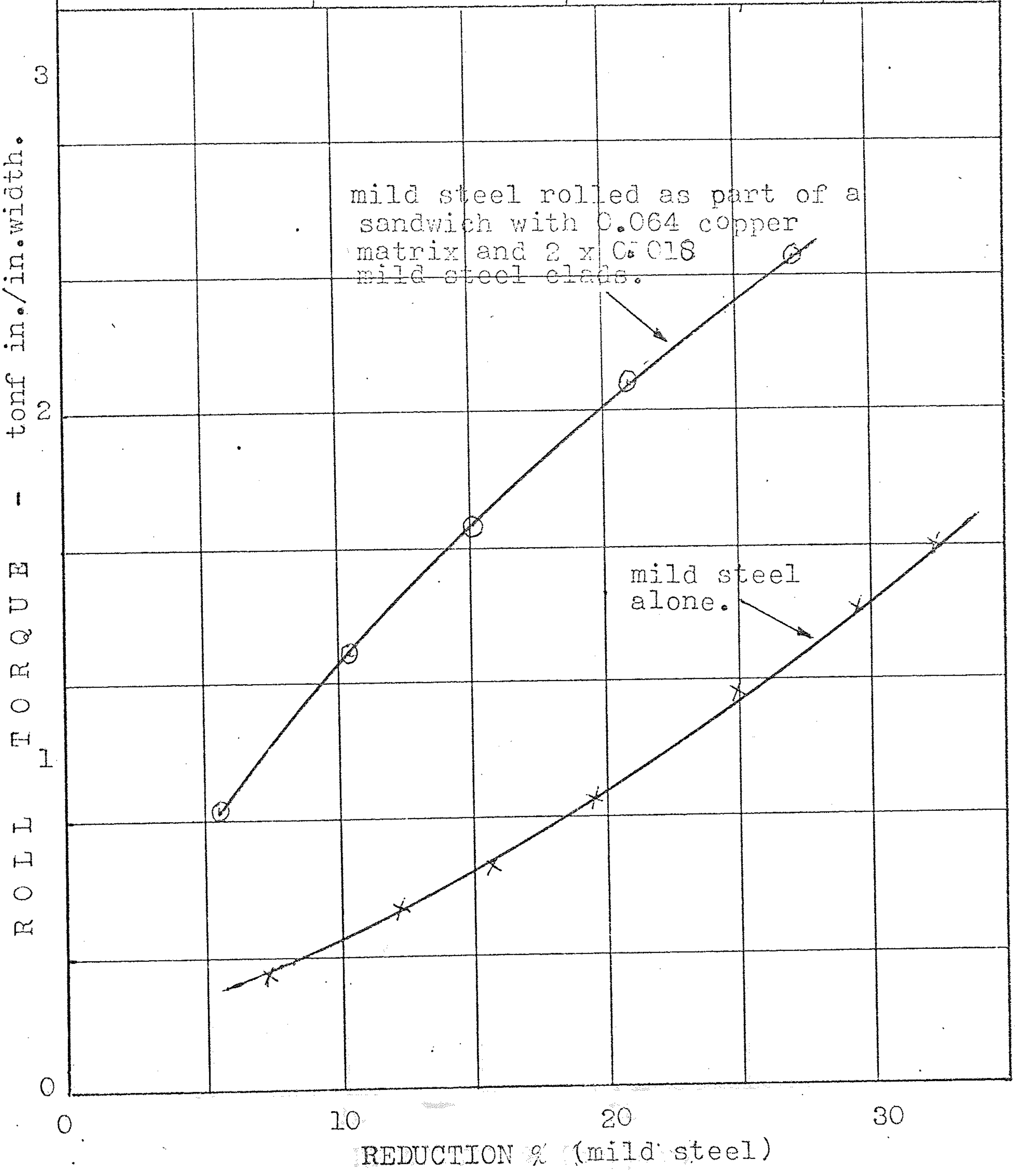
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 52
MATRIX :	1.25%C.steel	0.036	
CLAD :	mild steel	0.018 - 0.047	R = 2



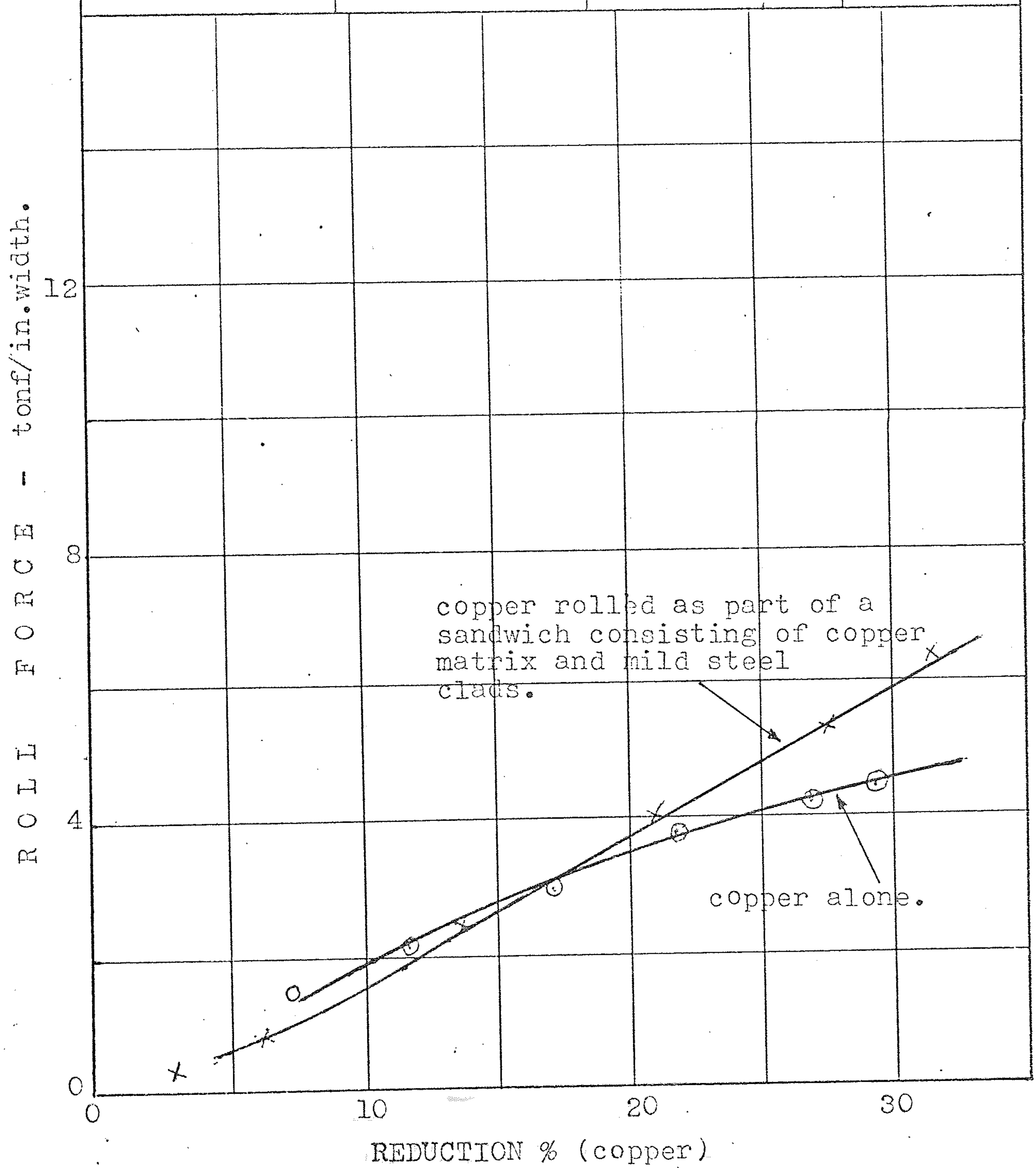
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 53
MATRIX:	copper	0.064	
CLAD :	mild steel	2 x 0.018	R = 2



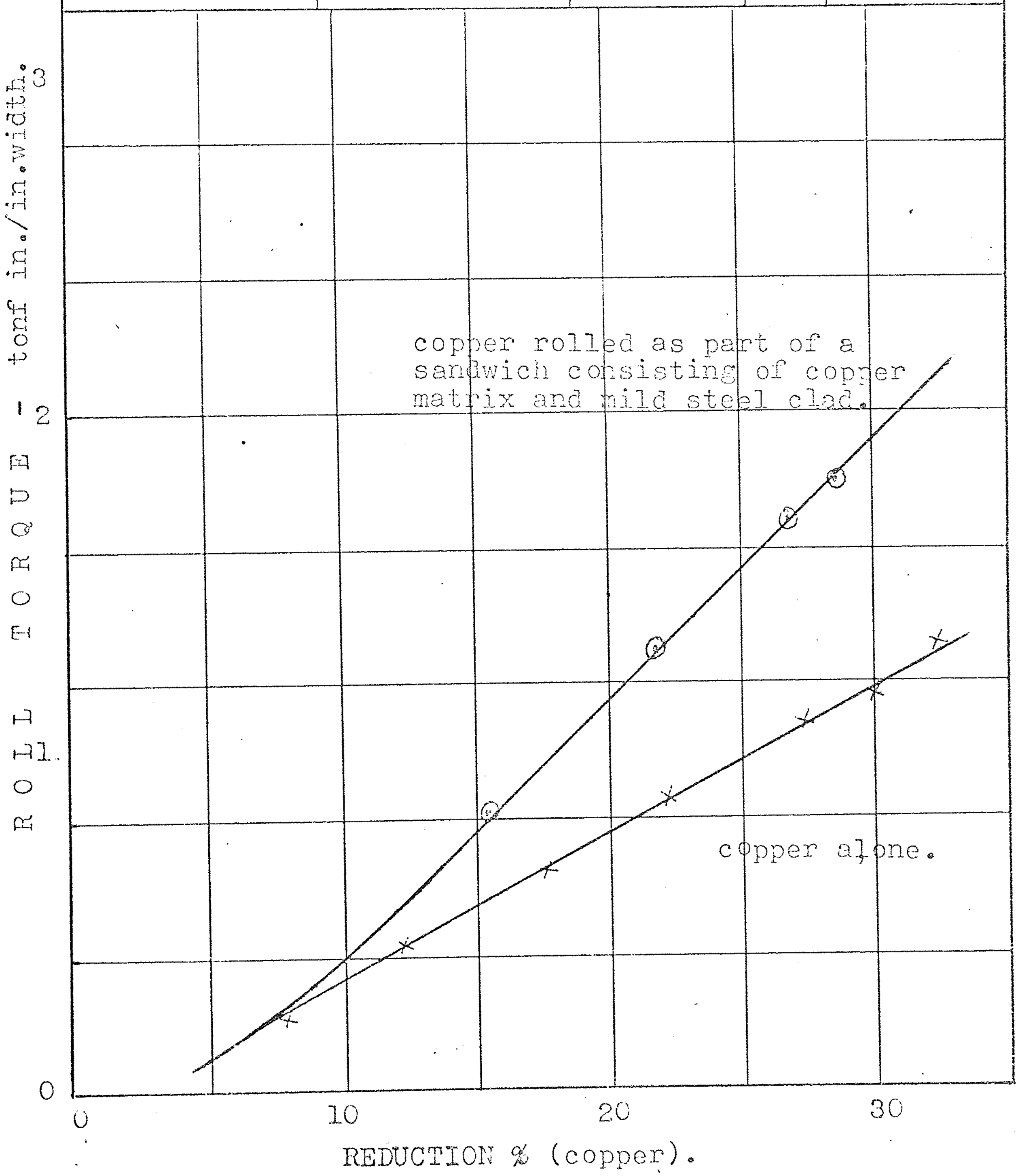
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 54
MATRIX :	copper	0.064	
CLAD :	mild steel	2 x 0.018	R = 2



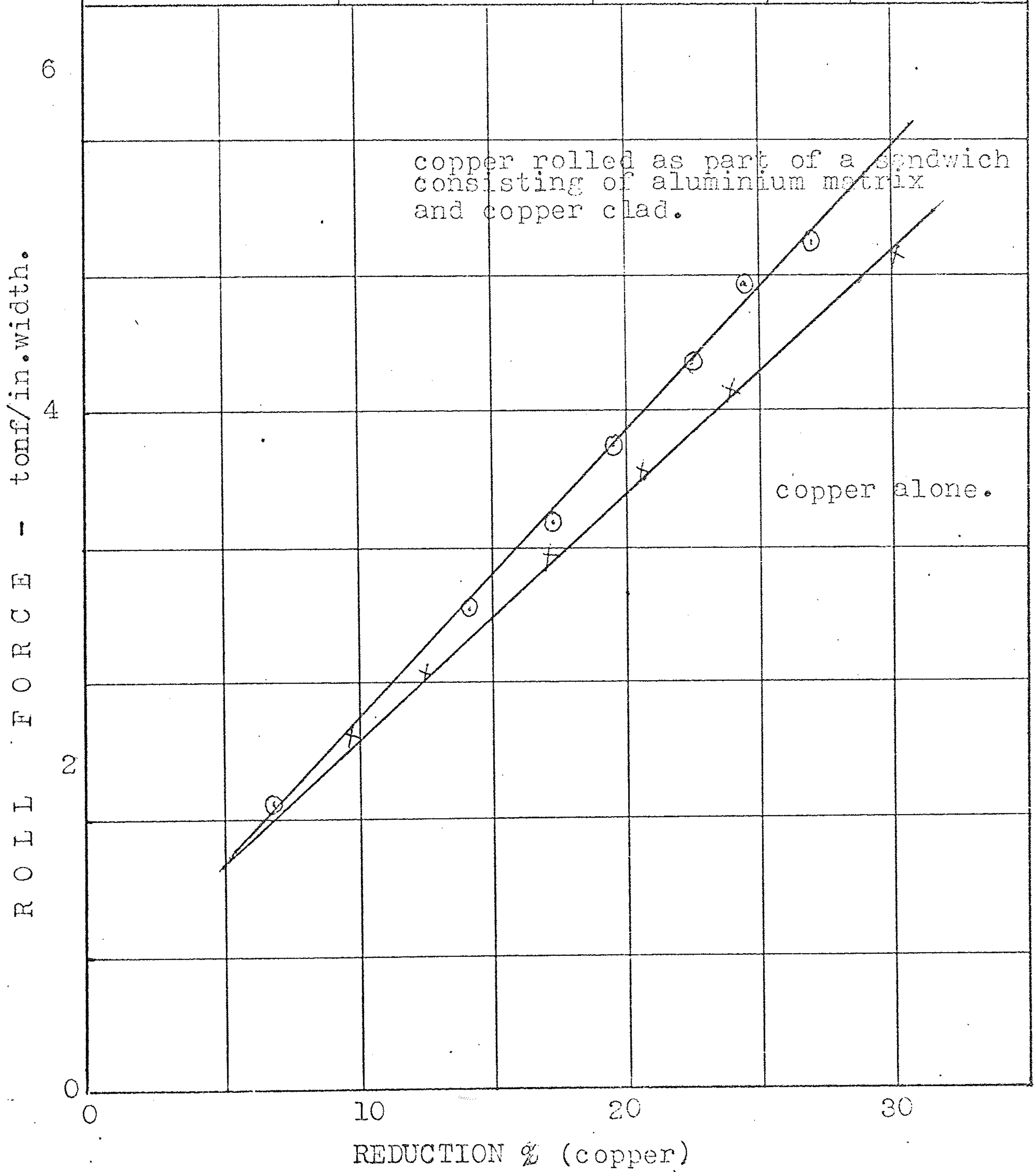
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 55
MATRIX :	copper	0.064	
CLAD :	mild steel	2 x 0.018	R = 2



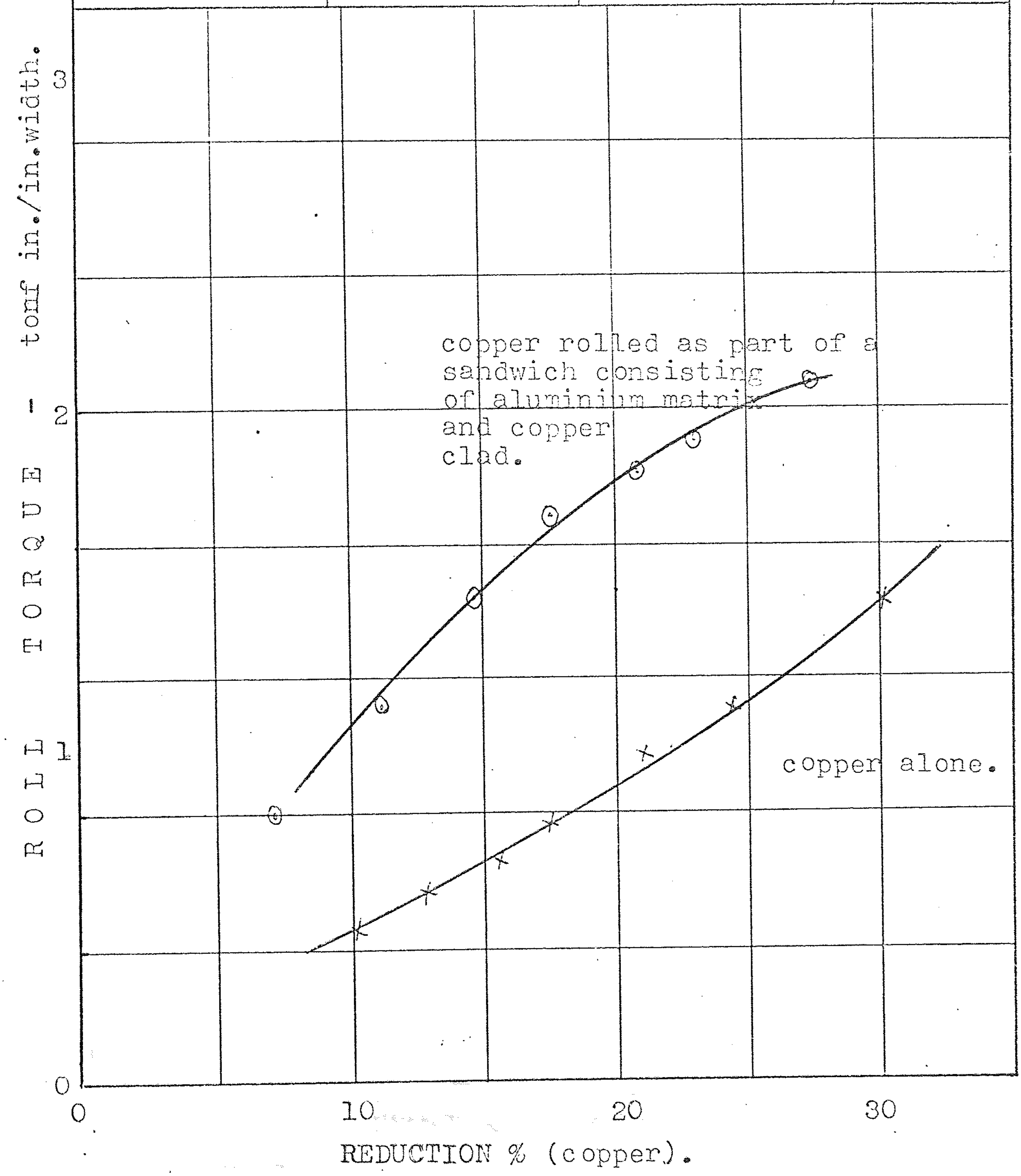
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 56
MATRIX :	copper	0.064	
CLAD :	mild steel	2 x 0.018	R = 2



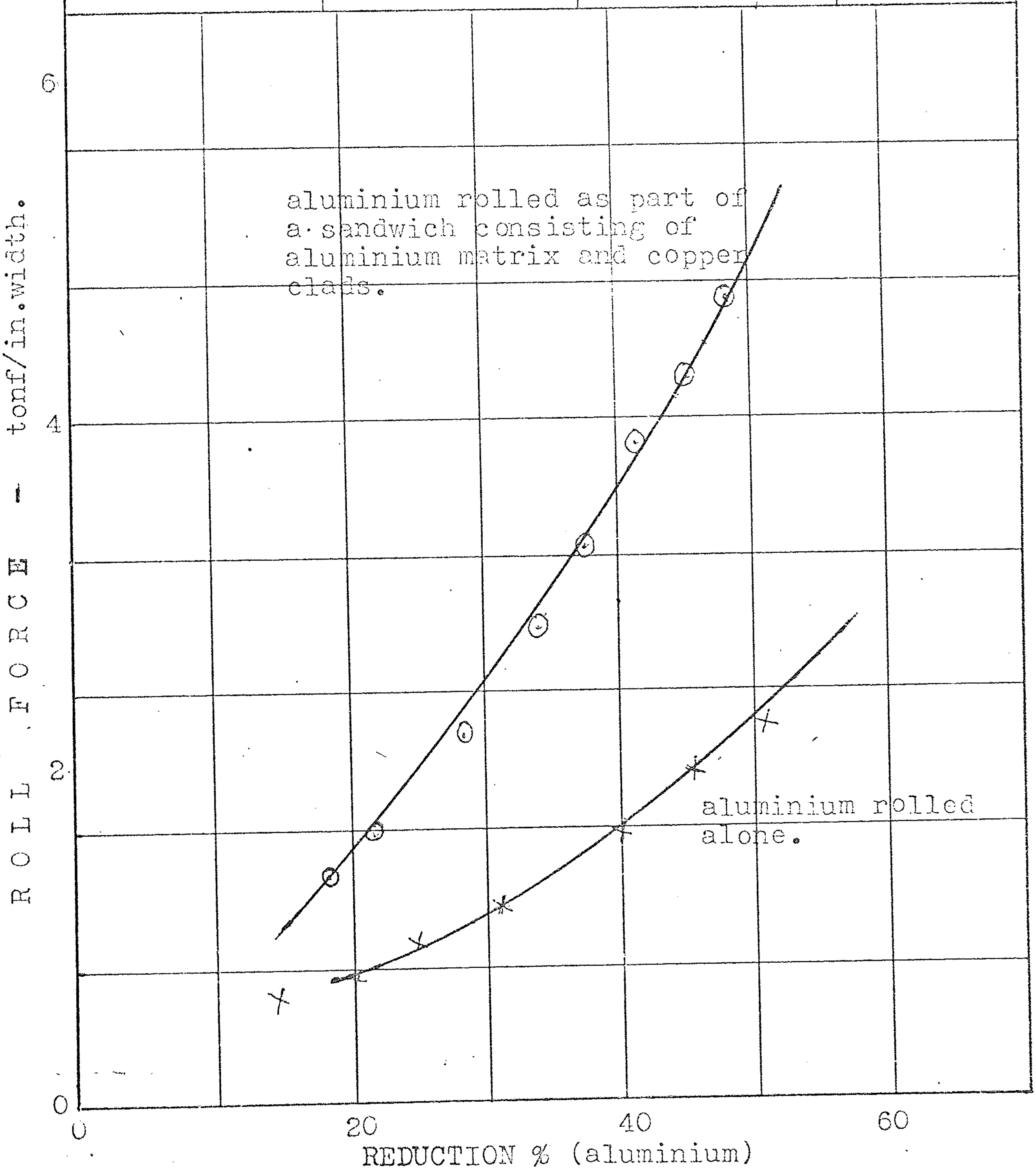
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 57
MATRIX :	aluminium	0.049	
CLAD :	copper	2 x 0.04	R = 2



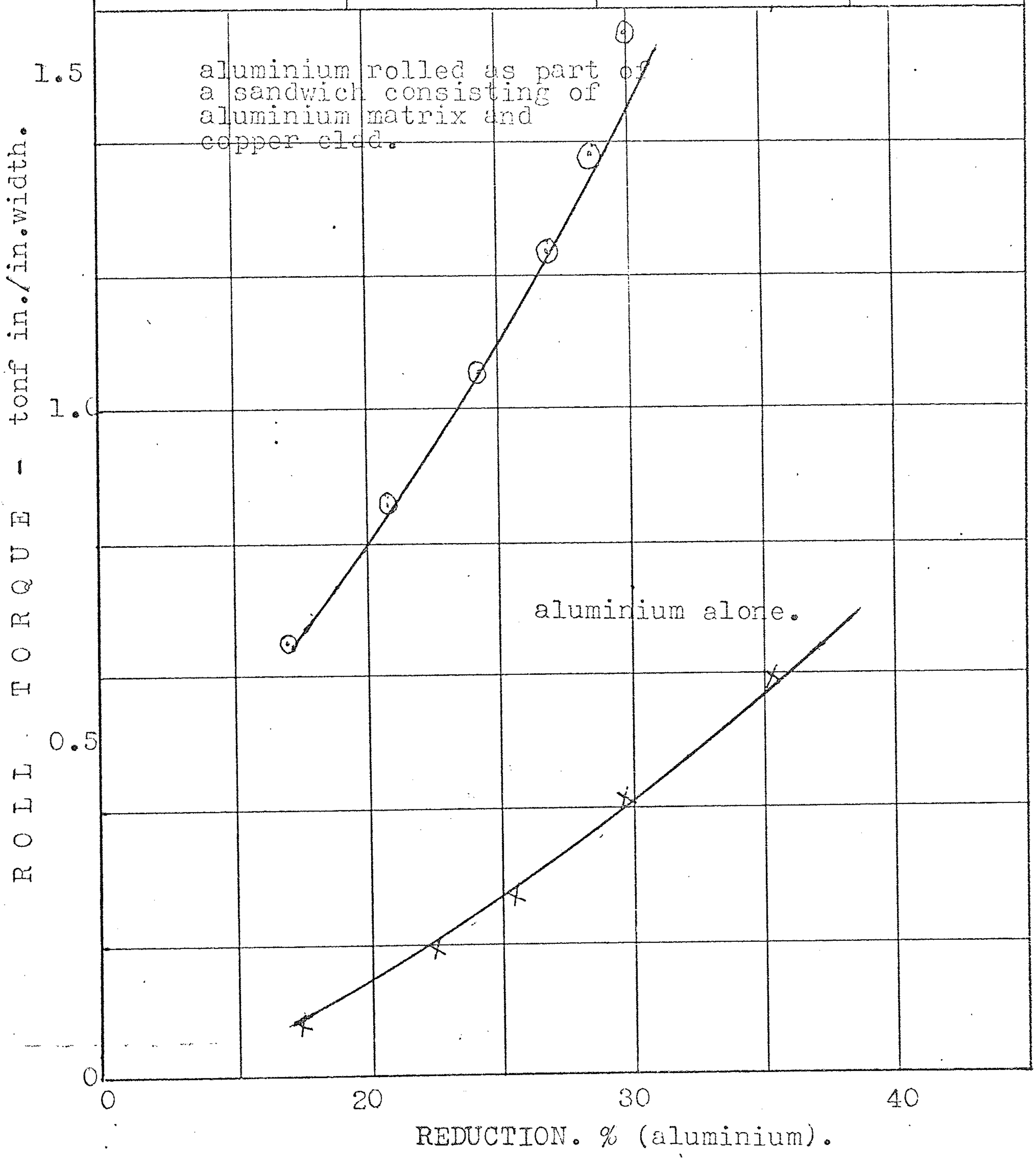
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 58
MATRIX :	aluminium	0.049	
CLAD :	copper	2 x 0.04	R = 2



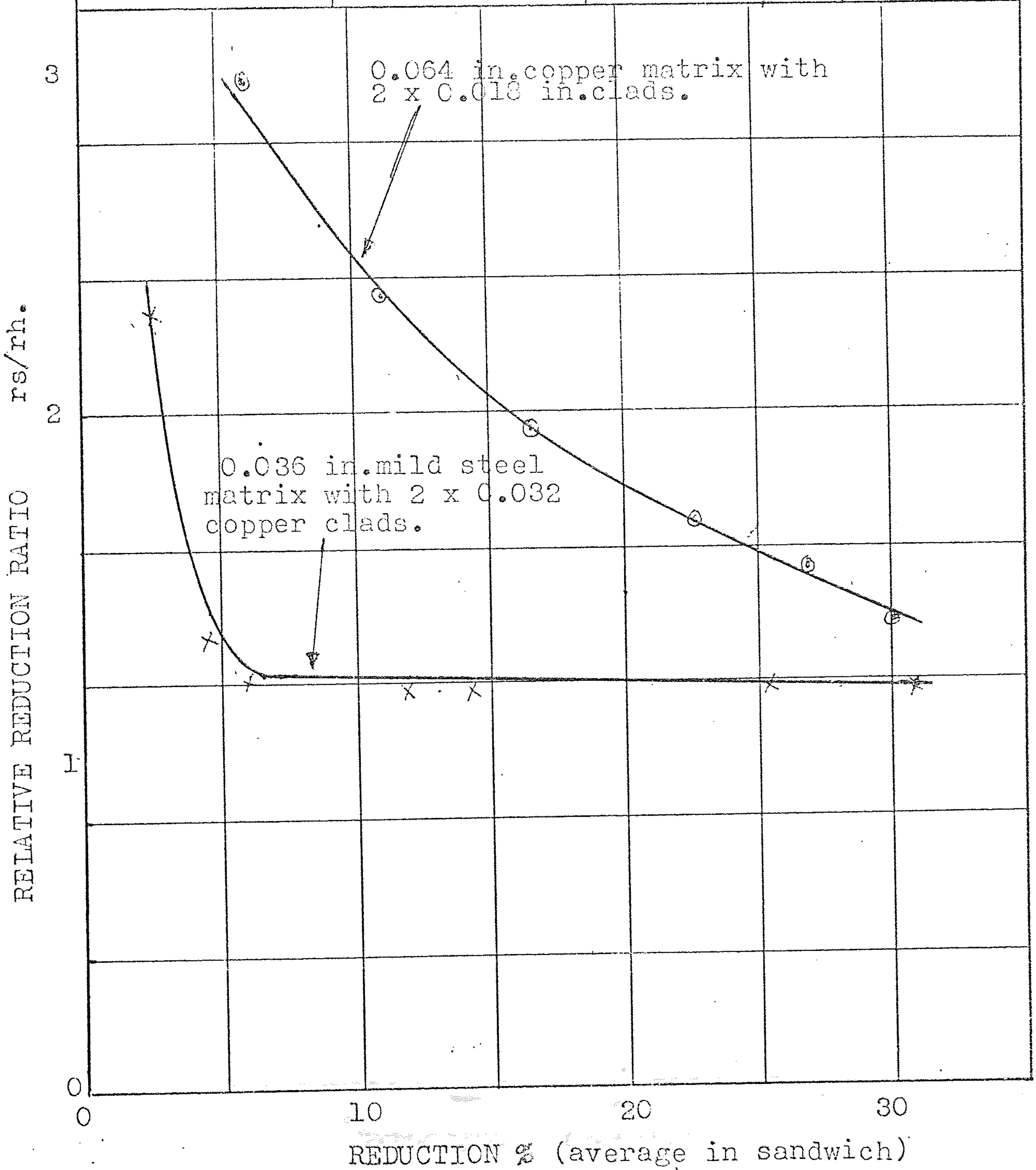
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 59
MATRIX :	aluminium	0.049	
CLAD :	copper	2 x 0.04	R = 2



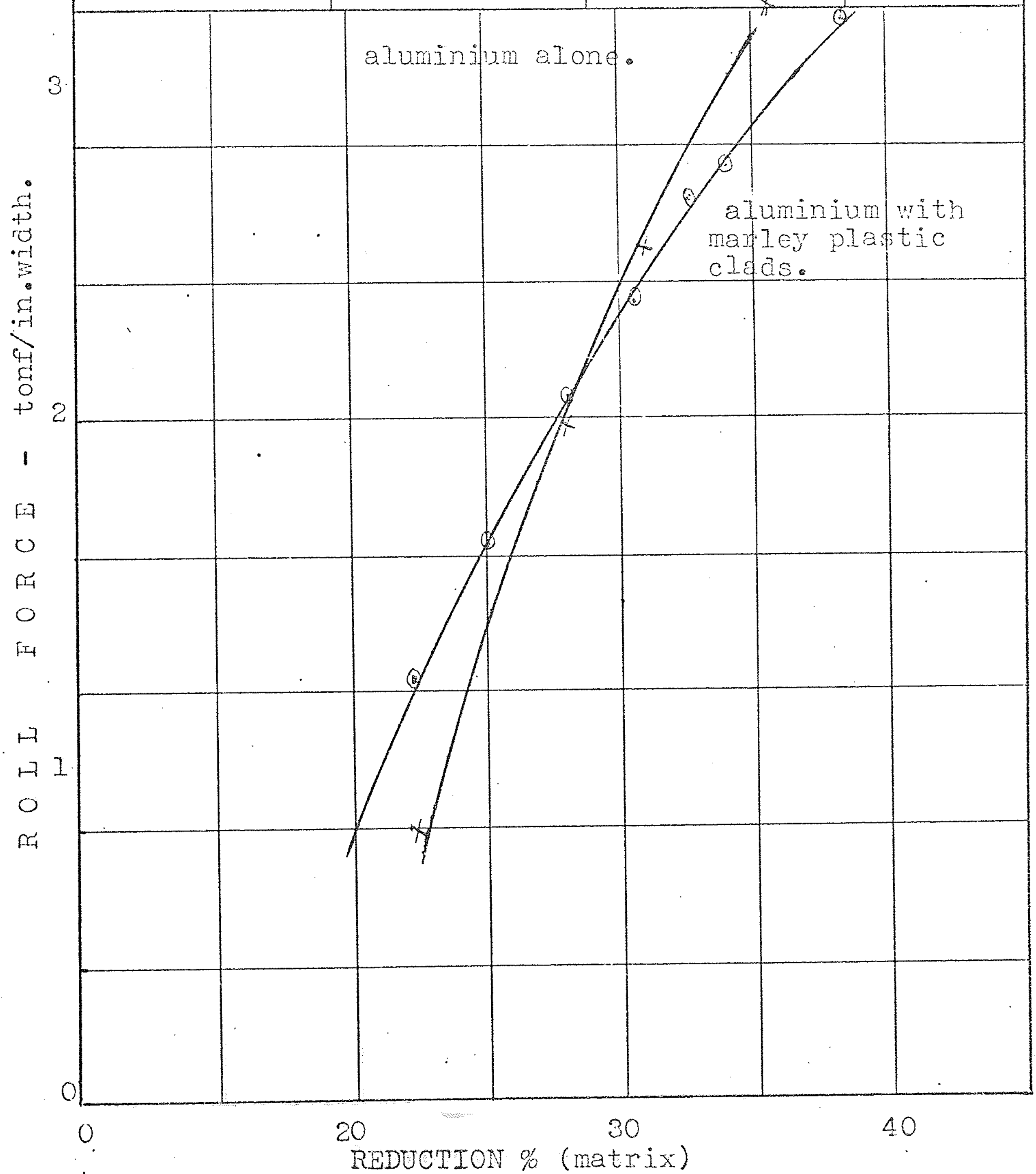
POSITION	MATERIAL	THICKNESS(In)	GRAPH NO 60
MATRIX :	aluminium	0.049	
CLAD :	copper	2 x 0.04	R = 2



