# RESIDUAL STRESSES
# IN ARC WELDED MILD STEEL BUTT JOINTS

BY

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"O ! LORD, GOD OF ISRAEL, THERE IS NO ONE LIKE THEE, IN HEAVEN ABOVE OR ON EARTH BENEATH, KEEPING COVENANT AND SHOWING STEADFAST LOVE TO THY SERVANTS WHO WALK BEFORE THEE WITH ALL THEIR HEART, WHO HATH KEPT WITH THY SERVANT DAVID, MY FATHER (VIASHIMA AGU) WHAT THOU DIDST DECLARE TO HIM; YEA THOU DIDST SPEAK WITH THY MOUTH, AND WITH THY HAND THOU HAST FULFILLED IT THIS DAY."

I KINGS 8:23,24.

DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work.

It has not been accepted in any previous application for a higher degree. Quotations are distinguished by quotation marks and the sources of information are specifically acknowledged by means of references.



Viashima Agu

6 July 1983

ABSTRACT

This thesis is a study of residual stresses in arc welded butt joints and the effect of joint geometry and electrode type on the stresses.

**Three** joint designs, the single- v, the double - v and square - butt joints have been considered. Two filler rods selected for this study are E6012 and E6013 of the American Voiding Society (AWS) classification. Each electrode type was used to weld the joint designs, by the electric arc process.

The stress relaxation sectioning technique using electrical resistance strain gauges was used in taking the readings.

The single - v joint was found to produce stresses of higher magnitude than the double - v and square - butt joints. The double - v and square - butt joints produced stresses of about the same magnitude. This study however showed that the two electrode types selected for the welding produced almost the same effect on the residual stresses.

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## LIST OF SYMBOLS

$\sigma$ - Tensile stress,

$\sigma_x, \sigma_y, \sigma_z$ - Tensile stress in the direction of x,y,z, respectively.

$\sigma_m$ - Maximum stress across weld region.

$\sigma_1, \sigma_2$ - Maximum and Minimum principal stresses, respectively.

$\sigma_r$ - Residual stress.

$\tau_{xy}$ - Shear stress on x plane in y direction.

$\varepsilon$ - Strain.

$\varepsilon_x, \varepsilon_y$ - Strain in the x and y directions, respectively.

$\gamma_{xy}$ - Shear strain on x plane in y direction

$\varepsilon_x', \varepsilon_y'$ - Elastic strains.

$\varepsilon_x'', \varepsilon_y''$ - Plastic strains.

$\gamma_{xy}'$ - Elastic shear strain.

$\gamma_{xy}''$ - Plastic shear strain.

$\bar{\varepsilon}_x$ - Strain change in the x-direction.

$\bar{\varepsilon}_y$ - Strain change in the y-direction.

$\bar{\gamma}_{xy}$ - Shear Strain change

$\varepsilon_A, \varepsilon_B, \varepsilon_C$ - Strains in the direction A,B,and C respectively.

$\varepsilon_1, \varepsilon_2$ - Principal strains.

$e_L$ - Longitudinal strain.

$e_w$ - Transverse strain.

$\nu$ - Poisson's ratio.

E - Young's Modulus.

| | |
|---|---|
| G | - Modulus of rigidity. |
| $\Delta T$ | - Change in temperature. |
| P | - Load (N) |
| N | - Newtons (unit of force). |
| mm | - Millimetre. |
| $N/mm^2$ | - Newtons per millimetre squared. |
| ø | - Principal angle. |
| $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}$ | - First differential with respect to x and y respectively. |
| $\frac{\partial^2}{\partial x^2}, \frac{\partial^2}{\partial y^2}$ | - Second differential with respect to x and y respectively. |
| $\mu_e$ | - Micro strain $10^{-6}$. |

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# CHAPTER ONE

## INTRODUCTION

Most welding processes involve local heating of the material to be welded. The heat supplied produces complex thermal cycles in the weldment and these in turn cause changes in the microstructure of the heat-affected zone, transient thermal stress and metal movement, and result in the creation of residual stress and distortion in the finished product.

What usually happens is that the weld metal and the base metal heat-affected zones are at a much higher temperature than the unaffected base metal. When the molten pool solidifies and shrinks, it exerts shrinkage stresses on the surrounding base metal and the unaffected heat zone area. The weld metal is relatively weak and exerts very little stress on first solidification. On further cooling to ambient temperatures, the shrinkage of the weld metal exerts increasing stress on the weld area and eventually reaches the yield point of the weld metal.

Also because a weld is made progressively, it causes the already solidified portions of the weld to resist the shrinkage of later solidifying portions. The portions welded first are thus strained in tension in a direction longitudinal to the weld. An additional factor in butt welds, is that there is transverse residual stress as well due to the fact that little motion of the weld is permitted in the transverse direction because of the weld joint prepaeation and the stiffening effect of underlying passes.

The types and distribution of these residual stresses are complex. A detailed analysis of these stresses can be found in literature; only a brief account has been attempted in this thesis and this can be found in Chapter Two.

Residual stresses have two major effects in weldments. First, they produce distortion and can cause premature failure in weldments. Non uniform contraction of the heated weld is the cause of distortion, for by causing shrinkage in one part of the weld, they exert eccentric forces on the cross-section. The weldment then strains elastically in response to these stresses and their non-uniform strain is seen as distortion. The distortion appears in butt joints as both longitudinal and transverse shrinkages and as angular change when the faces of the weld shrink more than the root. Distortion in fillet welds is similar to that in butt welds but can be much more complex, because fillet welds are usually made together with other welds. Also distortion in fillet welds is an important factor in their use. Distortion as related to butt welds has been discussed in Chapter Two of this dissertation, under the effect of residual stresses in weldments. Control of distortion can be achieved by the control of the geometry of joint before welding. Examples of techniques used to control distortion include, presetting the workpieces prior to welding so that weld distortion leaves them in the desired final geometry (Fig. 2.7) or restraining the joint to minimize distortion after welding. (Fig. 2.8) . The

welding process and welding sequence also influence residual stress and distortion. If the finished member is distorted it can be corrected by straightening mechanically or by thermal or flame straightening, after welding. Chapter Two also discusses some of the procedures for correcting distortion in weldments.

Residual stresses contribute to buckling and brittle fracture when these failures occur at low applied stress levels. Buckling may occur at lower compressive loads than expected when residual stresses and distortion are present. Residual stresses may also lead to high local stresses in tension, in weld regions of low toughness and as a result, may give rise to running cracks that can be propagated by low overall stresses that may be present.

Residual stresses may be eliminated by both thermal and mechanical means. Some of these means are described in Chapter Two.

Various techniques have been developed and used in determining qualitatively and quantitatively, the magnitudes of residual stresses in weldments. Chapter Two also surveys the techniques available for measuring residual stresses in welded structures. These techniques fall into four broad areas: stress relaxation techniques, X-ray diffraction techniques, techniques that use stress sensitive properties and cracking techniques. In each of these, there are many vaeiations. The technique used in this thesis comes under, "Stress Relaxation" techniques.

Chapter three discusses in detail the techniques used in determining the residual stresses and also other factors related to the investigation carried out in this thesis, such as specimen preparation, welding process, electrode type, etc.

In recent years, welding has replaced joining processes like bolting and reveting in many applications. It has thus become important to recognize the broad problem of improving the reliability of welded metal structures. Engineers must not only consider the effects of residual stresses and distortion, but also many other aspects including the reduction of cracks, porosity and other discontinueties; material degradation due to thermal effects during welding; the extent of non-destructive testing; and fabrication costs, to mention a few. Practising engineers must weight the advantages of processes and procedures from the various perspectives.

A considerable amount of work has been put in to study the causes, effects, elimination and the distortion occurring in weldments. The highlights could be summarized as follows:-

1. Reducing residual stress and distortion in the first place by selecting proper processes and procedures.
2. Developing better means for stress relieving and removing distortion.
3. Changing the structural design and thematerial so that the effects of residual stress and distortion can be minimized.

The field of welding is quite vast and it is rather difficult to cover all the aspects of welding in a project of this kind. Hence this investigation was confined to the study of the residual stresses in butt joints and the effect of joint geometry and electrode type on the same. The results obtained have been summarized and discussed in Chapter Four.

Chapter Five outlines the conclusions while Chapter Six gives the recommendations for further work.

## CHAPTER TWO

## RESIDUAL STRESSES, THEIR DISTRIBUTION AND MEASUREMENT IN WELDMENTS

Residual stresses are those stresses that would exist in a body after all applied loads were removed. Residual stresses have been referred to as internal stresses, initial stresses, inherent stresses, reaction stresses and lock-in stresses. Residual stresses that occur when a body is subjected to non-uniform temperature change are called thermal stresses.

In metal structures, residual stresses occur for many reasons during the various stages of manufacturing. They may be produced during forming and shaping of metal parts using such processes as rolling, forging, casting, shearing, bending, machining and grinding as well as during fabrication by welding.

Heat treatment at various stages of production can also influence residual stresses. For example, stress relieving heat treatment reduces residual stresses while quenching induces them.(2)

### 2.1. FORMATION OF RESIDUAL STRESSES IN WELDMENTS

Residual stresses produced during welding are as a result of the uneven distribution of the non-elastic thermal strains generated due to local heating. Complex thermal cycles are produced in weldments by the heat of the welding arc. These cycles in turn cause changes in the microstructure of the heat affected zone which give

rise to transient thermal stresses and metal movement and results in the creation of residual stresses in the finished product.

A schematic representation of temperature and thermal stresses during welding is shown in Fig. 2.1. A bead on the plate has been made along the x-axis. The welding arc is at this instant located at O, and is moving at a speed V as shown in Fig. 2.1(a).

Fig. 2.1(b) shows the temperature distribution along the corresponding sections shown in Fig. 2.1(a) in the x-direction.

Section A-A:

This section is ahead of the welding arc, and the temperature due to welding $\Delta T$, is almost zero. The thermal stress due to welding is also almost zero.

Section B-B:

Section B-B crosses the welding arc. Consequently the temperature change is extremely rapid and the distribution uneven. Because the molten metal will not support a load, stress underneath the welding arc is close to zero. The expansion of regions a short distance from the arc are restrained by the surrounding metal which is at a lower temperature. This gives rise to compressive stresses in these regions. Also stresses in these areas are as high as the yield strength of the material at corresponding temperatures. This is because at the high temperatures involved, the yield strength of the material is low.[1] These compressive stresses pass

through a maximum with increase in distance from the weld and therefore with decrease in temperature. However, stresses in areas farther away from the weld are tensile and balance with compressive stresses in areas near the weld; in other words,

$$\int \sigma_x \, dy = 0 \qquad \text{----------(2.1)}$$

across the section B-B.

Section C-C:

The distribution of temperature change across this section, which is some distance behind the arc, is shown in Fig. 2.1(b)-3. The stress distribution across the section is also shown in Fig. 2.1(c)-3. Here, the weld and base metal have both contracted due to cooling, thus causing tensile stresses in areas near the weld. As the distance from the weld increases, the stresses first change to compressive then become tensile.

Section D-D:

The temperature change along Section D-D diminishes to almost zero, due to its being a long distance away from the welding arc. Fig. 2.1(b)-4. High tensile stresses are produced in areas near the weld in this section, while compressive stresses are produced in regions away from the weld. The cross-hatched area M - M' in Fig. 2.1(a) shows the region where plastic deformation occurs during the welding thermal cycle, while the egg-shaped region indicates the area where the metal is molten. Fig. 2.1(c)-4 is the usual distribution of residual

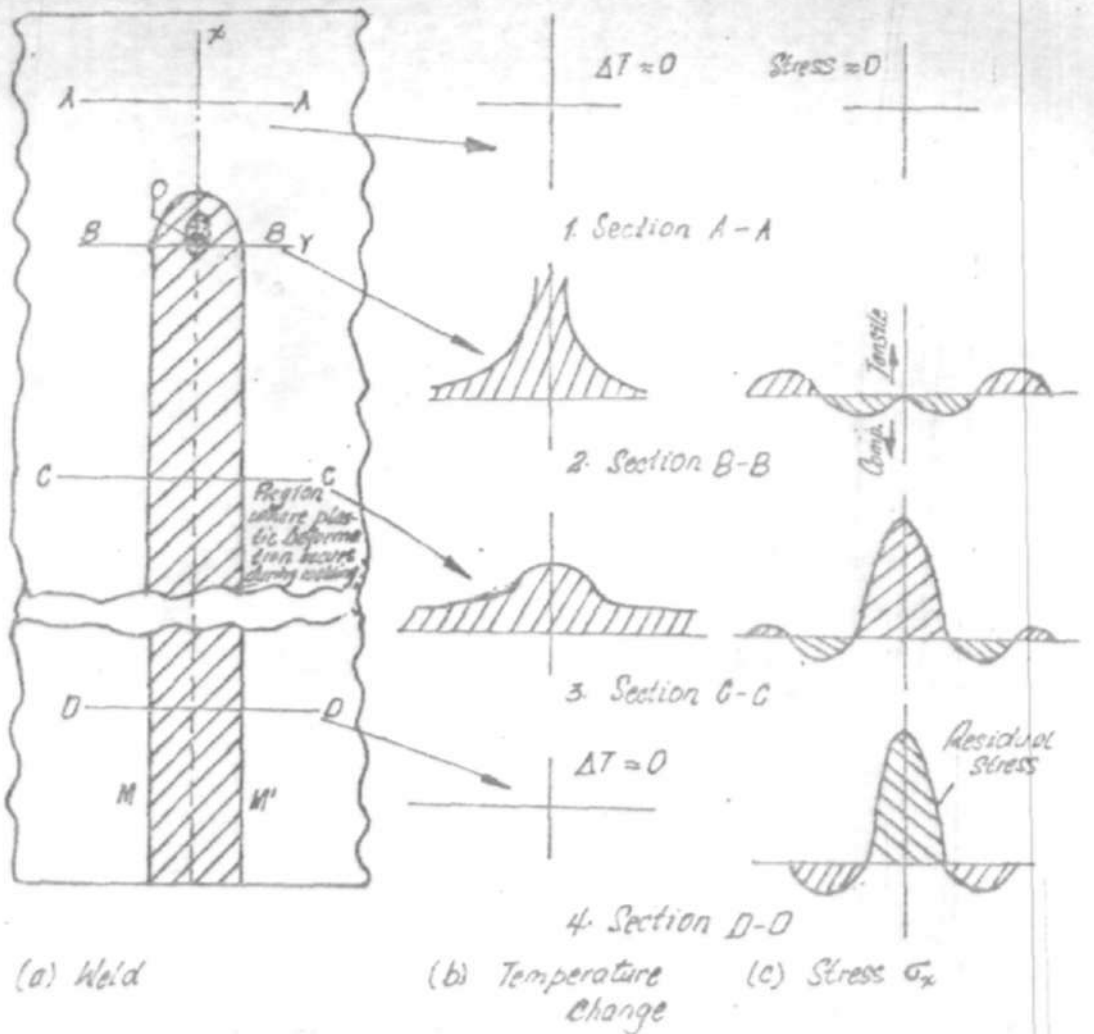



**Fig. 2.1: Changes of Temperature and Stress During Welding**
**After Masubuchi (1)**

stresses that remain after welding is completed.