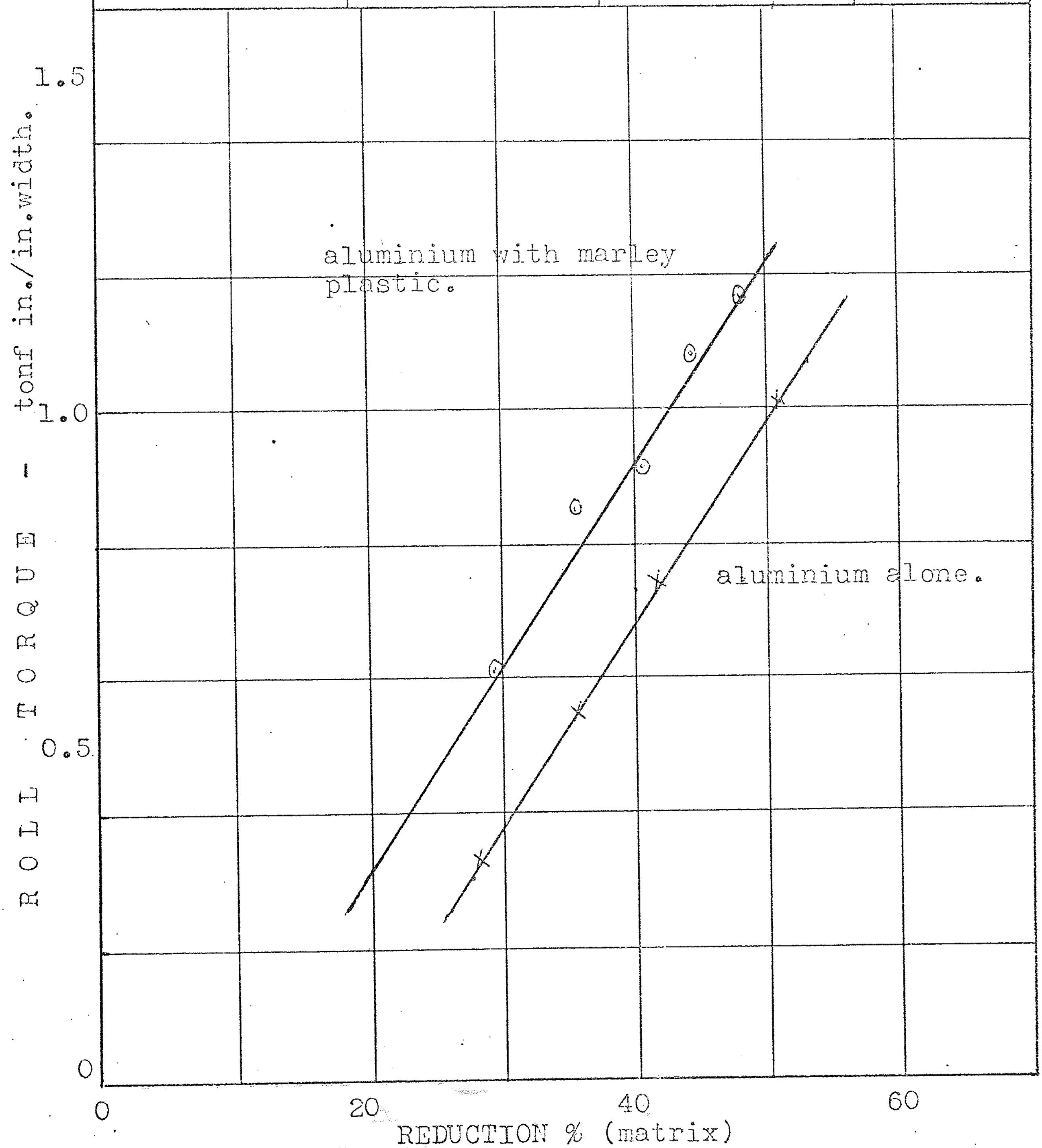
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 61
MATRIX :	cu. or m.steel	0.064 or 0.036	
CLAD :	copper	2 x 0.032	
	mild steel	2 x 0.018	R = 2



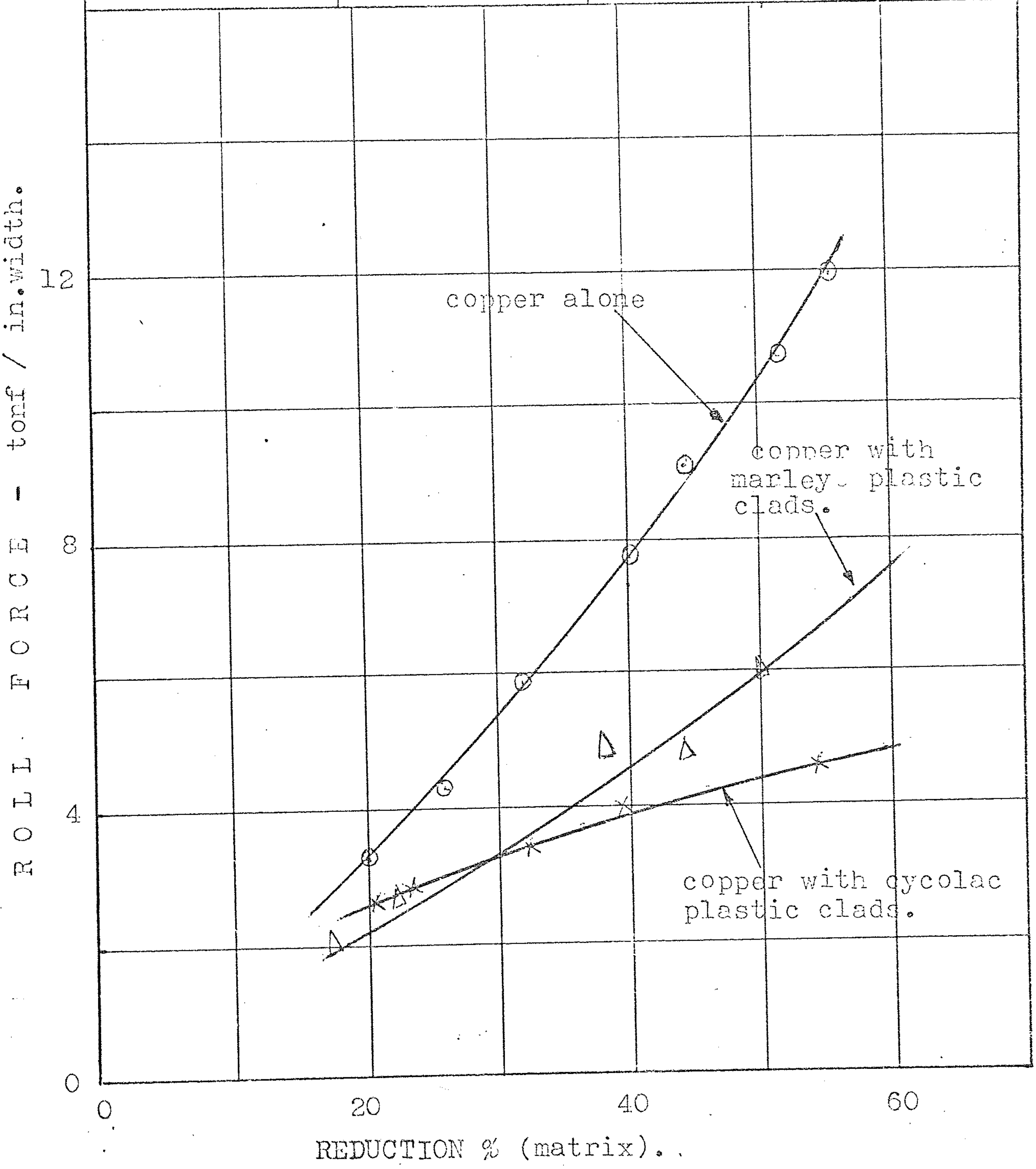
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 62
MATRIX :	aluminium	0.049	
CLAD :	plastic	2 x 0.043	R = 2.25



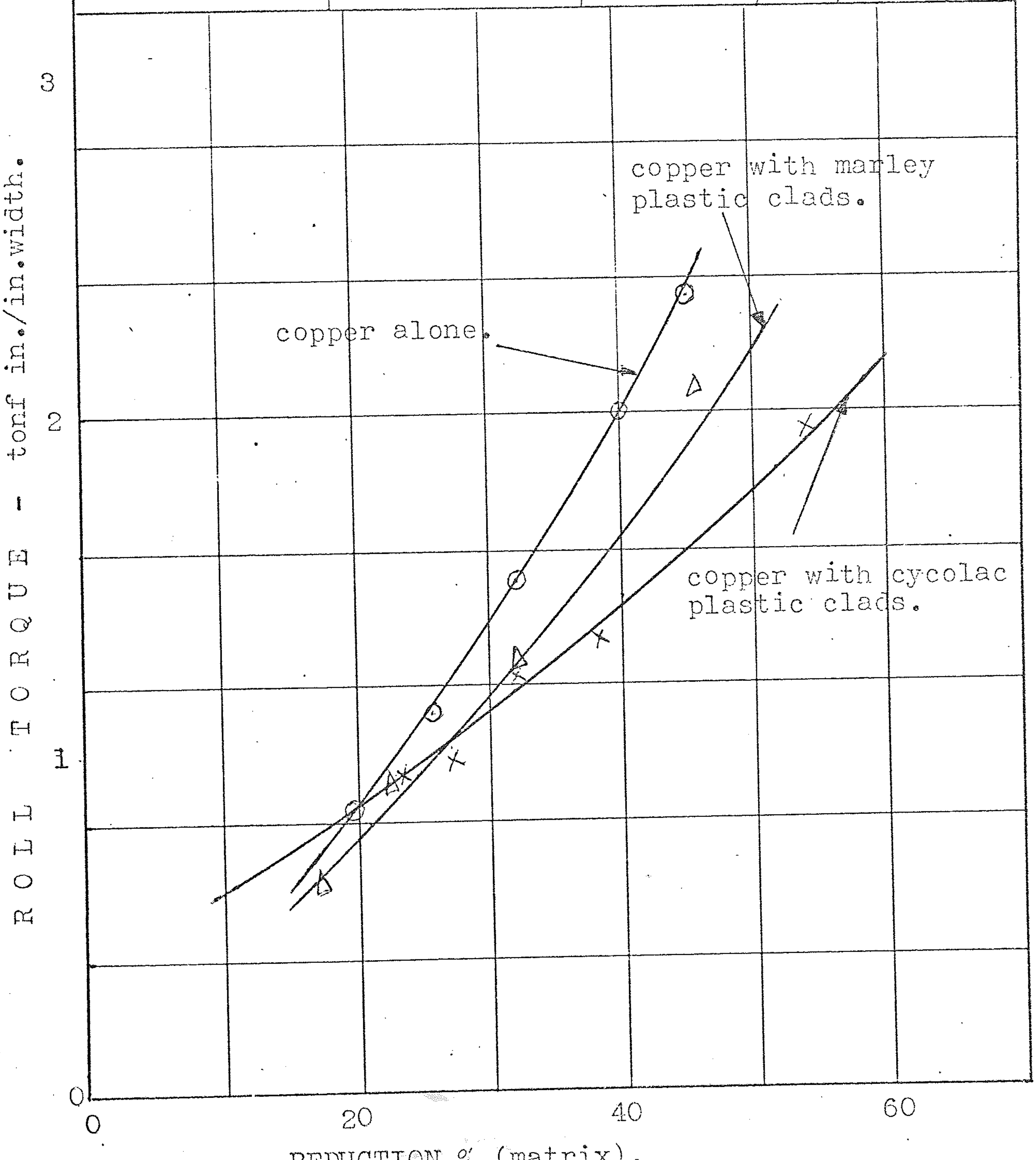
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 63
MATRIX :	aluminium	0.049	
CLAD :	plastic	2 x 0.043	R = 2.25



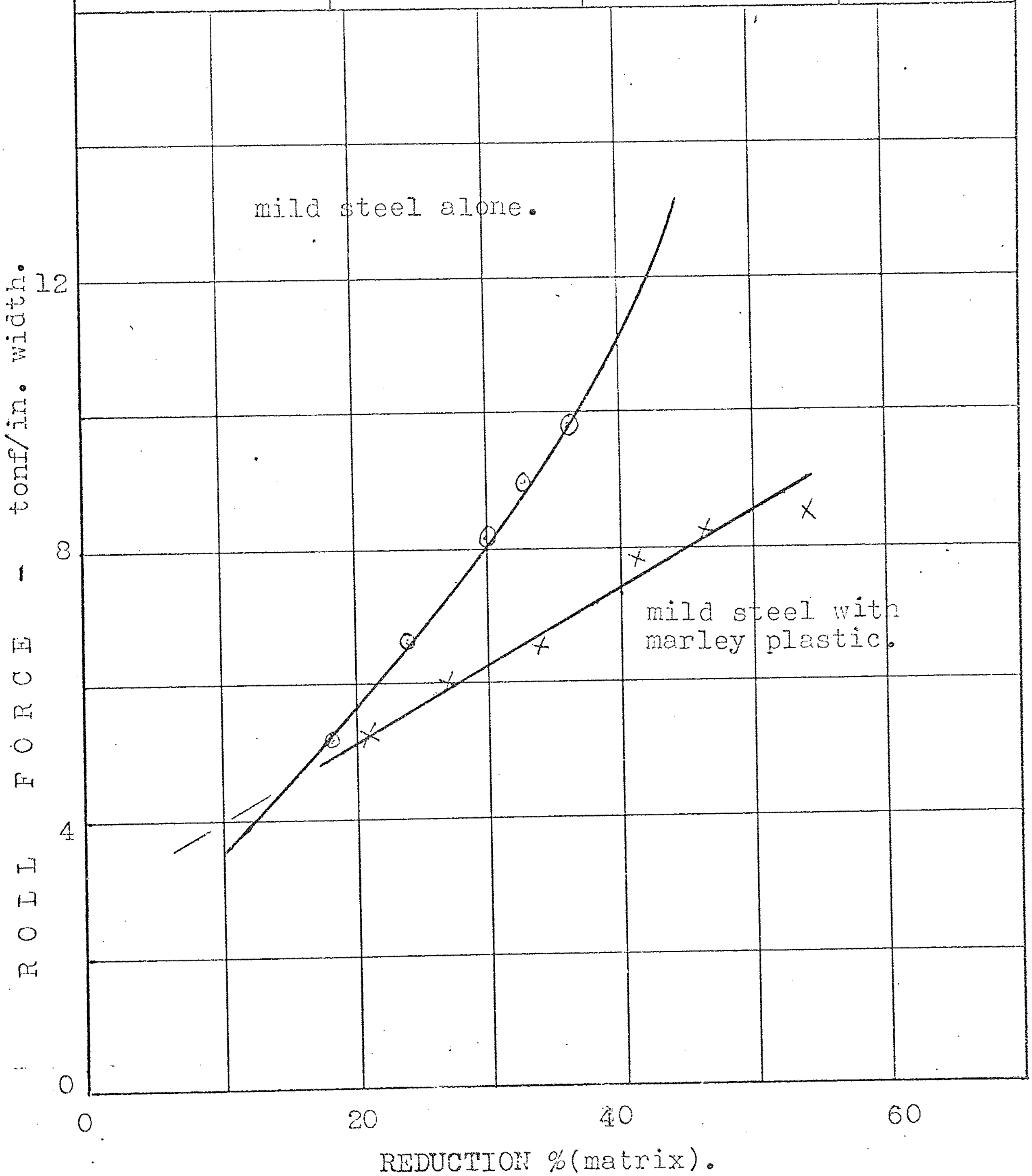
POSITION	MATERIAL	THICKNESS(in)	GRAPH NO 64
MATRIX :	copper	0.04	
CLAD :	marley plastic	2 x 0.043	
	cycolac plastic	2 x 0.033	R= 2.25



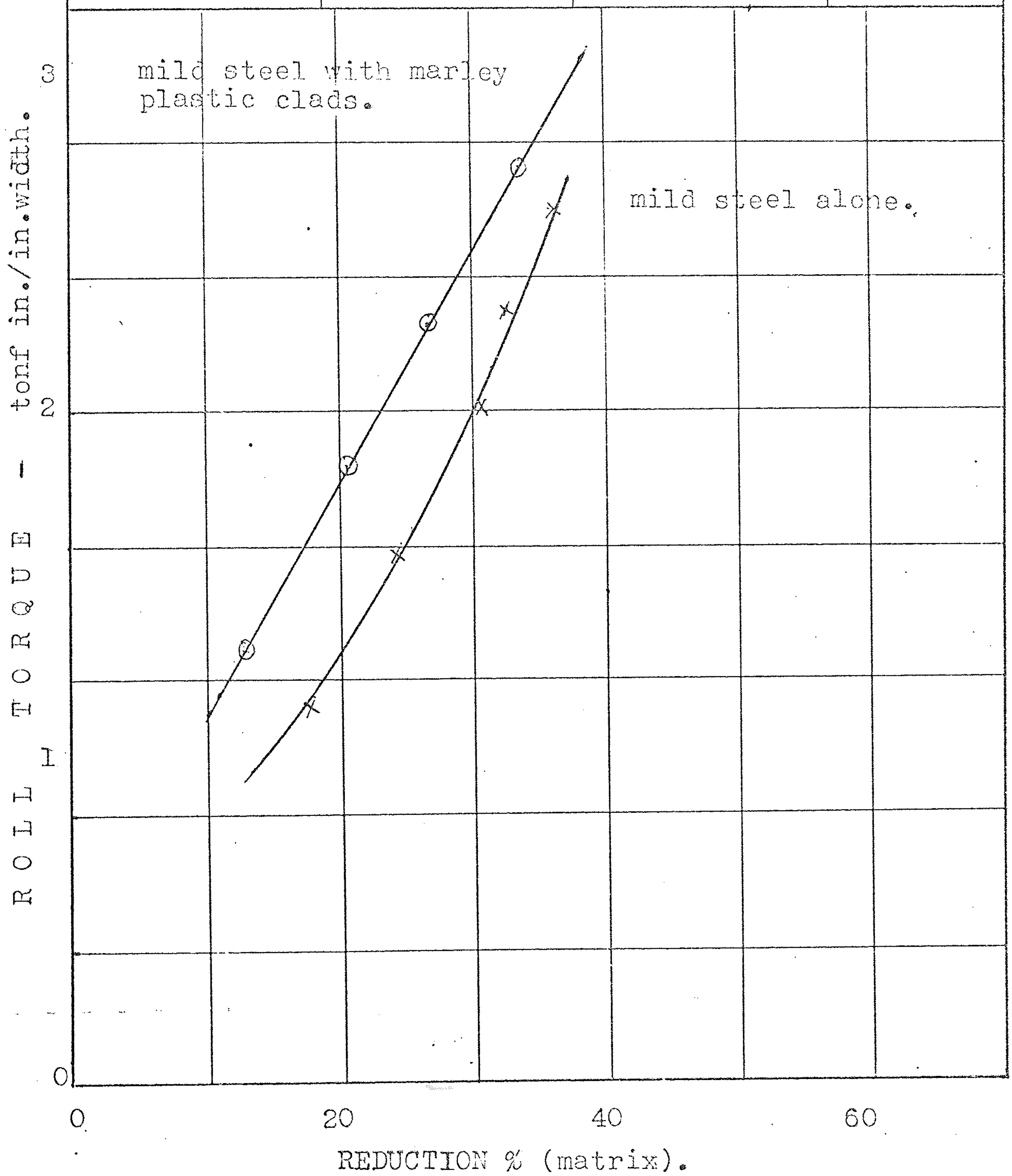
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 65
MATRIX :	copper	0.04	
CLAD :	marley plastic	2 x 0.043	R = 2.25
	cycolac plastic	2 x 0.033	



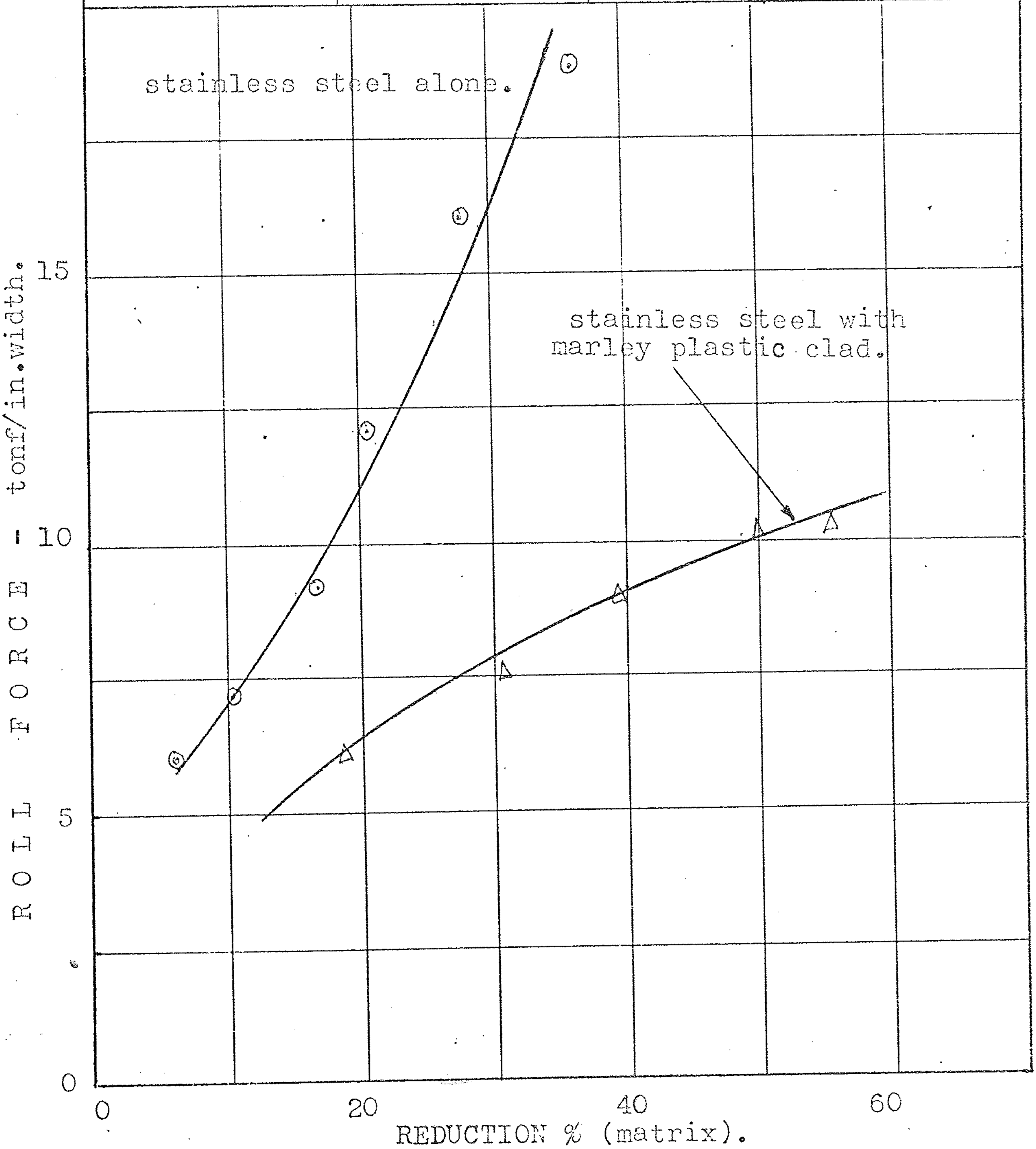
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 66
MATRIX :	mild steel	0.048	
CLAD :	plastic	2 x 0.043	R = 2.25



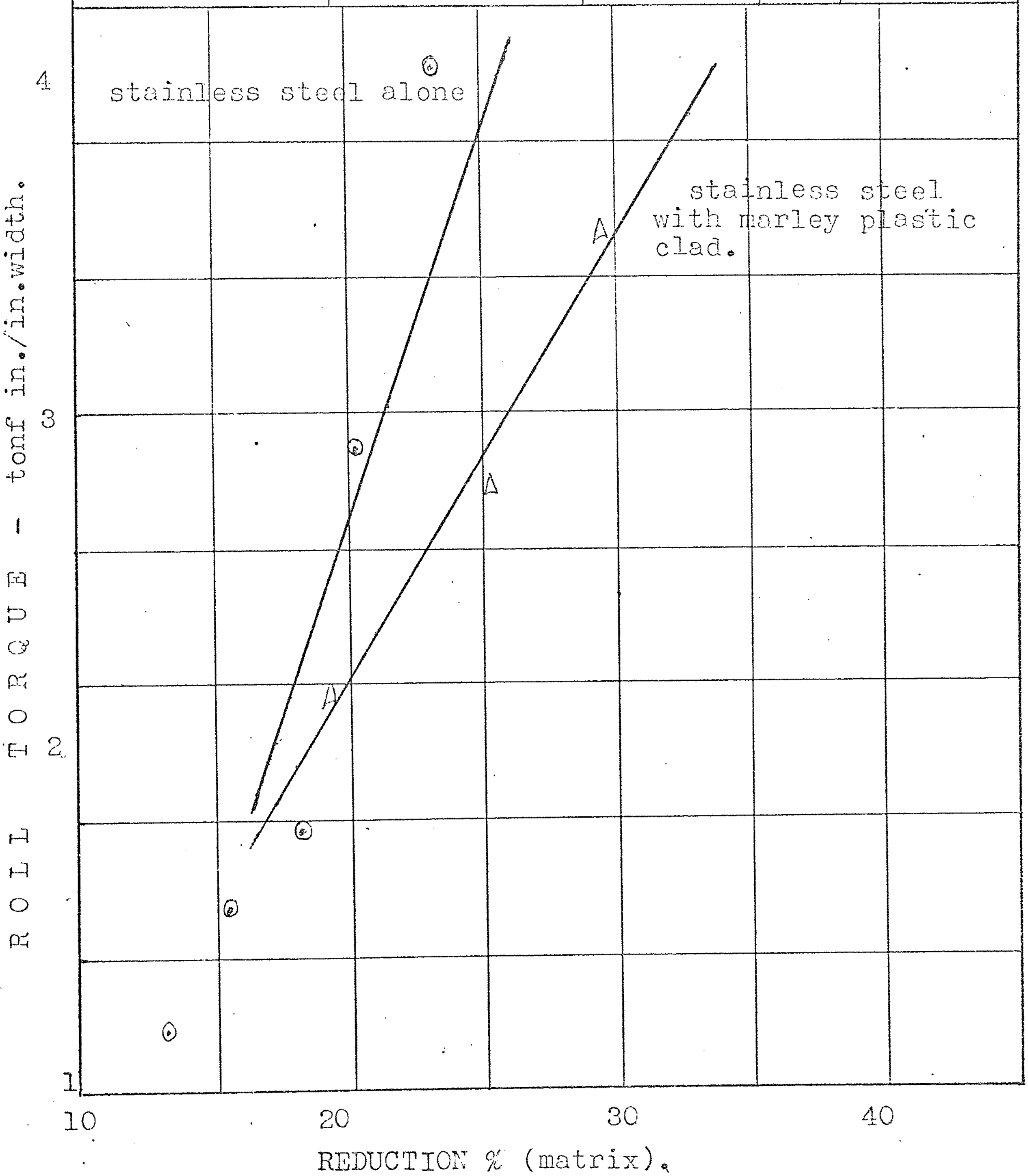
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 67
MATRIX :	mild steel	0.048	
CLAD :	plastic	2 x 0.043	R = 2.25



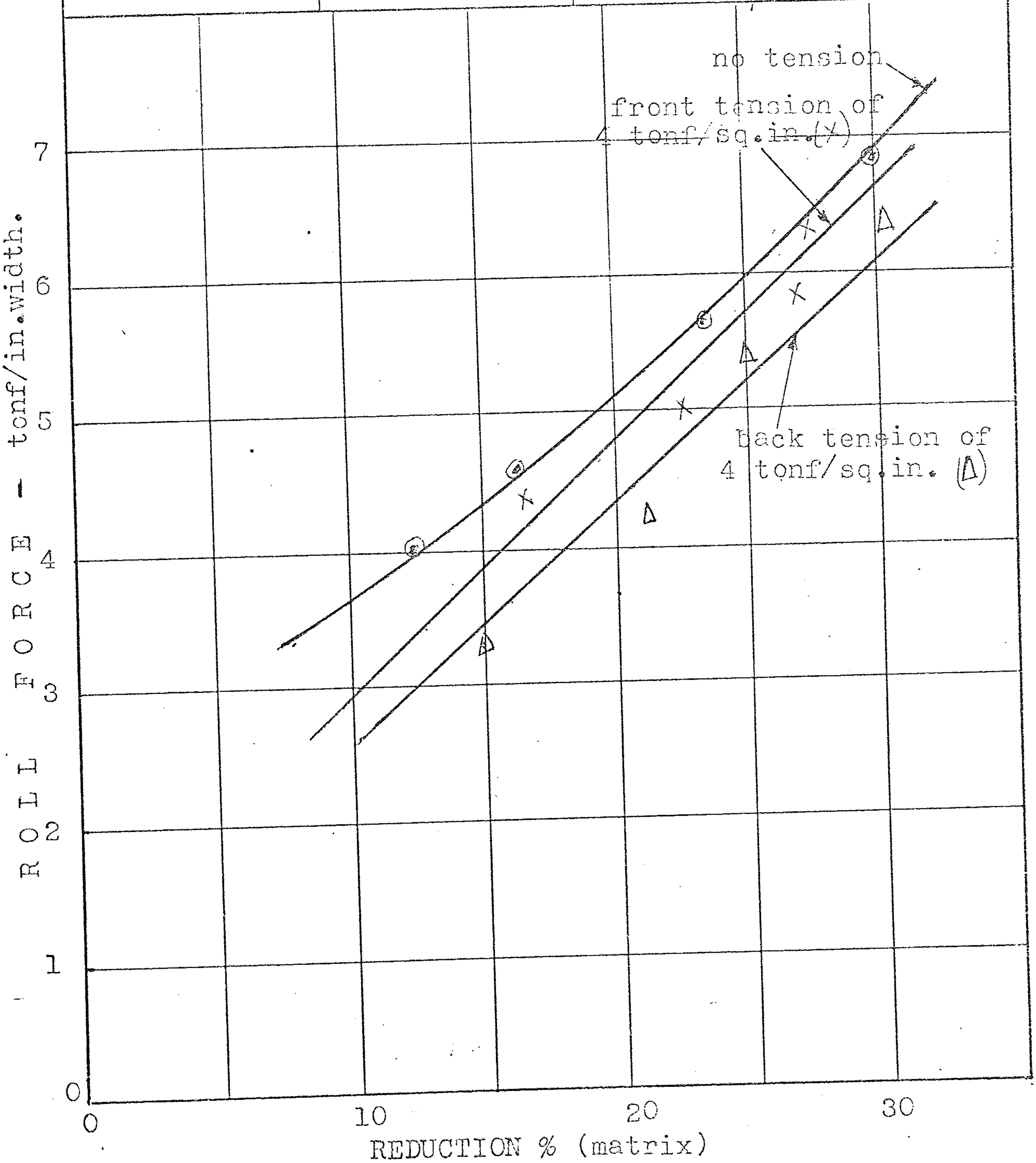
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 68
MATRIX :	stainless st.	0.047	
CLAD :	plastic		R = 2.25



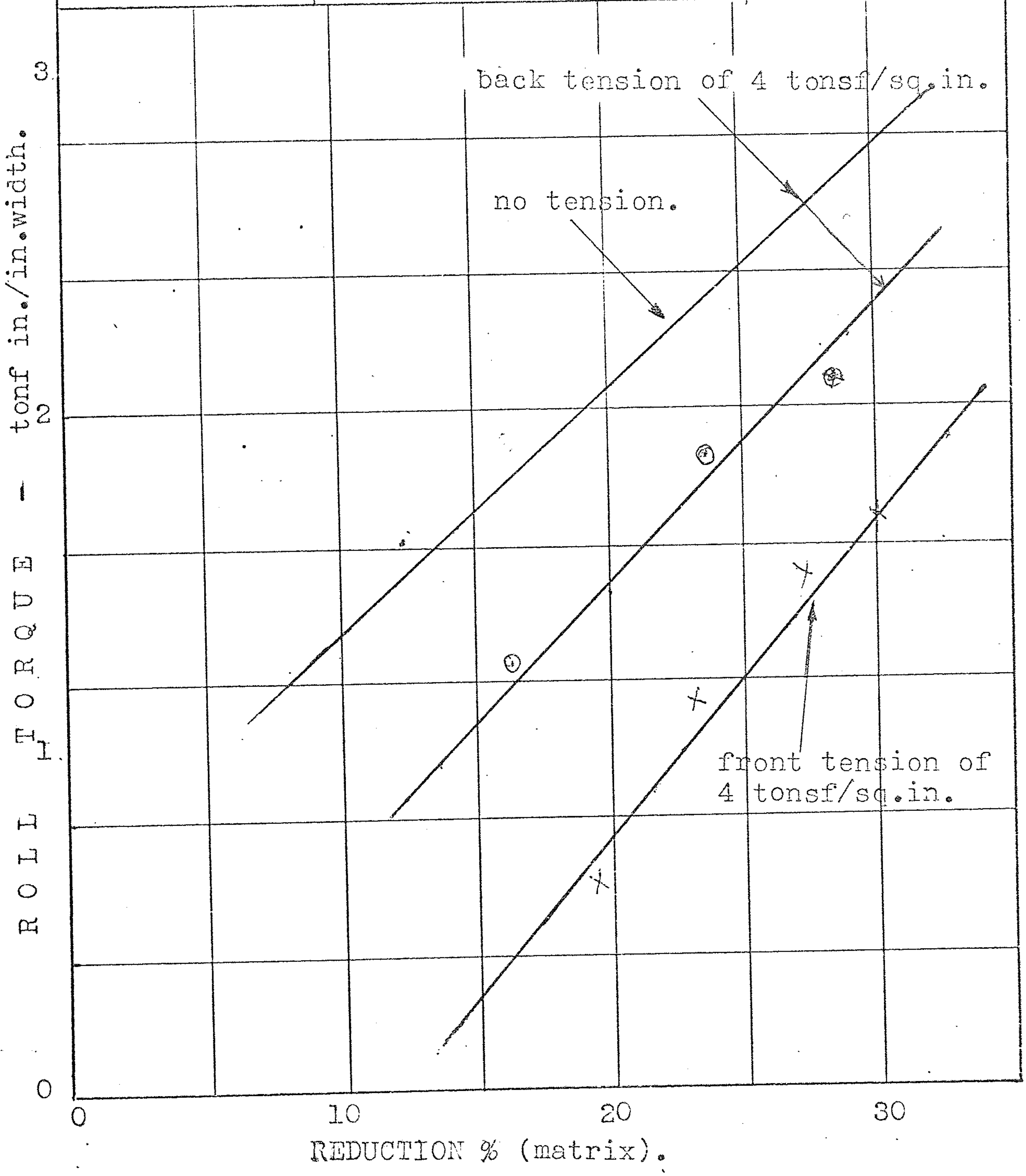
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 69
MATRIX :	stainless st.	0.047	
CLAD :	plastic	2 x 0.043	R = 2.25
		A	



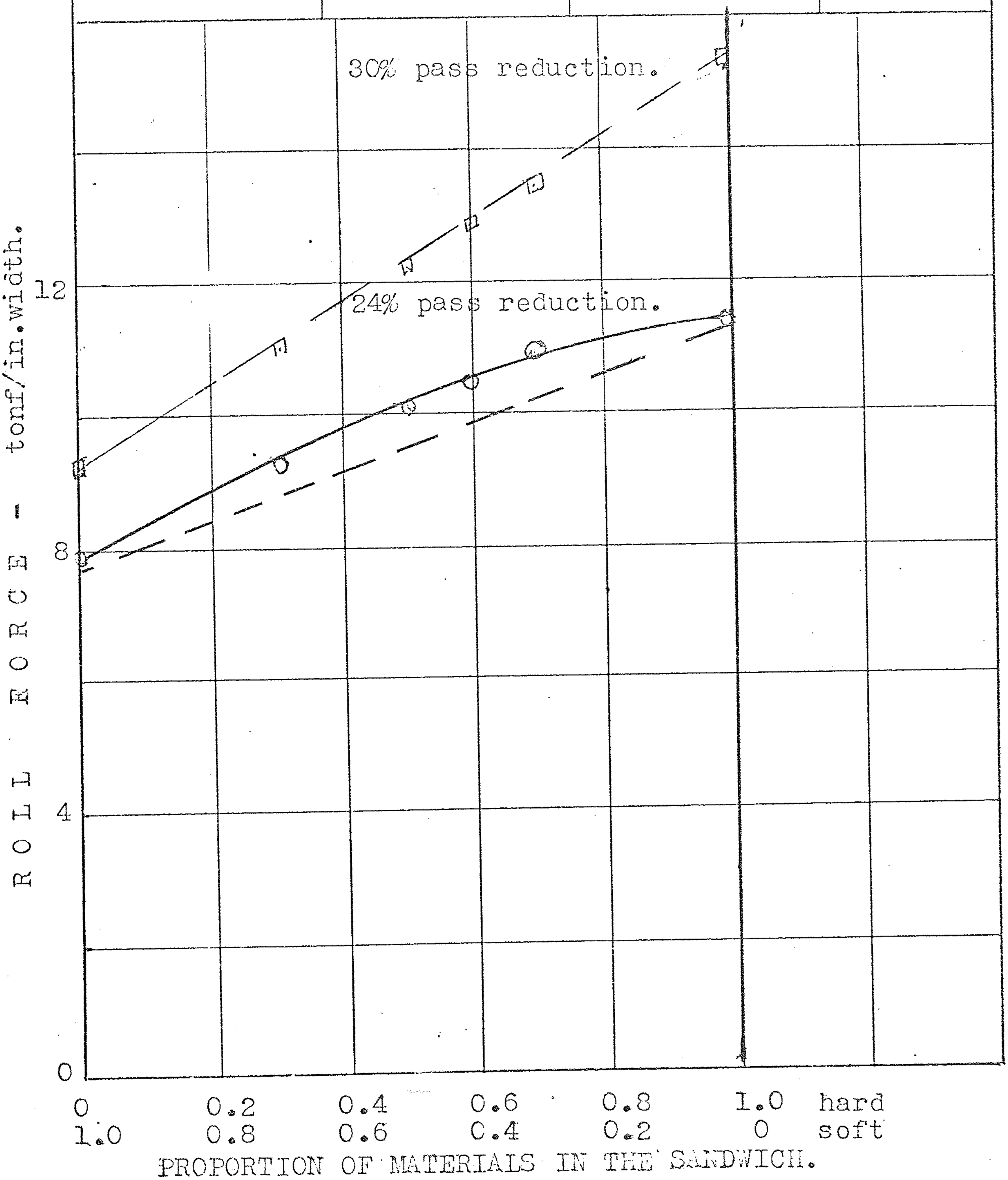
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 70
MATRIX :	mild steel	0.031	
CLAD :	copper	2 x 0.032	R = 2.25



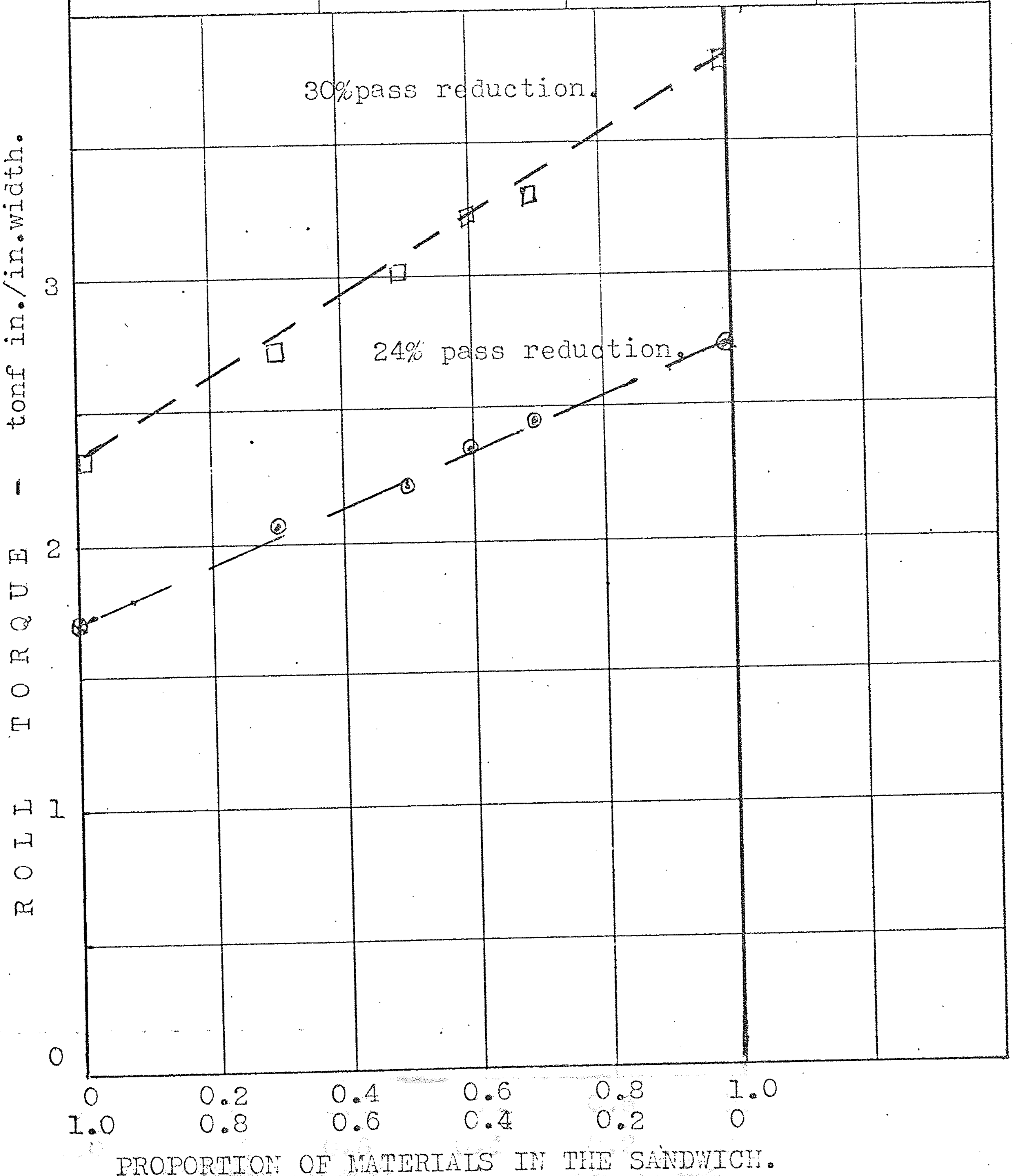
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 71
MATERIAL :	mild steel	0.031	
CLAD :	copper	2 x 0.032	R = 2.25



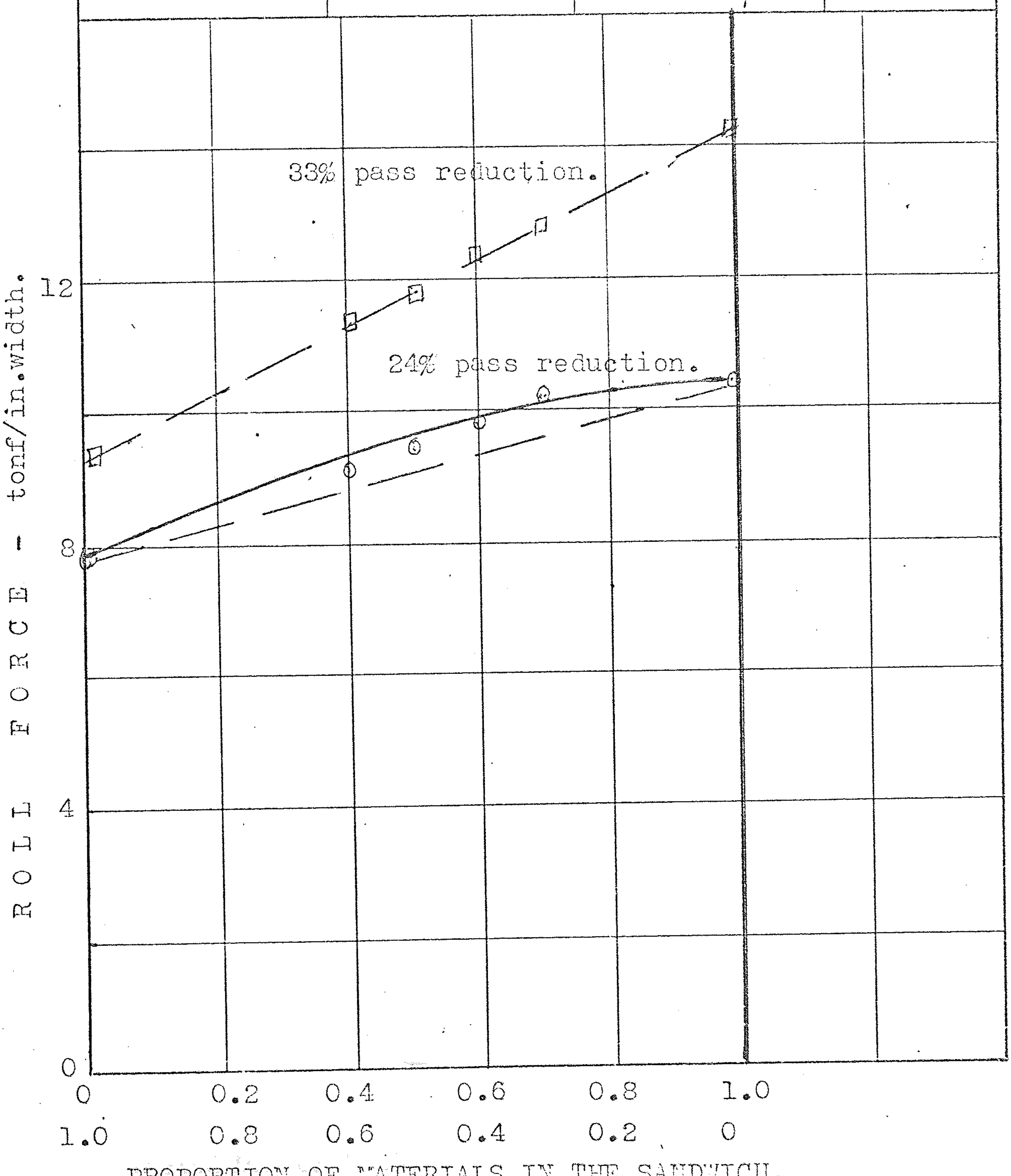
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 72
MATRIX :	stainless st.	0.047	
CLAD :	mild steel	varying th.	R = 2.25



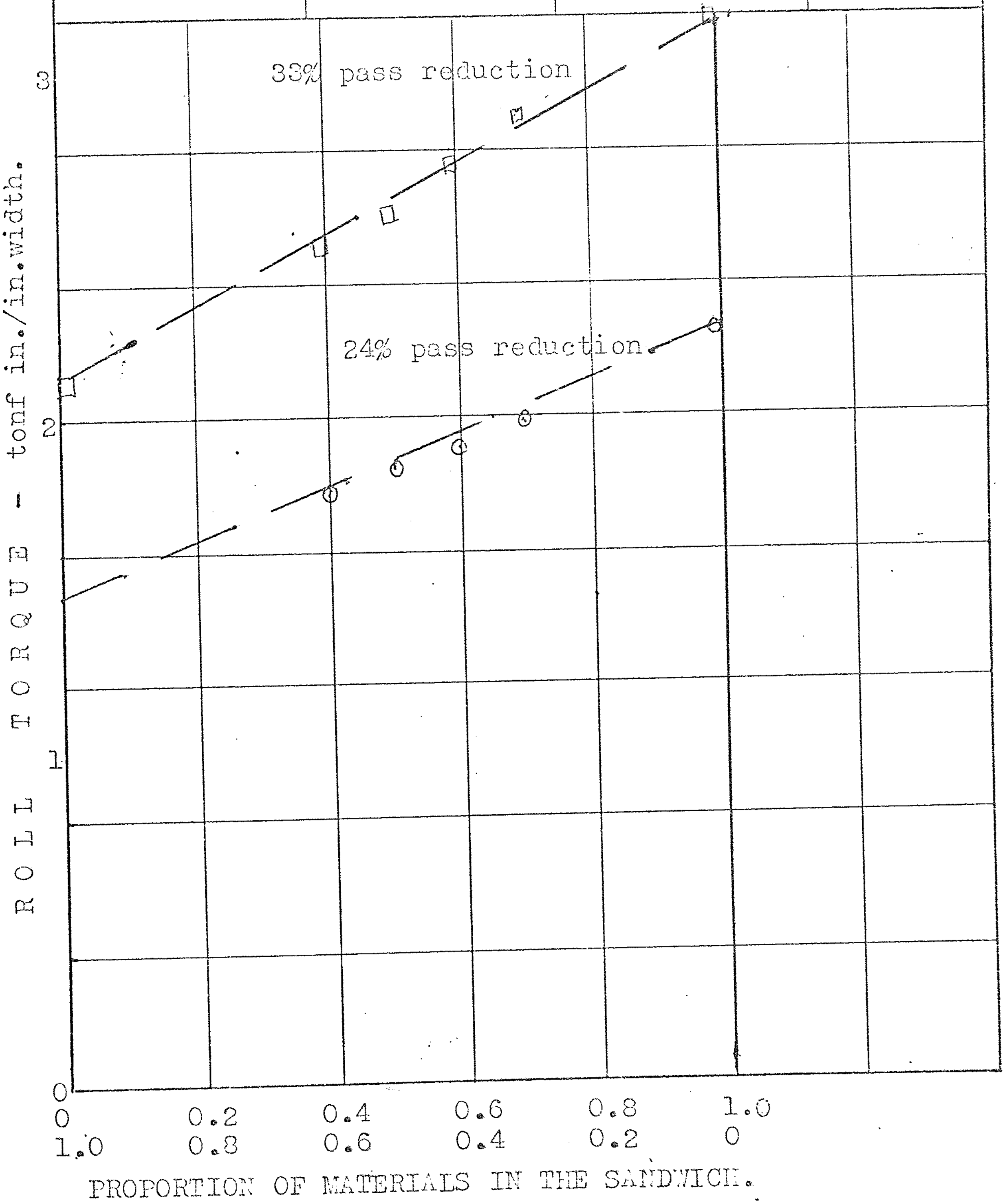
POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 73
MATRIX :	stainless st.	0.047	
CLAD :	mild steel	varying th.	R = 2.25



POSITION	MATERIAL	THICKNESS (in)	GRAPH NO 74
MATRIX:	0.71%C.steel	0.026	
CLAD :	mild steel	varying th.	R = 2.25



POSITION	MATERIAL	THICKNESS (in).	GRAPH NO 75
MATRIX	0.71%C.steel	0.026	
CLAD	mild steel	varying th.	R = 2.25



14. DISCUSSION OF EXPERIMENTAL RESULTS.

14. DISCUSSION OF EXPERIMENTAL RESULTS.

14.1. The effect of cladding on the roll force.

The effect of cladding on the roll force has been investigated for a wide range of clad-matrix combinations and the results are shown in Graphs 1 to 13. In all cases, the reduction in the hard material alone was considered, since it would enable the curves of the sandwich specimens to be compared with the results of rolling the matrix material without clad.

In all cases except in the case of mild steel cladded with copper (Graph 2), a reduction in the roll separating force is achieved as a result of cladding. The softer the clad with respect to the matrix, the greater the reduction in the roll separating force, the greatest reduction being for Nimonic 105 alloy cladded with aluminium (Graph 13). Also, the limiting reduction is greater for the cladded material than for the same material rolled without cladding, the greatest improvement again being for the thinnest matrix (Nimonic 105). The limiting reduction for Nimonic 105 rolled without clad is about 8.5 percent. (See Graph 13). However, a pass reduction of up to 35 percent can be achieved without difficulty if the the material is rolled between layers of copper or mild steel. (See Graph 13). A greater pass reduction could have been achieved without exceeding the safe load of the mill but for the limitation in the capacity of the main drive of the mill. The reduction in the roll force is lower for the hardest material rolled (1.25% C. Steel) than for the thinnest material (Nimonic 105) for the same clad material. (Compare Graphs 8 and 13). This indicates that the increase in the thickness of the workpiece due to cladding may be a more important factor than the tensile stresses induced in the matrix, from the point of view of load reduction. This is supported by the results obtained for other metals. (Compare Graphs 6 and 9, 7 and 10). The reduction in the roll separating force achieved is dependent also on the total pass reduction achieved. It will be seen from all the graphs that the reduction in the roll force is greater as the pass reduction increases. This is due to the fact that the ~~clad : matrix~~ clad : matrix interface friction increases as the pass reduction increases and also the thickness of the matrix decreses, so that the tensile stresses induced in the matrix will increase as pass reduction increases. Of course, the clad : matrix interface friction cannot increase indefinitely, the limit being when it attains the yield stress in shear of the softer metal, and the sandwich may become so thin as to cause a sharp increase in the roll force as a result of excessive roll flattening.

Graph 2 shows that the roll separating force is higher for the maild steel rolled between layers of copper than for mild steel rolled alone. Apparently, the increase in the roll force due to the overall increase in the thickness of the workpiece is more significant than the reduction in the roll force due to cladding.

14.2. <u>The effect of cladding on the roll torque.</u>

The effect of cladding on the roll torque is shown in Graphs 14 to 26. In most cases, the roll torque is higher for the cladded metals than the uncladded metals. In effect, the reduction in the roll torque which results from the reduction in the roll force due to cladding, is insufficient to offset the increase in the roll torque due to the overall increase in the thickness of the workpiece. It would be expected that, since the softest clad gives the greatest reduction in the roll separating force the increase in the roll torque due to cladding should be least for the softest clad also. It will be seen from the graphs that this is so, for pass reductions above about 10 percent. Below 10 percent reduction, the roll torque developed when aluminium clad is used is higher in many cases, than when copper or mild steel is used. (See graphs 18, 21, and 23). This is due to the fact that, at the low pass reductions, the clad : matrix interface friction has not developed sufficiently to affect the roll torque significantly, and the increase in the overall thickness of the workpiece is the predominant factor.

Graphs 16 to 18 show that the roll torque developed for the cladded stainless steel is lower than for the uncladded material. It had been expected that the former would be higher, particularly when the stainless steel is cladded with 0.048 in. thick mild steel. However, it will be seen in Graph 7 that a considerable reduction in the roll force is achieved for this metal combination and, apparently, the reduction in the roll torque as a result, is greater than the increase in torque due to the increased thickness. Furthermore, the coefficient of friction at the roll-workpiece interface (estimated to be at least 0.2 for stainless steel, 0.14 for mild steel, and 0.1 for copper), is higher for the stainless steel rolled without cladding than with cladding. This will contribute to the overall reduction in the roll separating force.

The effect of the clad : matrix hardness ratio on the roll torque is shown by Graphs 24 and 25.

whereas the roll torque is higher for Nimonic 90 rolled with 0.039 in mild steel clad than without cladding, the reverse is true for Nimonic 80, the thickness combination being the same in both cases. In effect, the greater the disparity in the strengths of the clad and matrix materials, the lower the torque developed for the sandwich.

14.3. The effect of the clad thickness on the roll force.

Graphs 27 to 38 show the effect of the clad thickness on the roll force for various material combinations. It will be seen that, in most cases, the effect of varying the clad thickness is not very great. For instance, in Graph 27, the difference between the values of roll force for copper rolled between layers of 0.028 in. and 0.049 in. aluminium, is only about 1 ton at 50 percent pass reduction.

In Graph 30, the curves for 0.02 in. and 0.032 in. copper clads are not drawn because they virtually coincide with the curve for 0.04 copper clad. However the points are shown. The roll force is considerably higher for the 0.01in. clad than for the other thicknesses, apparently because, in the former case, the matrix is considerably thicker than the clad. Consequently the tensile stresses induced in the matrix will be comparatively small. For the same reason, the compressive stresses induced in the clad will be comparatively high.

Graph 31 shows that the effect of the clad thickness on the roll force is a function of the pass reduction. Below 26 percent reduction, the thickest clad (0.048 in. mild steel) gives the highest roll separating force. Above this value of pass reduction, the roll force is lowest for this clad thickness. In effect, the increase in the work of deformation, and hence the roll force due to cladding, is initially higher for the thickest clad, but, as the pass reduction increases, the increase is progressively offset by the reduction in the roll force due to the tensile stresses induced in the matrix.

The effect of the clad thickness on the roll separating force is shown more clearly in Graphs 32 to 35. The lowest roll force is obtained when the proportion of clad in the sandwich is about 65 percent. (See Graph 33). For the mild steel clad, the optimum clad proportion is approximately 69 percent. (Graph 35). The effect of the pass reduction on the optimum clad proportion appears to be negligible. (See Graphs 33 & 35).

In Graph 37, for a given pass reduction, the roll force decreases with increasing clad thickness. Apparently, the optimum clad proportion, if it exists, is outside the range of proportions investigated. It was not possible to extend the pass reduction beyond about 20 percent because of considerable edge-cracking in the matrix. But it can be seen that the limiting reduction would not have been much higher than 20 percent for clad proportions less than 52 percent whereas a pass reduction of up to 30 percent could have been achieved for higher clad proportions.

Graphs 38 and 39 show that, above 16 percent pass reduction, a clad proportion of approximately 63 percent gives the lowest roll separating force. The points for clad proportions of 68.5 and 72.7 percent are so close that only one curve is drawn for both. Below 16 percent pass reduction, the thickest clad gives the lowest roll force, although, in general, the effect of the clad thickness on the roll force is negligible in this instance.

When mild steel was soaked in copper sulphate solution, a fine layer of copper was deposited on it. However, this did not have any measurable effect on the roll force and torque. It was expected that the effect, if any, would be to reduce the friction at the roll. workpiece interface.

14.4. The effect of the clad thickness on the roll torque.

The effect of the clad thickness on the roll torque is shown in Graphs 40 to 52. In most cases, the roll torque is increased as a result of cladding, the greatest increase being for the thickest clad. By contrast, the roll torque is lower when stainless steel is rolled between layers of aluminium, copper, or mild steel of various thicknesses. (See Graphs 43 to 45). Graphs 42, 48, and 51 show that there is an optimum proportion of clad which gives the lowest roll torque. This optimum condition is different for various material combinations and is a function of the pass reduction.. For instance, in Graph 51, the optimum condition exists only at pass reductions above 18.5 percent.

14.5. The effect of interchanging the positions of of the materials in the sandwich.

Graphs 53 to 60 show the results of rolling tests carried out on sandwich specimens in which the softer metal constituted the matrix. The roll separating force and torque for the matrix and clad rolled separately and as part of a sandwich have been compared. The results show that the roll force and torque developed for the sandwich is higher than for the components rolled separately. In effect, since the object of sandwich rolling is to achieve a reduction in the roll separating force and possibly torque, no benefit is derived when the softer metal constitutes the matrix and the harder metal constitutes the clad. However, since only two material combinations were investigated, the results are inconclusive and it is quite possible that a reduction in the roll force and torque can be achieved for other material combinations.

Graph 61 shows that, when the harder material constitutes the matrix, the differential reduction between the layers is smaller than when the softer metal constitutes the matrix. This is because, in the latter case, compressive stresses are induced in the hard material constituting the clad as a result of the friction at the tool-workpiece interface. Consequently, the deformation in the clad is slowed down. When the softer material constitutes the clad, it is the deformation in the soft material which is slowed down. In effect, the differential reduction between the layers is lower when the harder metal constitutes the matrix and the softer metal constitutes the clad than vice versa.

INTERFACE FRICTIONAL CONDITION	REDUCTION % MATRIX (rm)	CLAD (rc)	MEAN (rav)	rc / rm	ROLL FORCE tonf/in	ROLL TORQUE tonf-in/in
Polished and degreased.	21.4	24.7	23.0	1.15	6.5	2.3
Roughened and degreased.	20.5	25.2	21.8	1.22	6.1	2.2
Smooth and degreased.	19.5	25.5	22.5	1.31	6.0	2.2
Smooth and lubricated.	19.0	26.2	22.6	1.38	5.8	2.0
Polished and degreased.	32.0	34.6	33.3	1.08	8.4	3.6
Roughened and degreased.	30.8	35.1	32.9	1.14	8.1	3.4
Smooth and degreased.	29.8	36.0	32.9	1.21	7.9	3.4
Smooth and lubricated.	28.5	37.1	32.8	1.30	7.5	3.2

TABLE 6. The effect of the clad-matrix interface frictional condition on the roll force, torque, and the relative reduction of the layers.

14.6. The effect of the clad-matrix interface friction.

Table 6 shows the effect of varying the clad-matrix interface frictional condition on the differential reduction between the clad and the matrix and also on the roll force and torque. Apparently, the interface friction is highest when the interface is polished and degreased. This agrees well with the results of Boyarshinov[199] and is due to the fact that the tendency for the layers of the sandwich to bond is greatest for this interface condition. The roll force and torque are also highest for this interface condition, since the reduction in the harder matrix is higher than for other interface conditions.

The differential reduction between the layers is lower at the higher pass reduction for the interface frictional conditions investigated. This is not surprising, since the interface frictional shear stress will increase with increasing pass reductions until it attains the limiting value - the yield stress in shear of the softer material.

14.7. The effect of the clad width on edge-cracking in the matrix.

Figures 32(a) and 32(b) show the extent of edge-cracking in 1.25% C. steel rolled between layers of 0.049 in. and 0.107 in. aluminium respectively. In

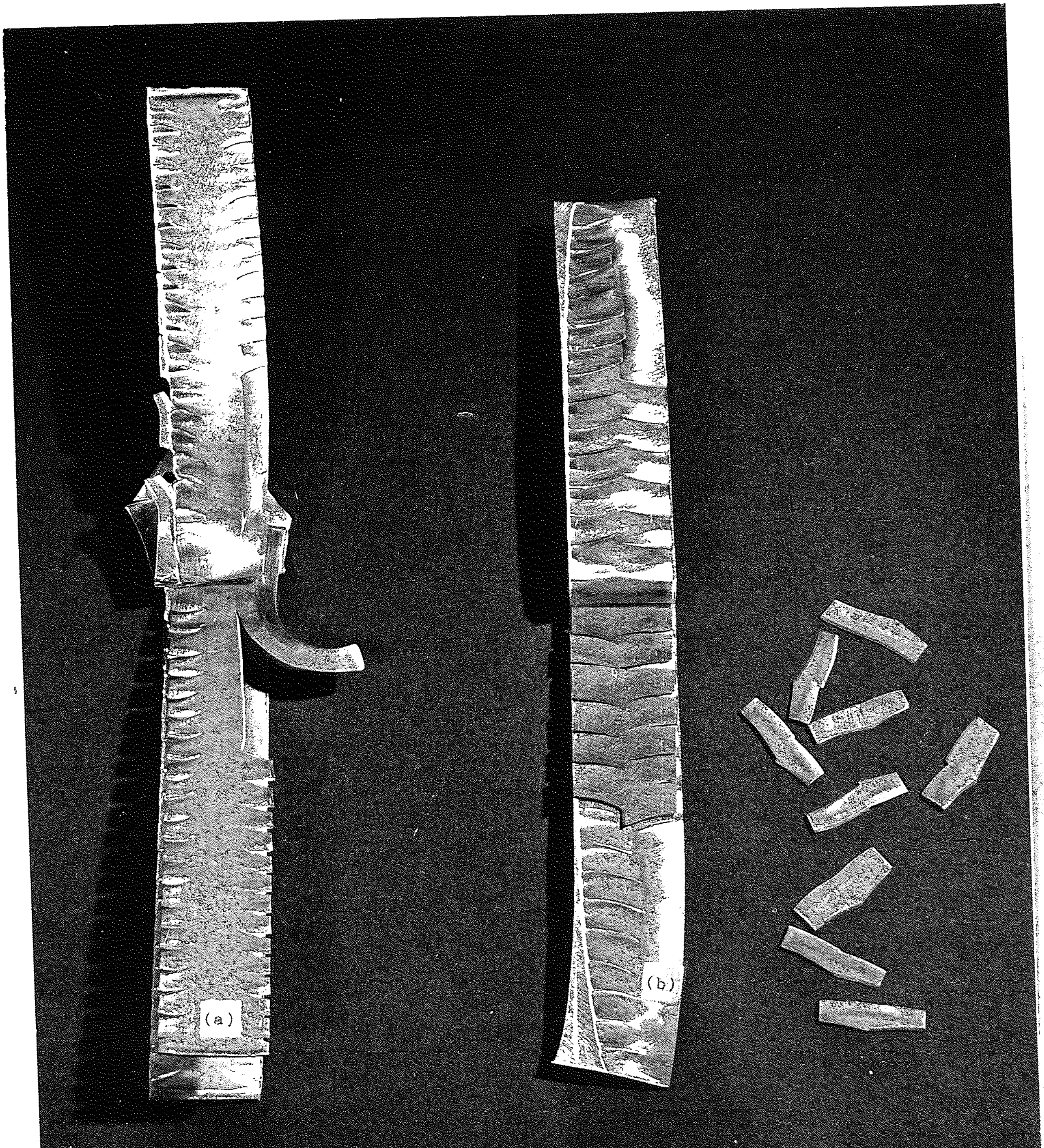


Figure 32. 1.25%C. steel rolled between (a) 2x0.049in. aluminium,13.9%redn. and(b) 2x0.107in. aluminium, 8%redn.

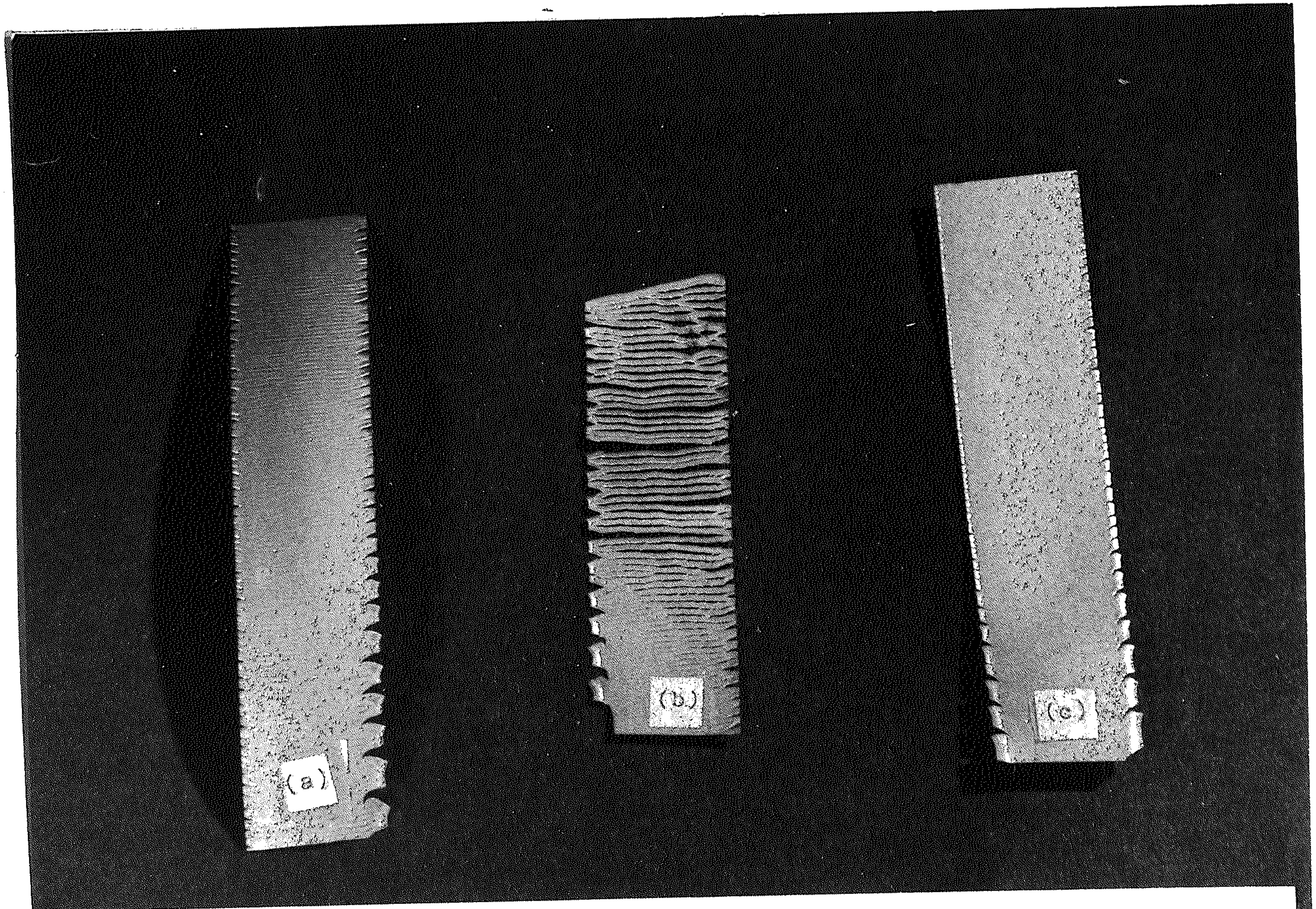


Figure 33. Nimonic 105 rolled between 2x0.02in.copper clads (a) 33.3%redn. (b)41.7%redn. and between 2x0.018in.mild steel clads(c)39%redn. Clad:matrix width ratio approx. 1 in all cases.

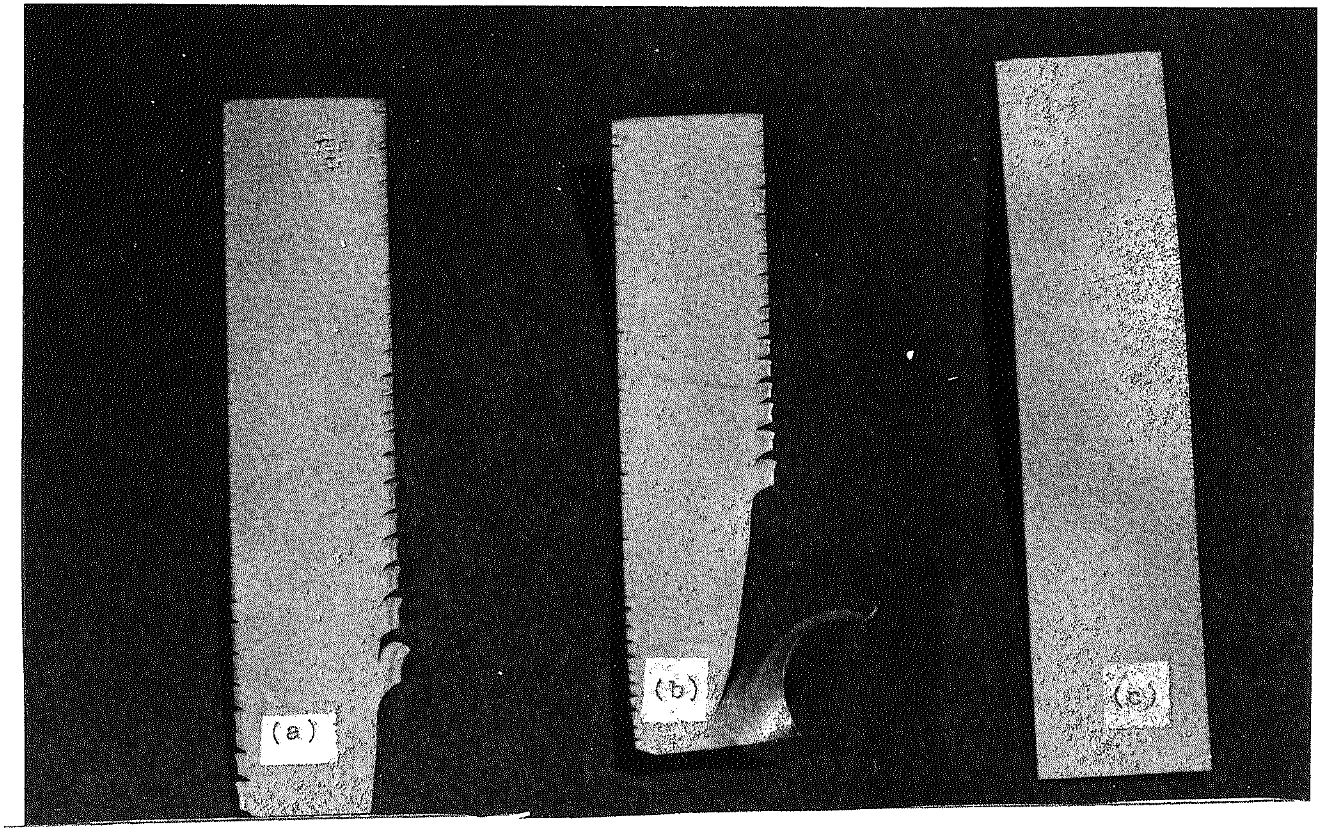


Figure 34. 0.012 in. Nimonic 105 rolled between 2x0.018 in. mild steel clads. (a) reduction 25%, width ratio 1.0
(b) reduction 39.2%, width ratio 1.05
(c) reduction 39.0%, width ratio 1.1

both cases, the clad : matrix width ratio, wr, was approximately 1. The edge-cracking is due principally to differential reduction between the edges and the centre of the strip, the latter being greater. The cracks originate from the edges and propagate to the centre of the strip.