These stresses are of two types:-

1. Residual welding stresses that are produced in the welding of unrestrained members - these are as a result of shrinkage of metal on cooling and a complex mechanism which involves plastic deformation at a wide range of temperatures from room temperature to melting temperature. These occur in all three dimensions in the absence of any external load or restraint.

2. Reaction stresses that are caused by external restraint - these stresses are additional stresses imposed on weldments over the residual stresses mentioned in (1) above, when the lateral contraction of the joint is restrained.

The mechanism of formation of residual stresses in restrained butt joints is discussed in the following paragraphs and the present investigation is confined to the study of stresses in such weldments.

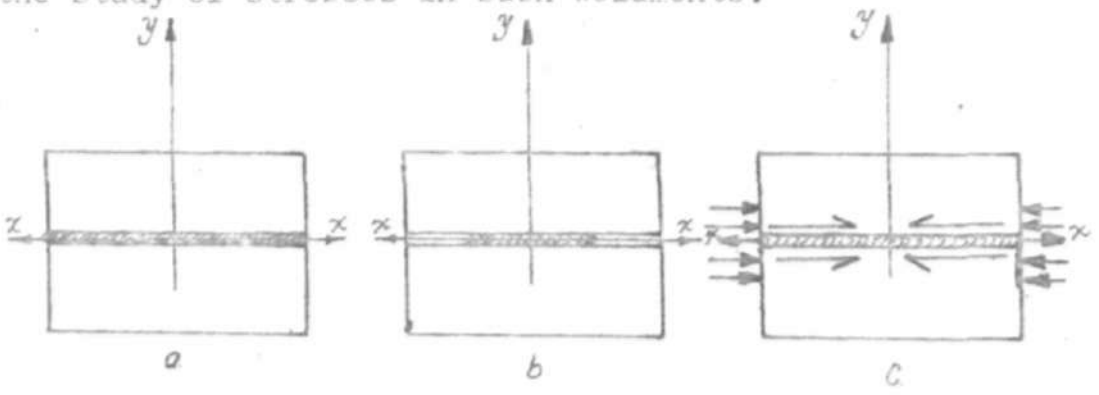



Fig. 2.2: Mechanism of Formation of Residual Stresses in a Butt Weld

It is assumed in Fig. 2.2(a) and (b) that immediately after welding, the weld and the region adjacent to it are hot and the remainder of the plate is cold. Under this assumption, the weld will contract on solidification while the plate retains its original length as illustrated in (b). In practice, however, the plate restricts the contraction of the molten material, thereby putting the weld in high tension in a direction parallel to the weld.

Compressive stresses, thus develop in the base metal as shown in Fig. 2.2(c).

A typical distribution of both longitudinal and transverse residual stresses resulting in the weldment from this set-up is shown in Fig. 2.3. The stresses of concern are those parallel to the weld direction designated $\sigma_x$ and those transverse to it, designated $\sigma_y$. Fig. 2.3(b) shows the distribution of the longitudinal residual stress, $\sigma_x$. From the figure it can be seen

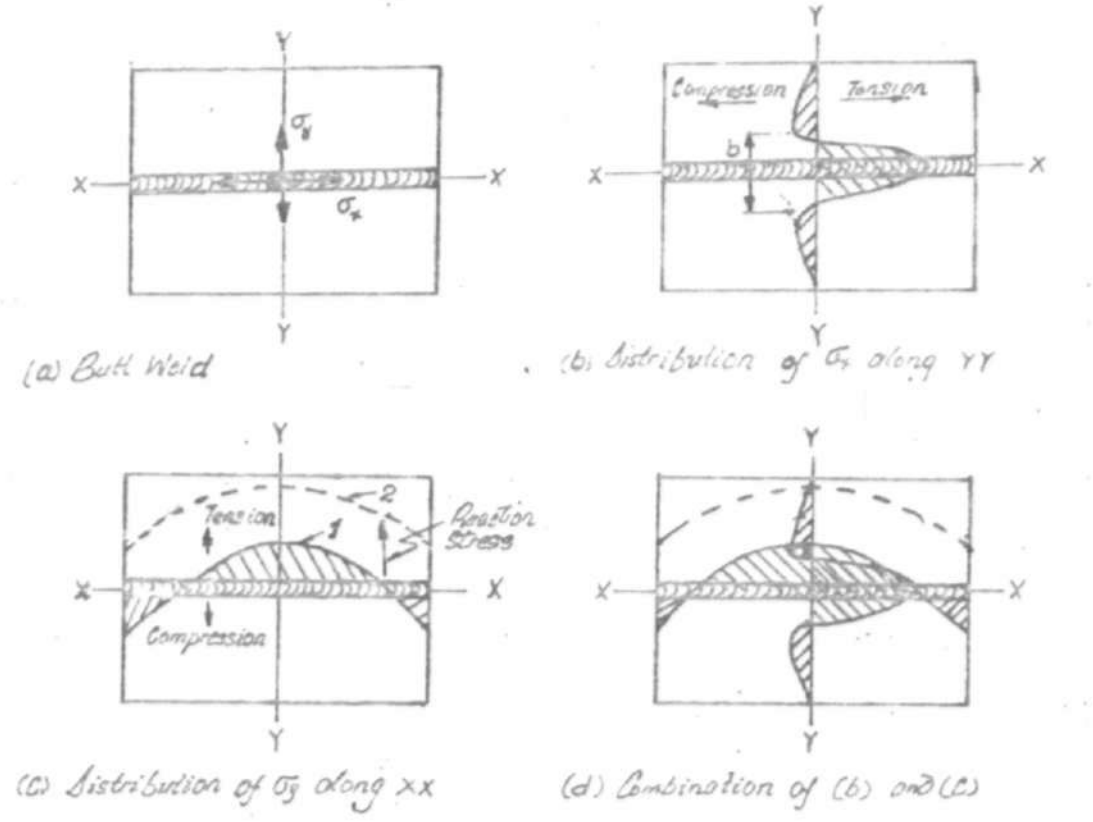



**Fig. 2.3: Typical Distribution of Residual Stresses in a Butt Weld After Masubuchi[1]**

that tensile stresses of high magnitude are produced in the region near the weld; these taper off rapidly and become compressive after a distance of several times the

width of the weld metal. The stress distribution is characterised by two parameters: the maximum stress at the weld region, $\sigma_m$ and the width of the tension zone of residual stress b.(1)

In weldments made of low-carbon steel, the maximum residual stress, $\sigma_m$, is usually as high as the yield stress of the weld metal.(1) The distribution of the transverse residual stress, $\sigma_y$, along the length of the weld is shown on curve 1 in Fig. 2.3.(c). Comparatively, tensile stresses of relatively low magnitude are produced in the middle part of the joint and compressive stresses at the ends of the joint.(1)

When the lateral contraction of the joint is restrained by an external constraint, tensile stresses approximately uniform along the weld are added as the reaction stress (curve 2 Fig. 2.3.c). An external constraint, however, has little influence on the distribution of the longitudinal residual stress, $\sigma_x$.(1,12)

If the welding is on a heavy plate of thickness over 25 mm, residual stresses in thickness direction become significant; otherwise they can be ignored.

The magnitude and distribution of residual stresses in weldments have been found to be affected by the temperature distribution in weldments, the thermal expansion characteristics of the material and the mechanical properties of the material at elevated temperatures.(1) The stress in the thickness direction of weldments in plates less than 25 mm thick is negligible.(12) A plane

state of stress exists in weldments less than 25 mm thick; the specimens tested in this thesis had a plane state of stress, since they were all 15 mm thick or less. The fundamental relationships in a two dimensional plane stress ( $\sigma_z = 0$), residual stress field are given below.

(i) Strains are composed of elastic and non-elastic strains.

$$\left.\begin{aligned} \varepsilon_x &= \varepsilon_x' + \varepsilon_x'' \\ \varepsilon_y &= \varepsilon_y' + \varepsilon_y'' \\ \gamma_{xy} &= \gamma_{xy}' + \gamma_{xy}'' \end{aligned}\right\} \text{----------(2.2)}$$

The components of non-elastic strain can be plastic or thermal strain.

(ii) Hooke's Law relationship exists between stress and elastic strain, thus:-

$$\left.\begin{aligned} \varepsilon_x' &= 1/E(\sigma_x - \nu\sigma_y) \\ \varepsilon_y' &= 1/E(\sigma_y - \nu\sigma_x) \\ \gamma_{xy}' &= 1/G\ \tau_{xy} \end{aligned}\right\} \text{----------(2.3)}$$

(iii) The stress must satisfy the equilibrium condition:

$$\left.\begin{aligned} \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} &= 0 \\ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} &= 0 \end{aligned}\right\} \text{----------(2.4)}$$

(iv) The total strain must satisfy the condition of compatibility:

$$\left[\frac{\partial^2 \varepsilon_x'}{\partial y^2} + \frac{\partial^2 \varepsilon_y'}{\partial x^2} - \frac{\partial^2 \gamma_{xy}'}{\partial x \partial y}\right] + \left[\frac{\partial^2 \varepsilon_x''}{\partial y^2} + \frac{\partial^2 \varepsilon_y''}{\partial x^2} - \frac{\partial^2 \gamma_{xy}''}{\partial x \partial y}\right] = 0 \text{----------(2.5)}$$

Residual stresses exist when the value of R, determined by the non-elastic strain so given in equation (2.6) below is not zero.

$$R = -\left[ \frac{\partial^2 \varepsilon_x''}{\partial y^2} + \frac{\partial^2 \varepsilon_y''}{\partial x^2} - \frac{\partial^2 \gamma_{xy}''}{\partial x \partial y} \right] \quad \text{-----(2.6)}$$

R is the cause of residual stress and is called 'incompatibility'. According to Masubuchi[1] important findings obtained from this analysis include:-

(i) When R = 0, residual stress will not occur.

(ii) Residual stress in a body cannot be determined by measuring the stress change that takes place when an external load is applied to the body, the body is cut to determine residual stress.

(iii) Residual stresses $\sigma_x$, $\sigma_y$ and $\tau_{xy}$ can be calculated when the elastic strain components $\varepsilon_x'$, $\varepsilon_y'$ and $\gamma_{xy}'$ are determined. However, components of non-elastic strains, $\varepsilon_x''$, $\varepsilon_y''$ and $\gamma_{xy}''$ which have caused residual stress cannot be determined without knowing the history of the formation of the residual stresses.

## 2.2. EFFECTS OF RESIDUAL STRESSES IN WELDMENTS

The strains produced during heating in a weld are accompanied by plastic upsetting. The stresses resulting from these strains combine and react to produce internal forces to cause bending, buckling and rotation in the finished product. These displacements are called

distortion, and are the major effect of residual stresses in welded structures. There are three main fundamental dimensional changes that occur during the welding process, giving rise to distortion. These are:-

(i) Transverse shrinkage perpendicular to the weld line.

(ii) Longitudinal shrinkage parallel to the weld line.

(iii) Angular distortion or rotation around the weld line.

All the above mentioned dimensional changes are shown in Fig. 2.4.

Fig. 2.4(a) shows a typical transverse shrinkage in a butt weld. The shrinkage here is shown to be at right angles to the weld line and uniform along the weld. Transverse shrinkage is, however, not always uniform in butt welds especially when they are long. Actual structures exhibit complex transverse shrinkage. The major cause of this non-uniform transverse shrinkage in butt welds is Rotational distortion shown in Fig. 2.4(d). This takes place in long welds when welding is done progressively, the unwelded portion of the joint moves in as shown, causing rotational distortion.

Rotational distortion is affected by the welding heat input and the location of tack welds. The weld sequence and the distribution of restraint along the weld also have a complex effect on rotational distortion.

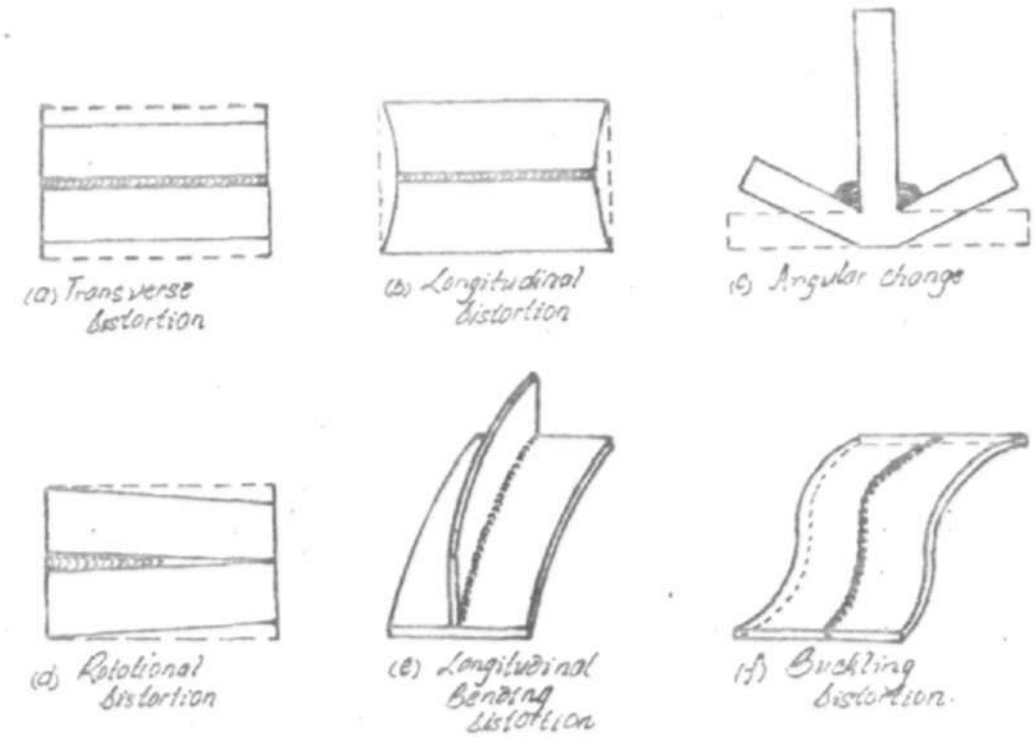



Fig. 2.4: Various Types of Weld Distortion After Masubuchi[1]

Restraint: The amount of shrinkage that occurs in a butt weld is also affected by the degree of restraint applied to the joint. The amount of shrinkage decreases as the degree of restraint increases.