It was found that, by increasing the clad : matrix width ratio from 1 to approximately 1.1, (that is, the clad is slightly wider than the matrix) , edge-cracking was suppressed up to a pass reduction of 25 percent. Even at 30 percent reduction, ripples were just beginning to form at the edges of the strip. When wr was increased to 1.25, edge-cracking was completely suppressed but both the matrix and the clad were distorted considerably, apparently because of the additional stresses imposed on the matrix metal by the elastic regions of the clad at the edges of the sandwich. When wr was varied from 1 to 1.25 for the sandwich consisting of 1.25% C. steel matrix and 0.107 0.107 in. aluminium, edge-cracking was not suppressed and fragmentation similar to Figure 32(b) occurred in all cases.

Figures 33(a) and 33(b) show the edge-cracking which occurred when Nimonic 105 alloy was given pass reductions of 33.3 and 41.7 percent respectively between layers of 0.02 in. copper. Figure 33(c) shows the same alloy given 39.2 percent reduction between layers of 0.18 in. mild steel. Edge cracking was considerably less when the mild steel clad was used than when the copper clad was used. Figure 34 shows the effect of varying the clad : matrix width ratio for the sandwich consisting of Nimonic 105 alloy matrix and 0.0i8 in. mild steel clad. Whereas an increase in wr from 1 to 1.05 was insufficient to suppress edge-cracking, (see figures 34(a) and (b)), there was no edge cracking when wr was increased to 1.1. (See figure 34(c). Again, when wr was increased to 1.25, the matrix and clad were distorted considerably.

14.8. Experiments with plastic clads.

Graphs 62 to 69 show the effect on the roll separating force and torque of rolling aluminium, copper, mild steel, and stainless steel between layers of plastic. For a pass reduction up to 33 percent, the roll separating force is higher for the aluminium cladded with plastic than for the same metal rolled without cladding. (See Graph 62). Above this reduction, the roll force for the former is lower. A reduction in the roll separating force is achieved for the other metals also, the greatest being for the hardest metal (stainless steel).

Graphs 63 and 67 show that there is an increase

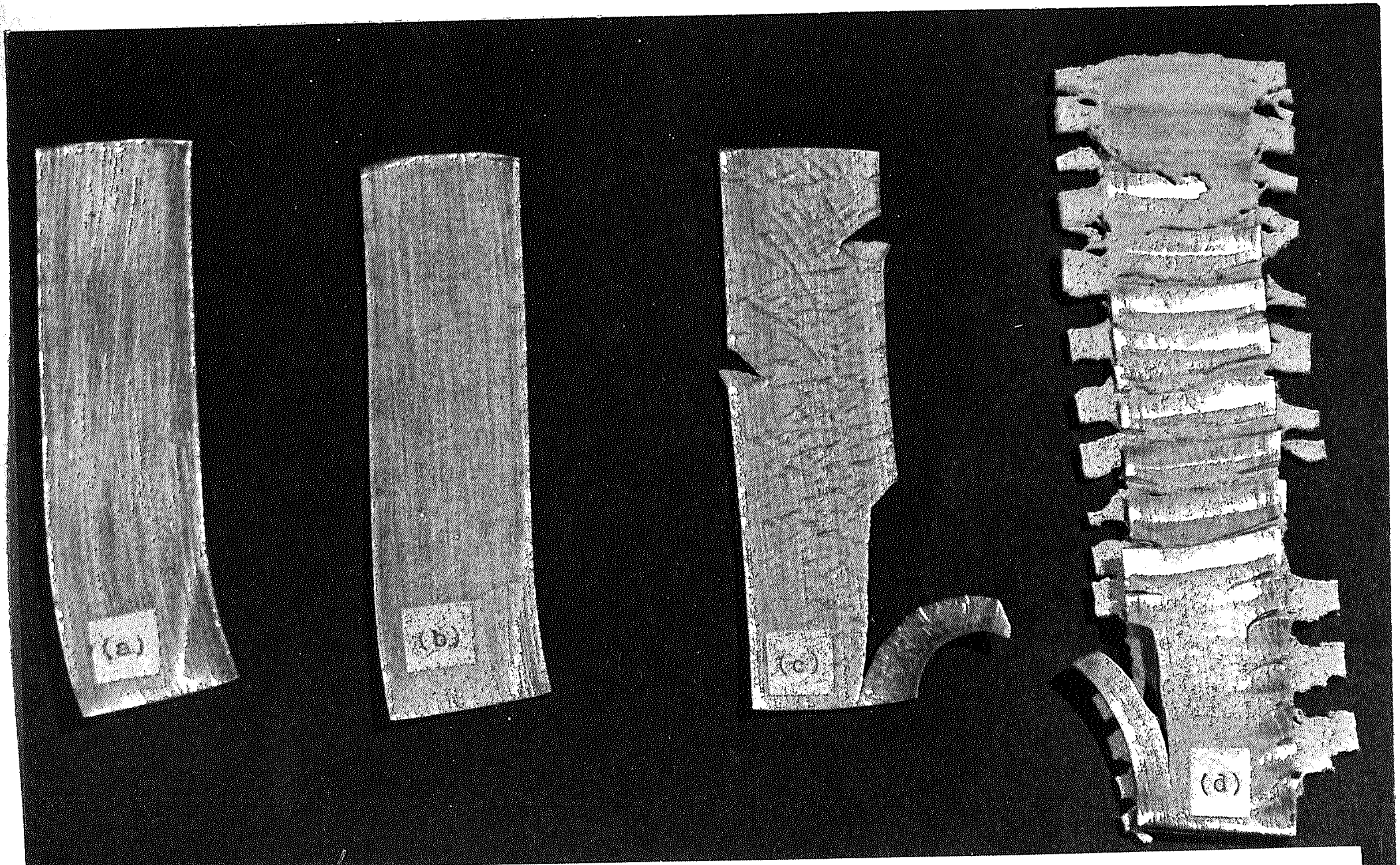


Figure 35. (a) copper with plastic clad. 22.5% redn.
(b) " " " " 38.8% "
(c) " " " " 45.0% "
(d) 1.25%C.steel with plastic clad. 2.2% redn.

in the roll torque aluminium or copper is rolled between plastic, compared with the metals rolled without cladding. The reverse is true for copper and stainless steel. (See Graphs 65 and 69).

Graphs 64 and 65 show that a greater reduction in the roll force and torque is achieved when copper is rolled between layers of cycolac plastic compared with Marley plastic. This is due to either the differences in the mechanical properties of the plastics or the differences in the thicknesses. Further tests could not be carried out because the plastics were not available in other thicknesses.

Figures 35 (a) to (c) show the effect of plastic cladding on the surface finish of copper. At 45 percent pass reduction (Figure 35 (c)), the surface of the strip is rippled and some tearing has occured. Figure 35 (d) shows the result of an attempt to roll 1.25% C. steel between layers of Marley plastic. The matrix is fragmented in a similar way to the results obtained with 0.107 in. aluminium clad. (See Figure 32 (b).

14.9. <u>The effect of applied front and back tensions.</u>

The effect of front and back tensions on the roll separating force and torque is shown in Graphs 70 and 71. The back tension is considerably more effective in reducing the roll force than the front tension. However, the roll torque is higher when back tension is applied than when no tension is applied. The reverse is true for the front tension. The considerable scatter in the points is probably due to the non-uniformity of the applied tensions accross the thickness of the sandwich, since the top clad layer will be subjected to a higher tension than the bottom clad. The results of the tension experiments are similar to those normally obtained in conventional rolling with applied tensions.

14.10 . Summary of results.

1. A reduction in the roll force can be achieved when a metal is cladded with a softer material, the highest reduction being achieved with the softest clad. When the disparity between the clad and matrix strengths is not sufficiently high, the roll force may increase as a result of cladding.

2. The roll torque may increase or decrease as a result of cladding , depending on the materials and thicknesses constituting the sandwich.

3. In sandwich rolling, a higher pass reduction can be achieved before the limiting reduction is reached than is possible when no clad is used. However, the roll torque may increase to the extent that it becomes the limiting factor.

4. The thicker the clad, the greater the reduction in

the roll force and the increase in the roll torque as a result of cladding. In some cases, there is an optimum value of the clad thickness which gives the lowest roll force and torque.

5. When the softer metal constitutes the matrix and the harder metal constitutes the clad, the roll force and torque are higher than when the components of the sandwich are rolled separately. The results may be different for other material combinations.

6. Differential reduction between the layers of the sandwich is least when the clad : matrix interface is polished and free from grease , for the interface conditions investigated.

7. Considerable edge-cracking may occur in the matrix and clad when the matrix is considerably stronger than the clad. Edge-cracking can be reduced or even eliminated by the use of a clad which is slightly wider than the matrix.

8. A considerable reduction in the roll force and torque can be achieved by the use of plastic clads.

9. A reduction in the roll force is achieved when tensions are applied to the sandwich than when no tension is applied. The back tension is more effective than the front tension. A reduction in the

roll torque is achieved also when front tension is applied to the sandwich, but the roll torque increases when back tension is applied.

15. THEORETICAL ANALYSIS OF THE SANDWICH ROLLING PROCESS.

15. THEORETICAL ANALYSIS OF THE SANDWICH ROLLING PROCESS.

15.1. The mechanism of load reduction.

When a three-layer composite comprising of a hard matrix and a soft clad is rolled, the softer clad will tend to deform in preference to the hard matrix. However, if the friction between the layers of the composite is high, tensile and compressive stresses are induced in the matrix and clad respectively, as a result of the frictional shear stress at the clad:matrix interfaces. As a result, deformation will be inhibited in the clad while the matrix becomes easier to deform. When the interlayer friction is high, the layers will deform at approximately the same rate, provided the difference in the strengths of the component materials is not very great. If the difference is great, preferential deformation will occur between the layers even when the friction at the interfaces is high.

The increase in the overall thickness of the workpiece as a result of cladding means also that roll flattening and hence the roll force will be reduced. A further reduction in the roll force is achieved when the clad material has lower frictional characteristics than the hard material.

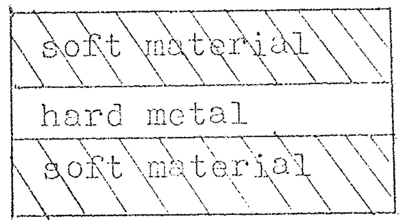


Figure 36(a). A sandwich specimen.

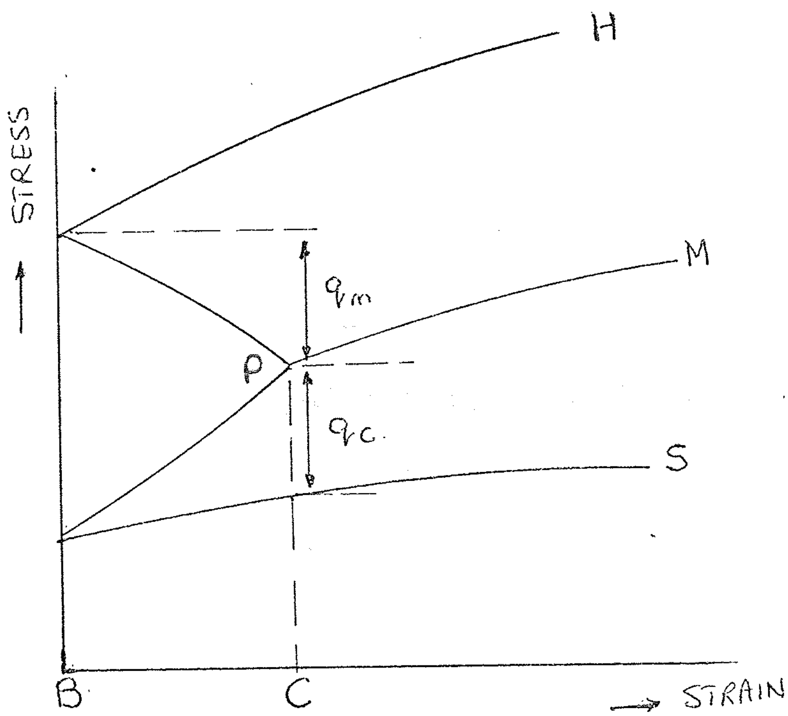


Figure 36(b). A graphical model for sandwich rolling.

15.2. A graphical model.

With reference to figure 36(b), the H and S curves represent the individual stress-strain curve of the hard and soft metal respectively. When the materials are deformed as components of a sandwich, the soft material will first start to yield while the hard material remains elastic. However, the yielding curve of the soft material will deviate from the S curve by an amount depending on the magnitude of the compressive stresses induced in it by the interlayer frictional shear stress. On the other hand, the external load required to initiate plastic deformation in the hard matrix will start to diminish as a result of the tensile stresses induced in it by the interlayer frictional shear stress. At the point P (figure 36(b)), the induced tensile has increased sufficiently to initiate yielding in the matrix. The joint deformation of the layers will now follow a new curve M, provided the interlayer friction is sufficiently high to prevent differential deformation and the difference between the strengths of the component materials is not very great. In the analysis which follows, it will be assumed that the region of preferential reduction represented by BC in figure 36(b), is small compared with the region of joint plastic deformation and can be ignored.

Figure 37(a) Section through the rolls and workpiece showing usual arrangement with the softer layers outermost.

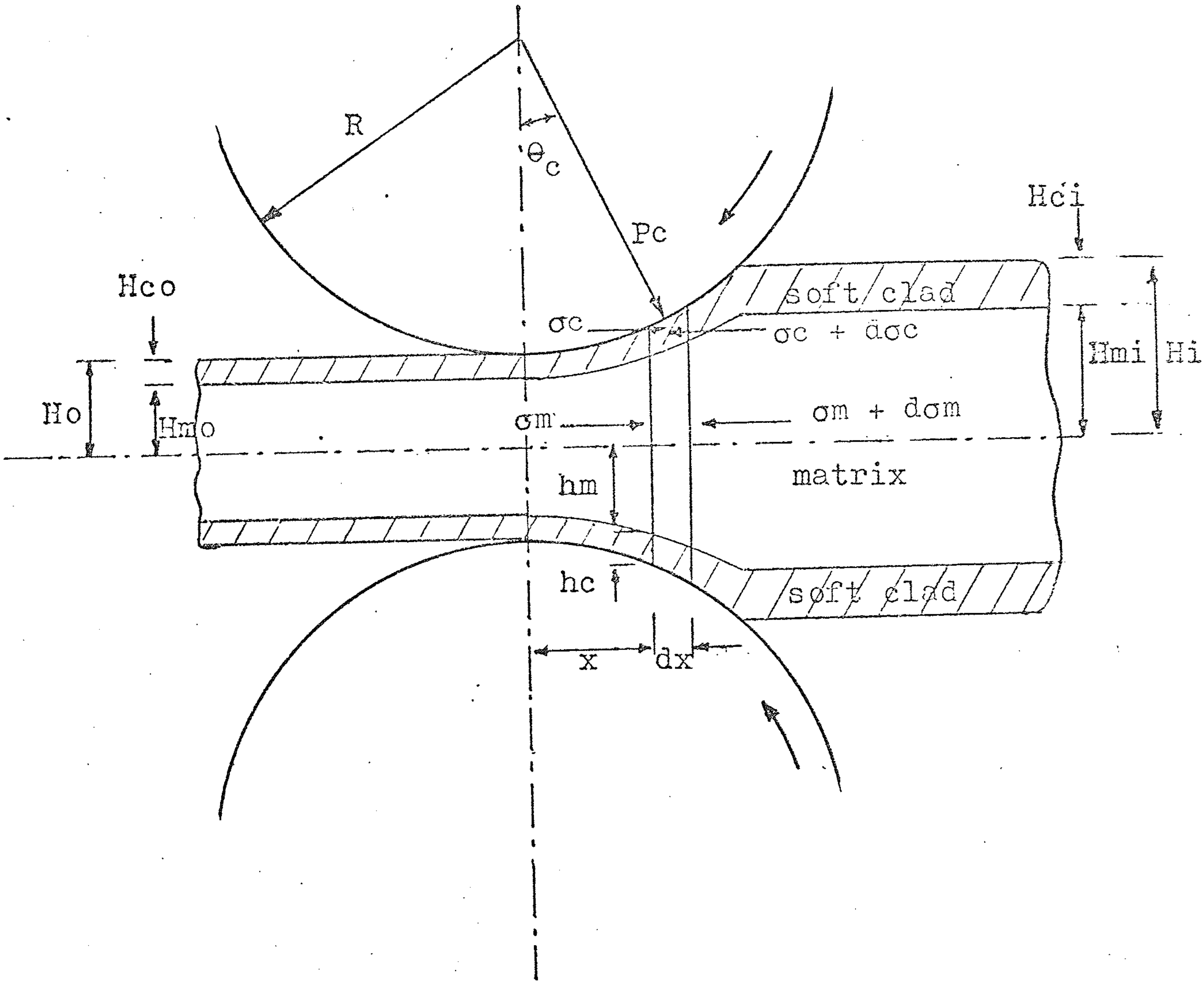
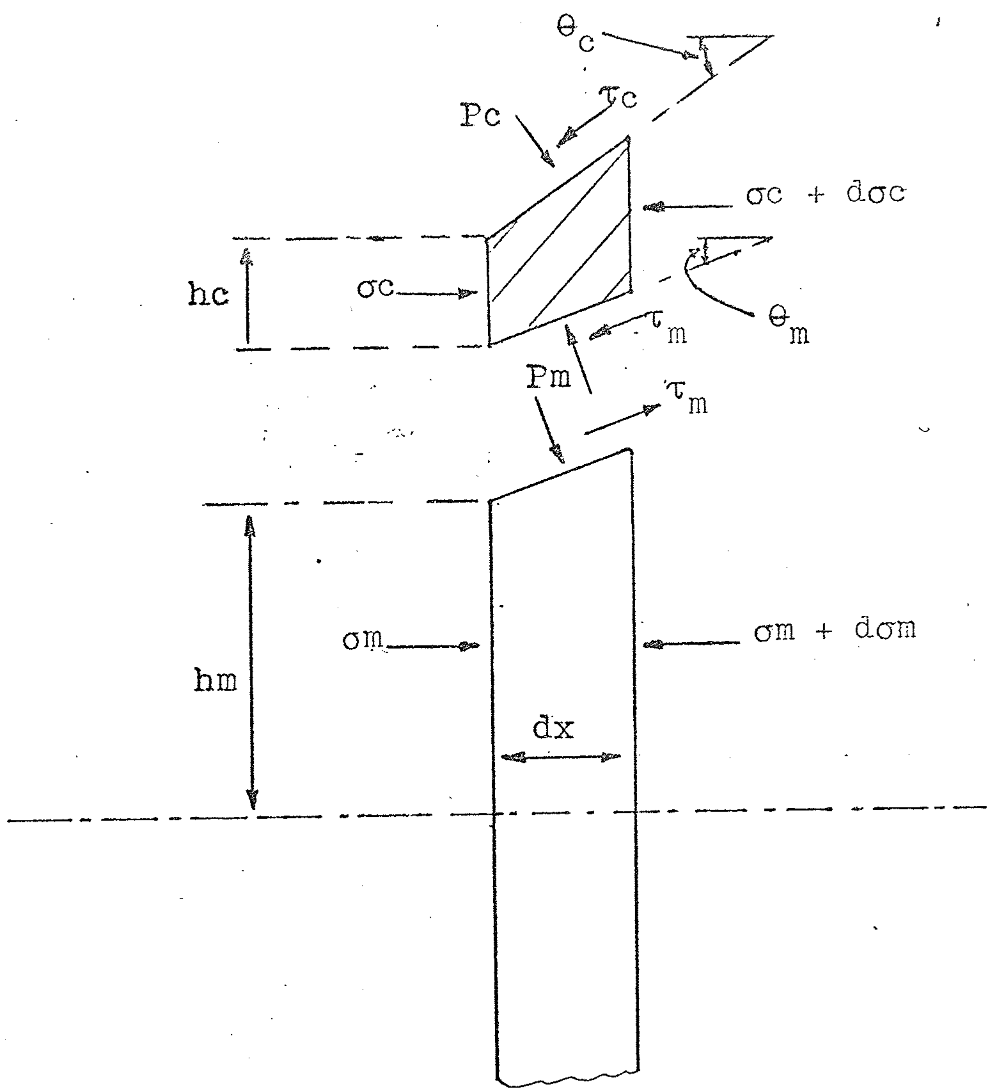


Figure 37(b) Magnified view of the elemental length of the compound workpiece in the entry zone.



15.3. Equations of the roll force and torque.

List of assumptions.

In addition to the basic postulates of the theory of plasticity stated in section 2.1, the following assumptions were made in the analysis:

(a) The strain is equal in the layers of the sandwich at any point along the arc of contact.

(b) The vertical and horizontal planes are coincident with the principal planes.

(c) Coulomb friction operates at the roll-clad interface over the entire arc of contact.

(d) The maximum shear strain energy yield criterion applies.

(e) Spread in the lateral direction is negligible.

Figure 37(a) shows the stresses acting on an element of the sandwich in the roll gap. A magnified view of the element is shown in figure 37(b).

Horizontal equilibrium of forces for the matrix of unit width:

$$\frac{d\sigma_m}{dx} = \frac{1}{h_m}\left[P_m \tan\theta_m \mp \tau_m - \sigma_m \frac{dh_m}{dx}\right] \quad (15.1)$$

Horizontal equilibrium equation for clad of unit width:

$$\frac{d\sigma_c}{dx} = \frac{1}{h_c}\left[P_c \tan\theta_c - P_m \tan\theta_m \pm \tau_c \pm \tau_m - \sigma_m \frac{dh_c}{dx}\right] \quad (15.2)$$

Vertical equilibrium equation for clad of unit width:

$$P_c = P_m \pm \tau_c \tan\theta_c \pm \tau_m \tan\theta_m \qquad (15.3)$$

By combining equations (15.2) and (15.3) and ignoring second order terms,

$$\frac{d\sigma_c}{dx} = \frac{1}{h_c}\left[P_m(\tan\theta_c - \tan\theta_m) \pm \tau_c \pm \tau_m - \sigma_c \frac{dh_c}{dx}\right] \qquad (15.4)$$

From the geometry of the arc of contact:

$$\tan\theta_m = \frac{dh_m}{dx} \qquad (15.5a)$$

and

$$\tan\theta_c - \tan\theta_m = \frac{dh_c}{dx}. \qquad (15.5b)$$

Equations (15.1) and (15.4) now become respectively:

$$\frac{d\sigma_m}{dx} = \frac{1}{h_m}\left[(P_m - \sigma_m)\frac{dh_m}{dx} \mp \tau_m\right] \qquad (15.6)$$

and

$$\frac{d\sigma_c}{dx} = \frac{1}{h_c}\left[(P_m - \sigma_c)\frac{dh_c}{dx} \pm \tau_c \pm \tau_m\right] \qquad (15.7)$$

Since the strains in the clad and matrix are assumed equal,

$$\frac{h_c}{h} = B = \text{Constant.} \qquad (15.8a)$$

and since $h_c + h_m = h$

$$\frac{h_m}{h} = (1 - B) \qquad (15.8b)$$

Differentiating equations (15.8a) and (15.8b) with respect to x,

$$\frac{dh_c}{dx} = B\frac{dh}{dx}. \qquad (15.9a)$$

and $$\frac{dh_m}{dx} = (1-B)\frac{dh}{dx} \tag{15.9b}$$

The criterion of yielding.

If θm and θc are small, as is usually the case in practice, it may be assumed that the last two terms in equation (15.3) are small compared with Pm. Hence,

$$P_c \simeq P_m$$

By applying the maximum shear strain energy criterion,

The clad will yield when:

$$(P_m - \sigma_c) = \bar{Y}_{pc} \tag{15.10}$$

and the matrix will yield when:

$$(P_m - \sigma_m) = \bar{Y}_{pm} \tag{15.11}$$

By combining equations (15.10) and (15.11) and differentiating with respect to x,

$$(\sigma_c - \sigma_m) = (\bar{Y}_{pm} - \bar{Y}_{pc}) \tag{15.12}$$

and $$\frac{d\sigma_c}{dx} = \frac{d\sigma_m}{dx} = \frac{dP_m}{dx} \tag{15.13}$$

By combining equations (15.6) - (15.13), we obtain,

$$\tau_m = \pm\left[B(1-B)(\bar{Y}_{pm} - \bar{Y}_{pc})\frac{dh}{dx} \mp (1-B)\tau_c\right] \tag{15.14}$$

and from equations (15.7), (15.9) and (15.14),

$$\frac{dP_m}{dx} = \frac{1}{h}\left[(\bar{Y}_{pm} - B(\bar{Y}_{pm} - \bar{Y}_{pc}))\frac{dh}{dx} \pm \tau_c\right] \tag{15.15}$$

In accordance with assumption (c),

$$\tau_c \simeq \mu P_c$$

and since $P_c \approx P_m$

$$\tau_c \simeq \mu P_m \tag{15.16}$$

Equation (15.15) then becomes:

$$\frac{dP_m}{dx} = \frac{1}{h}\left[\left(\bar{\gamma}_{pm} - B\left(\bar{\gamma}_{pm} - \bar{\gamma}_{pc}\right)\right)\frac{dh}{dx} \pm \mu P_m\right] \tag{15.17}$$

Also, from the geometry of the arc of contact,

$$x = R\theta_c \tag{15.18}$$

and

$$h = H_o + R\frac{\theta_c^2}{2} \tag{15.19}$$

since θ_c is small and

$$\cos\theta_c \simeq 1$$

and

$$\sin\theta_c = \tan\theta_c \simeq \theta_c$$

Differentiating equations (15.18) and (15.19) with respect or θ_c,

$$\frac{dx}{d\theta_c} = R \tag{15.20}$$

and

$$\frac{dh}{d\theta_c} = R\theta_c \tag{15.21}$$

From equations (15.17), (15.20) and (15.21), we obtain,

$$\frac{dP_m}{d\theta_c} = \frac{R}{h}\left[\left(\bar{\gamma}_{pm} - B\left(\bar{\gamma}_{pm} - \bar{\gamma}_{pc}\right)\right)\theta \pm \mu P_m\right] \tag{15.22}$$

From equation (15.3),

$$P_c = P_m \pm \tau_c \theta_c \pm \tau_m \theta_m \qquad (15.3)$$

and from equations (15.5) and (15.9),

$$\theta_m = (1-B)\theta_c \qquad (15.23)$$

By combining equations (15.3), (15.14), (15.16) and (15.23) we obtain:

$$P_c = \frac{P_m \pm B(1-B)^2 \theta_c^2 (\bar{Y}_{pm} - \bar{Y}_{pc})}{1 \mp \mu B(2-B)\theta_c} \qquad (15.24)$$

$(1-B)^2 \theta_c^2 (\bar{Y}_{pm} - \bar{Y}_{pc})$ is small compared with Pm and may be ignored. Equation (15.24) then becomes,

$$P_c = \frac{P_m}{1 \mp \mu B(2-B)\theta_c} \qquad (15.25)$$

The torque at any point along the arc of contact is given by:

$$T = \mu P_c R \qquad (15.26)$$

Equation (15.24) is not directly integrable and a step solution along the arc of contact is necessary, in order to obtain the distribution of Pm and also Pc and T along the arc. The Runge-Kutta method of numerical solution of differential equations was chosen because it is accurate and is particularly suitable for use on a computer.

15.4. Computational methods.

In order to check the validity of the above analysis, the roll force and torque were calculated as follows, for a number of sandwich specimens selected at random:

Notation for the computation.

K Approximation factor.

H Length of interval in the step solution.

f function.

Suffixes.

o Initial conditions for the calculation.

1,etc. denote stages in the approximation method.

Starting with initial values Pmo and θmo and proceeding at regular angular intervals, H along the arc of contact, the value of Pm at the first point (θmo + H) is calculated as follows:

$$K_1 = Hf\left[\theta_0 , P_{mo}\right]$$

$$K_2 = Hf\left[\theta_0 + \frac{H}{2} , P_{mo} + \frac{K_1}{2}\right]$$

$$K_3 = Hf\left[\theta_0 + \frac{H}{2} , P_{mo} + \frac{K_2}{2}\right]$$

$$K_4 = Hf\left[\theta_0 + H , P_{mo} + K_3\right]$$

$$P_{m_1} = P_{mo} + \frac{1}{6}\left[K_1 + 2K_2 + 2K_3 + K_4\right]$$

With Pm_1 and θm_1 as initial conditions, Pm_2 at $(\theta m_1 + H)$ is calculated, and so on.

The calculation procedure is the same for the entry and exit zones of the arc of contact, the points of difference being:

(a) Whenever there is a choice of signs in the roll force equations, the top sign refers to the exit zone and the bottom sign to the entry zone of the arc of contact.

(b) The interval H is negative for the entry zone and positive for the exit zone.

(c) The initial conditions for starting the calculations for either zone, are the end conditions for that zone.

Having obtained the values of Pm along the arc of contact, the corresponding values of Pc and T are obtained from equations (15.25) and (15.26) respectively.

The total roll force is given by:

$$F = \int_0^{\theta_n} P_c \, d\theta_c + \int_{\theta_n}^{\theta_i} P_c \, d\theta \qquad (15.27)$$

and the total roll torque for the two rolls is given by:

$$T_t = 2 \times \left[\int_{\theta_n}^{\theta_i} \mu P_c R \, d\theta - \int_0^{\theta_n} \mu P_c R \, d\theta \right] \qquad (15.28)$$

It should be noted that the suffix 'o' here refers to the exit zone of the arc of contact and should not be confused with the initial condition for the calculation procedure.

A programme was written in Elliot Algol language for the evaluation of equations (15.22) to (15.28) on the Elliot 803 computer.

Determination of the step interval, H.

The accuracy of the Runge-Kutta method depends on the interval used in the calculations. The shorter the interval, the better the accuracy. However, since the use of very small intervals would prolong the calculation time and the computer time available was limited, it was necessary to determine initially the optimum value of H which gave an acceptable level of accuracy. Sample calculations were made on the computer, for values of H from 0.05 in steps of 0.05, to 0.6. Up to $H = 0.5$, the results of the calculations were identical to four places of decimal. Above 0.5, the level of accuracy began to diminish. It was decided to use $H = 0.5$ for all the calculations.

In order to enable the results of the analysis to be compared with the equivalent yield stress method, the equation of the equivalent yield stress (7.2). was combined with the Bland and Ford[12] equations of roll force and torque for conventional rolling as follows:

The roll force F_b is given by:

$$F_b = \bar{Y}_{pe}\sqrt{R(H_i - H_o)} \cdot f_c(a,r) \qquad (15.29)$$

where
$$f_c = a\sqrt{\frac{1-r}{r}}\left[\int_0^{\psi_n}(1+a^2\psi^2)e^{2a\arctan a\psi}d\psi + (1-r)e^{2a\arctan\sqrt{\frac{r}{1-r}}}\int_{\psi_n}^{\psi_i}(1+a^2\psi^2)e^{-2a\arctan a\psi}d\psi\right] \qquad (15.30)$$

The roll torque is given by:

$$T_b = 2\times\bar{Y}_{pe}\,R\frac{H_i^2}{H_o}\cdot f_t(a,r) \qquad (15.31)$$

where
$$f_t = a^2(1-r)^2\left[\int_0^{\psi_n}(1+a^2\psi^2)e^{2a\arctan a\psi}\psi d\psi + (1-r)e^{2a\arctan\sqrt{\frac{r}{1-r}}}\int_{\psi_n}^{\psi_i}(1+a^2\psi^2)e^{-2a\arctan a\psi}\psi\, d\psi\right] \qquad (15.32)$$

The roll force and torque were calculated by this method for the rolling parameters used in the previous calculations, using the computer programme 2 given in Appendix 20.5.

The coefficient of friction.

For the calculations involving aluminium and copper clads, the values of the coefficient of friction were obtained from the data published by Whitton and Ford[123]. Since no data was available for mild steel having similar surface roughness as the specimens used in the the investigation, the coefficient of friction for specimens with mild steel clads, was estimated by substituting measured values of the roll force and other measured parameters into equation (15.29) so that the coefficient of friction was the only unknown in the equation and was calculated.

Correction for roll flattening.

Hitchcock's equation[139] for the radius of the deformed arc of contact is given by:

$$R' = R\left[1 + \frac{cF}{w\delta}\right]$$

where $c = 3.34 \times 10^{-4}$ for steel rolls.

By substituting the measured values of the roll force, roll radius, and width of the material into the above equation, the deformed radius, R' was obtained.

The yield stress.

For the calculations described above, mean yield stress values of the individual components of the sandwich were used. The values were obtained from the equation

$$\bar{Y}_p = \frac{1}{\theta_i}\int_0^{\theta_i} Y_p \, d\theta. \qquad (15.33)$$

The integration of equation (15.33) was carried out by using Simpson's rule.

It is more correct to use the value of the yield stress at each point along the arc of contact in the calculations of the roll force and torque. However, the calculations would be tedious, hence the decision to use mean values of the yield stress. In order to assess the error resulting from the use of mean values, some of the calculations described previously, were repeated, using point values of the yield stresses along the arc of contact. Two more programmes were written for this purpose and are given in Appendix 20.5. (Programmes 3 and 4).

15.5. <u>The relationship between the roll force and the proportion of clad in the sandwich.</u>

Based on the assumption that the roll force is approximately proportional to the yield stress of the workpiece, and considering the linear relationship between the equivalent yield stress and the individual yield stresses of the component metals of the sandwich, (equation 7.2), the roll force is determined often in sandwich or composite rolling practice as follows: The roll force is calculated for the clad and matrix in turn, for the same thickness and reduction as the sandwich. The roll force for the sandwich is then obtained by interpolating between these two values, according to the proportion of each material in the sandwich. This is tantamount to assuming that a linear relationship between the roll separating force and the proportion in which the sandwich is made up. The results of experiments by Pomp and Lueg (See Ref.1) indicate that the assumption is reasonably valid for hot rolling. It would be useful to determine the applicability of the method to cold sandwich rolling, but the range of materials and thicknesses available for the experimental work was limited and the method could not be tested.

However, theoretical calculations of the roll force and torque by the equivalent yield stress method outlined previously, were carried out for two material combinations:

(a) mild steel-stainless steel-mild steel.

(b) mild steel-0.71%C.steel-mild steel.

The proportion of the clad in the sandwich was varied from 0 to 100 percent, the total sandwich thickness being kept constant.