The major portion of transverse shrinkage in a butt weld is due to contraction of the base plate. The base plate expands during welding; when the weld metal solidifies, the expanded base metal must shrink, and this shrinkage accounts for the major part of transverse shrinkage. Shrinkage of the weld metal is only about ten percent of the total shrinkage.

Plate Thickness:

Investigations by Matsui[9] show that, transverse shrinkage in thicker plates starts earlier, but the final value of the shrinkage is smaller than in thin plates. It is to be noted, however, that welding thicker plates may require more than one pass which may change the whole picture.

Materials:

The amount of transverse shrinkage is different for various materials because the material properties differ from material to material. For example, aluminium alloys, because of their higher heat conductivity and thermal expansion coefficients, shrink more than steel. Phase transformations in ferrous materials also play an important role since they give rise to a certain amount of expansion/contraction.

Welding Procedures:

Kihara and Masubuchi[4,7], in their study on transverse shrinkage that occurs during mutipass welding of constrained butt joints in carbon steel, showed that transverse shrinkage increases during multipass welding as shown in Fig. 2.5. This is because the resistance against shrinkage increases as the weld gets larger. Shrinkage was pronounced during the early weld passes, but diminished during later passes.

They further studied how various factors, including joint design, root opening, type and size of electrode,

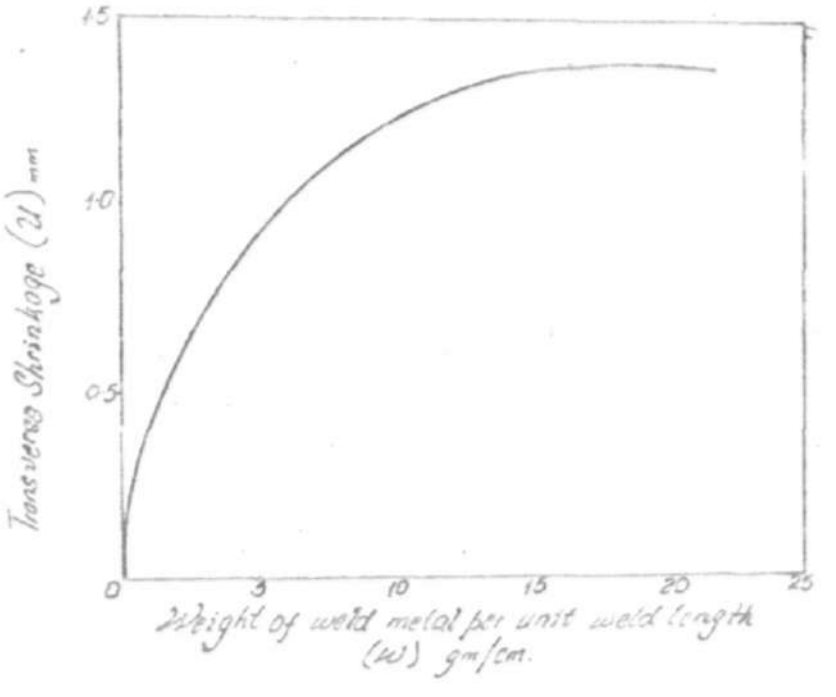



Fig. 2.5: Increase in Transverse Shrinkage During Multipass Welding of a Butt Joint After Masubuchi[1]

degree of constraint and peening, affect transverse shrinkage. The findings are shown in Table 2.1 below.

Table 2.1: Effect Of Various Procedures On Transverse Shrinkage In Butt Welds[1]

| Welding Parameters | Effect On Shrinkage |
|---|---|
| Root Opening | Shrinkage increases as root opening increases. Effect is large. |
| Joint Design | A single-V joint produces more shrinkage than a double-V joint. Effect is large. |
| Electrode Diameter | Shrinkage decreases by using larger size electrodes. Effect is medium. |
| Degree of Constraint | Shrinkage decreases as the degree of constraint increases. Effect is medium. |
| Electrode Type | Effect is minor. |
| Peening | Shrinkage decreases with peening. Effect is minor. |

## 2.3 EFFECT OF EXTERNAL LOAD ON A BODY CONTAINING RESIDUAL STRESSES(1)

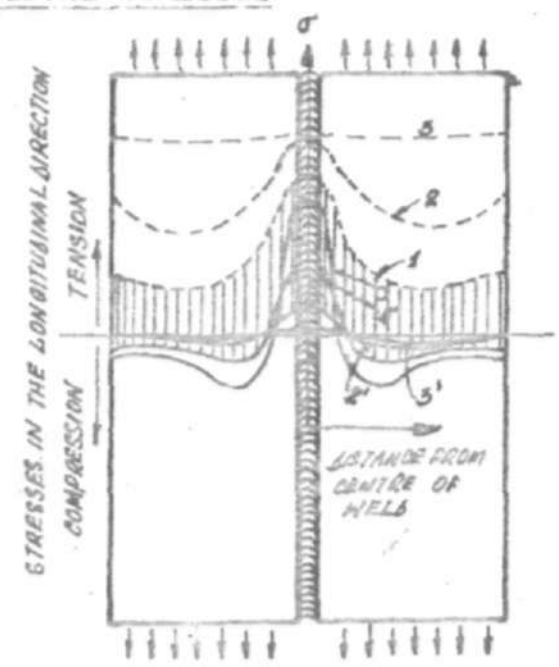



Fig. 2.6: Distribution of a Residual Stress in a Butt Weld when Uniform Tensile Loads are applied and the Residual Stresses that result after Loads are released After Masubuchi(1)

Curve 0: Residual Stresses in the as welded condition.
Curve 1: Stress Distribution at $\sigma = \sigma_1$
Curve 2: Stress Distribution at $\sigma = \sigma_2$
Curve 3: Distribution of stresses at general yielding.
Curve 1': Distribution of residual stress after $\sigma = \sigma_1$ is applied and then released.
Curve 2': Distribution of residual stress after $\sigma_1 = \sigma_2$ is applied and then released.

When a uniform tensile stress $\sigma = \sigma_1$ is applied to a body containing residual stresses, the uniform stress is superimposed on the residual stress and the resulting stress distribution as shown in Fig. 2.6 on Curve 1; when the uniform stress is released, the stress falls to the level shown by Curve 1', in the same figure.

When the uniform stress is applied, the stresses in areas near the weld reach yield stress and most of the

stress increase occurs in areas away from the weld, depending on the characteristics of the material. When the applied tensile stress is increased to $\sigma_2$, the stress distribution will be as shown in Curve 2. As the level of applied stress increases, the stress distribution across the weld becomes more even, that is, the effect of welding residual stress on the stress distribution decreases. General yielding takes place across the entire cross-section when the level of applied stress is further increased. The stress distribution at general yielding is shown by Curve 3. The effect of residual stress on stress distribution virtually disappears beyond general yielding.

When the applied stresses are removed the stress distribution evens out at a lower level than the original residual stress distribution shown by Curve 0.

The following basic fact has been arrived at about the effect of residual stresses:

1. Residual stresses significantly affect only those phenomena that occur under low applied stress such as brittle fracture.
2. As the level of applied stress increases, the effect of residual stress decreases.
3. The effect of residual stress on performance of a welded structure is negligible when the applied stress has been increased beyond the yield point.
4. Residual stress tends to decrease as the structure is subjected to repeated loading.

## 2.4. DESIGN AND PROCEDURES FOR REDUCING RESIDUAL STRESSES AND DISTORTION

In order to develop effective means for reducing residual stresses and distortion, it is essential to understand how residual stresses and distortion are affected by design and welding procedures as has been discussed in the preceding sections of this Chapter.

### 2.4.1. Reduction Of Residual Stresses

The extent of the effects of residual stresses on the service behaviour of welded structures varies significantly, depending upon a number of conditions. It is preferable generally to have less residual stresses (since to some structures, a certain amount of residual stress is allowable). It is advisable to take precautions to reduce residual stresses to a tolerable level, particularly when welding heavy sections.

Generally, a reduction in the amount of weld metal usually results in a reduction in residual stresses and distortion, since residual stresses and distortion are caused by thermal strains due to welding. For example a V-groove contains more filling space than a U-groove; the use of a U-groove instead of a V-groove should thus result in the reduction of the amount of weld metal. It is desirable to use bevel angles and root openings of the smallest possible size, that will not restrict accessibility. In general, a reduction of reaction stresses is accomplished by a reduction in the amount of free shrinkage in a butt joint.

2.4.2. Control Of Distortion

(i) Design:

The most economic design for a welded fabrication is the one which requires the fewest number of parts and a minimum of welding. Such a design also assists in reducing distortion and is to be recommended on that account. For unrestrained butt welds the type of joint preparation is important since it can influence the amount of angular distortion which will result from welding.

It is not possible to vary the joint preparation with fillet welded joints. Thus all that a good design can achieve is to specify the minimum sizes of welds with regard to strength requirements. In this way, overwelding can be avoided and distortion minimized.

Good design and well-chosen joint details serve to reduce the magnitude of the problem and make it easier during manufacturing to apply practical measures to achieve the desired results. They cannot, however, solely control distortion.

(ii) Assembly Procedure:

It has become necessary to consider how distortion can be controlled since distortion is inevitable in one form or another. It has been seen that success may be avhieved, not only in design, but by adopting one or the other of two assembly methods.

(a) By estimating the amount of distortion likely to occur during welding and then assembling the job

with the members preset to compensate for the distortion as shown below.

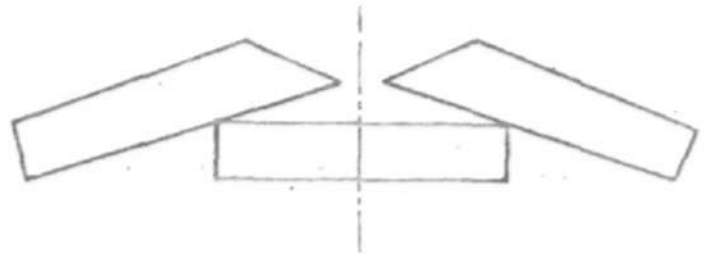


Fig. 2.7: Presetting of a Butt Weld

After welding the above specimen, the finished product becomes straight.

(b) By assembling the job so that it is nominally correct before welding and by employing some form of restraint to minimize the welding distortion after welding as shown below.

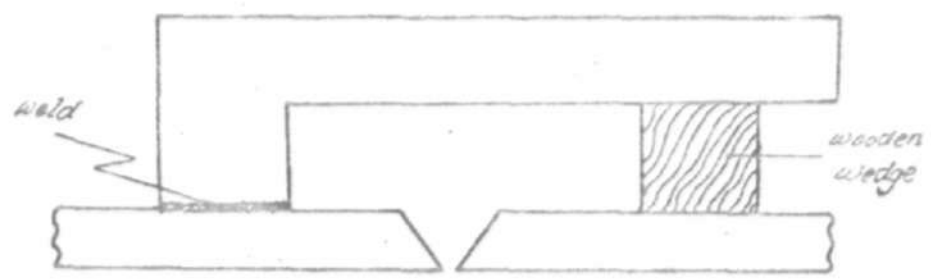



Fig. 2.8: Arrangement of Clamp to Prevent Angular Distortion While Permitting Transverse Shrinkage

During welding the wooden wedge restrains the curving-in of the joint.

2.4.3. Correction Of Distortion

When dealing with a new fabrication, it is not always possible to control distortion within acceptable

limits. There are instances where, despite the most careful planning, the distortion becomes excessive. In such circumstances, it is usually possible to rectify the problem by producing plastic deformation in the distorted member or section.

There are various thermal and mechanical methods that can be used to obtain the required amount of plastic deformation. These include: thermal straightening, hammering of locally heated areas and jacking. Others include preheat, peening, proof stressing and so on.

These methods are named above, detailed information on them can be found in appropriate literature.[1,12]

## 2.5. MEASUREMENT OF RESIDUAL STRESSES IN WELDMENTS

### 2.5.1. Classification Of Techniques For Measuring Residual Stresses

Several techniques have been used for measuring residual stresses in metals. A few that are applicable to weldments are discussed in the following section.

The available techniques used presently for measuring residual stresses can be classified into four major groups:

I. Stress-relaxation techniques.

II. X-ray diffraction techniques.

III. Techniques by use of stress sensitive properties.

IV. Cracking techniques.

In the stress-relaxation technique, residual stress is determined by measuring the elastic strain release that takes place when a specimen is cut into pieces or has a piece removed from it. In most cases, electric or

mechanical strain gauges are used for measuring this strain release.

A variety of these techniques exist as there are many ways of sectioning a specimen to determine residual stresses. Some are used in the study of stress in plates, others in cylinders, tubes or three dimensional solids.

The strain release can also be obtained by using grid systems, brittle coatings, or photoelastic coatings instead of mechanical or electrical strain gauges.

The main disadvantage of stress-relaxation techniques is that they are destructive; the specimen must be either partially or entirely sectioned. They, however, provide reliable quantitative data and are the most widely used for measuring residual stresses in weldments.

Elastic strains can be determined in metals with crystalline structures by measuring the lattice parameter with X-ray diffraction techniques. Elastic strains in the metal can be measured non-destructively without machining or drilling since the lattice parameter of a metal in the unstressed state is known or can be determined independent of the elastic strains. Two main techniques are available, viz:

(a) The X-ray film technique, and

(b) The X-ray diffractometer technique.

With the X-ray diffraction techniques, surface strains can be obtained within a small area (0.0025 mm in diameter) say, and to a depth of 0.025 mm. X-ray diffraction techniques have disadvantages. They are time-consuming

and not very accurate, especially in situations where high temperatures have distorted the crystal structure of the material.

Attempts have also been made to determine residual stresses in metals by measuring their stress sensitive properties.(1) The techniques which have been proposed include -

1. Ultrasonic techniques: These include:
   (a) The polarized ultrasonic wave technique which makes use of stress induced change in the angle of polarization of polarized ultrasonic waves.
   (b) The ultrasonic attenuation technique which makes use of a stress-induced change in the rate of absorption of ultrasonic waves.
2. Hardness techniques which make use of stress-induced changes in hardness.

None of these techniques have either been developed beyond the laboratory stage or used successfully for measuring residual stresses in weldments. These techniques are thus not discussed here.

Another technique developed for the study of residual stresses involves the observation of cracks induced in the specimen by hydrogen or stress corrosion. These, however, provide only qualitative and not quantitative data and are thus useful when studying residual stresses in complex structural models in which the residual stress distribution is complicated.