15.6. Analysis of the effect of the clad thickness on on the roll force.

The major factor on which the extent of the reduction in the roll separating force depends is the clad-matrix interface frictional shear stress, τ_m. It was shown in section 15.3. that:

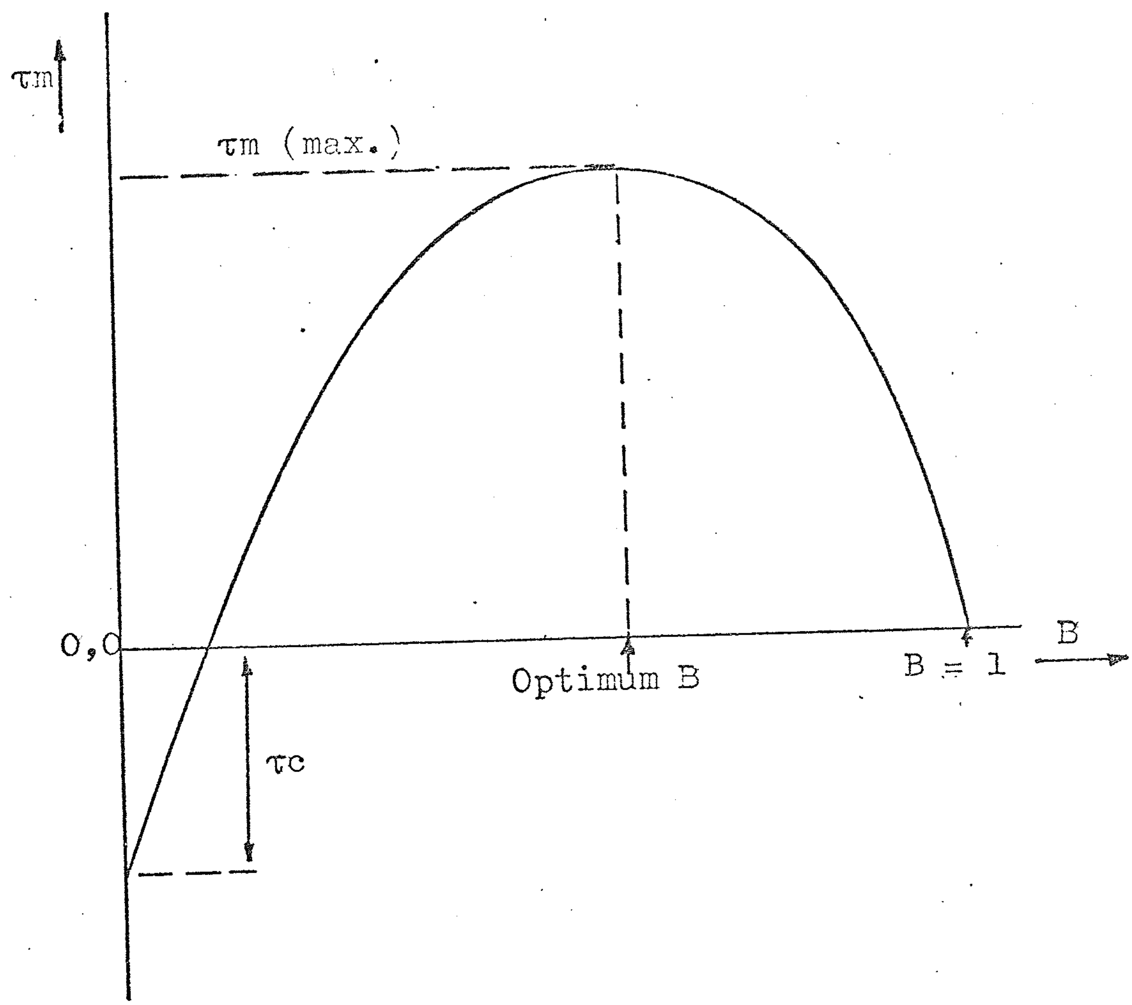
$$\tau_m = \pm\left[B(1-B)(\bar{Y}_{pm}-\bar{Y}_{pc})\frac{dh}{dx} \mp (1-B)\tau_c\right] \qquad (15.14)$$

In order to enable the above equation to be differentiated with respect to B, two assumptions will be made:

(i) τ_c may be regarded as the mean frictional shear shear stress at the roll-clad interface and is therefore constant.

(ii) The roll diameter is large compared with the length of the arc of contact and the latter may

Figure 38 Diagram showing variation of the interface frictional shear stress with the clad-sandwich thickness ratio.



be replaced by a chord inclined to the horizontal plane at a constant angle θ_c.

Differentiating equation (15.14) with respect to B,

$$\frac{d\tau_m}{dB} = \pm\left[(1-2B)(\bar{Y}_{pm}-\bar{Y}_{pc})\theta_c + \tau_c\right] \qquad (15.34)$$

At the turning point,

$$\frac{d\tau_m}{dB} = 0.$$

Hence

$$B = 0.5\left[1 + \frac{\tau_c}{(\bar{Y}_{pm}-\bar{Y}_{pc})\theta_c}\right] \qquad (15.35)$$

It can be shown that the turning point is maximum. Equation (15.35) is represented qualitatively by the curve shown in figure 38. The optimum value of B which gives the maximum value of τ_m lies somewhere between 0.5 and a higher value determined by the roll-clad interface friction, the difference between the yield stresses of the component materials of the sandwich, and the draft angle. It is reasonable to assume that the optimum condition for the lowest roll separating force is when τ_m attains the maximum value possible for the particular set of rolling parameters.

If τ_c is very low, as is the case in well lubricated plane strain compression, the optimum value of B will be close to 0.5. In flat rolling, the optimum value of B would be expected to be higher, since τ_c is usually significant . The results of an investigation of the plane strain compression of aluminium-copper composites by Davies[191] showed that the optimum value of B was approximately 0.55 for the particular combination of the materials and thicknesses investigated. Arnold and Whitton[1] suggested a value of 0.66 for sandwich rolling. From the results of the above analysis, it appears that both values are reasonable. However, the analysis is only approximate, since the reduction in the roll force does not depend on τ_m alone.

15.7. Comparison between calculated and measured results.

The results of the theoretical calculations of the roll force and torque for a number of sandwich specimens selected at random are shown in Tables 7 to 10. The equations developed in this analysis and also the equal strain method have been used. The measured values of the roll force and net roll torque are also included. The net total torque values were derived from total measured torque values by subtracting the redundant torque developed when the rolls are squeezed together with no strip between. The redundant torque values were obtained from the load-redundant torque curve for the mill, which is given in Appendix 20.3.

In general, the values of the roll force computed from equation (15.24) are within 7 percent of

CLAD : 2 × 0.049 in. ALUMINIUM — R_o = 2.25 in.

MATRIX : 0.029 in. MILD STEEL — μ = 0.11 in.

TABLE 7

TEST NO.	MEAN REDUCTION % OF THE SANDWICH	MEASURED		CALCULATED				ERROR %			
				METHOD 1		METHOD 2		METHOD 1		METHOD 2	
		ROLL FORCE Tonf/in.	ROLL TORQUE Tonf in/in	ROLL FORCE Tonf/in	ROLL TORQUE Tonf in/in	ROLL FORCE Tonf/in	ROLL TORQUE Tonf in/in	ROLL FORCE	ROLL TORQUE	ROLL FORCE	ROLL TORQUE
1	12.0	2.1	0.39	2.1	.36	2.0	.32	0	−7.7	−4.8	−18
2	15.5	2.45	0.56	2.3	.51	2.1	.46	−6.1	−8.9	−14.3	−17.9
3	21.5	2.95	0.86	2.8	.79	2.7	.70	−5.1	−8.2	−8.5	−18.6
4	27.0	3.5	1.13	3.4	1.05	3.2	.91	−2.9	−7.1	−8.6	−19.5
5	33.0	4.2	1.43	4.0	1.32	3.8	1.15	−5.0	−7.7	−9.5	−19.6
6	36.5	4.6	1.60	4.4	1.44	4.1	1.30	−4.3	−10.0	−10.9	−18.8
7	38.7	4.9	1.71	4.6	1.56	4.3	1.40	−6.1	−8.8	−12.2	−18.2

METHOD 1 — The Equations of the analysis

METHOD 2 — The Equivalent yield Stress Method

ERRORS — based on the measured values.

MATRIX : ·029" MILD STEEL $\quad R_o = 2\cdot25$ in

CLAD : ·2x·032in. COPPER. $\quad \mu = \cdot11$ in

TABLE 8

TEST NO.	MEAN REDUCTION % OF THE SANDWICH	MEASURED ROLL FORCE Tonf/in.	MEASURED ROLL TORQUE Tonfin/in	CALCULATED METHOD 1 ROLL FORCE Tonf/in	CALCULATED METHOD 1 ROLL TORQUE Tonfin/in.	CALCULATED METHOD 2. ROLL FORCE Tonf/in.	CALCULATED METHOD 2. ROLL TORQUE Tonfin/in	ERROR % METHOD 1 ROLL FORCE	ERROR % METHOD 1 ROLL TORQUE	ERROR % METHOD 2. ROLL FORCE	ERROR % METHOD 2. ROLL TORQUE
1	12·5	3·8	0·50	3·6	·48	3·4	·54	-5·3	-4·0	-10·5	+7·4
2	17·0	4·8	1·10	4·7	·95	4·4	·81	-2·1	-13·7	-8·4	-26·4
3	22·5	5·9	1·60	5·6	1·33	5·1	1·15	-5·1	-16·9	-13·6	-28·2
4	26·5	6·8	2·0	6·5	1·60	6·3	1·4	-4·4	-20·0	-7·4	-30·0
5	30·5	7·5	2·3	7·3	1·92	7·1	1·65	-2·7	-16·5	-5·4	-28·2
6	34·0	8·3	2·52	8·0	2·23	7·8	1·87	-3·6	-11·9	-6·0	-25·8
7	36·5	8·8	2·7	8·6	2·35	8·3	2·02	-2·3	-13·0	-5·7	-17·8

METHOD 1 — The Equations of the Analysis.

METHOD 2 — The Equivalent yield Stress method.

ERRORS. — Based on the measured values.

MATRIX : 0.026 in. .71% C. STEEL $R_o = 2.2$ in.

CLAD : 2 X .029 MILD STEEL $\mu = .14$

TABLE 9

TEST NO	MEAN REDUCTION % OF THE SANDWICH	MEASURED ROLL FORCE Tonf/in	MEASURED ROLL TORQUE Tonf in/in	CALCULATED METHOD 1 ROLL FORCE TONf/in	CALCULATED METHOD 1 ROLL TORQUE TONf in/in	CALCULATED METHOD 2 ROLL FORCE TONf/in	CALCULATED METHOD 2 ROLL TORQUE TONf in/in	ERROR % METHOD 1 ROLL FORCE	ERROR % METHOD 1 ROLL TORQUE	ERROR % METHOD 2 ROLL FORCE	ERROR % METHOD 2 ROLL TORQUE
1	16.0	7.5	1.18	7.2	1.07	7.2	1.08	-4.0	-9.3	-4.0	-8.5
2	19.0	8.5	1.50	8.2	1.35	8.1	1.38	-3.5	-10.0	-4.7	-8.0
3	23.5	9.9	2.0	9.7	1.90	9.5	1.83	-2	-5.0	-4.1	-8.5
4	27.7	11.3	2.46	11.1	2.31	10.8	2.25	-1.8	-6.1	-4.4	-8.5
5	30.0	12.0	2.70	11.7	2.59	11.5	2.48	-2.5	-4.1	-4.2	-8.2
6	34.5	13.5	3.2	13.3	3.07	13.0	2.93	-1.5	-4.1	-3.7	-8.5
7	37.0	14.3	3.47	14.0	3.30	13.8	3.17	-2.1	-4.9	-3.5	-8.7

METHOD 1 The Equations of the Analysis

METHOD 2 The Equivalent yield stress method

ERRORS: Based on the measured values.

TABLE 10

MATRIX: 0.047 in. STAINLESS STEEL $R_o = 2.25$ in

CLAD : 2 x 0.029 in. MILD STEEL $\mu = 0.14$

TEST NO.	MEAN REDUCTION % OF THE SANDWICH	MEASURED		CALCULATED				ERROR %			
				METHOD 1		METHOD 2		METHOD 1		METHOD 2	
		ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE	ROLL TORQUE	ROLL FORCE	ROLL TORQUE
1	15.0	7.2	.83	7.2	.96	7.3	1.18	+0	+15.7	+1.4	+42
2	19.3	8.8	1.43	9.1	1.60	9.2	1.78	+3.4	+11.9	+4.6	+24.6
3	24.0	10.5	2.06	10.7	2.30	11.0	2.42	+1.9	+11.7	+4.8	+17.5
4	27.5	11.8	2.54	12.2	2.73	12.5	2.90	+3.4	+7.9	+5.9	+14.2
5	31.0	13.0	3.01	13.4	3.26	13.8	3.40	+3.1	+8.3	+6.2	+13.0
6	34.6	14.3	3.50	14.8	3.78	15.4	4.01	+3.5	+8.0	+7.7	+12.7
7	36.5	15.0	3.76	15.7	4.12	16.3	4.30	+4.7	+9.6	+8.0	+11.3

METHOD 1 — The equations of the analysis.

METHOD 2 — The equivalent yield stress method.

ERRORS. — Based on the measured values.

MATRIX : 0.029 in. MILD STEEL — R_a = 2.25 in

CLAD : 2 × 0.049 in ALUMINIUM — μ = 0.11 in

TABLE 11

TEST NO	MEAN REDUCTION % OF THE SANDWICH	MEASURED VALUES		CALCULATED VALUES: MEAN YIELD STRESS				VARYING YIELD STRESS			
				METHOD 1		METHOD 2		METHOD 1		METHOD 2	
		ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE TON f/in	ROLL TORQUE TON f in/in	ROLL FORCE	ROLL TORQUE	ROLL FORCE	ROLL TORQUE
1	12.0	2.1	0.39	2.1	0.36	2.0	0.32	0.37	0.36	2.1	0.33
2	15.5	2.45	0.56	2.3	0.51	2.1	0.46	2.4	0.50	2.1	0.46
3	21.5	2.95	0.86	2.8	0.79	2.7	0.70	3.0	0.81	2.8	0.73
4	27.0	3.5	1.13	3.4	1.05	3.2	0.91	3.4	1.10	3.3	0.94
5	33.0	4.2	1.43	4.0	1.32	3.8	1.15	4.2	1.35	3.9	1.20
6	36.5	4.6	1.60	4.4	1.44	4.1	1.30	4.5	1.45	4.3	1.33
7	38.7	4.9	1.71	4.6	1.56	4.3	1.40	4.9	1.58	4.5	1.45

CALCULATION OF THE EFFECT OF TENSIONS		TABLE 12			
MATRIX: 0.031 in. MILD STEEL R = 2.25"		AVERAGE PASS REDUCTION %			
CLAD: 2 x 0.032 in COPPER. μ=0.11		18	24	30	36
FRONT TENSION = 0, BACK TENSION = 0	ROLL FORCE Ton f/in		5.9	7.0	8.0
	ROLL TORQUE Ton f in/in		1.25	1.65	2.05
FRONT TENSION = 2, BACK TENSION = 0	ROLL FORCE Ton f/in	—	5.8	6.8	—
	ROLL TORQUE Ton f in/in	—	0.91	1.34	—
FRONT TENSION = 0, BACK TENSION = 2	ROLL FORCE Ton f/in.		5.5	6.5	7.5
	ROLL TORQUE Ton f in/in		1.57	1.94	2.32
FRONT TENSION = 4, BACK TENSION = 0	ROLL FORCE Ton f/in	4.6	5.6	6.6	7.6
	ROLL TORQUE Ton f in/in.	—	0.57	1.07	1.48
FRONT TENSION = 0, BACK TENSION = 4	ROLL FORCE Ton f/in	4.2	5.1	6.1	6.9
	ROLL TORQUE Ton f in/in	—	1.89	2.24	2.59
FRONT TENSION = 6, BACK TENSION = 0	ROLL FORCE Ton f/in	4.3	5.3	6.4	7.4
	ROLL TORQUE Ton f in/in	—	0.22	0.70	1.18
FRONT TENSION = 0, BACK TENSION	ROLL FORCE Ton f/in	3.6	4.6	5.5	6.4
	ROLL TORQUE Ton f in/in	—	2.20	2.50	3.46

the measured values, compared with 15 percent for the values computed by the equivalent yield stress method. (equation (15.27)). The agreement between the roll torque values computed by both methods, and measured values is not so good, particularly for the stainless steel sandwich. (Table 10).

In order to estimate the contribution of the use of mean yield stress values to the errors, some of the calculations were repeated, using both methods of calculation and the distribution of the yield stress along the arc of contact. The results are given in Table 11 and appear to agree more closely with measured values in both cases. However, since the arc of contact was small, it was difficult to determine the yield stress at points along the arc of contact, particularly in the exit zone of the arc where work-hardening is usually small, and slight errors incurred in the process may have affected the results.

It was not possible to take into account in the determination of the stress-strain curves, the possible effect of the strain rate on the yield stress, because the facilities were not available. The consistently low results obtained from the calculations may be partly due to strain rate effect.

Graphs 72 to 75 show the results of the

calculations carried out to determine the validity of the interpolation method of estimating the roll force and torque in sandwich rolling described in section 15.5. It is clear from the graphs that the method is reasonably valid for the roll force, for pass reductions above about 30 percent. It is valid also for the roll torque for the two reductions investigated.

Since the effect of tension on the roll force and torque in sandwich rolling could not be investigated fully because of the difficulties outlined previously, it was decided to carry out some theoretical calculations using equation (15.24) and the computer programme 1. The results are shown in Table 12. The results support the previous conclusion that the effect of tensions on the roll force and torque is similar to the effect in conventional cold rolling with applied tensions.

15.8. A discussion on the theoretical analysis.

The equations developed in the analysis have been shown to predict the roll force to within 7 percent of the measured values. Agreement between measured and calculated values of the roll torque is less good possibly because the torque values were small for most of the cases investigated and slight errors in the measured or calculated results would have an exaggerated effect on the results. The equivalent yield stress method yields results which agree with the measured values to within about 15 percent. The agreement for the roll torque is poor, probably for the same reason given previously .

The analysis has shown that the optimum value of clad proportion which gives the lowest roll separating force cannot be predicted easily, but the best proportion is probably between 50 and 70 percent, depending on the frictional conditions at the tool-workpiece interface, the disparity in the strengths of the component materials, and the geometry of the arc of contact. It has been shown experimentally in sections 14.3 and 14.4 that an optimum value does not always exist in sandwich rolling.

The method of calculating the roll force and torque in sandwich rolling by interpolating between the roll force and torque developed when the clad and matrix materials of the same thickness as the sandwich are rolled separately, has been shown to be reasonably valid, particularly when the pass reduction is above about 30 percent.

16. CONCLUSIONS.

16. CONCLUSIONS.

The results of the experimental investigation have shown that a considerable reduction in the roll separating force can be achieved when a hard metal is rolled between layers of softer metal, particularly when the hard metal is thin also. The magnitude of the reduction in the load depends principally on the relative strength and thickness of the clad with respect to the hard matrix. The softer the clad, the greater the reduction in the roll separating force, the limit being when the deformation is restricted to the soft metal and the hard matrix emerges from the roll gap undeformed. In general, the roll force decreases as the proportion of the clad material in the sandwich increases. However, for some material combinations, an optimum clad proportion which gives the lowest roll separating force may exist. Beyond this proportion, the roll force starts to increase. The optimum proportion of clad is probably between 60 and 70 percent. Also, the roll force may be higher for a material rolled between softer clads than for the same material rolled without cladding. This probably occurs when the matrix is not sufficiently harder than the clad.

The greatest reduction in the roll force is achieved for the thinnest, but not necessarily the hardest matrix metal . This is not surprising since, in addition to the tensile stresses induced in the hard metal as a result of the tendency for the softer material to deform more readily, roll flattening is reduced as a result of an increase in the overall thickness of the workpiece due to cladding. Furthermore, the friction at the roll-clad interface may be reduced, since the softer metal tends to behave like a solid lubricant. Both roll flattening and friction are usually ost significant in the rolling of thin strip.

The reduction in the roll force and roll flattening due to cladding, enable reductions to be achieved than would be possible without cladding. However, the roll torque usually increases as a result of cladding and also as the clad thickness increases. Consequently, the capacity of the mill drive may determine the maximum reduction which can be achieved. In certain cases, the roll torque may decrease as a result of cladding. Also, there may be an optimum clad proportion which gives the lowest increase (or highest reduction) in the roll torque. The optimum proportion is not necessarily the same for the roll force and torque.

The clad does not have to be a metal. The results of this investigation show that a considerable reduction in the roll force and torque can be achieved with plastic clads. This may be very important from the economic point of view, since the clad is usually discarded after use, and plastic may be cheaper than most of the conventional clad materials. Economic considerations may also determine the choice of the clad material, when it is a metal. A greater reduction in the roll separating force can be achieved with aluminium or copper clads than with mild steel clads. However, since mild steel is cheaper than the other metals, it may be used in preference.

From the theoretical point of view, a reduction in the roll force can be achieved also, when the positions of the hard and soft materials in the sandwich are interchanged, so that the harder material constitutes the clad. The results of the investigation show that the roll force is higher when the harder metal constitutes the clad than when it is rolled individually. However, since only two material combinations were investigated, the results are inconclusive and a reduction in the roll force may be achieved for other metal combinations.

The clad-matrix interface frictional condition is important in sandwich rolling because it determines in part, the tensile stresses induced in the harder metal. The best interface condition was found to be when the interfaces were polished and degreased. This is probably because the tendency for the layers to weld is high.

The tendency for the harder metal constituting the matrix to edge-crack is greater than when the metal is rolled without cladding because of the non-uniform distribution of tensile stresses at the clad-matrix interface in the former case. Edge-cracking can be reduced or even eliminated by using clads which are slightly wider than the matrix, provided the disparity in the strengths of the hard and soft materials is not too great. If the clad is too wide compared with the matrix, a distortion in both may occur.

The application of tensions in sandwich rolling is difficult. The sandwich may be assembled before it is wound on the decoiler drum, and coiled on the same drum after rolling or, alternatively, the layers are wound on three separate decoiler drums and, after rolling, on three separate coiler drums. In either case, the dificulties are immense and the results of this investigation show that the reduction in the roll force due to applied tensions may not be significant. Furthermore, the greatest potentiality of sandwich rolling is for the production of thin wide sheets of difficult metals where the application of tension is difficult.

The equations of the roll force developed in the theoretical analysis of sandwich rolling have been shown to predict the roll force to within 7 percent of measured values, compared with 15 percent for the equivalent yield stress method. The agreement between the roll torque calculated by both methods, and measured values is poor. The application of the equations developed in the analysis is difficult, compared with the equivalent yield stress method or the interpolation method. The last two methods may be used when the roll force and torque do not need to be known accurately, or when a computer is not available.

The major advantages of sandwich rolling are summarised below:

(1) A reduction in the roll separating force is achieved.

(2) A higher pass reduction can be achieved than is possible without cladding.

(3) The sandwich rolling technique enables wide sheets of difficult metals to be rolled on existing conventional rolling mills.

(4) There is less roll damage since the soft clad acts as a cushion. Furthermore, small fragments which break-off often during the rolling of hard sheets, are retained in the clad envelope and prevented from damaging the rolls or the following sheets.

The disadvantages are:

(1) The clad is usually discarded after use.

(2) Considerable preparations are necessary before rolling.

(3) The surface finish of the hard material is poor. Usually this can be improved by giving the hard metal a subsequent skin pass reduction.

17. SUGGESTIONS FOR FURTHER WORK.

17. SUGGESTIONS FOR FURTHER WORK.

It was stated previously that one major disadvantage of the sandwich rolling process is the fact that the clad is discarded after use. For this reason, the technique may be found to be uneconomic except for the production of some special alloys on a small scale. The field of applications can be increased considerably if a cheap clad material can be found. The results of the experiments with plastic clads are sufficiently encouraging to justify further research. The major problem is finding the right plastic from the wide range available and this can be done only by rolling trials.

During this investigation, it was found that there was considerable metal transfer between the component metals of the sandwich. This was particularly obvious when copper was one of the components. Occlusion may not pose any serious metallurgical problems for non-ferrous metals, since annealing, shot blasting and pickling will get rid of most of the particles from the surface of the hard metal. There may be no problems also when the clad and matrix are ferrous. However, an investigation of the possible implications of metal transfer may be worthwhile.

The results of the investigation of edge-cracking in one-inch wide strips may not be strictly valid for wider sheets. Furthermore, a more comprehensive investigation of the effects on edge-cracking, of such factors as the matrix:clad width, hardness and thickness ratios, and the matrix:clad interface frictional conditions, is desirable.

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20. APPENDICES.

20. APPENDICES.

20.1. Description of the rolling mill.

The general lay-out of the rolling mill is shown in figure 39. The mill was designed in four units consisting of the roll housing and platform, and three drive lines for the rolls, coiler and decoiler. The sections were bolted together.

The design of the housing is shown in figures 40 and 41. All the parts were made from mild steel except the screws which were made from Vibrac 45 alloy steel.

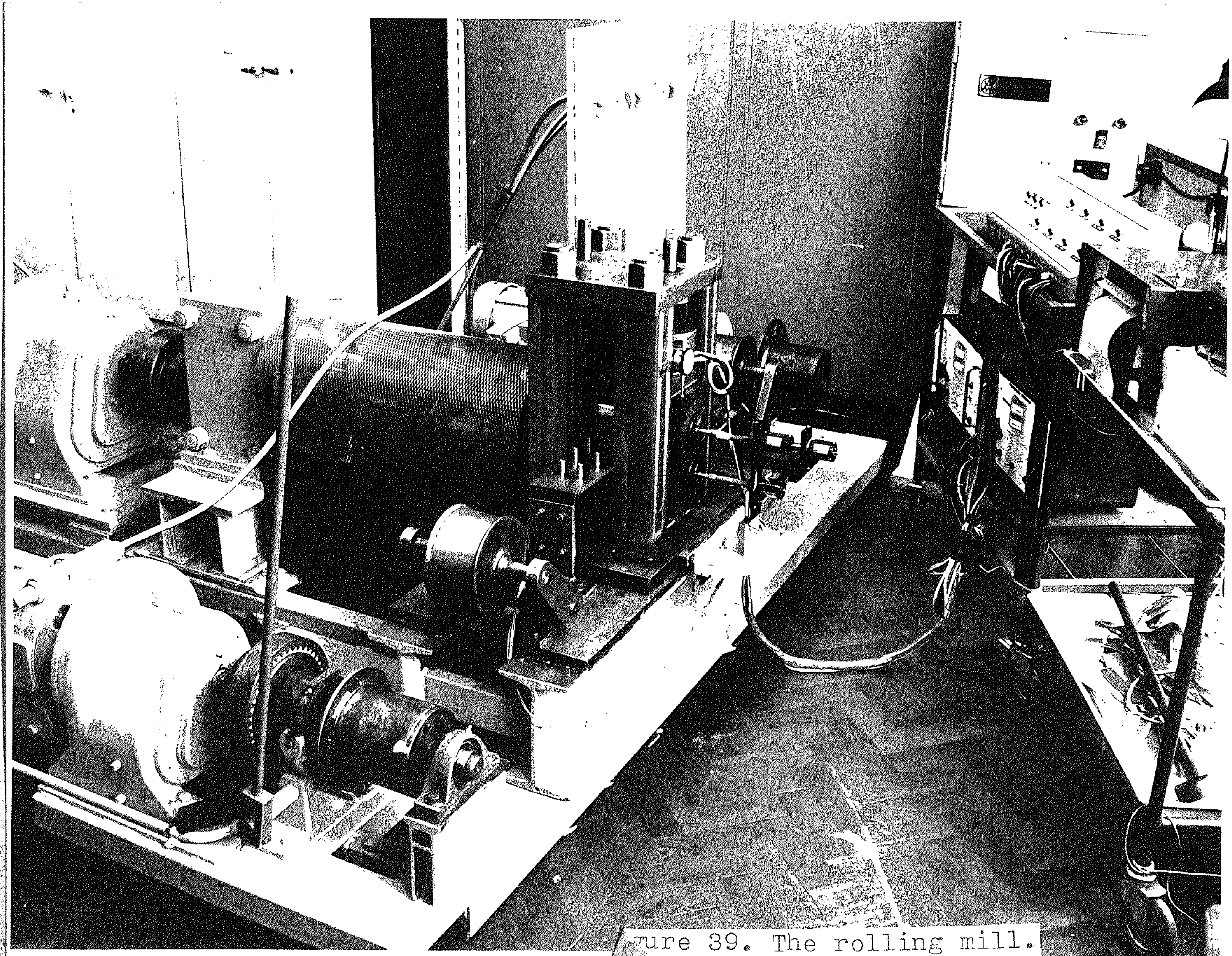
The main drive consists of a 7.5 horse power motor-Kopp variator unit and a reduction gear box. The speed range is 6 to 54 revs/min. . The drive is split into two by a Hille 25 pinion box incorporating two double helical 1:1 ratio steel gears running in bronze bearings and splash lubricated. The dimensions are shown in figure 42. The rolls are driven from the pinion box through two short universal shafts and torque meters shown in figure 43. The universal shafts are the Series K. 1510 supplied by Hardy Spicer Ltd. The chucks incorporating roller bearings, and also the rolls were designed by Quaiser[124]. The rolls are shown in figure 44.

The coiler drive consists of a 5 horse power

Size 20 Kopp variator unit with flange mounted gear box. The output speed range is 9 to 54 revs./min. . A 7-in. diameter coiler drum is mounted on the gear box shaft.

The decoiler drive consists of a 3.5 horse power Size 18 variator unit also with flange mounted gear box and a speed range of 9 to 54 revs./min. . The gear box shaft is connected to a 6.4 in. diameter decoiler drum through a manual clutch shown in figure 45.

All the Kopp variator units were supplied by All Speeds Ltd. and have mechanical remote controls controls which were installed on a panel near the mill stand.



gure 39. The rolling mill.

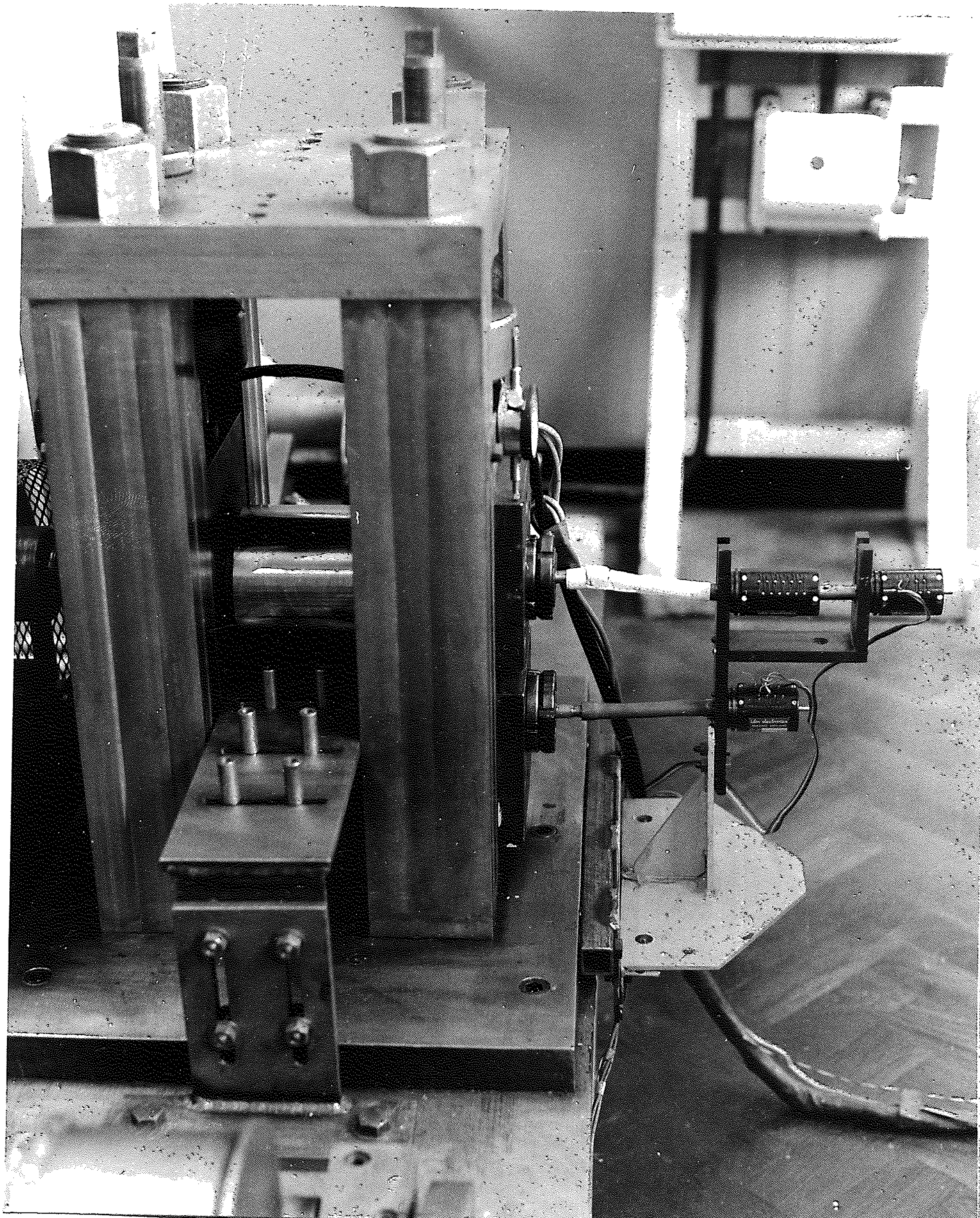


Figure 40. The mill housing.

FIGURE 41. DESIGN OF THE MILL HOUSING.