2.5.2. Measurement Of Residual Stresses By Stress-Relaxation Techniques

Stress-relaxation techniques are based on the principle that strains created during unloading are elastic even when the material has undergone plastic deformation. This makes it possible to determine residual stresses without knowing the history of the loading of the material.

Over the years many methods have been developed based on this principle. These methods include: brittle coating and drilling techniques; grid systems dividing techniques; photoelastic coating drilling technique and sectioning techniques.

A detailed description of these techniques can be found in literature.[1,11,12]

2.5.3 Sectioning Techniques Using Electrical Resistance Strain Gauges

Electrical resistance strain gauges are mounted on the specimen after the surface has been prepared to a surface finish suitable for the seating of the gauges. A small slice containing the gauges is removed from the structure as shown in Fig. 2.9 below.

In the resistance type bonded strain-gauge, the resistance of the gauge changes as the specimen is strained, the magnitude of the strain is determined by measuring the resistance of the gauges. Information on

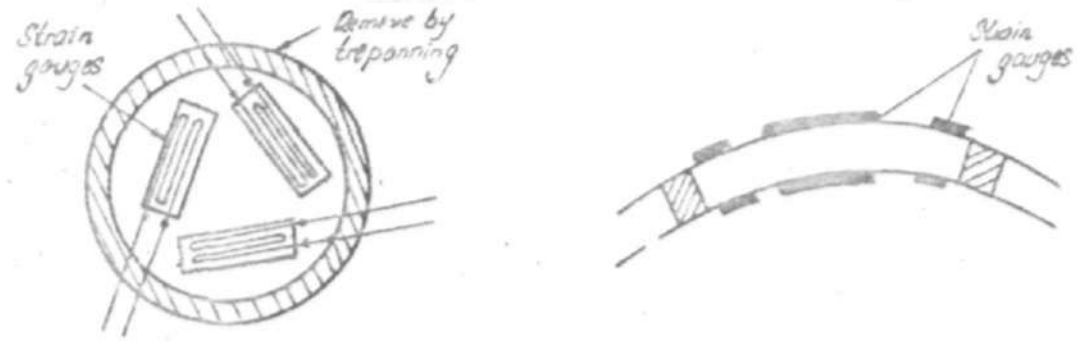



Fig. 2.9: Complete Stress Relaxation Technique Applied to a Plate After Masubuchi[1]

electrical resistance strain gauges is available in numerous sources including the 'Handbook of Experimental Stress Analysis.'[5]

Changes in temperature tend to cause an apparent strain; therefore some type of temperature compensation is needed. Frequently, a 'dummy gauge', which is not subjected to the strain, is exposed to the same temperature as the actual gauge to provide a basis for compensation. A temperature-compensated gauge can also be used.

Various cements have been developed for binding the gauges securely to the specimen. The gauges have to be protected from metal chips produced during machining, the coolant used to cool the specimen as well as from humid atmospheric conditions.

Measurement is taken of the strain changes $\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$, and $\bar{\gamma}_{xy}$, that take place during the removal of the slice. If the piece is small enough, it is assumed that residual stresses no longer exist in the piece and that the

following holds good:-

$$\bar{\varepsilon}_x = -\bar{\varepsilon}_{x'};\ \bar{\varepsilon}_y = -\bar{\varepsilon}_{y'};\ \bar{\gamma}_{xy} = -\bar{\gamma}_{xy} \qquad \text{-----(2.7)}$$

The negative signs in equation (2.7) indicate that when tensile residual stresses exist, shrinkage not elongation takes place during stress relaxation. The residual stresses are:

$$\sigma_x = -\frac{E}{1-\nu^2}(\bar{\varepsilon}_x + \nu\bar{\varepsilon}_y)$$

$$\sigma_y = -\frac{E}{1-\nu^2}(\bar{\varepsilon}_y + \nu\bar{\varepsilon}_x) \qquad \text{----------(2.8)}$$

$$\tau_{xy} = -G\,\bar{\gamma}_{xy}$$

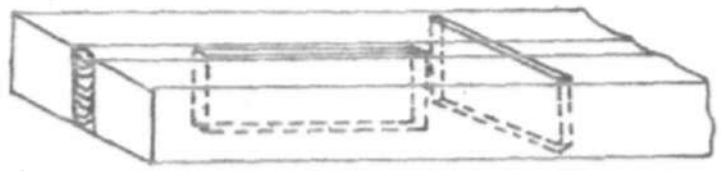
It is advisable to measure the strain on both surfaces since there may be residual stresses due to bending. The mean value of the strains measured on both surfaces represents the plane stress components while the difference represents the stress component caused by bending.

The method can be used any where with the working surface placed in any position; it is reliable and highly accurate. The principle involved is also simple. It is, however, a destructive method and gives only an average stress for the area of specimen from which the piece was removed and does not measure locally concentrated stresses. Also the machining involved is sometimes expensive and time-consuming.

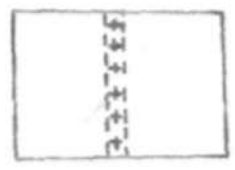
2.5.4. The Rosenthal-Norton Sectioning Technique

The technique is used for determining residual stresses in heavy weldments.

Two narrow blocks are cut with their long axes directed along the axis of the weld and transverse to the weld as shown below.



(a) Sectioning of Weldments to prepare Longitudinal and Transverse blocks



(b) Further Sectioning of block

Fig. 2.10: Rosenthal-Norton Sectioning Method

The blocks should be made narrow with respect to the thickness; then it may be assumed that the operation has relieved practically all of the residual stresses acting perpendicular to the long axis. At the same time the blocks should be made long enough with respect to the thickness (twice the thickness or more if possible).

To determine residual stresses still left in the block, strain gauges are mounted on the sectioned blocks and it is further split into smaller sections.

## 2.6. SELECTION AND USE OF APPROPRIATE MEASUREMENT TECHNIQUES AND EVALUATION OF RESULTS

In determining residual stresses in metals and metal structures, it is important to select measurement techniques that are most appropriate for a particular job.

Factors to be considered include:-

(a) Permissible extent of damage to the structure.

(b) Required quality of measurement.

(c) Effects of variations in metal properties.

(d) Applicability to field tests.

(e) Cost and time.

2.6.1. Permissible Extent Of Damage To The Structure

It is important to decide whether destructive or non-destructive techniques will be used for the tests. Some methods reviewed in Section 2.5 are destructive, e.g. those of stress relaxation. Even among these some can be classified as semi-non-destructive. If no damage to the structure under test is permissible, the only presently available technique is the X-ray diffraction technique. The ultrasonic technique for measuring residual stresses is still in the development stage. The hardness technique and cracking technique are not suitable to be applied to actual structures.(1)

2.6.2. Required Quality And Accuracy Of Measurement

The residual stresses obtained should meet the requirements of quality, accuracy and completeness, according to situational demands must be provided by the technique used.

Some techniques are more accurate than others and some are only qualitative. The accuracy of measured values in actual cases depends upon various factors including methods of cutting in the case of stress relaxation techniques, condition of measuring devices and equip-

ment, surface condition of the specimens, the strain sensitivity of the gauges used and the skill and experience of operators. Bonded strain gauges provide the best sensitivity. Some of the techniques do provide information on the stress components so that the magnitudes and directions of the principal stresses can be determined, while others do not provide enough information on stress components. Bonded strain gauges, extensometers, grid systems, photoelastic coatings and the X-ray diffraction techniques are techniques that belong to the first group which gives information on stress components.

The gauge length used in the test must be short enough for variations in the stress to be detected; however, too short a gauge length is not useful since one may not be able to even fix the gauges on the specimen.

2.6.3. Effects Of Variations In Material Properties

Variation in metal properties is common in large fabricated structures. A welded structure consists of the weld metal, the heat affected zone and the base metal having widely varying microstructures and properties. Heat treatment also changes material properties. These variations in material properties can cause serious problems especially when X-ray and ultrasonic techniques are used.

Literature has it that diffraction lines are broadened, resulting in lower accuracy in strain measurements when the X-ray diffraction technique is used on heat-treated materials.(1)

2.6.4. Field Application

In the techniques reviewed, some are applicable to field tests, some to laboratory tests and some to both. In selecting a technique, it should be determined before-hand whether readings can be taken under field conditions or not and also whether the structures under test may be exposed to environments other than air, i.e. water and oil.

The use of bonded strain gauges is more appropriate than other techniques in most respects.

2.6.5. Cost And Time

Factors which determine the cost and time required for the determination of residual stresses are the shape and size of the specimen, the number of measuring points and the accuracy of measurement required.

Electric-resistance strain gauges are relatively simple to operate and not expensive, but the cost and time required for such stress relaxation procedures as drilling or sectioning can be tremendous. The X-ray diffraction technique is a slow process, because each measuring point requires a time exposure of 20 to 30 minutes.

It can thus be seen from the foregoing discussion that there is no single residual stress measuring technique that is quick, easy, non-destructive, sensitive to high strain, applicable to field testing and low in cost. Each technique does, however, present certain advantages

over others and each has its own appropriate area or areas of application; for example, bonded strain gauges are widely used in residual stress measurement, since they provide high quality data at low cost. They are attached directly to the structure so that strain changes which take place during fabrication can be determined. Whenever portions of the metal are removed during a fabrication process, such as by the drilling or cutting of holes, the stress relaxation that results will be indicated by the bonded strain gauges.

2.6.6. Choice Of Residual Stress Measuring Technique For This Investigation

The stress relaxation sectioning technique using electrical resistance strain gauges was selected for this investigation. This is because reliable, quantitative data in terms of magnitudes of the residual stresses was required at several points on the specimen surface. The method is also simple to use. The equipment and materials required for the application of the technique were also available.

## CHAPTER THREE

## EXPERIMENTAL PROCEDURE

The specimens, strain gauges and experimental method used in this investigation are discussed in the following paragraphs.

### 3.1. SPECIMENS USED

The materials used in the investigation were chosen due to their importance in the construction industry as well as their availability, while the welding process and technique were selected due to their popularity in the structural construction field.

#### 3.1.1. Selection Of Base Metal And Filler Metal

Mild steel was selected in this investigation as the base metal because it is the most common structural material in industry and also because of its easy availability.

The material was in plates, its chemical composition was not known, but the material constants were experimentally determined and given in Table 3.1. The method and calculations used in determining the constants are outlined in Appendix 3.

TABLE 3.1: MATERIAL CONSTANTS OF BASE METAL

| QUANTITY | VALUE |
|---|---|
| Yield Stress | 267.40 $N/mm^2$ |
| Ultimate Stress | 394.70 $N/mm^2$ |
| Poissons Ratio | 0.281 |
| Young's Modulus | 213000 $N/mm^2$ |

Two filler rods selected for this study are E6012 and E6013 of the American Welding Society (AWS) classification. Other specifications and details of the filler rods are given in Table 3.2.

TABLE 3.2: SPECIFICATIONS OF ELECTRODES USED

| AWS Specification | Electrode Diameter(mm) | Length (mm) | Typical Welding Currents(mm) |
|---|---|---|---|
| E6012 | 3.25 | 450 | 95/130 |
| E6013 | 4 | 350 | 130/190 |

3.1.2. Joint Design

Three joint designs were investigated: the single-V, double-V and square-butt, as shown in Fig.3.1.

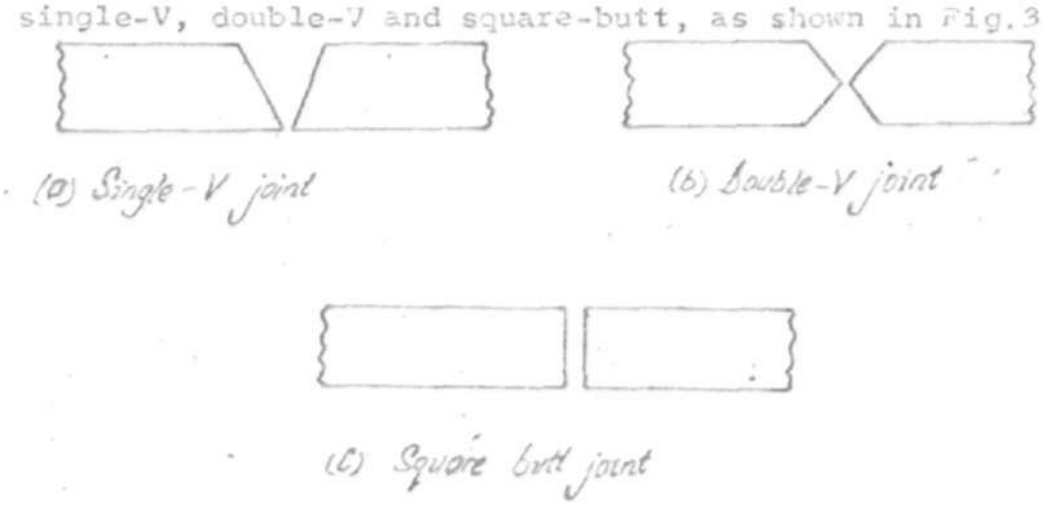



Fig. 3.1: Joint Designs Used in the Experiment

Each piece was carefully machined on a shaping machine to desired size and bevel angle at the joining end. The single-V and double-V joints were bevelled according to convention at an angle of $60^{o}$ in all the specimens tested.

Three sets of specimens were tested, the first set containing twelve specimens, the second six and the last one specimen. In the first set, four specimens with each of the joints designs were made, their actual shape and dimensions are shown to scale in Fig. 3.2.