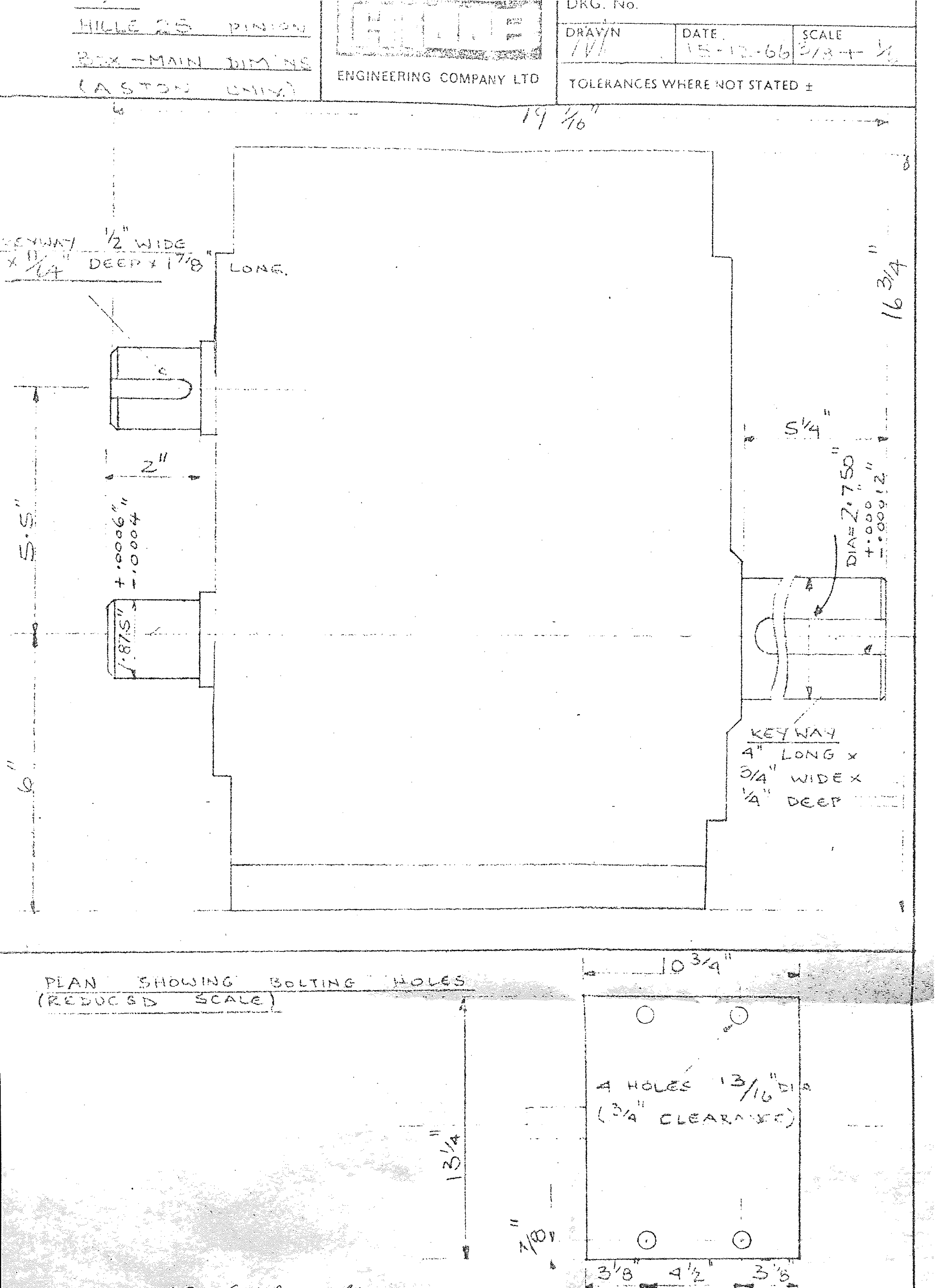


FIGURE 42. THE PINION BOX

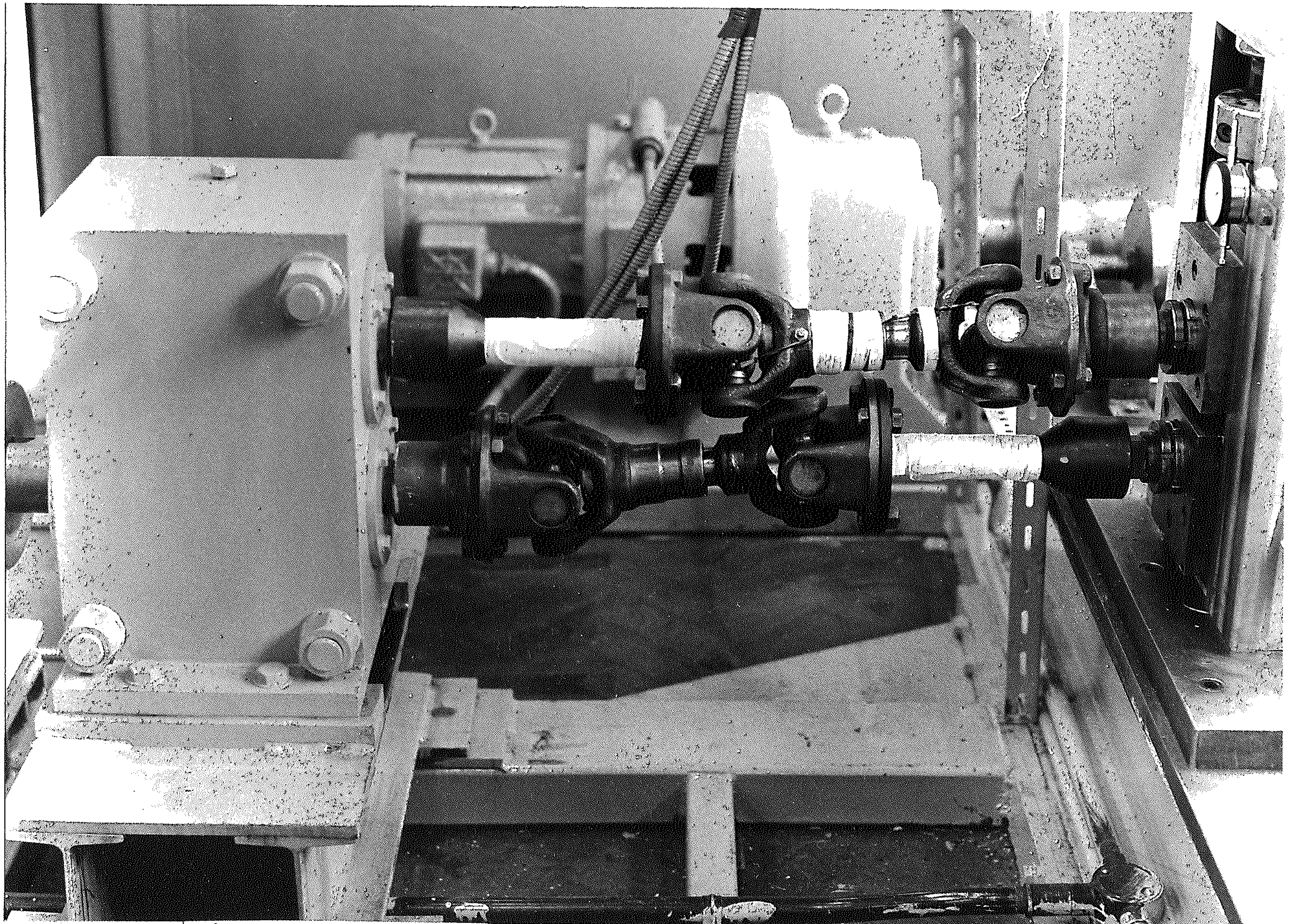


Figure 43. The universal shafts in position.

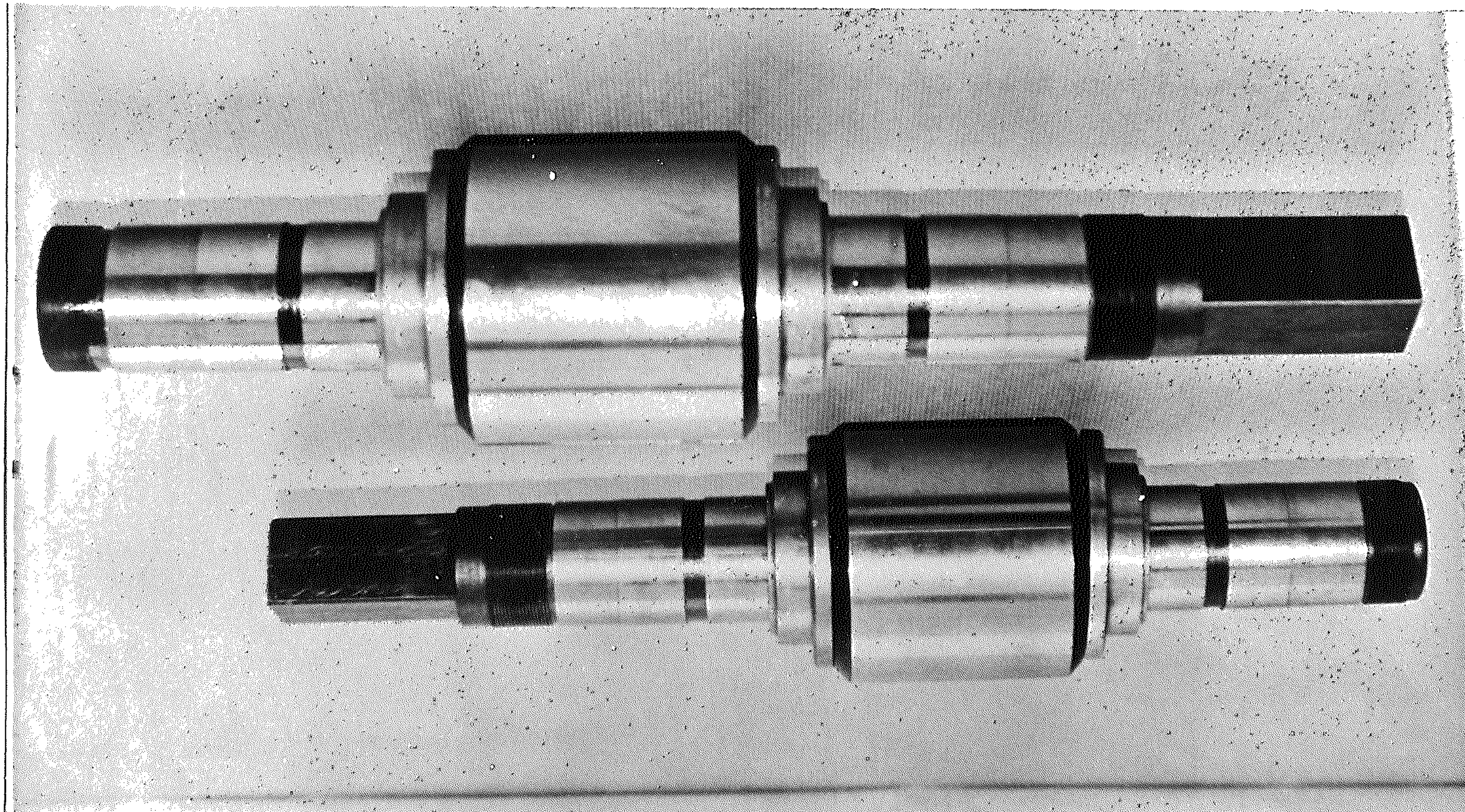


Figure 44. The rolls.

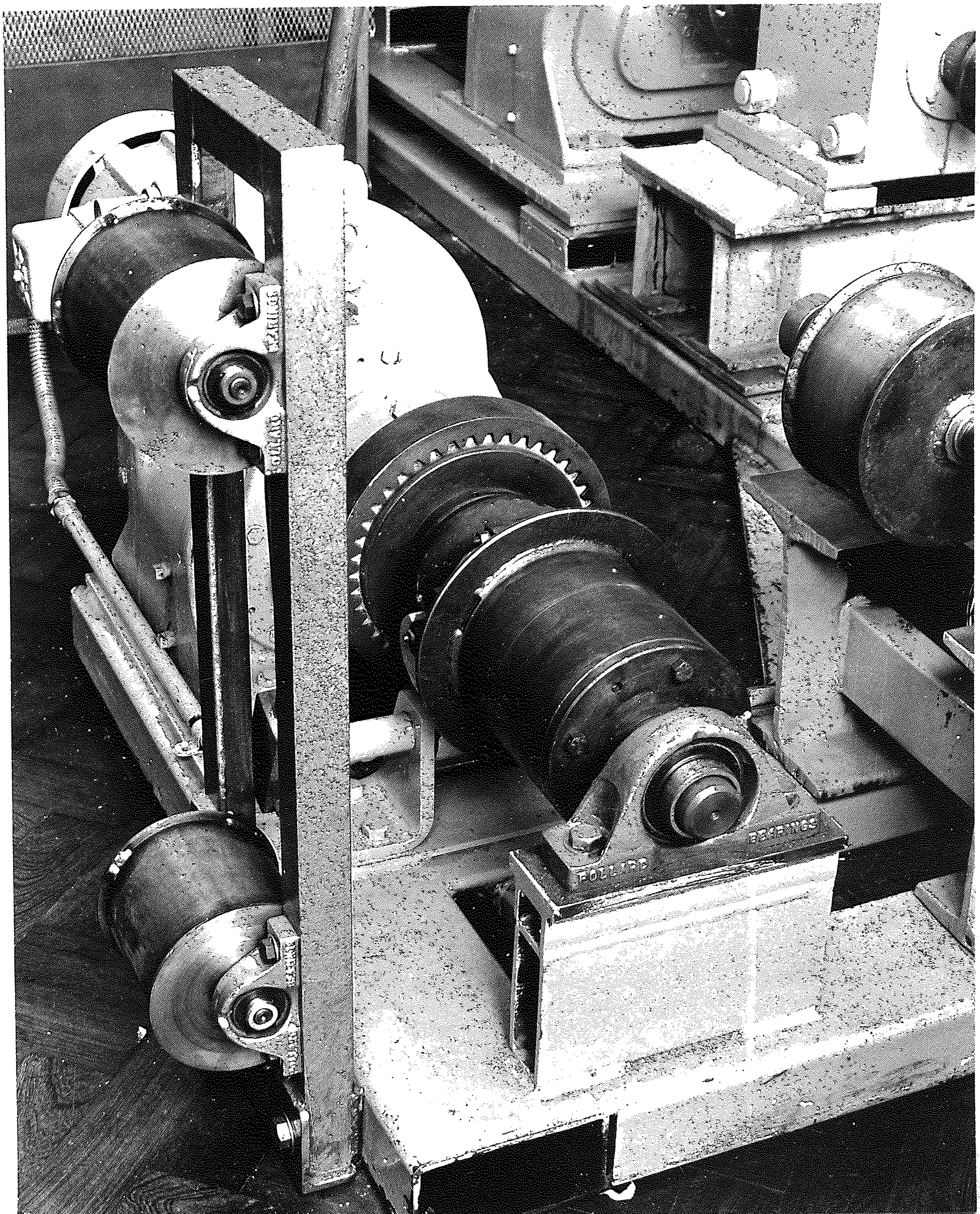


Figure 45. The decoiler clutch.

20.2. MATERIAL AND EQUIPMENT SPECIFICATIONS.

20.2. Material and Equipment Specifications.

20.2.1. Materials.

Vibrac 45 Alloy Steel (for the measuring meters.)

Carbon	0.038 to 0.045 %
Nickel	2.30 to 2.80 "
Chromium	0.50 to 0.70 "
Molybdenum	0.55 to 0.65 "
Silicon	0.30 max.
Manganese	0.05 to 0.70 "

Heat treated at 850°C. for 30 minutes, quenched in oil and tempered at 150°C. for one hour.

V. M. C. Steel (for the 4.5 in. dia. rolls.)

Carbon	0.32 to 0.37 %
Manganese	0.40 to 0.50 "
Silicon	0.80 to 1.2 "
Chromium	4.75 to 5.25 "
Molybdenum	1.30 to 1.70 "
Vanadium	0.90 to 1.10 "

Salt bath hardened from 1020°C. to 570°C. Tripple tempered at 580°C., 600°C., and 610°C.

Supplied by Walter Somers Ltd.

SIC 99% Commercial Purity Aluminium.

Aluminium	99	% min.
Copper	0.1	" max.
Silicon	0.5	" "
Iron	0.7	" "
Manganese	0.1	" "

Annealed condition.

Oxygen free High Conductivity Copper.

Copper	99.5	% min.
Lead	0.005	" max.
Bismuth	0.001	" "

0.03% impurities excluding oxygen and silver.

Aluminium Killed Mild Steel

Carbon	0.07	% max.
Sulphur	0.025	" "
Phosphorus	0.015	" "
Manganese	0.2/0.4	"
Nickel	0.10	" "
Copper	0.10	" "
Tin	0.020	" "
Soluble aluminium	0.03/0.06	wt.%
Silicon	Nil.	

Austenitic Stainless Steel.

Quality SF 304 (19% Cr./ 10% Ni.)

Softened and descaled.

Supplied by Samuel Fox and Co. Ltd.

1.25 % C. Steel.

Carbon	1.25	%	
Manganese	0.30	%	
Silicon	0.22	"	
Sulphur	0.015	"	max.
Phosphorus	0.025	"	"
Nickel	0.15	"	"
Chromium	0.24	"	
Copper	0.15	"	"

In lightly cold rolled condition.

0. 71 % C. Steel

Carbon	0.71	%
Silicon	0.26	"
Manganese	0.60	"
Sulphur	0.009	
Phosphorus	0.009	"

Supplied by J. B. S. Lees Ltd.

Nimonic Alloys.

	N.80	N.90	N.105
Carbon	0.10 % max.	0.13 % max.	0.2 % max.
Silicon	1.0 " "	1.5 " "	1.0 " "
Copper	0.2 " "	-	0.5 " "
Iron	3.0 " "	3.0 " "	2.0 " "
Manganese	1.0 " "	1.0 " "	1.0 " "
Chromium	18/21 %	18/21 %	13.5/15.75 %
Titanium	1.8/2.7 %	1.8/3.0 %	0.9/1.5 %
Aluminium	1.0/1.8 %	0.8/2.0 %	4.5/4.9 %
Cobalt	2.0% max.	15.0/21.0 %	18.0/22.0 %
Boron	0.008% max.	-	-
Tin	0.015% max.	-	-
Lead	-	0.005% max.	0.005% max.
Molybdenum	-	-	4.5/5.5 %
Nickel	B A L A N C E .		

Plastic.

(1) Marley floor tiles.

(2) Cycolac Supplied by M. C. M. (tools) Ltd.

20.2.2. Equipment.

Stabilised Voltage Supply.

Thorn Electronics	Type VP 21
Output Voltage	3 - 30 d.c. continuously variable.
Output Current	Up to 1 amp.
Output impedance	- d.c. less than 0.01 ohm.
	a.c. less than 0.3 ohm at 10×10^3 c/s
Ripple	Less than 2 millivolt peak to peak.
Mains variation	Up to ± 10 % from nominal permissible.

Direct Recording Ultra-Violet Recorder.

Southern Instruments. Type M 1300

Channel	10
Galvanometer	Miniature tubular Series SM1
Maximum deflection	6 in. (152 mm).
Paper Speed	0.15 to 100 ins./sec.
Speed stability	Better than ± 5 %

Slip Ring Assemblies.

Current rating	2.5 amp R. M. S. Max.
Circuit resistance (between slip ring and 2 brushes in parallel)	40 milliohms Max.
Starting torque	0.25 lbf.in. Max.

Slip Ring Assembly contd.

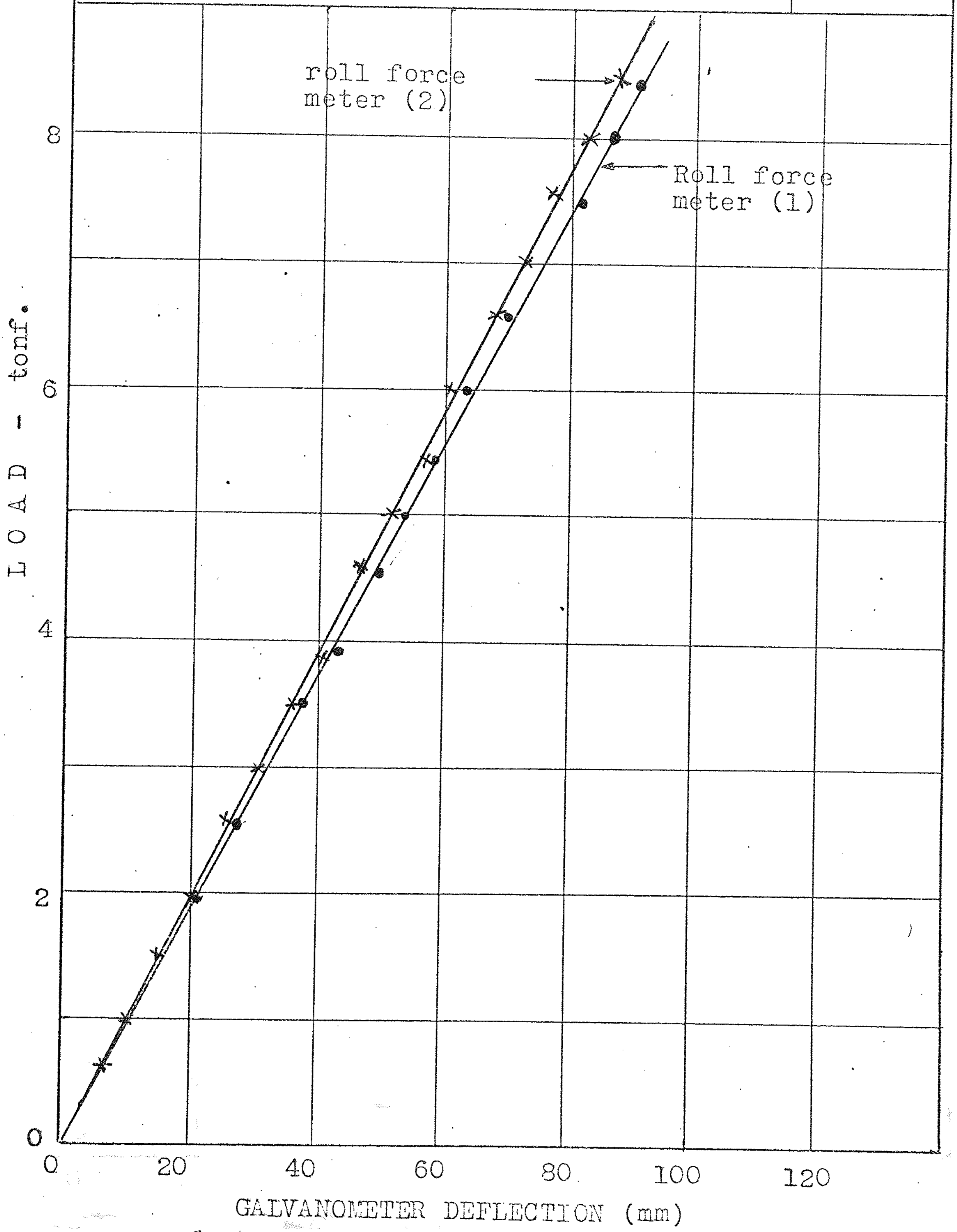
Noise level	Less than 8 micro VoH/milliamp.
Brushes	Silver Graphite.

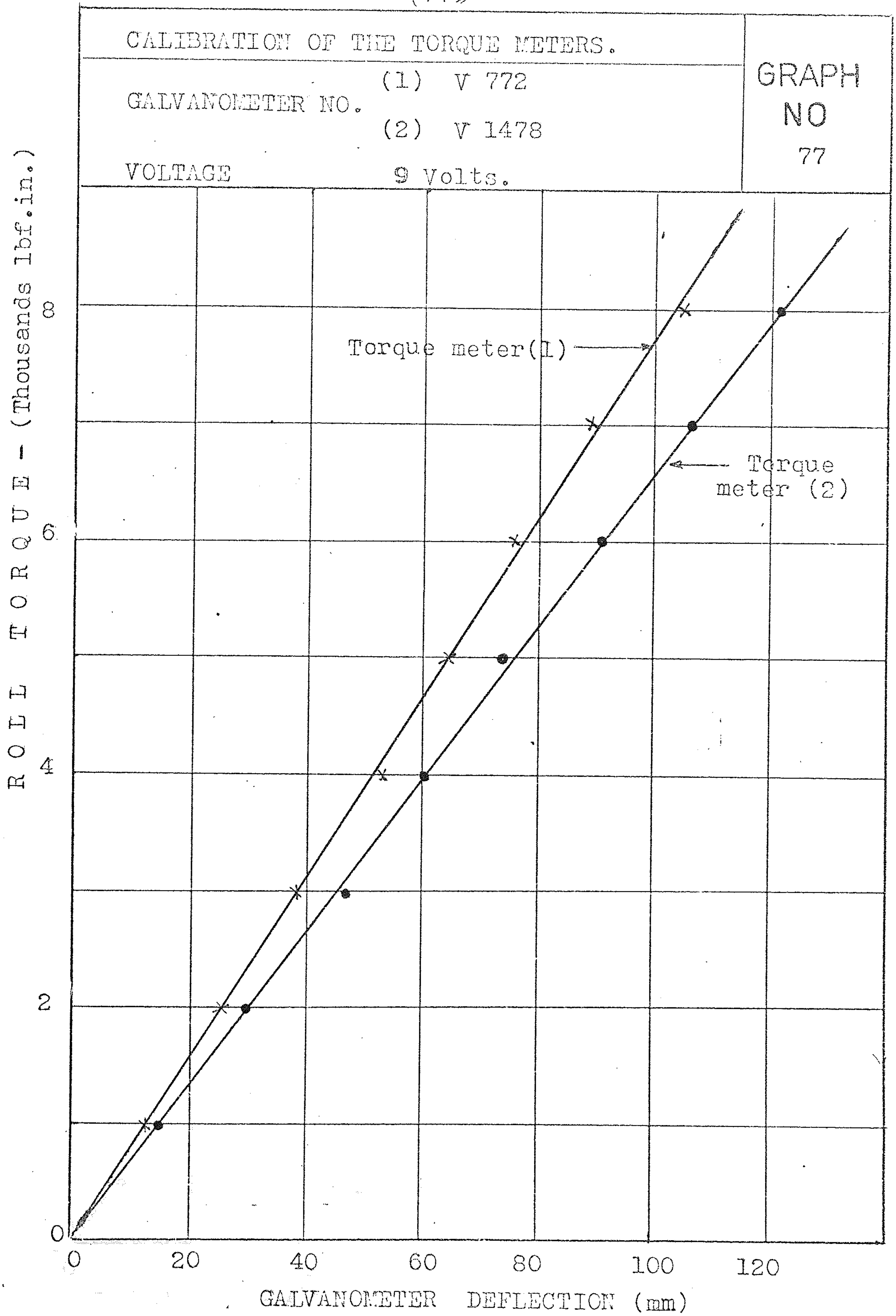
20.3. CALIBRATION CURVES FOR THE MEASURING EQUIPMENT.

CALIBRATION OF THE ROLL FORCE METERS.

GALVANOMETER NO. (1) V 1615
(2) V 1471
VOLTAGE 9 volts.

GRAPH NO 76



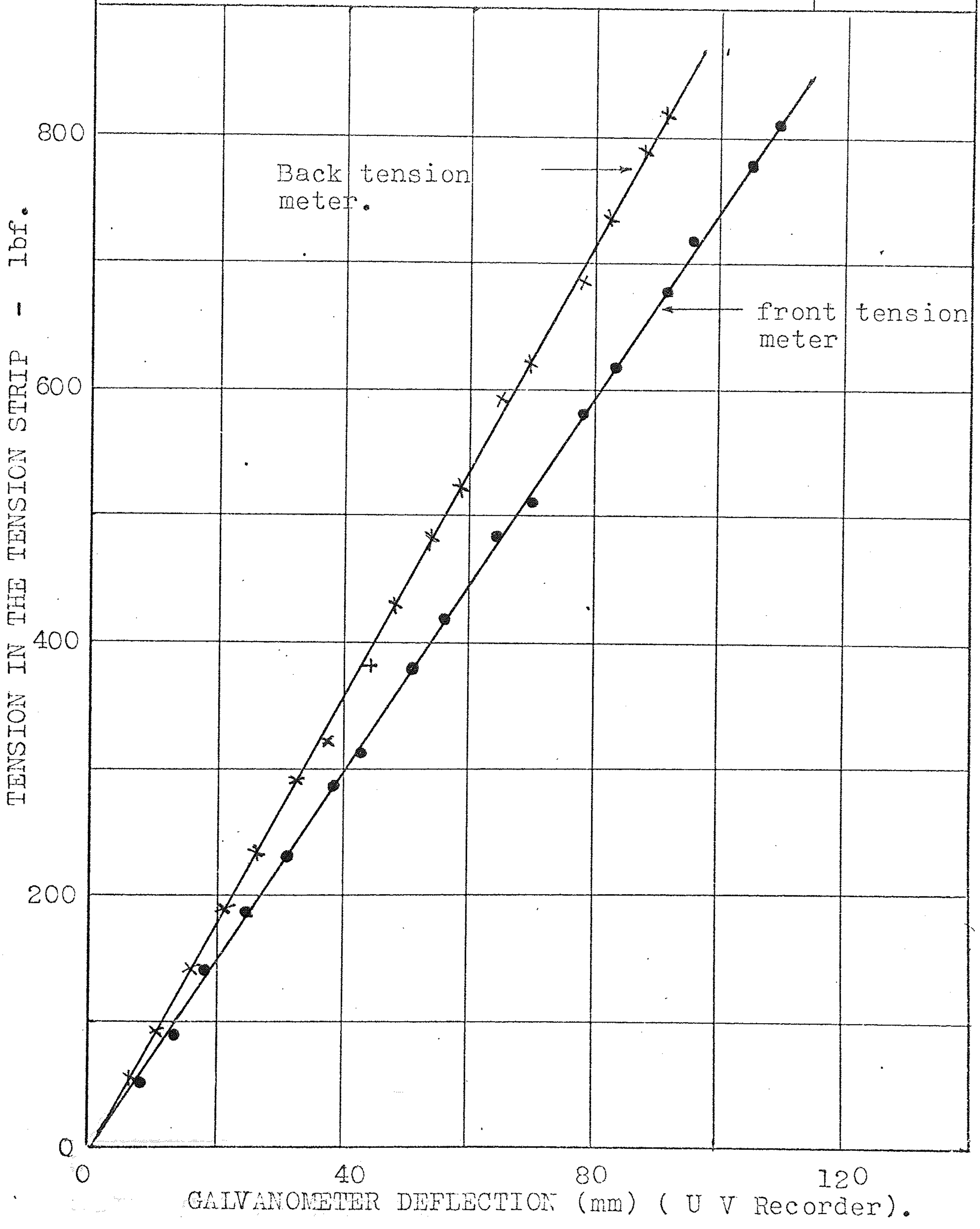

CALIBRATION OF THE TORQUE METERS.
GALVANOMETER NO. (1) V 772
(2) V 1478
VOLTAGE 9 Volts.
GRAPH NO 77
ROLL TORQUE - (Thousands lbf.in.)
0
2
4
6
8
Torque meter(1)
Torque meter (2)
0
20
40
60
80
100
120
GALVANOMETER DEFLECTION (mm)

CALIBRATION OF THE FRONT & BACK TENSION METERS.

GRAPH NO 78

GALVANOMETER NO. Front tension: Z 618
Back tension : Z 621

VOLTAGE 2.8 Volts.



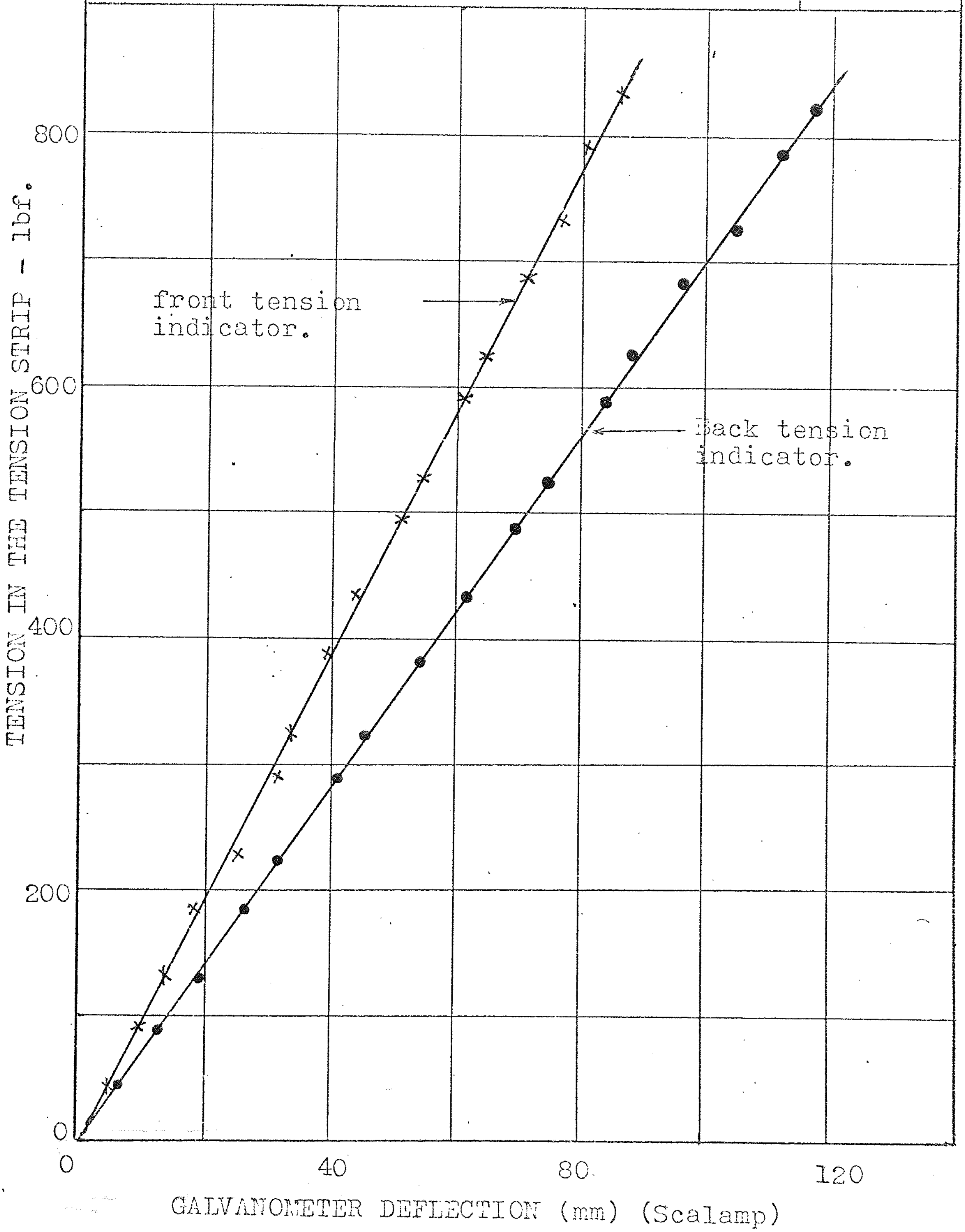
CALIBRATION OF THE TENSION INDICATORS.

Front tension indicator
Back tension indicator

Scalamp Galvanometers 7904/T

VOLTAGE. 9 Volts.

GRAPH NO 79

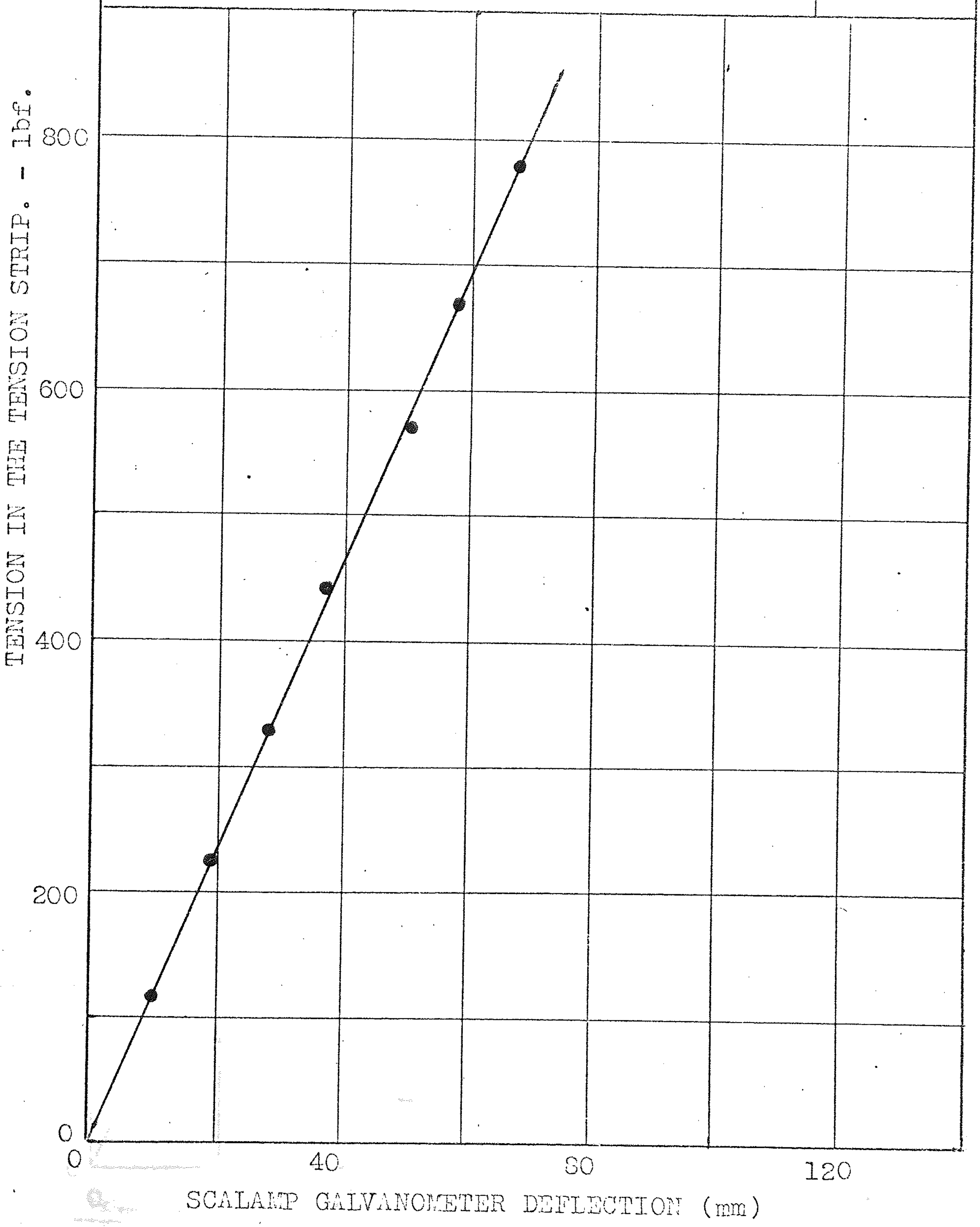


CALIBRATION OF THE TENSION STRIP.

SCALAMP GALVANOMETER 7904/T.

VOLTAGE 10 Volts.

GRAPH NO 80

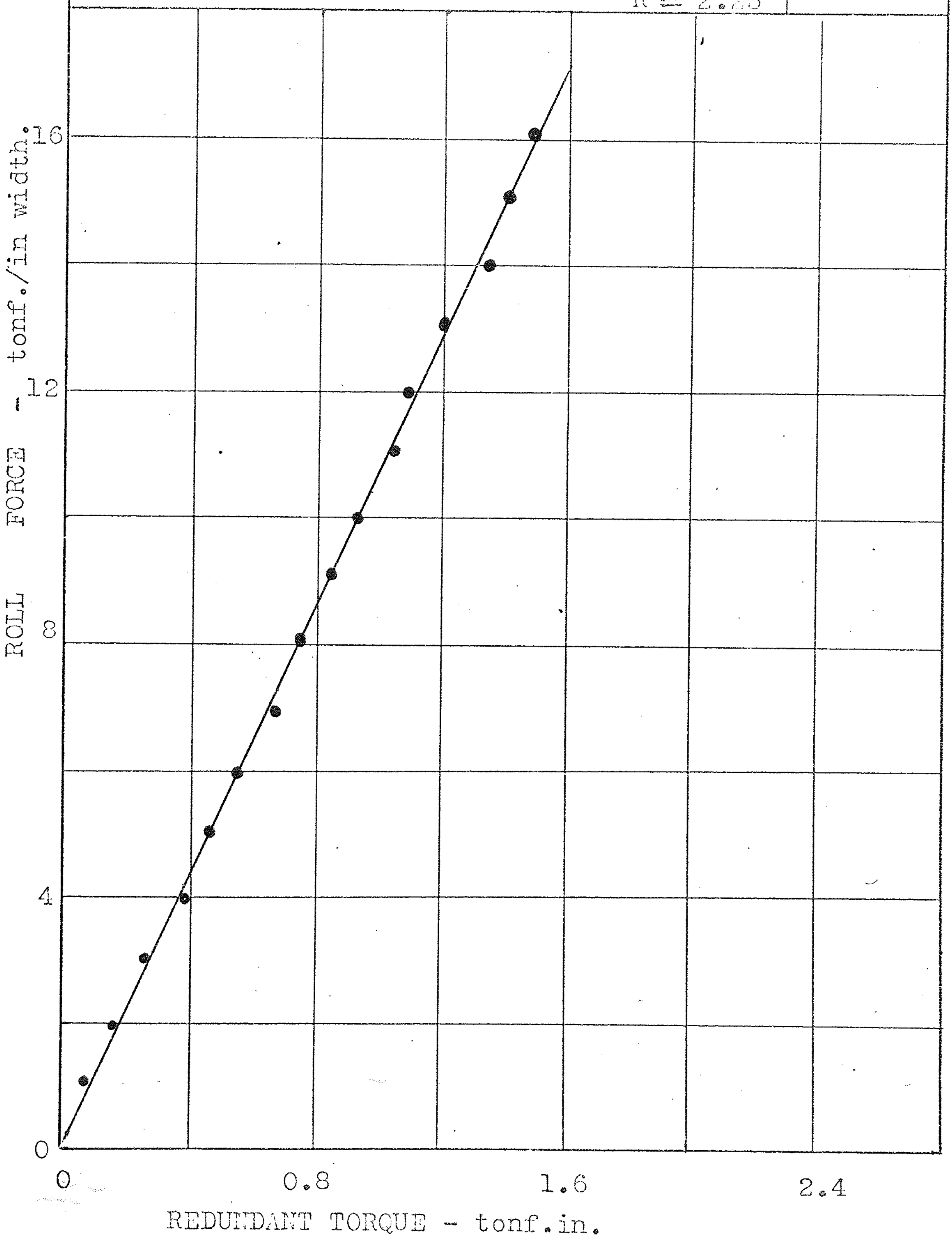


CALIBRATION OF THE MILL FOR REDUNDANT TORQUE.

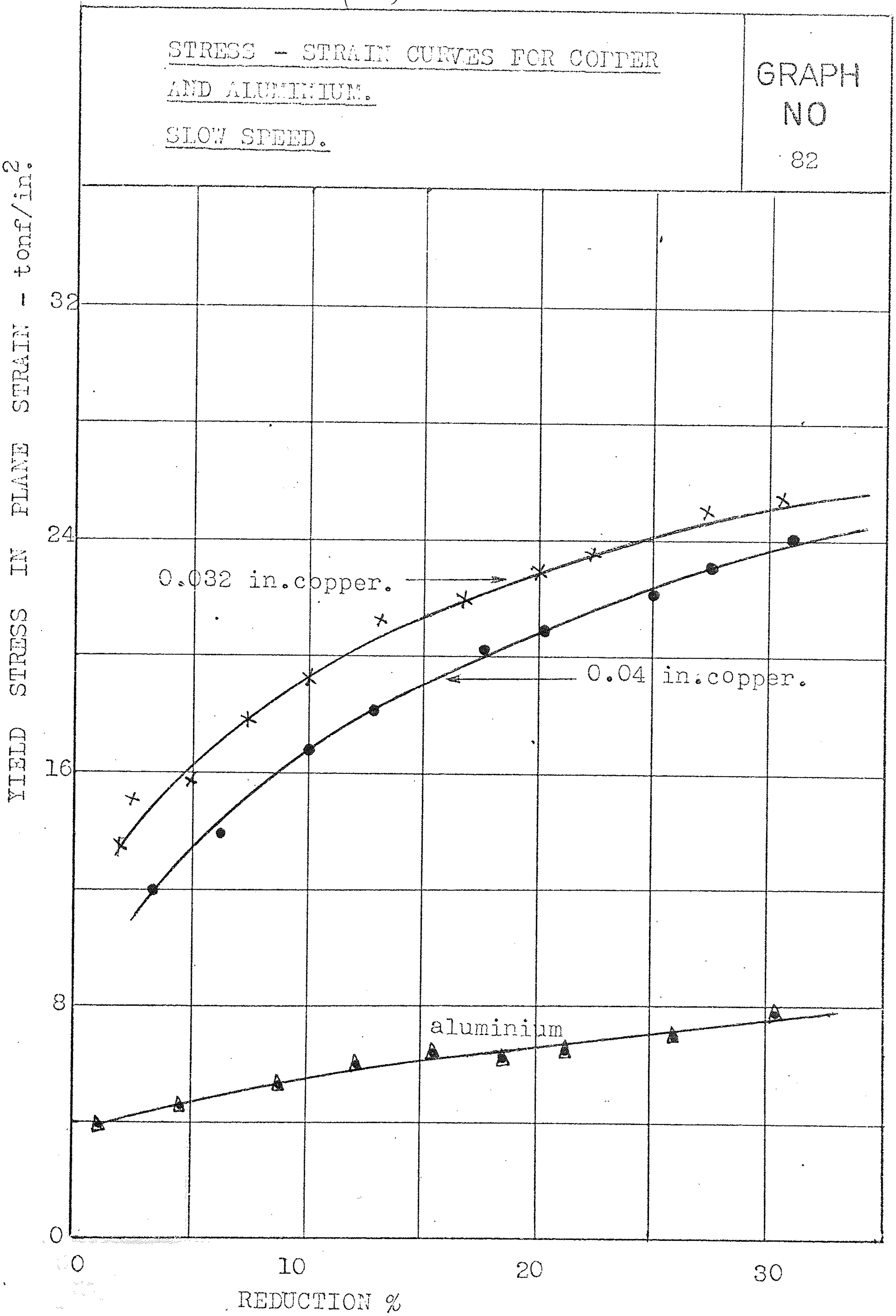
Rolls squeezed together with no strip between.

R = 2.25

GRAPH NO 81



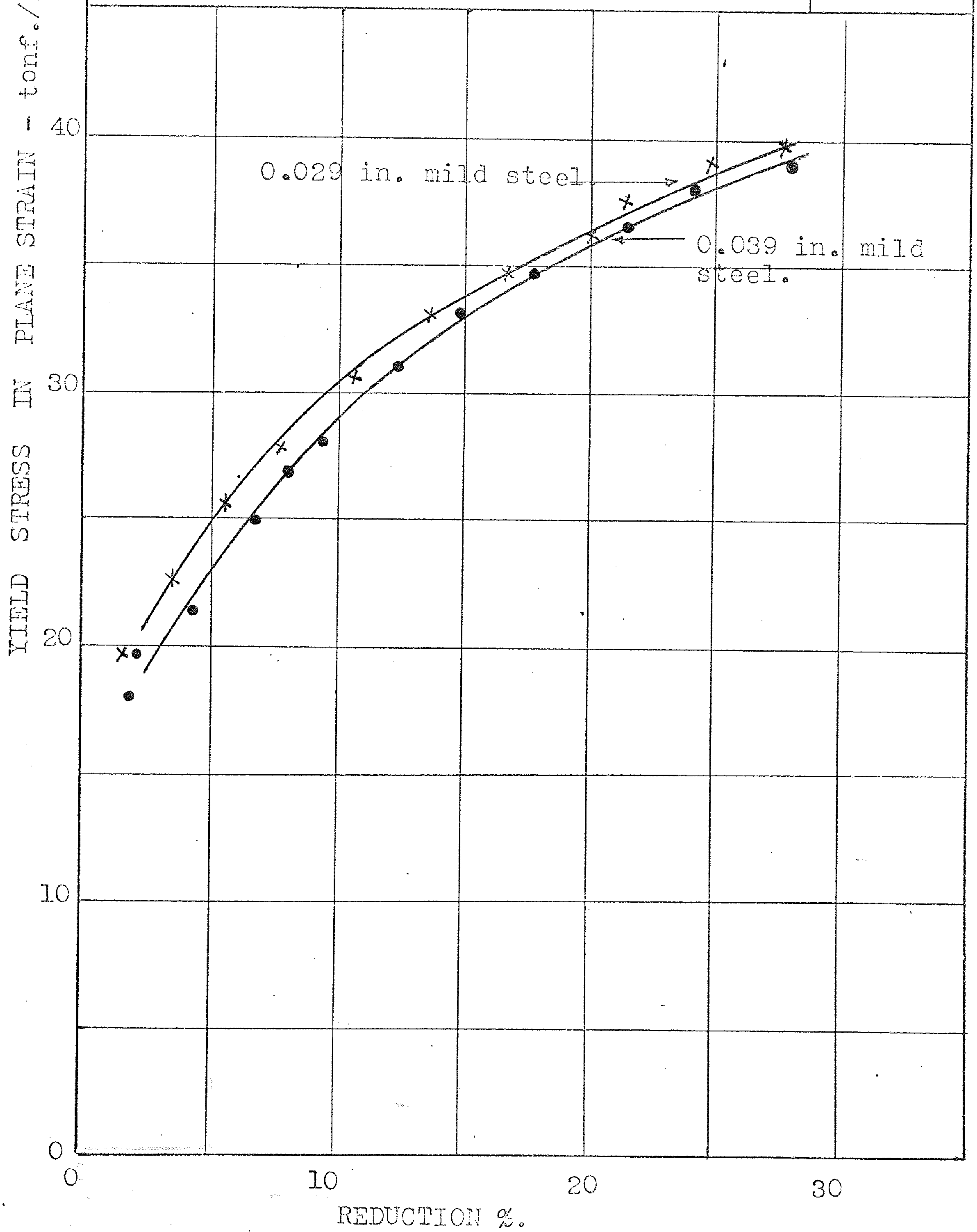
20.4. STRESS - STRAIN CURVES.


STRESS - STRAIN CURVES FOR COPPER AND ALUMINIUM.
SLOW SPEED.
GRAPH NO 82
YIELD STRESS IN PLANE STRAIN - tonf/in.^{2}
0
8
16
24
32
0.032 in.copper.
0.04 in.copper.
aluminium
0
10
20
30
REDUCTION %

STRESS - STRAIN CURVES FOR STABILISED MILD STEEL.

SLOW SPEED.

GRAPH NO 83



20.4. COMPUTER PROGRAMS.

NOMENCLATURE FOR THE COMPUTER PROGRAMS.

MU	The coefficient of friction.
MUMIN	Initial value of the coefficient of friction.
MUINT	Increment of the coefficient of friction.
MUMAX	Maximum value of the coefficient of friction.
THETASTART	Angle of bite at the exit plane of the deformation zone.
PMSTART	Vertical pressure at the exit plane.
KSTAR,KMEAN	Equivalent yield stress of the sandwich.
THETAEND	angle of bite at the entry plane.
H	Step interval for integration.
MAXIMA MINIMA	Values of the angle of bite at which integration from either side of the deformation zone, is to stop.
KM	Yield stress of the hard material.
KC	Yield stress of the soft material.
SIGMAF	Front tension
SIGMAB	Back tension.
CLDPROPA, B	Proportion of clad in the sandwich.
RED	Pass reduction.
PSIEXIT	Angle of bite at the exit zone divided by the coefficient of friction.
PSINEUT	Neutral angle divided by the coefficient of friction.
PSIENTRY	Angle of bite at the entry zone divided by the coefficient of friction.
R	Radius of the deformed arc of contact.
HEX,HEN	Integration intervals at the exit and entry zones of deformation respectively.

PROGRAM 1

```
              RUNGE KUTTA EVALUATION OF SANDWICH ROLLING EQUATION'
BEGIN
COMMENT
THIS PROGRAM EVALUATES THE DIFFERENTIAL EQUILIBRIUM EQN.
OF SANDWICH ROLLING WITH OR WITHOUT TENSION,FOR MEAN YIELD
STRESS VALUES,USING THE RUNGE-KUTTA METHOD OF STEP SOLUTION'

REAL MU,MUMIN,MUINT,MUMAX,THETA,PM,THETASTART,THETAEND,
PMSTART,HO,KSTAR,R,H,HEX,HEN,MAXIMA,MINIMA,K1,K2,K3,K4,KAV,
B,KM,KC,PC,T,SIGMAF,SIGMAB,PEND,RO'
SWITCH S:= L1,L2'
PRINT ££L2S4?  RUNGE KUTTA EVALUATION £L2??'
READ THETASTART,THETAEND,HO,B,KM,KC,R,RO,HEX,HEN,MAXIMA,
MINIMA,MUMIN,MUINT,MUMAX,SIGMAF,SIGMAB'
BEGIN
THETASTART := THETASTART * ARCTAN(1)/45'
THETAEND  := THETAEND   * ARCTAN(1)/45'
  HEX     :=   HEX      * ARCTAN(1)/45'
 HEN      :=   HEN      * ARCTAN(1)/45'
MAXIMA    :=  MAXIMA    * ARCTAN(1)/45'
MINIMA    :=  MINIMA    * ARCTAN(1)/45'
KSTAR := KM - B*(KM - KC)'
PMSTART := KSTAR  - SIGMAF'
PEND := KSTAR - SIGMAB'
PRINT £KC=?,SAMELINE,ALIGNED(2,2),KC,££S4?KM =?,KM,££S4?KSTAR =?,
      KSTAR,££L2??'
PRINT SAMELINE,ALIGNED(2,2),£SIGMAF =?,SIGMAF,££S4?SIGMAB =?,
      SIGMAB'
END'
FOR MU:=MUMIN STEP MUINT UNTIL MUMAX DO
```

```
BEGIN
PRINT ££L2S6? MU=?,SAMELINE, ALIGNED (1,3), MU'
PRINT  ££L2S6? EXIT ZONE£L2??'
PRINT££S4?THETA=£S6?PM=£S6?K1=£S6?K2=£S6?K3=£S6?K4=£S6??,
     £KAV=£S6?PC=£S6? T=£L2??'
THETA := THETASTART'
 PM   := PMSTART'
 H    := HEX'
PRINT PREFIX(££S2??),ALIGNED (2,4),THETA*45/ARCTAN(1),
      PM,££L2??'
L1: K1:= H*(THETA*KSTAR+MU*PM)/(HO/R + ((THETA)**2*0.5))'
   K2 := H*((THETA+(H/2))*KSTAR + MU*(PM+(K1/2)))/(HO/R+
         ((THETA+(H/2))**2*0.5))'
  K3 := H*((THETA+(H/2))*KSTAR+MU*(PM+(K2/2)))/(HO/R+((THETA+(H/2))*
         *2*0.5))'
 K4 := H*((THETA+(H))*KSTAR+MU*(PM+(K3)))/(HO/R+((THETA+(H))**2*
       0.5))'
   KAV := ((K1) + 2*(K2) + 2*(K3) +(K4))/6'
   PM  := PM + (KAV)'
 PC := PM/(1 - MU*B*(2-B)*(THETA+(H)))'
 T  := MU * PC * RO'
PRINT PREFIX(££S2??),ALIGNED(2,4), (THETA+(H))*45/ARCTAN(1),
      PM, K1, K2, K3, K4, KAV,PC, T,££L2??'
THETA := THETA + (H)'
IF THETA LESS MAXIMA THEN GOTO L1'
```

```
BEGIN
PRINT ££L2S6? ENTRY ZONE £L2??'
THETA := THETAEND'
  PM  :=  PEND'
   H  := HEN'
PRINT PREFIX(££S2??),ALIGNED(2,4),THETA*45/ARCTAN(1),
      PM,££L2??'
L2:K1:= H*(THETA*KSTAR - MU*PM)/(HO/R + ((THETA)**2*0.5))'
   K2 := H*((THETA+(H/2))*KSTAR - MU*(PM+(K1/2)))/(HO/R+
         ((THETA+(H/2))**2*0.5))'
  K3 := H*((THETA+(H/2))*KSTAR -MU*(PM+(K2/2)))/(HO/R+
        ((THETA+(H/2))**2*0.5))'
 K4 := H*((THETA+(H))*KSTAR -MU*(PM+(K3)))/(HO/R+((THETA+
        (H))**2*0.5))'
   KAV := ((K1) + 2*(K2) + 2*(K3) +(K4))/6'
   PM  := PM + (KAV)'
PC:= PM/(1 - MU*B*(2-B)*(THETA+(H)))'
 T := MU * PC * RO'
PRINT  PREFIX(££S2??),ALIGNED(2,4), (THETA+(H))*45/ARCTAN(1),
       PM, K1, K2, K3, K4, KAV,PC,T,££L2??'
THETA := THETA + (H)'
IF THETA GR MINIMA THEN GOTO L2'
END'
END'
END'
```

PROGRAM 2.

```
BLAND AND FORD EQN. OF FLAT ROLLING FOR SANDWICH AND
HOMOGENEOUS SHEETS,USING MEAN YIELD STRESS VALUES'
BEGIN
COMMENT
THIS PROGRAM EVALUATES THE NON-DIMENSIONAL EQNS. OF
ROLL FORCE  AND TORQUE FOR ROLLING WITH OR WITHOUT  TENSIONS'
REAL A,R,HO,HI,RED,MU,MUMIN,MUMAX,MUINT,PSI,PSIENTRY,
PSIEXIT,PSINEUT,Y,J,B,C,EXINT,ENTRINT,THETA,I,KMEAN,
PTOTAL,EXFUNCTION,ENFUNCTION,TOTFUNCTION,M,N,G,KM,KC,CLADPROP,
X,SF,SB,RO,SIGMAF,SIGMAB,EXTORFUN,ENTORFUN,TOTORFUN,TOTALT'
ARRAY F(0:15), T(0:15)'
BEGIN
READ R,HO,HI,MUMIN,MUMAX,MUINT,KM,KC,CLADPROP,RO,SIGMAF,SIGMAB'
   RED := 1 - HO/HI'
    Y   := SQRT( RED/(1-RED) )'
KMEAN := KM - CLADPROP*(KM - KC)'
END'
PRINT ££L2S12? BLAND AND FORD EVALUATION £L2??'
  FOR MU := MUMIN STEP MUINT UNTIL MUMAX DO
BEGIN
      A := MU *  SQRT( R/HO )'
      C := 2 * A * ARCTAN(Y)'
     SF :=  1 - SIGMAF/KMEAN'
     SB :=  1 - SIGMAB/KMEAN'
     PSIENTRY := Y/A'
 PSIEXIT  := 0'
    M := SIN(0.5*ARCTAN(Y) - LN(SF/SB)/(4*A)  - (LN(1/(1-RED)))/
(4*A))'
```

```
   N   := A*COS(0.5*ARCTAN(Y) - LN(SF/SB)/(4*A) - (LN(1/(1-RED)))/
 (4*A))'
PSINEUT := M/N'
 EXINT  := PSINEUT/6'
ENTRINT := (PSIENTRY - PSINEUT)/8'
PRINT £££L2S4??,SAMELINE,£MU=?,ALIGNED(1,3),MU,££L2??'
PRINT SAMELINE, ALIGNED(2,4),£A=?,A,££S3?RED=?,RED,££S3?KMEAN=?,
      KMEAN'
PRINT ££L2S8??,SAMELINE, ALIGNED (2,4),£PSINEUT=?, PSINEUT *
       45/ARCTAN(1)*MU'

PRINT ££L2??,£CLADPROP=?,SAMELINE,ALIGNED(2,3),CLADPROP,££S4?KM=?,
      KM,££S4?KC=?,KC'
PRINT ££L2S8? EXIT ZONE £L2??'
PRINT ££S2?THETA=£S4?F(I)=£S6?I=£S8?J=£S10?B=£S12? T(X)=£L2??'
I := 0'
X := 0'
  FOR PSI:= PSIEXIT STEP EXINT UNTIL ( PSINEUT + 0.0005 ) DO
BEGIN
 J := 1 + A*A*PSI*PSI'
 B := 2*A*(ARCTAN(A*PSI))'
 F(I) := J * EXP(B)'
T(X)  := F(I) * PSI'
PRINT PREFIX(££S2??),ALIGNED(2,4),MU*PSI*45/ARCTAN(1),F(I),I,J,B,
       T(X),
££L2??'
   I  :=  I + 1'
   X  :=  X + 1'
END'
```

(187)

```
   I  :=  15'
   X  :=  15'
PRINT ££L2S8? ENTRY ZONE £L2??'
PRINT ££S2?THETA=£S4?F(I)=£S6?I=£S8?J=£S10?B=£S12?T(X)=£L2??'
 FOR PSI := PSIENTRY STEP (-ENTRINT) UNTIL ( PSINEUT - 0.0005 ) DO
 BEGIN
 J := 1 + A*A*PSI*PSI'
 B := 2*A*(ARCTAN(A*PSI))'
F(I) := J * EXP(-B)'
T(X) := F(I) * PSI'
PRINT PREFIX(££S2??),ALIGNED(2,4),MU*PSI*45/ARCTAN(1),F(I),I,J,B,
 T(X),££L2??'
   I  :=  I - 1'
   X  :=  X - 1'
END'
BEGIN


G := (1 - RED) * EXP(C)'

EXFUNCTION:= SF*A*EXINT* ((F(0)+F(6))+4*(F(1)+F(3)+F(5))+2*(F(2)+
 F(4)))/(3*Y)'

ENFUNCTION:= SB*A*G*ENTRINT*((F(15)+F(7))+4*(F(14)+F(12)+F(10)+
 F(8))+2*(F(13)+F(11)+F(9)))/(3*Y)'

 TOTFUNCTION  :=EXFUNCTION + ENFUNCTION'
EXTORFUN :=SF*((A*(1-RED))**2)*EXINT*((T(0)+T(6))+4*(T(1)+T(3)+T(5))+
 2*(T(2)+T(4)))/3'
ENTORFUN := SB*G*((A*(1-RED))**2)*ENTRINT*((T(15)+T(7))+4*(T(14)+
 T(12)+T(10)+T(8))+2*(T(13)+T(11)+T(9)))/3'
```

```
TOTORFUN := EXTORFUN + ENTORFUN'
PRINT ££L? EXIT ZONE££S3?F(EXIT)=?,SAMELINE,ALIGNED(2,3),EXFUNCTION,
 ££L2??'
PRINT££L? ENTRY ZONE £S3? F(ENTRY )=?,SAMELINE,ALIGNED(2,3),
 ENFUNCTION,££L2??'

PRINT £FP=?,SAMELINE,ALIGNED(2,3),TOTFUNCTION, ££L2??'
 PRINT ££L? EXIT ZONE££S3?T(EXIT)=?,SAMELINE,ALIGNED(2,3),
 EXTORFUN,££L2??'
PRINT ££L? ENTRY ZONE££S3?T(ENTRY)=?,SAMELINE,ALIGNED(2,3),
 ENTORFUN ,££L2??'

PRINT ££L?TP =?,SAMELINE,ALIGNED(2,3), TOTORFUN, ££L2??'
    PTOTAL := KMEAN * SQRT(R*(HI-HO)) * TOTFUNCTION'
   TOTALT  := (KMEAN * RO*(HI**2)/HO*TOTORFUN +(RO*(SIGMAB*HI -
 SIGMAF*HO)/2))*2'

PRINT £PTOTAL=?,SAMELINE,ALIGNED(3,4), PTOTAL, ££L2??'

 PRINT £TOTALT=?,SAMELINE,ALIGNED(3,4), TOTALT,££L2??'
END'
END'
END'
```

PROGRAM 3


```
RUNGE KUTTA EVALUATION OF SANDWICH ROLLING EQUATION'
 BEGIN
COMMENT
THIS PROGRAM EVALUATES THE DIFFERENTIAL EQUILIBRIUM EQN.
OF SANDWICH ROLLING WITH OR WITHOUT TENSION,FOR VARYING YIELD
STRESS VALUES,USING THE RUNGE-KUTTA METHOD OF STEP SOLUTION'

REAL MU,MUMIN,MUINT,MUMAX,THETA,PM,THETASTART,THETAEND,
PMSTART,HO,KSTAR,R,H,HEX,HEN,MAXIMA,MINIMA,K1,K2,K3,K4,KAV,
 B ,KM,KC,PC,T,SIGMAF,SIGMAB,PEND,RO'
SWITCH S:= L1,L2'
PRINT ££L2S4?  RUNGE KUTTA EVALUATION £L2??'
READ THETASTART,THETAEND,HO,B,R,RO,HEX,HEN,MAXIMA,
MINIMA,MUMIN,MUINT,MUMAX,SIGMAF,SIGMAB'
BEGIN
THETASTART := THETASTART * ARCTAN(1)/45'
THETAEND  := THETAEND   * ARCTAN(1)/45'
  HEX    :=    HEX     * ARCTAN(1)/45'
 HEN      :=   HEN     *  ARCTAN(1)/45'
MAXIMA   :=   MAXIMA   * ARCTAN(1)/45'
MINIMA   :=  MINIMA    * ARCTAN(1)/45'
PRINT SAMELINE,ALIGNED(2,2),£SIGMAF =?,SIGMAF,££S4?SIGMAB =?,
      SIGMAB'
END'
FOR MU:=MUMIN STEP MUINT UNTIL MUMAX DO
BEGIN
PRINT ££L2S6? MU=?,SAMELINE, ALIGNED (1,3), MU'
PRINT  ££L2S6? EXIT ZONE£L2??'
PRINT££S4?THETA=£S6?PM=£S6?K1=£S6?K2=£S6?K3=£S6?K4=£S6??,
     £KAV=£S6?PC=£S6? T=£L2??'
THETA := THETASTART'
READ KM , KC'
KSTAR := KM - B*(KM - KC)'
```

```
PMSTART :=  KSTAR - SIGMAF'
 PM   := PMSTART'
 H    := HEX'
PRINT PREFIX(££S2??),ALIGNED (2,4),THETA*45/ARCTAN(1),
      PM,££L2??'
L1: K1:= H*(THETA*KSTAR+MU*PM)/(HO/R + ((THETA)**2*0.5))'
    K2 := H*((THETA+(H/2))*KSTAR + MU*(PM+(K1/2)))/(HO/R+
         ((THETA+(H/2))**2*0.5))'
  K3 := H*((THETA+(H/2))*KSTAR+MU*(PM+(K2/2)))/(HO/R+((THETA+(H/2))*
         *2*0.5))'
 K4 := H*((THETA+(H))*KSTAR+MU*(PM+(K3)))/(HO/R+((THETA+(H))**2*
       0.5))'
   KAV := ((K1) + 2*(K2) + 2*(K3) +(K4))/6'
   PM  := PM + (KAV)'
 PC := PM/(1 - MU*B*(2-B)*(THETA+(H)))'
 T  := MU * PC * RO'
PRINT PREFIX(££S2??),ALIGNED(2,4), (THETA+(H))*45/ARCTAN(1),
      PM, K1, K2, K3, K4, KAV,PC,T,££L2??'
THETA := THETA + (H)'
IF THETA LESS MAXIMA THEN READ KM,KC'
KSTAR := KM - B*(KM - KC)'
IF THETA LESS MAXIMA THEN GOTO L1'
BEGIN
PRINT ££L2S6? ENTRY ZONE £L2??'
THETA := THETAEND'
READ KM,KC'
KSTAR := KM - B*(KM - KC)'
PEND :=  KSTAR - SIGMAB'
  PM  :=  PEND'
   H  := HEN'
```

```
PRINT PREFIX(££S2??),ALIGNED(2,4),THETA*45/ARCTAN(1),
      PM,££L2??'
L2:K1:= H*(THETA*KSTAR - MU*PM)/(HO/R + ((THETA)**2*0.5))'
    K2 := H*((THETA+(H/2))*KSTAR - MU*(PM+(K1/2)))/(HO/R+
          ((THETA+(H/2))**2*0.5))'
  K3 := H*((THETA+(H/2))*KSTAR -MU*(PM+(K2/2)))/(HO/R+
         ((THETA+(H/2))**2*0.5))'
 K4 := H*((THETA+(H))*KSTAR -MU*(PM+(K3)))/(HO/R+((THETA+
         (H))**2*0.5))'
   KAV := ((K1) + 2*(K2) + 2*(K3) +(K4))/6'
   PM  := PM + (KAV)'
PC:= PM/(1 - MU*B*(2-B)*(THETA+(H)))'
 T := MU * PC * RO'
PRINT  PREFIX(££S2??),ALIGNED(2,4), (THETA+(H))*45/ARCTAN(1),
         PM, K1, K2, K3, K4, KAV,PC,T,££L2??'
THETA  := THETA + (H)'
IF THETA GR MINIMA THEN READ KM, KC'
 KSTAR := KM -B*(KM -KC)'
IF THETA GR  MINIMA  THEN GOTO L2'
END'
END'
END'
```

PROGRAM 4.


```
BLAND AND FORD EQN. OF FLAT ROLLING FOR SANDWICH AND
HOMOGENEOUS SHEETS,USING VARYING YIELD STRESS VALUES'
BEGIN
COMMENT
THIS PROGRAM EVALUATES THE NON-DIMENSIONAL EQNS. OF
ROLL FORCE  AND TORQUE FOR ROLLING WITHOUT  TENSIONS,
TAKING INTO ACCOUNT THE VARIATION OF THE YIELD STRESS OF
THE MATERIAL ALONG THE ARC OF CONTACT'
REAL A,R,HO,HI,RED,MU,MUMIN,MUMAX,MUINT,PSI,PSIENTRY,
PSIEXIT,PSINEUT,Y,J,B,C,EXINT,ENTRINT,THETA,I,KMEAN,
PTOTAL,EXFUNCTION,ENFUNCTION,TOTFUNCTION,M,N,G,KM,KC,CLADPROP,
X,RO,EXTORFUN,ENTORFUN,TOTORFUN,TOTALT'
ARRAY F(0:15), T(0:15)'
BEGIN
READ R,HO,HI,MUMIN,MUMAX,MUINT,CLADPROP,RO'
   RED := 1 - HO/HI'
    Y   := SQRT( RED/(1-RED) )'
END'
PRINT ££L2S12? BLAND AND FORD EVALUATION £L2??'
  FOR MU := MUMIN STEP MUINT UNTIL MUMAX DO
BEGIN
      A := MU *  SQRT( R/HO )'
      C := 2 * A * ARCTAN(Y)'
     PSIENTRY := Y/A'
 PSIEXIT  := 0'
    M := SIN(0.5*ARCTAN(Y) -  (LN(1/(1-RED)))/(4*A))'
   N  := A*COS(0.5*ARCTAN(Y) -(LN(1/(1-RED)))/(4*A))'
PSINEUT := M/N'
 EXINT  := PSINEUT/6'
ENTRINT := (PSIENTRY - PSINEUT)/8'
PRINT ££L2S4??,SAMELINE,£MU=?,ALIGNED(1,3),MU,££L2??'
PRINT SAMELINE, ALIGNED(2,4),£A=?,A,££S3?RED=?,RED'
```

```
PRINT ££L2S8??,SAMELINE, ALIGNED (2,4),£PSINEUT=?, PSINEUT *
 45/ARCTAN(1)*MU'
PRINT ££L2??,£CLADPROP=?,SAMELINE,ALIGNED(2,3),CLADPROP'
PRINT ££L2S8? EXIT ZONE £L2??'
PRINT ££S2?THETA=£S4?F(I)=£S6?I=£S8?J=£S10?B=£S8? T(X)=?,SAMELINE,
      ££S4?KMEAN=£L2??'
I := 0'
X := 0'
  FOR PSI:= PSIEXIT STEP EXINT UNTIL ( PSINEUT + 0.0005 ) DO
BEGIN

READ KM,KC'

KMEAN := KM - CLADPROP * (KM - KC)'

 J := 1 + A*A*PSI*PSI'
 B := 2*A*(ARCTAN(A*PSI))'
 F(I) := KMEAN* J * EXP(B)'
T(X)  := F(I) * PSI'
PRINT PREFIX(££S2??),ALIGNED(2,4),MU*PSI*45/ARCTAN(1),F(I),I,J,
      B,T(X),KMEAN,££L2??'
   I  :=  I + 1'
   X  :=  X + 1'
END'
   I  :=  15'
   X  :=  15'
PRINT ££L2S8? ENTRY ZONE £L2??'
PRINT ££S2?THETA=£S4?F(I)=£S6?I=£S8?J=£S10?B=£S8?T(X)=?,SAMELINE,
      ££S4?KMEAN=£L2??'
  FOR PSI := PSIENTRY STEP (-ENTRINT) UNTIL ( PSINEUT - 0.0005 ) DO
BEGIN
```

```
READ KM,KC'

KMEAN := KM - CLADPROP * (KM - KC)'
 J := 1 + A*A*PSI*PSI'
 B := 2*A*(ARCTAN(A*PSI))'
F(I) := KMEAN* J * EXP(-B)'
T(X) := F(I) * PSI'
PRINT PREFIX(££S2??),ALIGNED(2,4),MU*PSI*45/ARCTAN(1),F(I),I,J,
        B,T(X),KMEAN,££L2??'
   I  :=  I - 1'
   X  :=  X - 1'
END'
BEGIN


G := (1 - RED) * EXP(C)'

EXFUNCTION:= A*EXINT* ((F(0)+F(6))+4*(F(1)+F(3)+F(5))+2*(F(2)+
F(4)))/(3*Y)'
ENFUNCTION:=A*G*ENTRINT*((F(15)+F(7))+4*(F(14)+F(12)+F(10)+
F(8))+2*(F(13)+F(11)+F(9)))/(3*Y)'
 TOTFUNCTION  :=EXFUNCTION + ENFUNCTION'
EXTORFUN :=((A*(1-RED))**2)*EXINT*((T(0)+T(6))+4*(T(1)+T(3)+
T(5))+2*(T(2)+T(4)))/3'
ENTORFUN :=G*((A*(1-RED))**2)*ENTRINT*((T(15)+T(7))+4*(T(14)+
T(12)+T(10)+T(8))+2*(T(13)+T(11)+T(9)))/3'
TOTORFUN := EXTORFUN + ENTORFUN'
PRINT ££L? EXIT ZONE£S3?F(EXIT)=?,SAMELINE,ALIGNED(2,3),EXFUNCTION,
££L2??'
PRINT££L? ENTRY ZONE £S3? F(ENTRY )=?,SAMELINE,ALIGNED(2,3),
ENFUNCTION,££L2??'
```

```
PRINT £FP=?,SAMELINE,ALIGNED(2,3),TOTFUNCTION, ££L2??'
PRINT ££L? EXIT ZONE££S3?T(EXIT)=?,SAMELINE,ALIGNED(2,3),EXTORFUN,
££L2??'
PRINT ££L? ENTRY ZONE££S3?T(ENTRY)=?,SAMELINE,ALIGNED(2,3),ENTORFUN ,
££L2??'

PRINT ££L?TP =?,SAMELINE,ALIGNED(2,3), TOTORFUN, ££L2??'
   PTOTAL := SQRT(R*(HI-HO)) * TOTFUNCTION'
  TOTALT  :=( RO*(HI**2)/HO*TOTORFUN)*2'

PRINT £PTOTAL=?,SAMELINE,ALIGNED(3,4), PTOTAL, ££L2??'

PRINT £TOTALT=?,SAMELINE,ALIGNED(3,4), TOTALT,££L2??'
END'
END'
END'
```