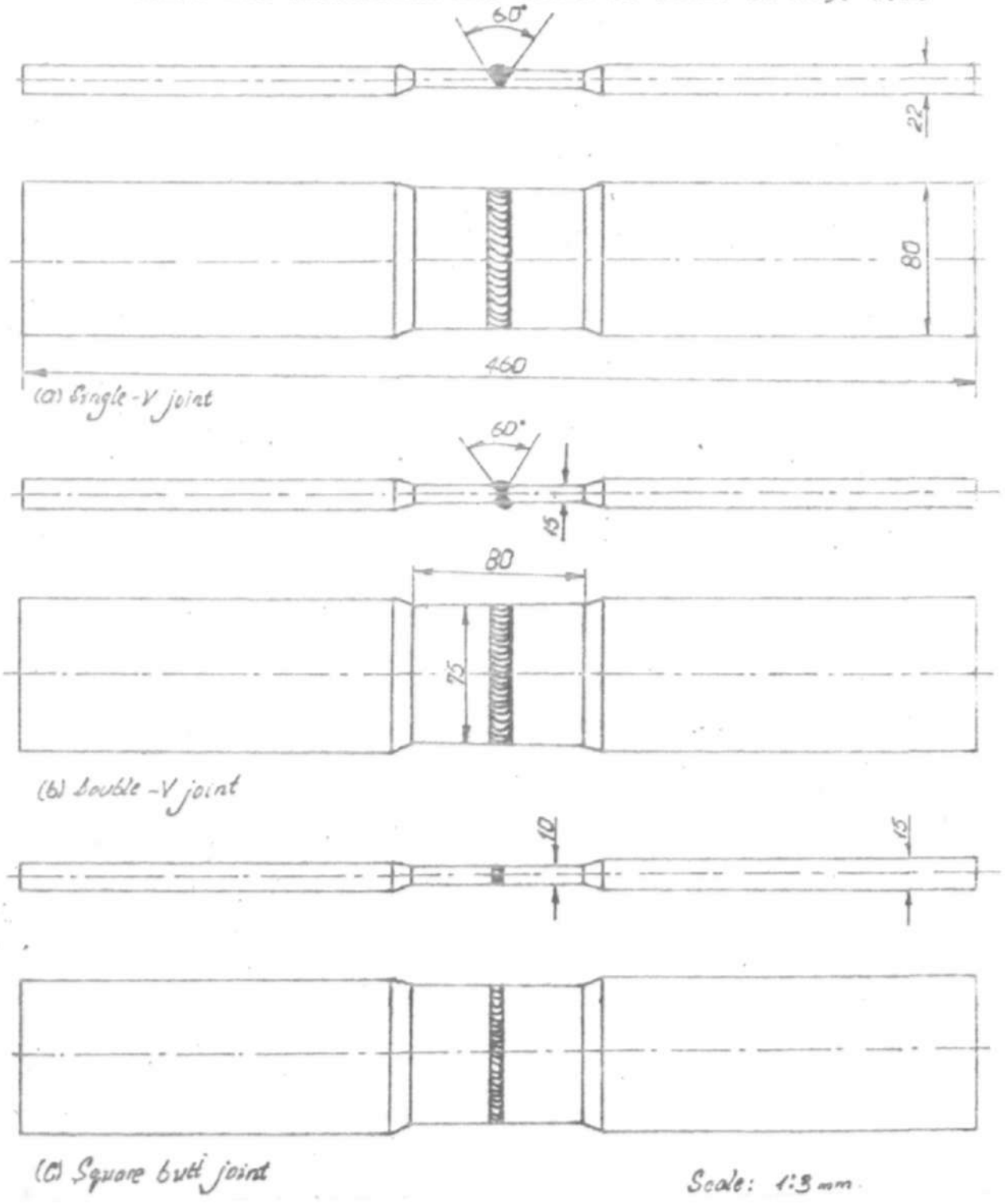



Fig. 3.2: Specimens Drawn to Scale

3.1.3. Welding Of The Specimens

The first batch of specimens were welded using a 180 Amps A.C. Welding set, manufactured by the British Oxygen Company Limited, London, and has the following specifications:

Serial No. LDF 5829

Rated to BS 638-1954-Group X.

Primary Voltage Tappings 230 V; 400-440 V, 1 PH, 50 cls.

Maximum Continuous Welding Current = 120 Amps at 50 Volts or 75 Amps at 80 V. (6 kVA)

Above 6 kVA the machine should be used for intermittent welding only.

Welding current range is 20 - 180 Amps.

The second batch of specimens were made with a thickness of 15 mm throughout their length as shown in Fig. 3.3.

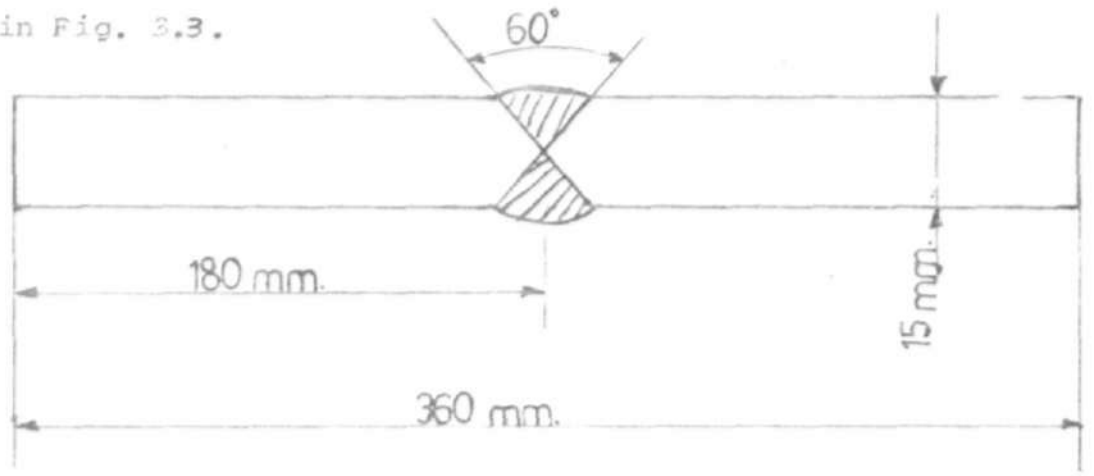



Fig. 3.3: Specimen Used in the Second Set of Experiments

All the six specimens used in this batch were of the same dimensions and were welded with E6013 electrodes.

For easy identification of these specimens, after welding, the two types of electrodes and joint designs were classified as below:

E6012 ≡ 1 E6013 ≡ 2.

Joint Design:-

Double-V ≡ 1

Single-V ≡ 2

Square-butt ≡ 3

After welding, each specimen was identified by two numbers; the first digit to indicate the electrode and the second to indicate the joint type. For example, a specimen marked 1-1 would show that it had been welded with electrode type 1, E6012 and joint design 1, that is double-V. A specimen welded with electrode type 1 and having a single-V joint design was marked 1-2.

Three of the specimen in the second batch were welded in one day, two on another day and the last ones on yet another day by the same welder, due to power failure. There was a variation in the voltage on these days of 3 volts between the first day and the last two days.

The electrode diameter remains the same as that stated in Table 3.3, for electrode type E6013, ie. 3.25 mm. The welding current for the first five specimens was 224 Amps while the welding voltage was 100 volts. The root gap and the arc length also remained

the same at 3 mm.

The last specimen was welded with a current of 170 Amps and 60 volts.

It is to be noted that due to the variation in grid voltage mentioned above, the last two specimens were full of weld imperfections due to improper melting of the electrode. Also the welding speed varies between 1.5 mm/sec in the root passes to a maximum of 3 mm/sec in the later passes. This was because the root was narrower than the surface of the joint.

During welding, the welding parameters were kept as constant as possible for each electrode. To minimize variations caused by human error, all the specimens were welded by one welder manually. Other parameters kept constant for each electrode included: welding current, voltage, root gap, welding speed, arc length and the number of runs for each joint design.

The two pieces to be joined together were clamped in a vice as shown in Plate 1, to restrain the transverse expansion and contraction of the joint and thus minimize distortion.

After welding, the specimen was left to air-cool to room temperature in the vice before removal. Table 3.3 gives details of the welding parameters for the first batch of specimens.

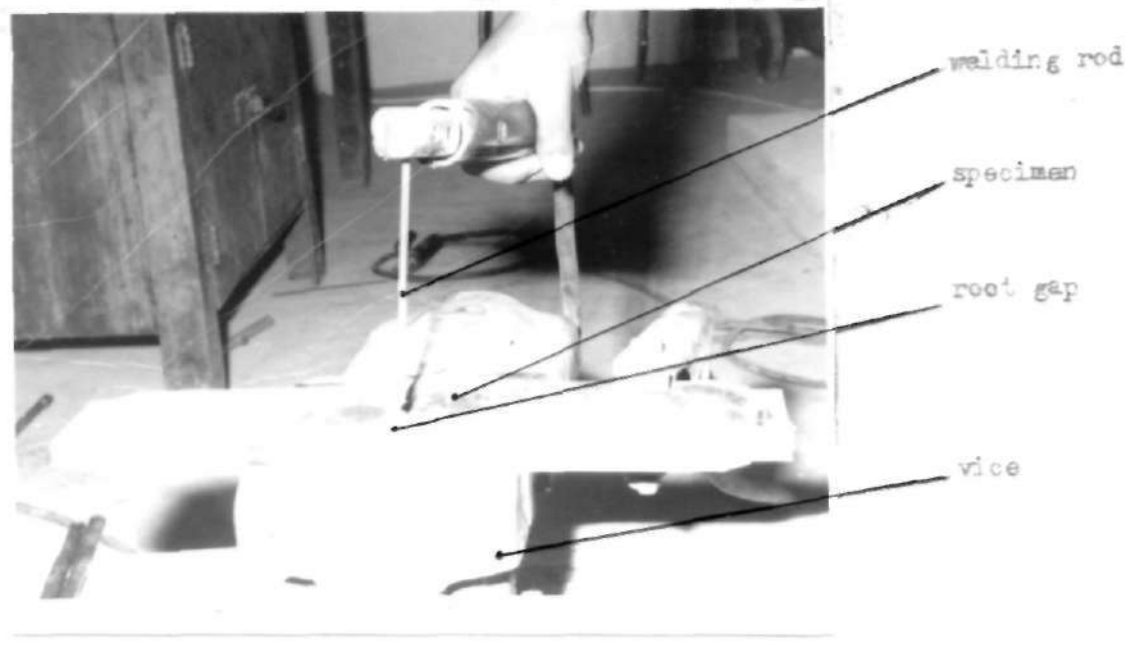



Plate 1: Specimen Set-Up for Welding.

TABLE 3.3: WELDING PARAMETERS FOR SPECIMENS USED

| Identification No. | Electrode Type | Joint Design | Electrode Diameter (mm) | Root Gap (mm) | Welding Current (Amps) | No. of Runs |
|---|---|---|---|---|---|---|
| 1-1 | E6012 | Double-V | 4 | 3 | 180 | 3 each side |
| 1-2 | E6012 | Single-V | 4 | 3 | 180 | 6 plus back pass |
| 1-3 | E6012 | Square butt | 4 | 6.35 | 180 | 2 each side |
| 2-1 | E6013 | Double-V | 3.25 | 3 | 140 | 3 each side |
| 2-2 | E6013 | Single-V | 3.25 | 3 | 140 | 6 plus 1 back pass |
| 2-3 | E6013 | Square butt | 3.25 | 6.35 | 140 | 2 each side |

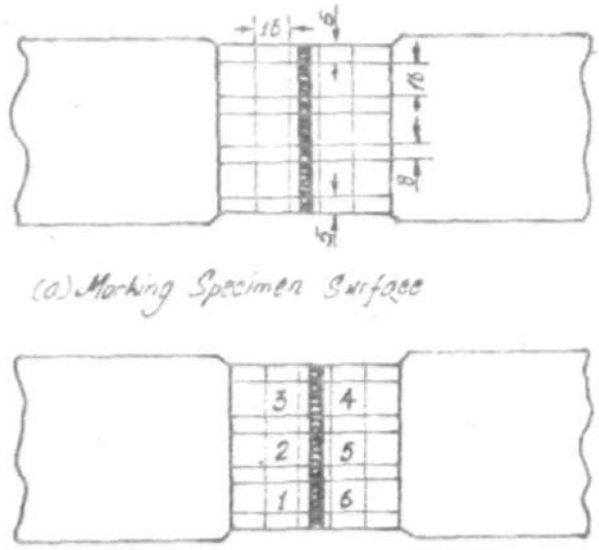
3.1.4. Preparation Of Specimen Surface After Welding

A cut of 1 mm was taken on both sides of each specimen after welding to clear the weld metal and then

the surface ground smooth on a grinding machine. The grinding operation was done to make the surface smooth enough for the strain gauges to be seated properly when placed in position. It is to be noted that the two machining operations, that is shaping and grinding, might introduce residual stresses in the specimens, but according to Masubuchi[1], these stresses cannot be recorded by the strain gauges and therefore considered to have negligible effect on the strain gauge readings recorded in this investigation.

3.2. EXPERIMENTAL SET UP

After the surfaces of the specimens were prepared to the required surface finish, the surfaces of the first and second sets of specimens were marked as shown in Fig. 3.4(a) below and after cleaning with mythylated spirit, the gauges were placed at the 1 to 6 locations, shown in Fig. 3.4(b).




(a) Marking Specimen Surface

(b) Gauge Positions

Fig. 3.4: Specimen Markings Showing Gauge Positions

In the second batch of specimens, the gauges were placed on the under-side of the specimen directly below the ones on top, to check for bendings.

In the last specimen, gauges were placed on the top and under-side as shown in Fig. 3.5(a) and (b) below.

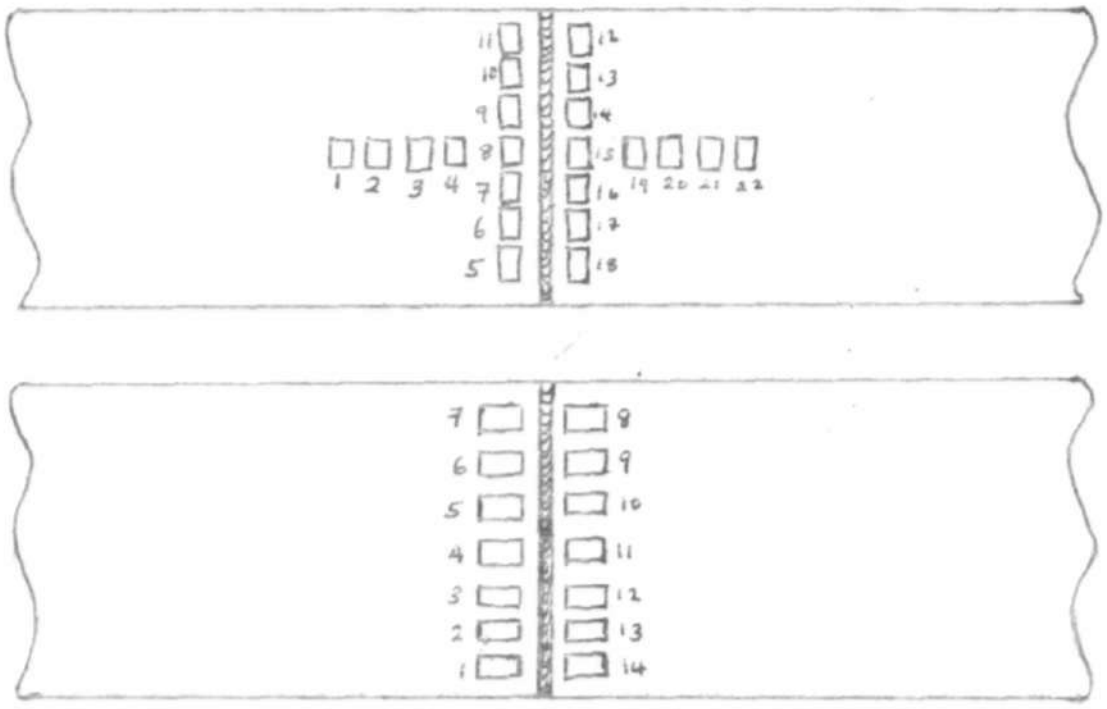



Fig. 3.5: Gauge Positioning on Last Specimen

All the gauges here were single element gauges.