20.5 TABULATED RESULTS.

MEASURED RESULTS					TABLE 13
MATERIAL	REDUCTION %	ROLL FORCE TON f/in. WIDTH	ROLL TORQUE – TON f in/in.		
			TOTAL	REDUNDANT	NETT
0.048 in. MILD STEEL R = 2.25	18.0	5.3	1.16	0.5	0.66
	24.0	6.8	1.62	0.64	0.98
	30.0	8.3	2.10	0.78	1.32
	33.0	9.1	2.36	0.88	1.48
	36.5	10.0	2.68	0.95	1.73
0.036 in. MILD STEEL R. = 2.25	7.5	2.1	0.36	0.18	0.18
	12.5	2.9	0.56	0.26	0.30
	16.0	3.8	0.70	0.35	0.35
	20.0	4.8	0.9	0.44	0.46
	25.5	5.8	1.22	0.54	0.68
	30.0	6.8	1.46	0.64	0.82
	33.0	7.5	1.66	0.7	0.96
0.064 in. COPPER. R = 2.0	7.5	1.5	0.24	0.11	0.13
	12.0	2.2	0.46	0.17	0.29
	17.5	3.0	0.67	0.24	0.43
	22.2	3.8	0.88	0.31	0.57
	27.5	4.3	1.10	0.36	0.76
	30.1	4.5	1.18	0.37	0.81
	32.6	4.8	1.34	0.4	0.94

MEASURED RESULTS					TABLE 14
MATERIAL	REDUCTION %	ROLL FORCE Tonf/in. WIDTH	ROLL TORQUE - Tonf in/in.		
			TOTAL	REDUNDANT	NETT.
0.049 in. ALUMINIUM R = 2.25	25.0	0.8	0.24	0.06	0.18
	28.5	1.2	0.35	0.1	0.25
	36.7	2.0	0.57	0.18	0.39
	43.0	2.6	0.77	0.23	0.54
	52.0	3.3	1.05	0.3	0.75
0.029 in. MILD STEEL. R = 2.25 in.	10.3	2.8	0.71	0.25	0.46
	17.2	4.1	1.12	0.38	0.74
	29.0	6.5	1.74	0.61	1.13
	37.9	9.1	2.77	0.86	1.91
	44.8	11.4	3.48	1.08	2.4
0.39 in. MILD STEEL R = 2.0 in.	10.3	3.0	0.94	0.24	0.70
	13.5	3.9	1.10	0.32	0.78
	20.6	5.3	1.48	0.44	1.04
	24.3	6.4	1.64	0.54	1.10
	29.4	7.8	1.93	0.66	1.27
	32.7	10.0	2.16	0.85	1.31
	33.7	11.0	2.20	0.94	1.26

MEASURED RESULTS.			TABLE 15		
MATERIAL	REDUCTION %	ROLL FORCE TONf/in. WIDTH	ROLL TORQUE - TONf in/in. TOTAL	REDUNDANT	NETT
0.04 in. COPPER R = 2.0 in.	12.5	1.9	0.52	0.14	0.38
	20.0	3.0	0.86	0.24	0.62
	26.0	3.9	1.12	0.32	0.80
	31.8	4.6	1.45	0.38	1.07
	46.2	8.0	2.46	0.67	1.79
	48.3	9.2	2.64	0.77	1.87
0.04 in. COPPER R = 2.25 in.	20.0	3.4	0.83	0.31	0.52
	26.0	4.4	1.15	0.41	0.74
	32.5	6.0	1.54	0.56	0.98
	40.5	7.9	2.04	0.76	1.28
	45.0	9.3	2.40	0.88	1.52
	52.1	11.0	—	1.5	
	56.2	12.3	—	1.8	
0.049 in. ALUMINIUM R = 2.0 in	15.0	0.6	0.078	0.004	0.074
	18.1	0.7	0.10	0.005	0.095
	24.0	0.7	1.10	0.44	0.66
	30.0	1.1	0.26	0.08	0.18
	36.2	1.3	0.33	0.10	0.23

MEASURED RESULTS					TABLE 16
MATERIAL	REDUCTION %	ROLL FORCE TON f/in. WIDTH	ROLL TORQUE-TON f in/in. TOTAL	REDUNDANT	NETT
0.08 in. COPPER. R = 2.0 in.	10.0	2.1	0.46	0.18	0.28
	12.7	2.5	0.56	0.2	0.36
	15.6	2.9	0.66	0.24	0.42
	17.5	3.4	0.78	0.28	0.50
	21.0	3.8	0.98	0.32	0.66
	24.5	4.2	1.13	0.34	0.79
0.047 in STAINLESS STEEL R = 2 in.	8.5	4.1	1.08	0.72	0.36
	14.1	7.0	2.0	0.58	1.42
	16.0	9.1	2.28	0.77	1.51
	17.5	9.8	2.75	0.84	1.91
	18.5	11.0	3.0	0.93	2.07
0.047 in. STAINLESS STEEL R = 2.25 in.	12.8	6.2	1.18	0.58	0.60
	15.3	7.4	1.55	0.7	0.85
	18.1	9.5	1.79	0.9	0.89
	20.2	12.5	2.95	1.19	1.76
	23.4	16.5	4.11	1.58	3.11
	27.7	19.5	4.44	1.86	2.58
	28.7	21.6	4.86	2.06	2.8

MEASURED RESULTS — TABLE 17

MATERIAL	REDUCTION %	ROLL FORCE TON f/in WIDTH	ROLL TORQUE - TON f in/in TOTAL	REDUNDANT	NETT
0.026 in. 0.71% C. STEEL R = 2.0 in.	5.0	5.5	0.75	0.42	0.33
	7.7	7.5	0.95	0.64	0.31
	10.5	10.0	1.12	0.84	0.28
	12.3	12.2	1.3	1.14	0.16
	15.0	15.6	1.6	1.42	0.18
0.026 in. 0.71% C STEEL. R = 2.25	11.5	7.2	1.03	0.68	0.35
	13.5	7.8	1.34	0.74	0.6
	19.2	11.1	2.0	1.06	0.94
	25.0	14.1	3.91	1.34	2.57
	30.8	16.7	3.51	1.60	1.91
0.036 in. 1.25% C STEEL R = 2.0 in.	6.0	7.8	1.1	0.66	0.44
	10.2	10.2	1.53	0.86	0.67
	12.6	12.0	1.88	1.02	0.86
	14.8	13.8	2.55	1.18	1.37
	17.0	15.9	3.40	1.36	2.04
0.031 in. NIMONIC 80 R = 2.25	7.5	6.5	0.62	0.60	0.02
	10.1	10.8	2.00	1.02	1.98
	19.4	13.9	2.60	1.12	1.48
	21.0	15.1	2.75	1.44	1.31
	22.6	15.2	3.00	1.46	1.54
	24.2	18.2	3.10	1.66	1.44

MEASURED RESULTS — TABLE 18

MATERIAL	REDUCTION %	ROLL FORCE TON f/in. WIDTH	ROLL TORQUE – TON f in/in.		
			TOTAL	REDUNDANT	NETT
0.031 in. NIMONIC 90 R = 2.25 in.	9.5	11.3	1.60	1.08	0.52
	11.3	12.6	1.95	1.2	0.75
	14.5	15.0	2.65	1.44	1.21
	16.1	16.8	3.3	1.61	1.69
	17.7	17.5	3.45	1.68	1.77
	19.0	18.8	3.95	1.8	2.15
0.012 in. NIMONIC 105 R = 2.25 in.	5.0	13.1	1.29	1.25	0.04
	6.8	15.0	1.49	1.44	0.05
	8.3	16.5	1.85	1.58	0.27
	8.4	17.9	2.35	1.72	1.63

MEASURED RESULTS

TABLE NO 19

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.049in ALUMINIUM MATRIX: 0.04in COPPER R_o = 2"						
15.5	24.0	20.3	1.55	1.7	1.00	0.88
23.0	33.4	28.2	1.45	2.7	1.40	1.18
26.5	37.6	32.1	1.42	3.4	1.52	1.24
31.0	42.1	36.6	1.36	3.9	1.86	1.54
36.0	48.2	42.1	1.34	4.5	2.20	1.82
43.5	54.5	49.0	1.25	6.0	3.20	2.70
50.0	57.0	53.5	1.14	7.4	3.52	2.90
CLAD: 2x 0.04in COPPER MATRIX: 0.039in MILDSTEEL R_o = 2"						
8.7	12.3	10.5	1.41	2.9	0.90	0.68
12.8	17.8	15.3	1.39	4.1	1.34	1.00
17.1	23.3	20.2	1.36	5.5	1.80	1.34
20.5	27.6	24.1	1.35	6.1	2.26	1.74
22.8	30.1	26.5	1.32	7.0	2.48	1.90
27.5	34.4	30.9	1.26	7.8	3.00	2.34
30.8	36.4	33.6	1.18	8.1	3.34	2.66

MEASURED RESULTS

TABLE NO 20

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TONf in/in.	TONf in/in
CLAD: 2x 0.039in MILD STEEL MATRIX: 0.047in STAINLESS STEEL Ro = 2"						
8.7	9.2	8.9	1.06	5.5	1.05	0.59
12.5	13.3	12.9	1.06	6.1	1.65	1.13
15.1	15.7	15.4	1.04	7.0	1.98	1.40
20.0	20.6	20.3	1.03	8.8	2.80	2.06
23.1	23.2	23.1	1.01	10.0	3.25	2.41
25.0	25.0	25.0	1.0	10.3	3.68	2.80
28.7	28.8	28.8	1.01	13.3	4.55	3.42
CLAD: 2x 0.048in MILD STEEL MATRIX: 0.047in Ro = 2"						
9.5	10.0	9.8	1.05	5.0	1.40	0.98
11.8	12.5	12.2	1.06	5.9	1.74	1.25
17.1	17.8	17.5	1.04	8.0	2.56	1.89
20.2	20.8	12.5	1.03	9.4	3.24	2.44
22.5	23.2	22.9	1.03	10.1	3.50	2.64
26.5	26.6	26.6	1.01	11.1	4.16	3.22
29.3	29.3	29.3	1.0	11.8	4.60	3.60

MEASURED RESULTS

TABLE NO 21

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2X 0.029in MILD STEEL MATRIX: 0.047in STAINLESS STEEL Ro = 2"						
12.5	13.4	13.0	1.07	5.7	1.60	1.12
16.0	16.8	16.4	1.05	6.9	1.80	1.22
19.0	20.0	19.5	1.05	8.1	2.25	1.57
21.4	22.7	22.1	1.06	9.4	2.68	1.88
24.5	25.5	25.0	1.04	10.3	3.00	2.12
30.7	31.3	31.0	1.02	12.8	3.93	2.84
CLAD: 2X 0.028in ALUMINIUM MATRIX: 0.047in STAINLESS STEEL Ro = 2"						
12.5	25.2	18.9	2.01	3.3	1.30	1.04
18.2	35.6	26.9	1.95	5.4	1.88	1.43
21.5	40.8	31.2	1.9	5.8	2.28	1.80
23.5	40.0	31.8	1.7	7.2	2.45	1.85
30.7	47.6	39.2	1.55	9.5	3.15	2.35
38.7	55.0	46.8	1.42	11.5	4.05	3.07

MEASURED RESULTS

TABLE NO 22

REDUCTION %				ROLL FORCE TONf/in.	TOTAL ROLL TORQUE TONfin/in.	NET ROLL TORQUE TONfin/in
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE			
CLAD: 2x 0.049in ALUMINIUM MATRIX: 0.047in STAINLESS STEEL Ro = 2						
8.4	16.0	12.2	1.90	3.5	1.36	1.08
13.0	25.4	19.2	1.95	4.2	1.64	1.30
17.1	31.2	19.2	1.82	5.0	2.02	1.60
20.6	36.7	28.7	1.78	5.9	2.40	1.91
22.5	40.5	31.5	1.80	6.6	2.71	2.15
26.6	43.8	35.2	1.65	7.1	3.1	2.45
28.7	46.2	37.5	1.61	8.3	3.52	2.82
CLAD: 2x 0.039in MILDSTEEL MATRIX: 0.026in 0.71%C STEEL Ro = 2"						
6.0	10.2	8.1	1.7	5.4	2.22	1.77
9.5	15.3	12.4	1.61	7.1	2.52	1.92
15.0	24.2	19.6	1.52	9.0	3.01	2.31
20.6	26.8	23.7	1.3	12.4	3.9	2.85
29.3	30.8	30.1	1.05	13.3	4.45	3.32

MEASURED RESULTS

TABLE NO 23

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in	TON f in/in
CLAD: 2x	·04in	COPPER				
MATRIX: 0.	047 in	STAINLESS	STEEL			
Ro = 2"						
8·8	13·2	11·0	1·5	4·9	1·00	0·60
13·2	19·1	16·2	1·45	6·0	1·68	1·18
14·9	19·4	17·2	1·3	6·5	1·90	1·36
20·3	26·4	23·5	1·3	8·0	2·72	1·05
25·6	32·0	28·8	1·25	10·3	3·55	2·68
30·6	34·2	32·4	1·11	12·0	4·25	3·63
CLAD: 2x	0·04in	COPPER				
MATRIX: 0.	026in	0·71% C	STEEL			
Ro = 2"						
6·0	10·9	8·5	1·83	3·1	1·80	1·55
9·5	17·2	12·4	1·81	4·2	2·15	1·80
13·0	23·4	18·2	1·80	5·3	2·5	2·06
17·5	30·6	24·1	1·75	6·6	3·00	2·45
22·1	33·6	27·8	1·52	7·9	3·58	2·90
27·0	36·4	31·7	1·35	8·9	3·95	3·20
29·5	38·6	34·1	1·31	9·4	4·20	3·40

MEASURED RESULTS

TABLE NO 24

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.032in COPPER MATRIX: 0.026in 0.71%C STEEL Ro = 2"						
7.5	13.5	10.5	1.80	3.6	0.93	0.63
12.5	22.6	17.6	1.81	5.1	1.28	0.86
16.0	28.0	22.0	1.75	6.1	1.55	1.04
21.5	32.4	27.0	1.51	7.1	2.05	1.45
29.0	43.5	36.3	1.50	8.4	2.78	2.07
32.6	47.3	40.0	1.45	9.5	3.20	2.40
CLAD: 2x 0.02in COPPER MATRIX: 0.026in. 0.71%C STEEL Ro = 2"						
5.8	17.2	11.5	2.01	3.1	0.80	0.55
13.5	25.0	19.3	1.85	5.3	1.30	0.86
17.5	30.6	24.1	1.75	6.3	1.55	1.02
22.7	38.8	30.8	1.67	7.4	2.00	1.38
27.5	45.3	36.4	1.65	8.0	2.30	1.63
30.5	45.8	38.2	1.50	8.6	2.61	1.88
32.5	46.3	39.4	1.42	8.7	2.82	2.09

MEASURED RESULTS

TABLE NO 25

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f / in.	TON f in / in.	TON f in / in
CLAD: 2x 0.01in COPPER						
MATRIX: 0.026in 0.71%C STEEL						
R_o = 2"						
8.0	10.4	9.2	1.3	3.9	0.95	0.63
12.0	15.3	13.7	1.27	5.4	1.20	0.75
19.2	24.0	21.6	1.25	6.9	1.40	0.88
25.5	30.4	28.0	1.19	9.1	1.92	1.15
29.0	32.0	30.5	1.10	10.0	2.30	1.45
32.5	34.5	33.5	1.06	12.4	2.41	1.36
CLAD: 2x 0.048in MILD STEEL						
MATRIX: 0.026in 0.71%C STEEL						
R_o = 2"						
3.9	9.1	6.5	2.32	4.9	1.37	0.97
7.5	12.3	9.9	1.64	6.0	1.83	1.33
10.6	15.0	12.8	1.41	7.5	2.33	1.70
15.0	19.4	17.2	1.29	9.2	3.08	2.20
19.8	24.6	22.2	1.24	11.2	3.65	2.90
22.7	26.6	24.7	1.17	11.9	4.10	3.09
24.5	27.2	25.8	1.11	12.3	4.30	3.26
27.5	28.9	28.2	1.05	13.3	4.75	3.62

MEASURED RESULTS

TABLE NO 26

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f / in.	TON f in / in.	TON f in / in
CLAD : 2x 0.029" MILD STEEL MATRIX : 0.026" 0.71% C STEEL Ro = 2"						
7.7	12.8	10.3	1.65	6.2	1.66	1.14
11.5	17.4	14.5	1.51	7.7	2.14	1.49
15.5	21.7	18.6	1.40	8.9	2.77	2.02
19.3	24.5	21.9	1.27	9.9	3.34	2.50
23.2	26.7	24.9	1.15	11.3	3.94	2.98
27.5	31.6	29.6	1.11	12.1	4.56	3.53
29.5	31.0	29.8	1.05	12.7		
CLAD : 2x 0.018" MILD STEEL MATRIX : 0.028" 0.71% C. STEEL Ro = 2"						
7.7	13.1	10.4	1.7	6.1	1.61	1.10
11.8	18.5	15.2	1.57	7.9	2.06	1.40
15.5	21.8	18.7	1.41	9.9	2.44	1.60
21.0	27.6	24.3	1.31	12.2	2.84	1.80
24.8	31.3	28.1	1.26	13.5	3.26	2.11
27.5	30.8	29.2	1.12	14.6	3.50	2.26

MEASURED RESULTS

TABLE NO 27

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f / in.	TON f in / in.	TON f in / in
CLAD: 2x 0.049 in ALUMINIUM MATRIX: 0.026" 0.71 % C. STEEL Ro = 2 in						
3.9	24.6	14.3	6.3	2.6	1.02	0.82
7.7	30.1	18.9	3.9	3.2	1.20	0.94
13.5	36.5	25.0	2.7	4.0	1.61	1.28
15.4	37.0	26.2	2.4	4.5	1.68	1.31
20.0	38.0	29.0	1.9	5.3	1.88	1.44
25.1	40.2	32.7	1.6	6.0	2.08	1.58
30.6	42.8	36.7	1.4	6.8	2.45	1.87
CLAD: 2x 0.028" ALUMINIUM MATRIX: 0.036" 1.25 % C STEEL Ro = 2"						
4.0	33.2	18.6	8.3	5.1	1.42	1.00
8.3	35.7	22.0	4.3	6.0	1.55	1.05
14.0	43.4	28.5	3.1	7.1	2.21	1.61
16.2	47.0	31.6	2.9	7.5	2.35	1.90
20.0	50.0	35.0	2.5	8.9	2.65	

MEASURED RESULTS

TABLE NO 28

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.04" COPPER MATRIX: 0.036" 1.25% C. STEEL $R_0 = 2"$						
5.0	13.4	9.2	2.67	5.05	1.62	1.20
9.5	21.7	15.6	2.28	7.2	2.15	1.55
14.0	28.1	21.1	2.01	9.0	2.75	1.79
17.0	32.7	24.9	1.92	10.3	3.4	2.53
20.2	36.6	28.4	1.81	10.8	4.02	3.10
CLAD: 2x 0.032" COPPER MATRIX: 0.036" 1.25% C STEEL $R_0 = 2"$						
8.5	21.4	14.9	2.41	7.0	1.75	1.16
9.7	22.5	16.1	2.32	7.6	1.90	1.26
12.7	26.7	19.7	2.10	8.5	2.45	1.73
15.2	31.2	23.2	2.05	9.6	2.9	2.09
19.5	38.0	28.8	1.95	10.8	3.55	2.63

MEASURED RESULTS

TABLE NO 29

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.02 in COPPER; MATRIX: 0.036 in 1.25% C STEEL; Ro = 2 in						
5.5	14.9	10.2	2.71	5.4	1.21	0.76
8.2	20.1	14.2	2.45	7.0	1.5	0.91
11.1	26.0	18.6	2.32	8.4	2.0	1.5
13.9	31.7	22.8	2.28	9.7	2.4	1.58
17.5	36.0	26.8	2.05	11.4	3.02	2.05
19.8	36.0	27.9	1.82	12.5	3.31	2.25
CLAD: 2x 0.01 in COPPER; MATRIX: 0.036 in 1.25% C STEEL; Ro = 2"						
2.0	4.2	3.1	2.10	5.0	0.51	0.09
8.2	14.1	11.1	1.72	7.0	1.08	0.49
10.9	16.4	13.7	1.51	8.3	1.25	0.55
12.6	17.9	15.3	1.42	9.1	1.55	0.78
15.2	18.9	17.1	1.24	10.5	1.95	1.06
19.0	23.0	21.0	1.21	12.6	2.35	1.28

MEASURED RESULTS

TABLE NO 30

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.048in MILD STEEL MATRIX: 0.036in 1.25% C.STEEL Ro = 2"						
6.8	11.0	8.9	1.61	6.6	1.9	1.35
9.5	14.7	12.1	1.54	7.8	2.38	1.72
11.2	16.7	13.9	1.49	8.8	2.68	1.94
15.0	20.7	17.9	1.38	10.8	3.55	2.63
19.4	25.6	22.5	1.32	12.8	4.91	3.82
CLAD: 2x 0.039in MILD STEEL MATRIX: 0.036in 1.25% C.STEEL Ro = 2in						
2.7	10.3	6.5	3.8	5.9	1.35	0.86
10.2	16.4	13.3	1.61	8.4	2.35	1.64
15.0	21.3	18.2	1.42	10.7	3.12	2.40
16.7	23.2	19.9	1.39	11.9	3.43	2.42
21.0	27.5	24.3	1.31	13.8	4.45	3.27

MEASURED RESULTS

TABLE NO 31

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TONf/in.	TONf in/in.	TONf in/in.
CLAD: 2x 0.029in MILD STEEL MATRIX: 0.036in 1.25% C.STEEL R_o = 2in.						
7.5	12.9	10.2	1.72	7.5	1.88	1.25
11.0	17.7	14.3	1.61	9.3	2.41	1.68
15.3	21.4	18.4	1.40	10.9	2.93	2.01
17.5	24.0	20.8	1.37	11.8	3.22	2.22
21.0	27.6	24.3	1.31	12.9	3.62	2.52
CLAD: 2x 0.018 MILD STEEL MATRIX: 0.036in 1.25% C.STEEL R_o = 2in.						
7.5	13.6	10.6	1.81	7.0	1.52	0.93
10.0	16.1	13.1	1.61	8.5	1.82	1.10
15.1	21.3	18.2	1.41	11.2	2.65	1.71
17.5	24.0	20.8	1.37	12.8	3.10	2.01
20.1	26.2	23.1	1.30	14.8	3.72	2.46

MEASURED RESULTS

TABLE NO 32.

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.04" COPPER MATRIX: 0.031 in NIMONIC 80 Ro = 2.25						
12.5	20.2	16.4	1.62	6.0	1.31	0.81
16.1	24.3	20.2	1.51	7.0	1.92	1.33
19.4	28.7	24.1	1.48	8.2	2.43	1.74
24.2	35.1	29.7	1.45	10.4	3.41	2.53
27.5	37.8	32.7	1.37	10.9	3.68	2.76
30.7	40.2	35.5	1.31	11.9	4.04	3.04
32.3	41.4	36.7	1.28	12.1	4.41	3.38
CLAD: 2x 0.039 in MILD STEEL MATRIX: 0.031 in NIMONIC 80 Ro = 2.25						
12.5	17.6	15.1	1.41	8.8	2.15	1.41
16.1	22.1	19.1	1.37	9.5	2.64	1.84
18.7	24.5	21.6	1.31	10.8	3.05	2.33
22.5	24.8	23.7	1.10	11.6	3.41	2.43
25.8	28.1	26.9	1.09	12.8	3.9	2.82
30.7	33.5	32.1	1.09	14.0	4.83	3.64
32.3	34.6	33.5	1.07	15.2	5.37	4.07

MEASURED RESULTS

TABLE NO 33

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TONfin/in.	TONfin/in
CLAD: 2x 0.04in COPPER MATRIX: 0.031in NIMONIC 90 Ro = 2.25						
9.5	18.5	14.0	1.95	7.1	1.35	0.75
14.5	27.1	20.8	1.86	8.0	1.42	0.75
16.1	28.6	22.4	1.78	8.7	2.43	1.70
22.7	34.3	28.5	1.51	10.6	3.25	2.35
25.0	36.8	30.9	1.47	11.0	3.91	2.98
29.0	41.8	35.4	1.44	11.9	3.72	2.71
32.3	45.9	39.1	1.42	13.2	4.91	3.79
CLAD: 2x 0.039in MILD STEEL MATRIX: 0.031 NIMONIC 90 Ro = 2.25in.						
10.0	15.1	12.5	1.51	8.0	1.70	1.03
14.5	19.6	17.1	1.35	9.3	2.45	1.67
17.7	22.5	20.1	1.27	10.4	2.81	1.93
20.0	24.0	22.0	1.20	11.1	3.42	2.48
24.5	28.2	26.3	1.15	13.1	4.15	3.04
32.3	36.2	34.3	1.12	16.0	5.62	4.26

MEASURED RESULTS

TABLE NO 34

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TONf/in.	TONfin/in	TONfin/in
CLAD: 2x 0.01in COPPER MATRIX: 0.047in STAINLESS STEEL Ro = 2 in						
11.7	16.6	14.2	1.42	5.3	1.26	0.82
14.5	19.6	17.1	1.35	6.5	1.56	1.02
18.0	22.4	20.2	1.24	8.0	1.95	1.28
21.7	25.8	23.8	1.19	10.0	2.21	1.37
25.6	30.1	27.8	1.17	11.6	2.64	1.66
27.5	31.6	29.6	1.15	12.9	2.80	1.70
CLAD: 2x 0.02in COPPER MATRIX: 0.047in STAINLESS STEEL Ro = 2 in.						
12.7	18.1	15.4	1.42	5.1	1.46	1.04
16.2	21.2	18.7	1.31	6.7	1.80	1.24
20.2	24.2	22.2	1.20	7.8	2.54	1.88
25.5	30.6	28.1	1.20	10.6	3.18	2.28
27.5	32.2	29.8	1.17	10.9	3.51	2.59
34.0	39.2	36.6	1.15	13.2	4.11	2.99

MEASURED RESULTS

TABLE NO 35

REDUCTION %				ROLL FORCE TON f/in.	TOTAL ROLL TORQUE TONf in/in.	NET ROLL TORQUE TONf in/in
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE			
CLAD: 2x 0.032in COPPER MATRIX: 0.047in STAINLESS STEEL Ro = 2 in						
12.5	17.6	15.1	1.41	5.8	1.52	1.04
14.8	20.3	17.5	1.37	6.4	1.82	1.28
19.0	23.6	21.3	1.24	7.8	2.34	1.68
22.8	27.8	25.3	1.22	8.9	2.88	2.12
24.7	29.9		1.21	9.4	3.12	2.32
27.8	32.8	27.3	1.18	11.1	3.51	2.57
32.5	37.7	35.1	1.16	12.6	4.04	2.98
CLAD: 2x 0.018in MILD STEEL MATRIX: 0.047in STAINLESS STEEL Ro = 2 in						
14.5	16.7	15.6	1.15	6.4	1.64	1.10
17.0	18.7	17.8	1.10	7.7	1.86	1.24
20.5	22.6	21.6	1.10	9.1	2.25	1.48
24.5	26.5	25.5	1.08	10.5	2.84	1.95
28.8	30.8	29.8	1.07	11.5	3.42	2.44
32.5	34.2	33.4	1.05	12.3	4.16	3.12

MEASURED RESULTS

TABLE NO 36

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in	TON f in/in
CLAD: 2x 0.02in COPPER MATRIX: 0.012in NIMONIC 105 Ro = 2.25						
6.0	17.4	11.7	2.9	6.5	0.55	0.02
12.5	26.2	19.4	2.11	7.6	1.01	0.37
16.7	30.4	23.6	1.82	10.0	1.45	0.61
25.0	32.8	28.9	1.31	10.5	2.5	1.61
29.8	35.8	32.8	1.2	12.2	3.01	1.97
33.3	40.1		1.2	13.8	3.72	2.54
CLAD: 2x 0.018in MILDSTEEL MATRIX: 0.012in NIMONIC 105 Ro = 2.25						
5.0	13.6	9.3	2.72	8.2	1.02	0.33
8.3	17.6	12.9	2.11	9.1	1.42	0.66
14.5	24.8	19.7	1.71	10.6	2.25	1.35
16.7	25.8	21.3	1.55	11.2	2.45	1.50
25.0	38.5	31.8	1.54	14.5	3.55	2.32
30.9	44.2	37.6	1.43	16.3	4.51	3.13
33.0	44.9	38.9	1.36	17.5	4.72	3.23
39.2	50.2	44.7	1.28	17.7	5.35	3.85

MEASURED RESULTS

TABLE NO 37

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f / in.	TON f in / in.	TON f in / in
CLAD: 2x 0.028in ALUMINIUM MATRIX: 0.040in COPPER Ro = 2 in						
15.0	23.2	19.1	1.55	1.8	0.60	0.46
20.0	26.6	23.3	1.33	2.1	0.86	0.70
25.5	33.4	29.5	1.31	2.7	1.16	0.94
30.0	39.0	34.5	1.30	3.4	1.45	1.17
38.8	47.4	43.1	1.22	4.7	2.04	1.66
46.1	55.5	50.8	1.20	6.0	2.58	2.08
CLAD: 2x 0.01in COPPER MATRIX: 0.039in MILD STEEL Ro = 2in						
8.1	14.8	11.5	1.82	2.8	0.70	0.48
12.5	20.4	16.5	1.63	3.8	1.18	0.88
16.9	26.2	21.6	1.55	4.65	1.52	1.14
20.5	29.1	24.8	1.41	5.45	1.88	1.42
27.5	33.2	30.4	1.21	7.0	2.30	1.72
30.5	34.2	32.4	1.12	7.7	2.46	1.81
32.5	35.8	34.2	1.10	8.2	2.61	1.93

MEASURED RESULTS

TABLE NO 38

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f / in.	TON f in / in.	TON f in / in
CLAD: 2x 0.02 in COPPER MATRIX: 0.039 in MILD STEEL R_o = 2 in						
7.7	17.1	12.4	2.21	3.2	0.91	0.65
14.0	22.2	18.1	1.58	4.4	1.38	1.02
17.5	26.3	21.4	1.50	5.0	1.61	1.19
21.9	31.6	26.8	1.44	5.9	1.91	1.41
28.2	28.4	28.3	1.36	7.5	2.41	1.78
32.5	41.6	37.1	1.28	8.5	2.72	2.00
CLAD: 2x 0.032 in COPPER MATRIX: 0.039 in MILD STEEL R_o = 2 in						
5.0	11.1	8.1	2.42	2.3	0.64	0.46
10.0	17.2	13.6	1.72	3.8	0.91	0.61
14.5	22.9	18.7	1.58	4.5	1.28	0.91
18.0	27.4	22.7	1.52	5.2	1.57	1.14
23.0	32.9	27.9	1.43	5.9	2.01	1.61
28.2	38.1	33.2	1.35	6.9	2.12	1.54
34.8	42.8	38.8	1.23	7.8	2.66	2.00

MEASURED RESULTS

TABLE NO 39

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.018 in MILD STEEL MATRIX: 0.064 in COPPER Ro = 2 in						
5.5	14.1	9.8	2.55	2.5	0.81	0.61
10.6	21.5	16.1	2.03	4.1	1.32	0.98
15.2	28.0	21.6	1.86	5.5	1.71	1.11
21.0	32.5	26.8	1.55	6.5	2.16	1.62
27.5	37.8	32.7	1.37	7.5	2.56	1.93
32.3	40.8	36.6	1.26	7.5	2.73	2.10
CLAD: 2x 0.043 in MARLEY PLASTIC MATRIX: 0.049 in COPPER Ro = 2.25 in.						
25.0				1.3	0.48	0.38
30.5				1.7	0.64	0.52
37.0				2.1	0.89	0.73
42.0				2.4	0.95	0.76
46.1				2.7	1.12	0.91
49.2				2.8	1.21	0.99

MEASURED RESULTS

TABLE NO 40

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	Ton f/in.	Ton f in/in	Ton f in/in
CLAD: 2x 0.043 in MARLEY PLASTIC MATRIX: 0.04 in COPPER R_o = 2.25 in						
17.5				2.0	0.62	0.37
22.5				2.6	0.94	0.74
32.5				3.4	1.31	1.03
39.0				4.9	1.36	0.96
45.0				5.1	2.14	1.72
50.5				6.1	2.42	1.91
CLAD: 2x 0.033 in CYCOLAC PLASTIC MATRIX: 0.04 in COPPER R_o = 2.25						
21.0				2.7	0.88	0.67
24.2				2.9	0.94	0.71
32.5				3.5	1.26	0.98
40.1				4.1	1.36	1.02
55.				4.7	1.58	1.20

MEASURED RESULTS

TABLE NO 41

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in	TON f in/in
CLAD: 2x 0.043in MARLEY PLASTIC MATRIX: 0.048in MILD STEEL R_0 = 2.25						
21.0				5.3	1.91	1.47
27.1				6.1	2.33	1.82
34.1				6.6	2.80	2.25
42.2				7.9	3.36	2.70
47.0				8.3	3.73	3.03
55.0				8.6	4.18	3.46
CLAD: 2x 0.043 MARLEY PLASTIC MATRIX: 0.047in STAINLESS STEEL R_0 = 2.25						
18.0				5.1		
19.2				6.3	2.20	1.41
25.5				7.8	2.83	2.09
29.8				9.2	3.60	2.73
35.1				10.4	4.42	3.43
38.3				10.6	4.67	
46.9				8.3	3.7	2.92

MEASURED RESULTS

TABLE NO 42

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.032" COPPER MATRIX: 0.029" MILD STEEL Ro = 2.25						
6.9	7.8	7.4	1.13	2.2	0.80	0.60
17.2	18.8	18.0	1.09	4.9	2.0	1.54
24.1	25.0	24.6	1.04	6.5	2.66	2.06
29.3	29.7	29.5	1.0	7.3	2.97	2.29
32.8	34.4	33.6	1.05	8.1	3.41	2.65
CLAD: 2x 0.029" MILD STEEL MATRIX: 0.047 STAINLESS STEEL Ro = 2.25						
16.0	17.2	16.6	1.08	7.7	1.88	1.16
20.2	20.7	20.5	1.02	9.0	2.44	1.6
25.5	27.6	26.6	1.08	11.5	3.42	2.32
31.9	32.8	32.5	1.03	13.6	4.75	3.45
38.3	39.7	39.0	1.04	15.9	5.53	4.01

MEASURED RESULTS

TABLE NO 43

REDUCTION %				ROLL FORCE	TOTAL ROLL TORQUE	NET ROLL TORQUE
HARD MATERIAL	SOFT MATERIAL	MEAN	RELATIVE	TON f/in.	TON f in/in.	TON f in/in
CLAD: 2x 0.029in MILD STEEL MATRIX: 0.026" 0.71%C STEEL Ro = 2.25"						
17.3	20.7	19.0	1.20	8.3	2.28	1.5
19.2	24.1	21.7	1.26	9.7	2.77	1.85
25.0	27.6	26.3	1.1	10.7	3.39	2.37
26.9	31.0	29.0	1.15	12.0	3.72	2.58
36.5	39.7	38.1	1.09	14.4	4.88	3.47
CLAD: 2x 0.049in ALUMINIUM MATRIX: 0.029" MILD STEEL Ro = 2.25						
13.8	20.4	17.1	1.48	2.6	0.85	0.62
17.2	23.5	20.4	1.37	2.8	1.03	0.78
20.7	25.5	23.1	1.23	3.3	1.25	0.95
29.3	32.7	31.0	1.12	4.2	1.65	1.27
32.8	40.8	36.8	1.24	4.4	1.88	1.48
39.7	45.9	42.8	1.16	6.0	2.63	2.07