All the gauges used were placed with P-2 adhesive, and left for about twelve hours to set before new ones were placed. After setting, the surface of the gauges were covered with wax to prevent the coolant from moistening the gauge surfaces during the milling process which was used in slicing the specimens for taking readings in this work. The gauges were then connected to

The first and second batches of specimens were cut at three positions as shown in Fig. 3.6. The last specimen was cut only at the middle position.

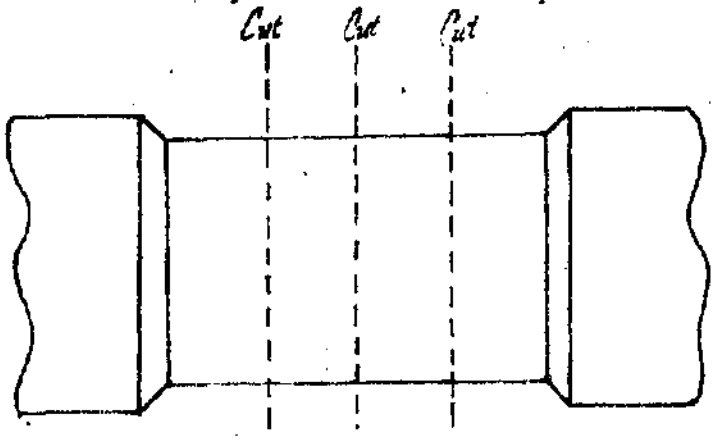



Fig. 3.6: Specimens Showing Positions of Cutting

When the specimen had been cut, the strain meter was switched back on; it was balanced and the readings for each channel were recorded. The procedure was repeated for each specimen.

It is to be noted that the milling operation might have introduced some machining stresses which the strain gauges would not record additionally. These stresses are due to vibrations and the heat produced by the milling operation during sectioning of the specimen. To minimize vibrations, the cutting was done in steps through the thickness of the specimens, at a slow rate of feeding. A lot of coolant was also used to cool the work during the machining operation and the gauges were used with dummies to compensate the heating effect.

The readings have been recorded in Appendix A and the calculations shown in the next Chapter.

# CHAPTER FOUR

## CALCULATIONS, RESULTS AND DISCUSSION

### 4.1. CALCULATIONS AND RESULTS

All the calculations for the stresses were based on Hooke's Law, as given by the following equation:

$$\sigma_r = \varepsilon E \qquad \text{----------(4.1)}$$

The principal stress calculations were based on relationships in a three element gauge, rectangular resette as given below.

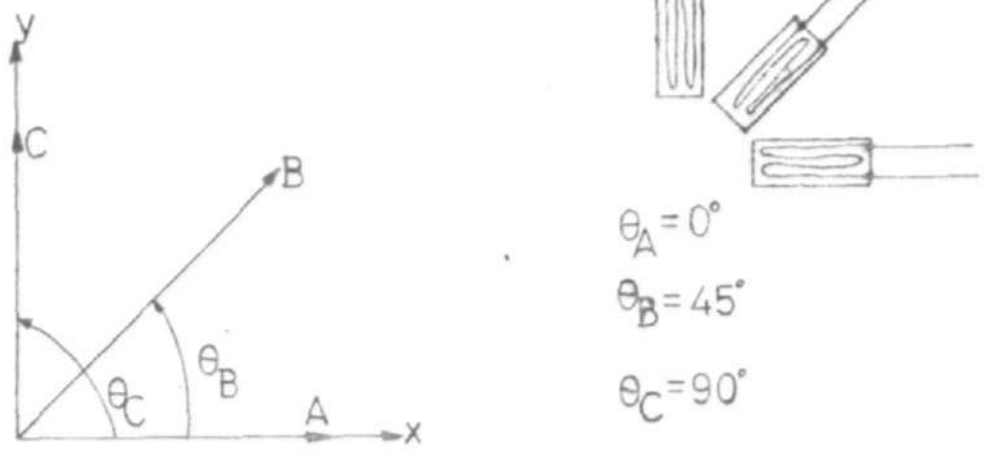



Fig. 4.1: Gauge Positions in a Three-Element Rectangular Rosette

The equations for the principal strains $\varepsilon_1$ and $\varepsilon_2$ are given as:

$$\left.\begin{aligned} \varepsilon_1 &= \tfrac{1}{2}(\varepsilon_A + \varepsilon_C) + \tfrac{1}{2}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2} \\ \varepsilon_2 &= \tfrac{1}{2}(\varepsilon_A + \varepsilon_C) - \tfrac{1}{2}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2} \end{aligned}\right\} \text{--(4.2}$$

The principal angle $\phi$ is given by

$$\tan 2\phi = \frac{2\varepsilon_B - \varepsilon_A - \varepsilon_C}{\varepsilon_A - \varepsilon_C} \qquad \text{----------(4.3)}$$

The stress strain relations relating principal strains to principal stresses are:

$$\left.\begin{aligned} \sigma_1 &= \frac{E}{1-\nu^2}(\varepsilon_1 + \nu\varepsilon_2) \\ \sigma_2 &= \frac{E}{1-\nu^2}(\varepsilon_2 + \nu\varepsilon_1) \end{aligned}\right\} \qquad \text{--------(4.4)}$$

Substituting $\varepsilon_1$ and $\varepsilon_2$ in equation (4.4) gives the principal stresses

$$\left.\begin{aligned} \sigma_1 &= E\left[\frac{\varepsilon_A + \varepsilon_C}{2(1-\nu)} + \frac{1}{2(1+\nu)}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2}\right] \\ \sigma_2 &= E\left[\frac{\varepsilon_A + \varepsilon_C}{2(1-\nu)} - \frac{1}{2(1+\nu)}\sqrt{(\varepsilon_A - \varepsilon_C)^2 + (2\varepsilon_B - \varepsilon_A - \varepsilon_C)^2}\right] \end{aligned}\right\} \text{--}$$

.....(4.5)

Sample Calculations:

(i) Stress:

For the double-V joint welded with E6012 electrode, the strain recorded parallel to the weld direction, i.e. Channel 1 on gauge 1, Table 4.1 is $245 \times 10^{-6}$.

Substituting this value in equation (4.1) we get

$$\sigma_r = 245 \times 10^{-6} \times 213000 = 52.19 \text{ N/mm}^2.$$

Except for the principal stresses, all the other values of stresses recorded in this work were similarly calculated.

(ii) Principal Stresses

Using the strain values recorded in Table 4.1, Channels 1, 2 and 3 for gauge 1, the principal stresses were calculated as follows:

$$\varepsilon_A = -245 \times 10^{-6}$$

$$\varepsilon_B = +677 \times 10^{-6}$$

$$\varepsilon_C = -85 \times 10^{-6}$$

$$E = 213000 \text{ N/mm}^2$$

$$\nu = 0.281$$

Substituting these values in equation (4.5) we get

$$\sigma_{1,2} = \frac{[(-245) + (-85)] \times 10^{-6}}{2(1 - 0.281)}$$

$$\pm \frac{1}{2(1+0.281)} \sqrt{[(-245+85)\times10^{-6}]^2 + [(2\times677+245+55)\times10^{-6}]^2}$$

$$\sigma_{1,2} = -2.357 \times 10^{-4} \pm 6.506 \times 10^{-4}$$

$$\sigma_1 = -2.357 \times 10^{-4} + 6.506 \times 10^{-4}$$

$$= 88.37 \text{ N/mm}^2$$

$$\sigma_2 = -2.357 \times 10^{-4} - 6.506 \times 10^{-4}$$

$$= -188.78 \text{ N/mm}^2$$

All the other values of principal stresses recorded in Tables A.1 to A.6 were calculated in the same manner.

(iii) Principal Angle:

Using equation (4.3) the principal angles were calculated and recorded in the last columns of Tables A.1 to A.6 as shown below for the same set of readings used in the other sample calculations.

For same $\varepsilon_A$, $\varepsilon_B$ and $\varepsilon_C$ given the calculation of principal stresses above, substituting in equation(4.3)

$$\tan 2\phi = \frac{2 \times 677 \times 10^{-6} + 245 \times 10^{-6} + 35 \times 10^{-6}}{-245 \times 10^{-6} + 35 \times 10^{-6}}$$

$$\tan 2\phi = -10.525$$

$$2\phi = 95.43^{\circ}$$

$$\therefore \quad \phi = 47.72^{\circ}$$

The same procedure was followed for all the calculations; and the results tabulated as shown in Appendix A and then plotted as shown in Fig. 4.2 through to Fig. 4.17.

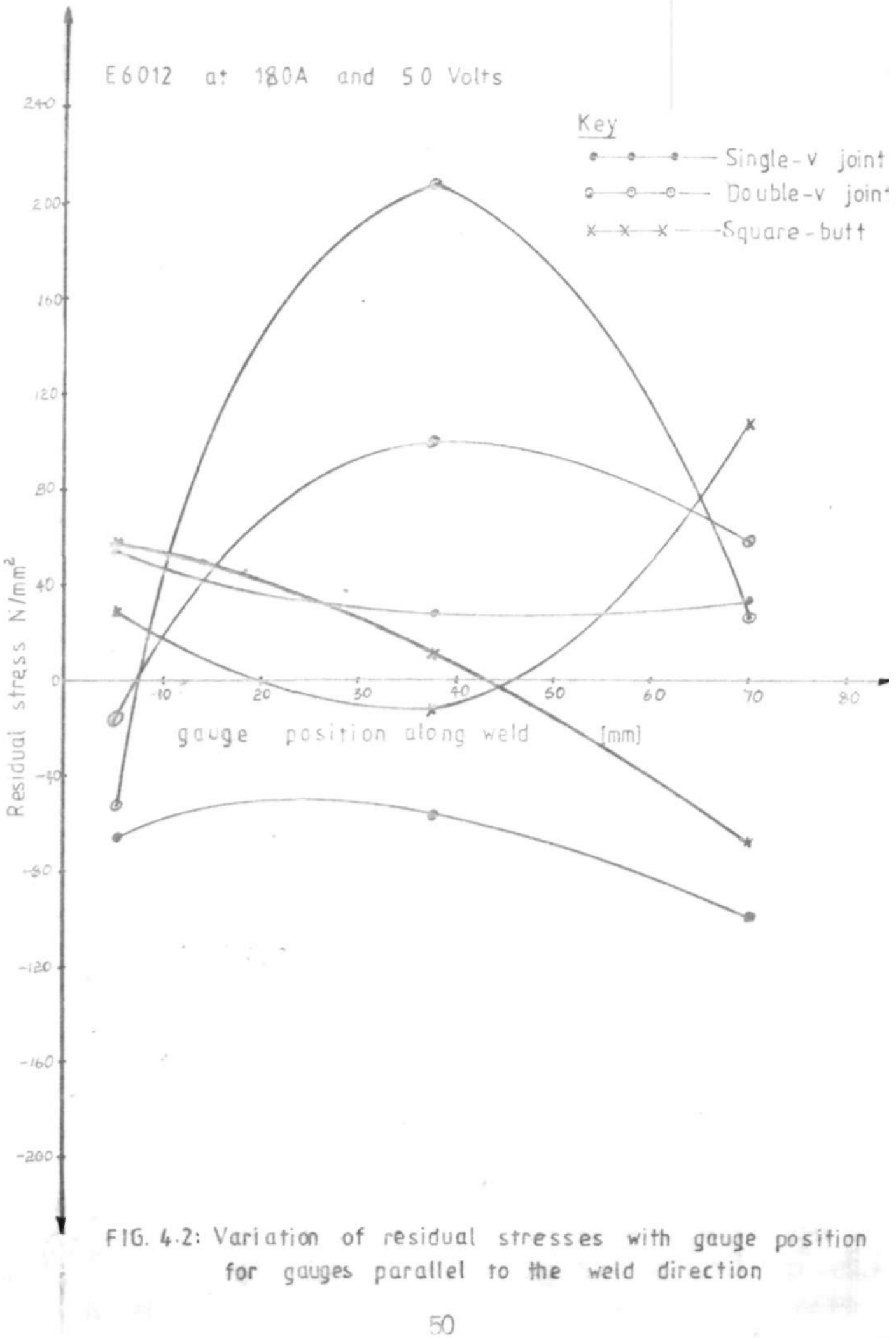
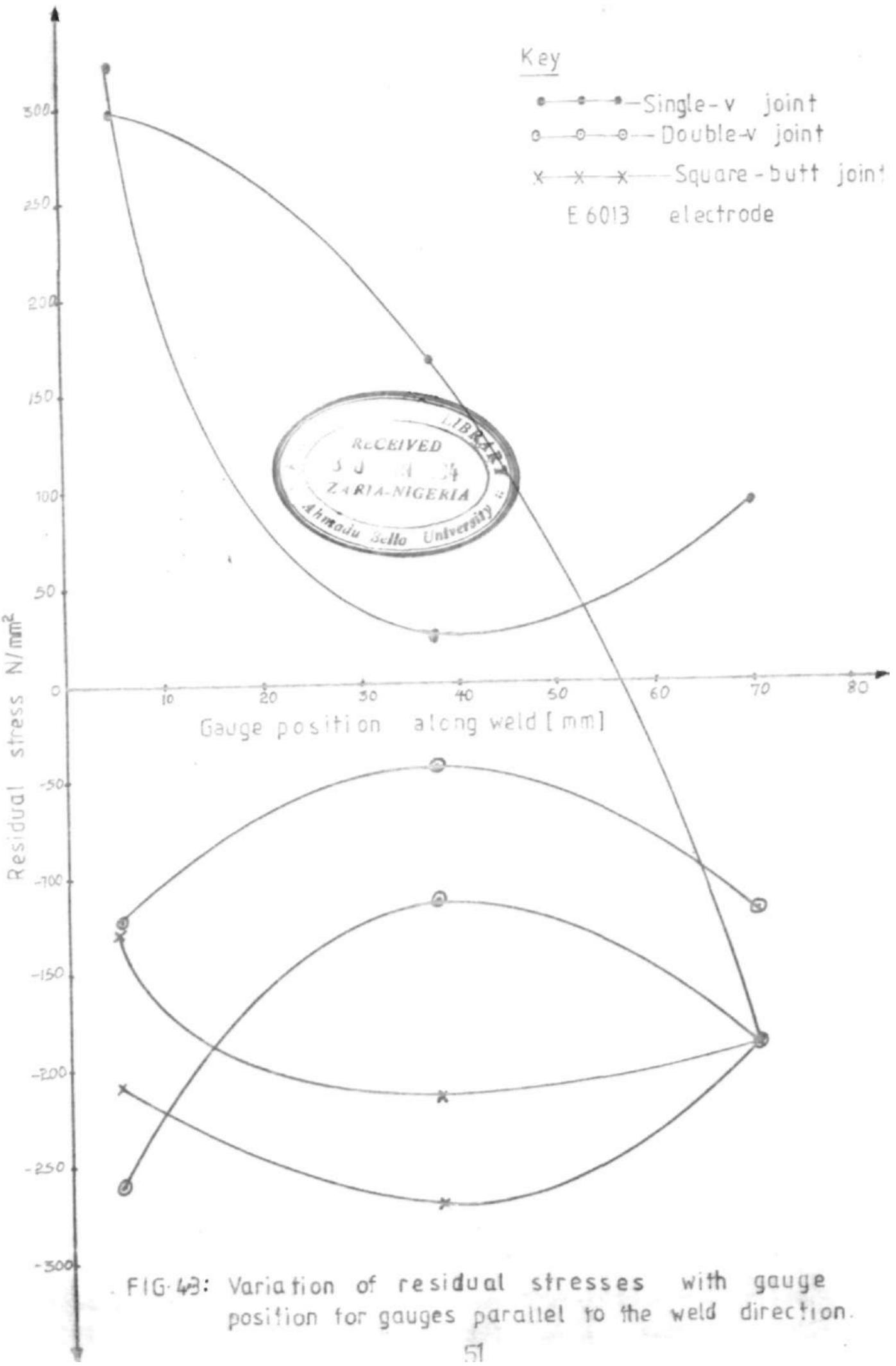



FIG. 4.2: Variation of residual stresses with gauge position for gauges parallel to the weld direction




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FIG 43: Variation of residual stresses with gauge position for gauges parallel to the weld direction.

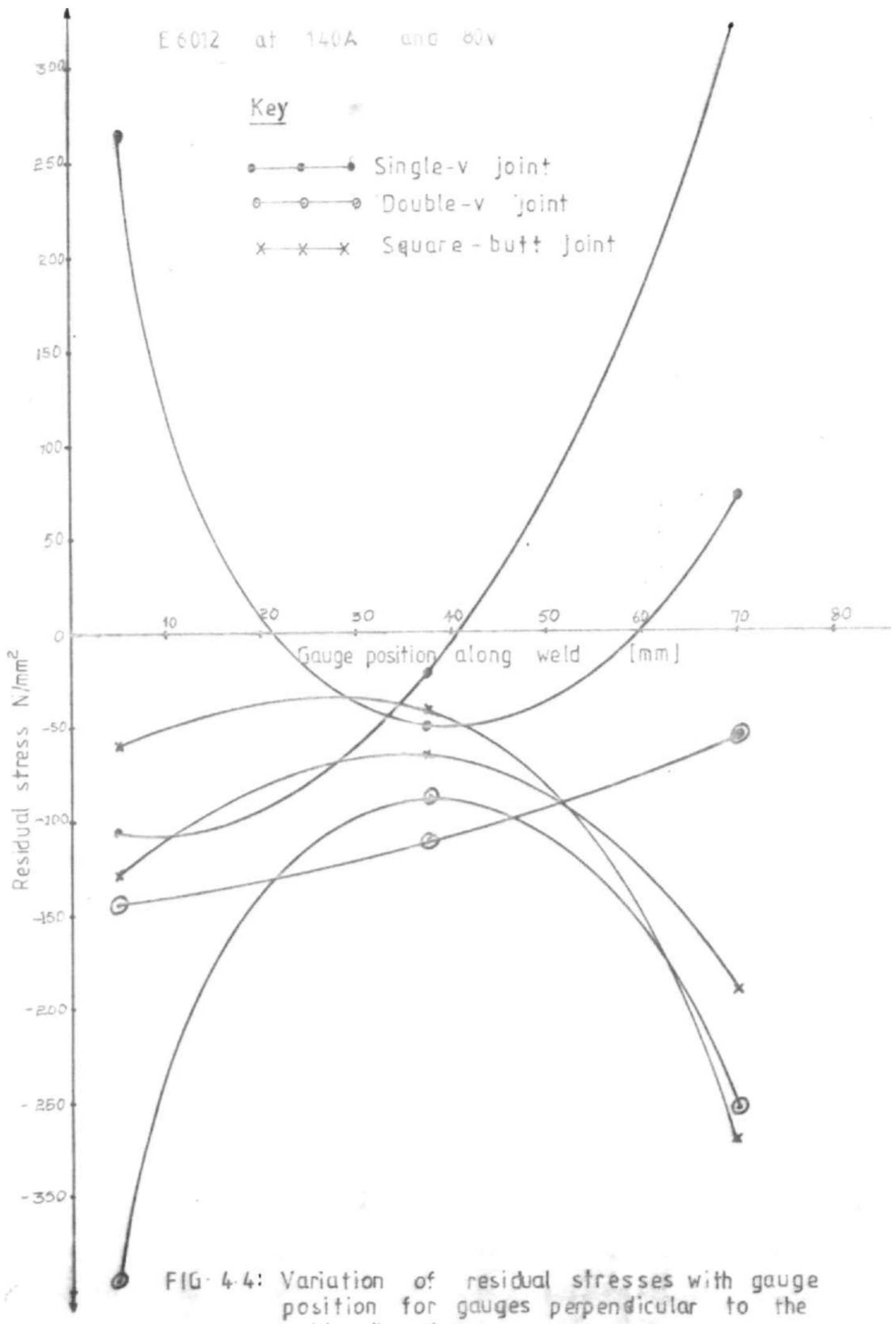



FIG 4.4: Variation of residual stresses with gauge position for gauges perpendicular to the weld direction.

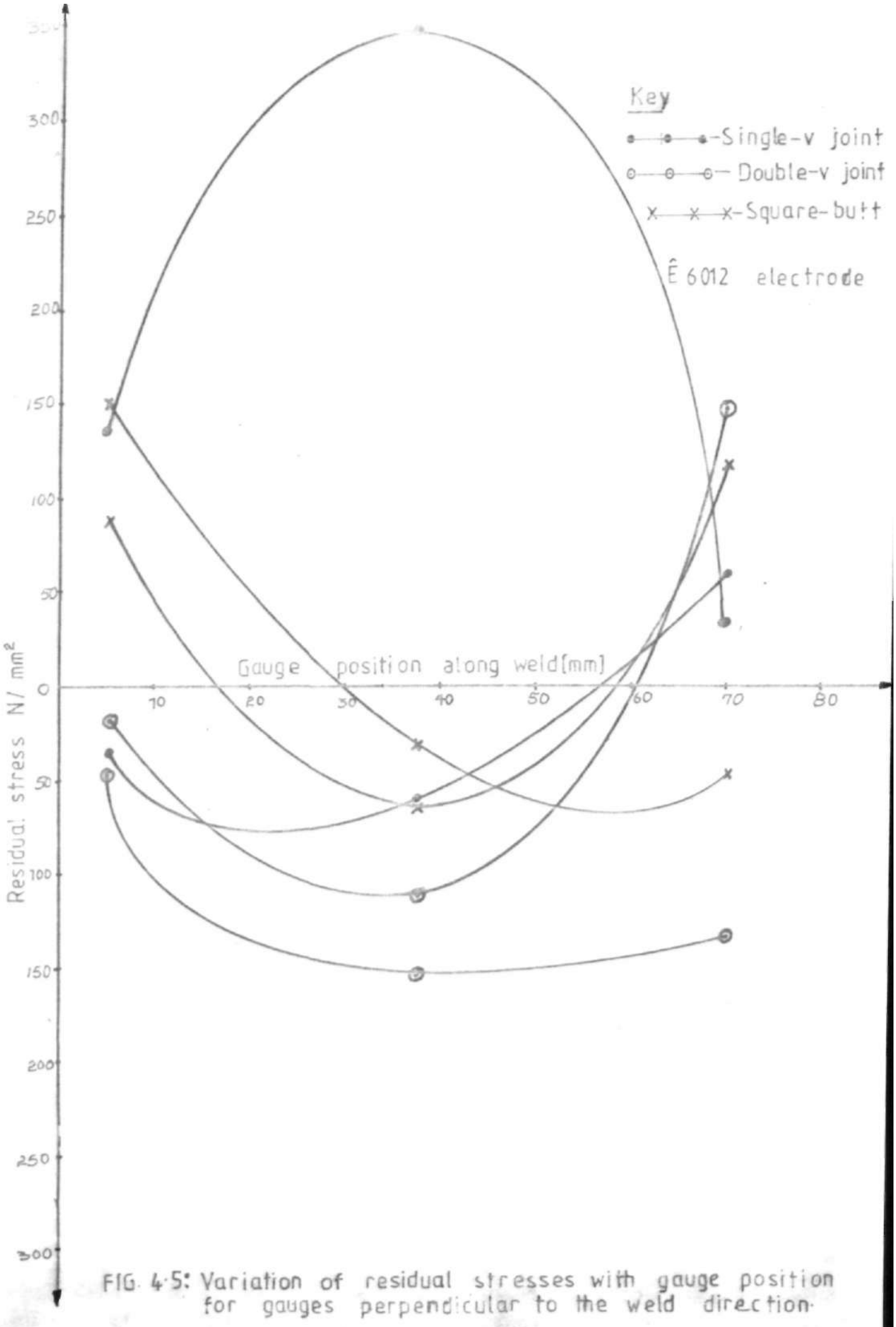



FIG. 4·5: Variation of residual stresses with gauge position for gauges perpendicular to the weld direction.

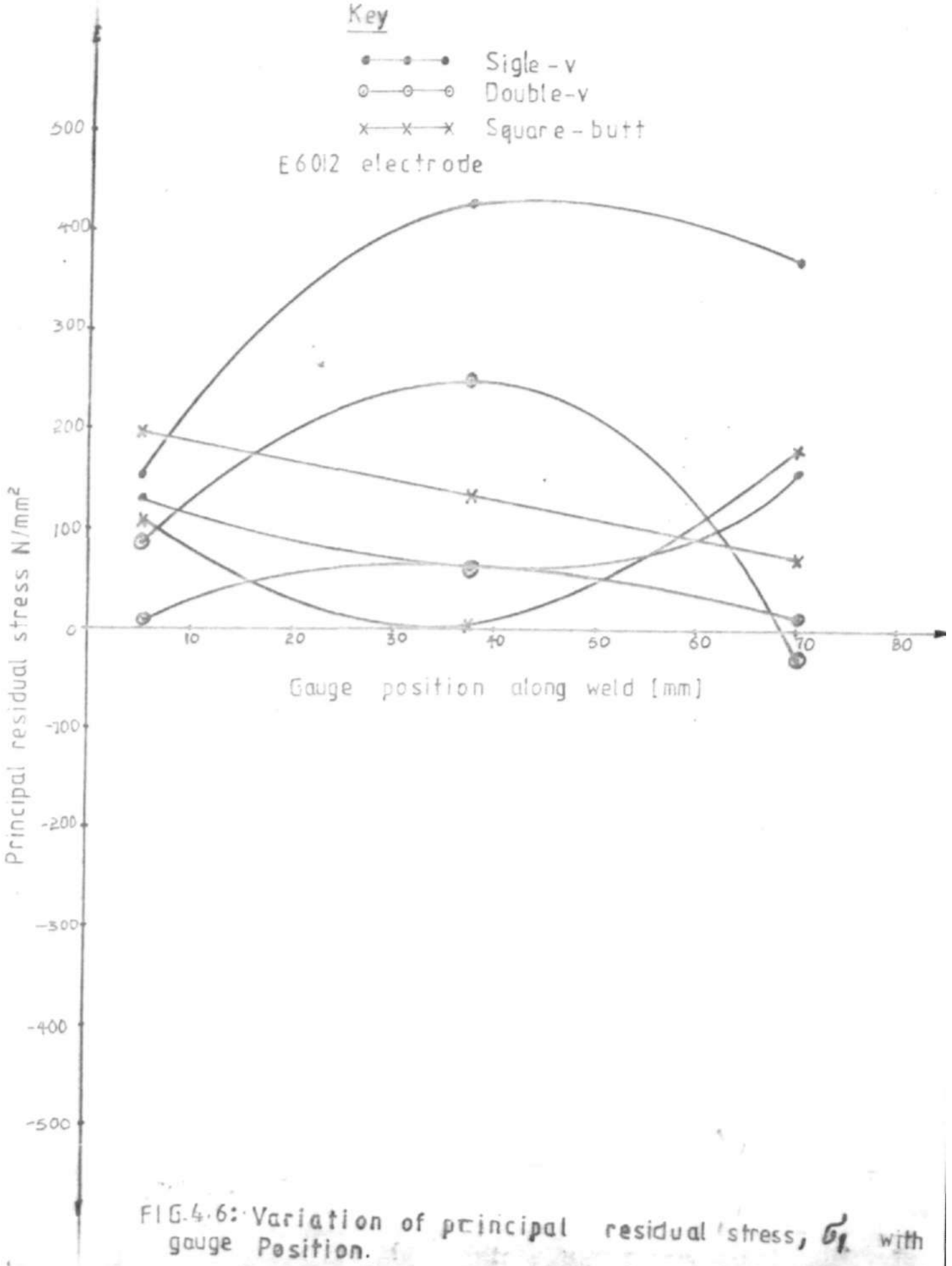
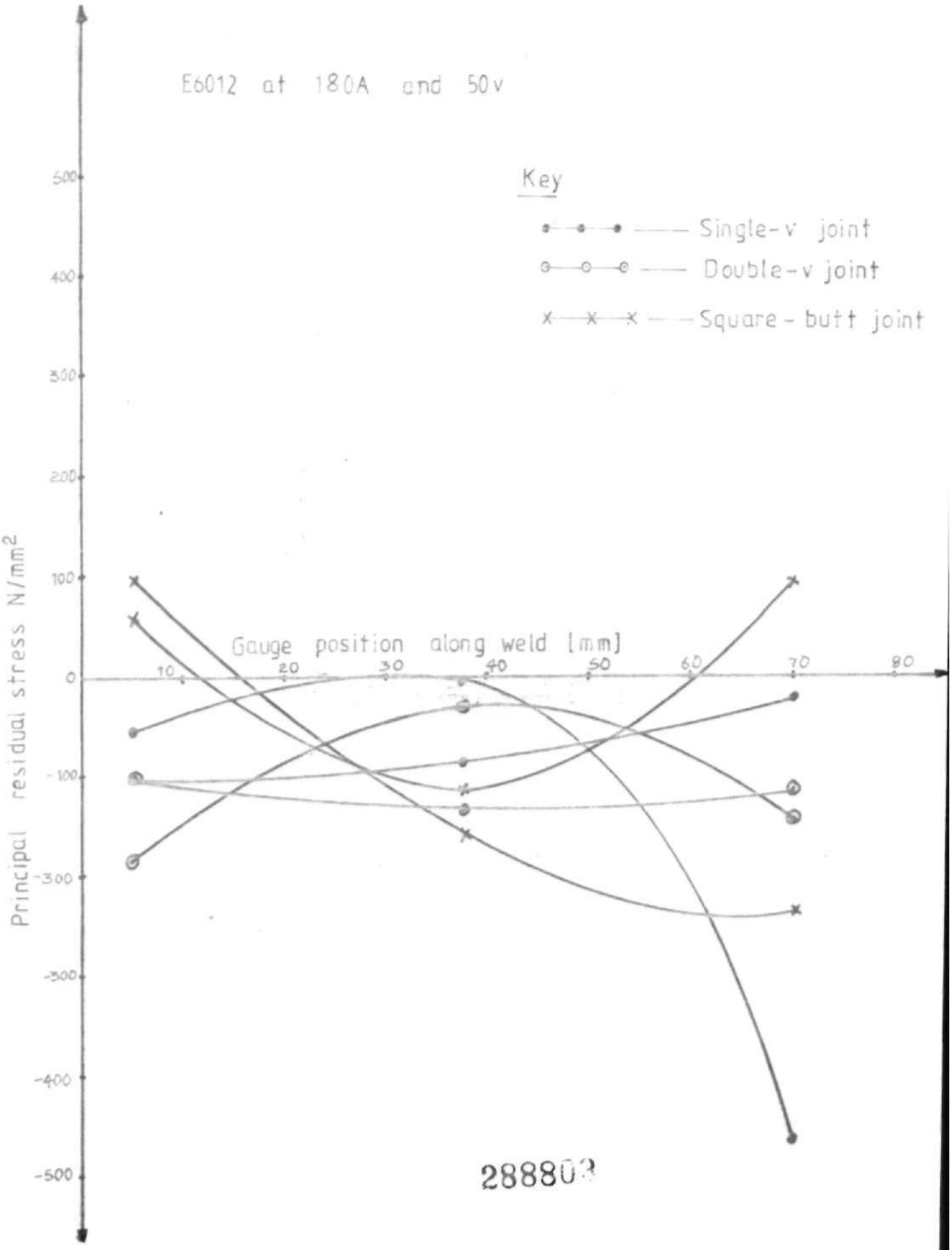



FIG.4.6: Variation of principal residual stress, $\sigma_1$ with gauge Position.




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FIG. 4-7: Variation of principal stress, $\sigma_2$ with gauge position.

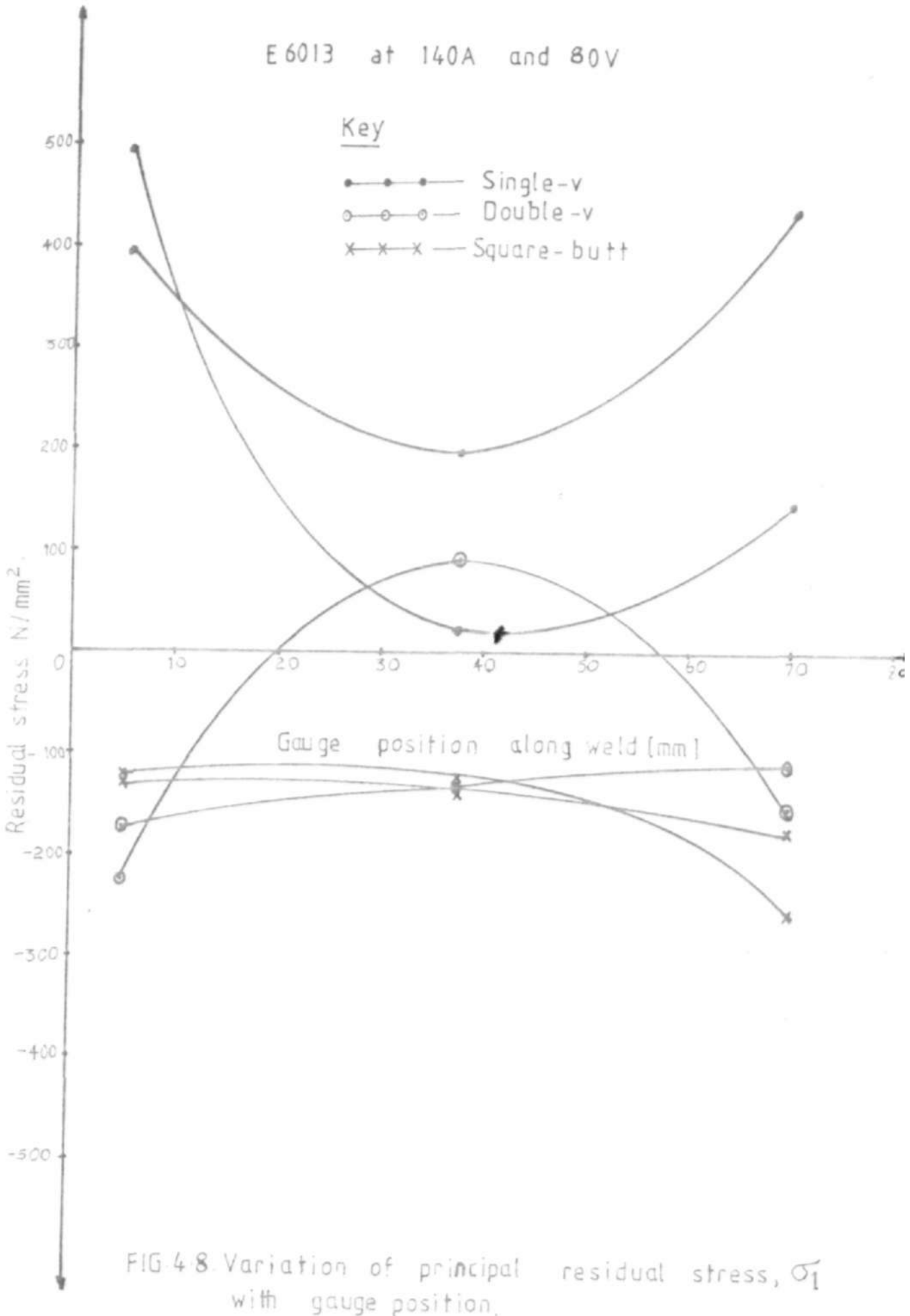



FIG 4.8 Variation of principal residual stress, $\sigma_1$ with gauge position.

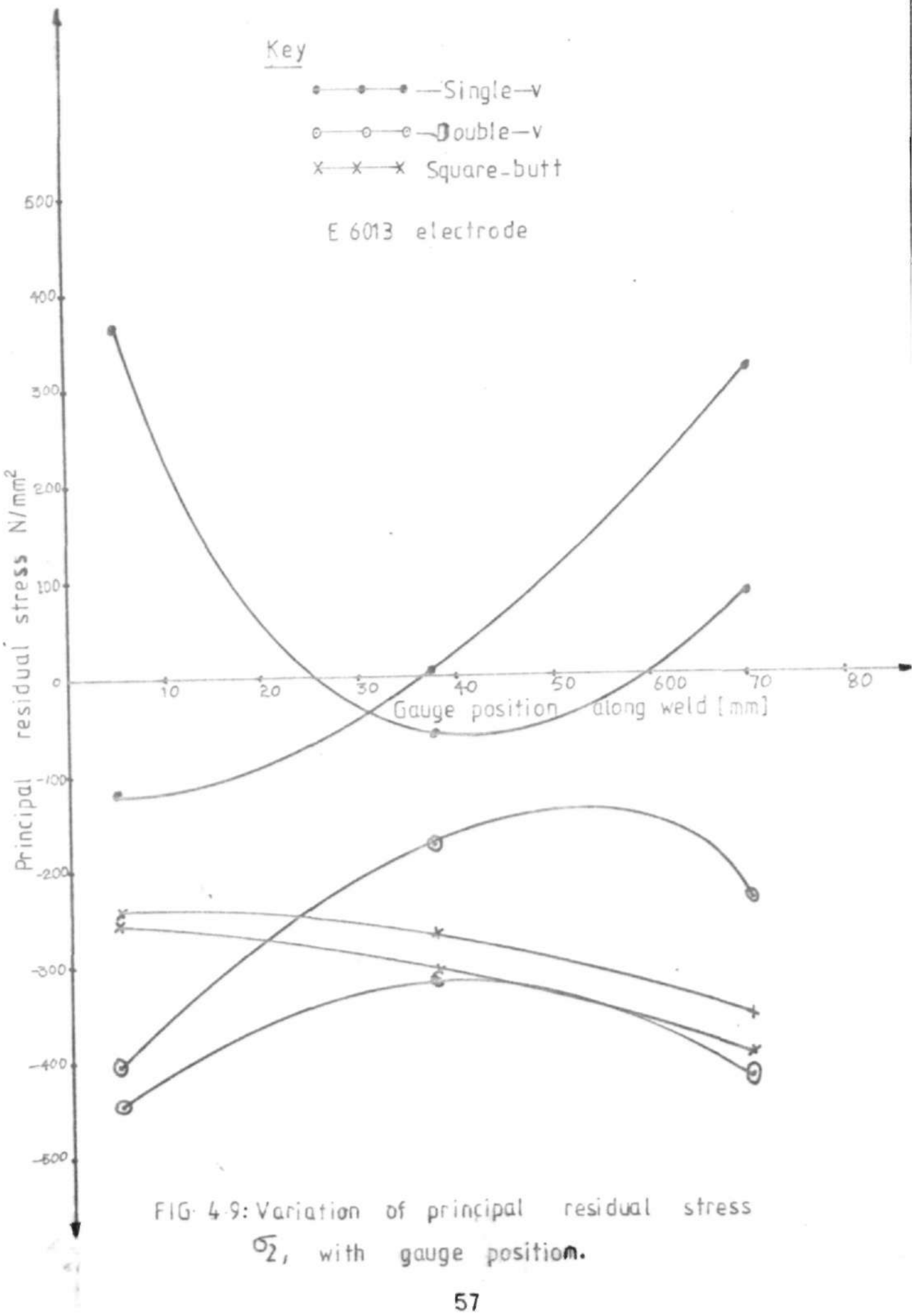



FIG 4.9: Variation of principal residual stress $\sigma_2$, with gauge position.

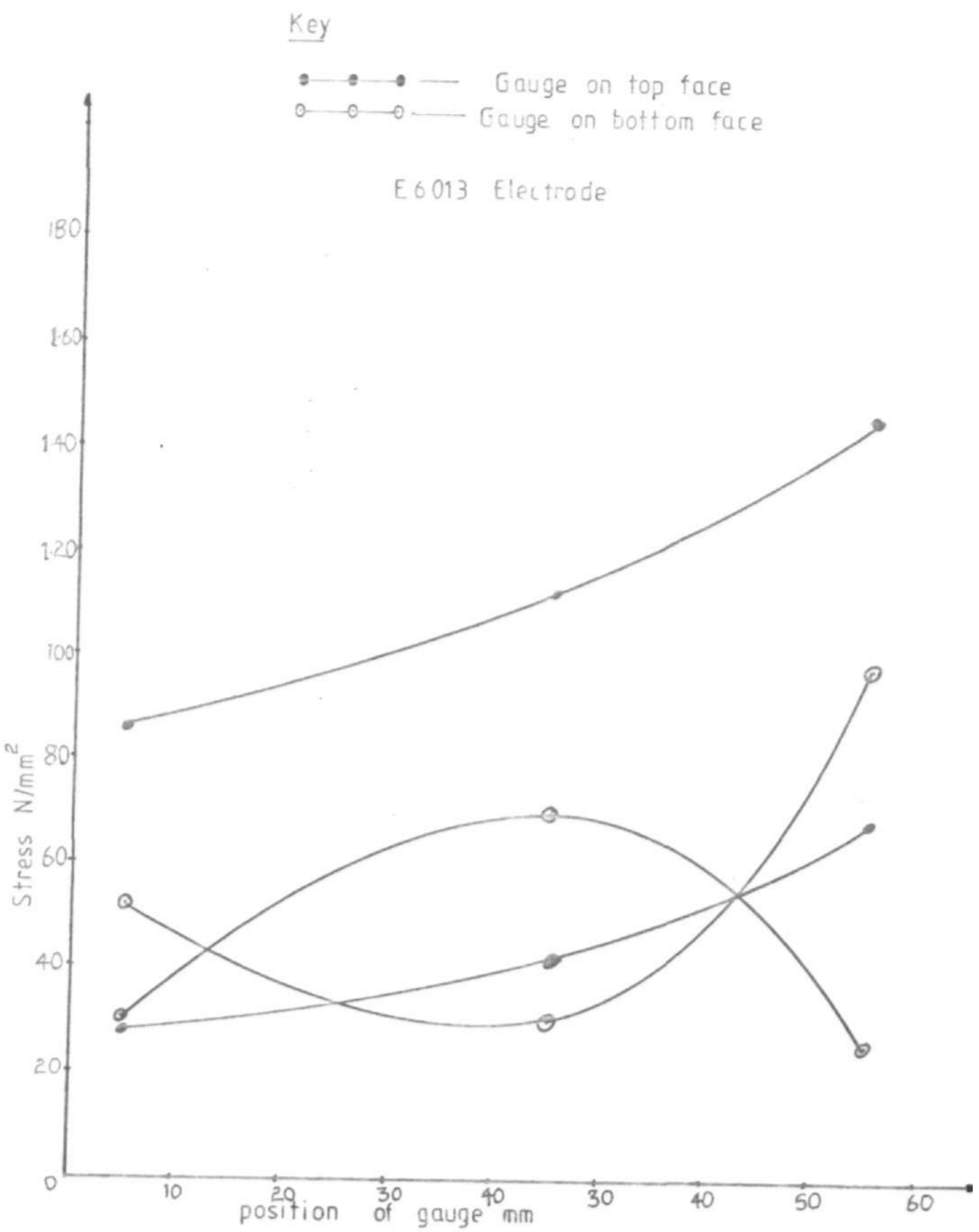



FIG. 4.10: Variation of residual stresses with gauge position for gauges parallel to the weld direction.

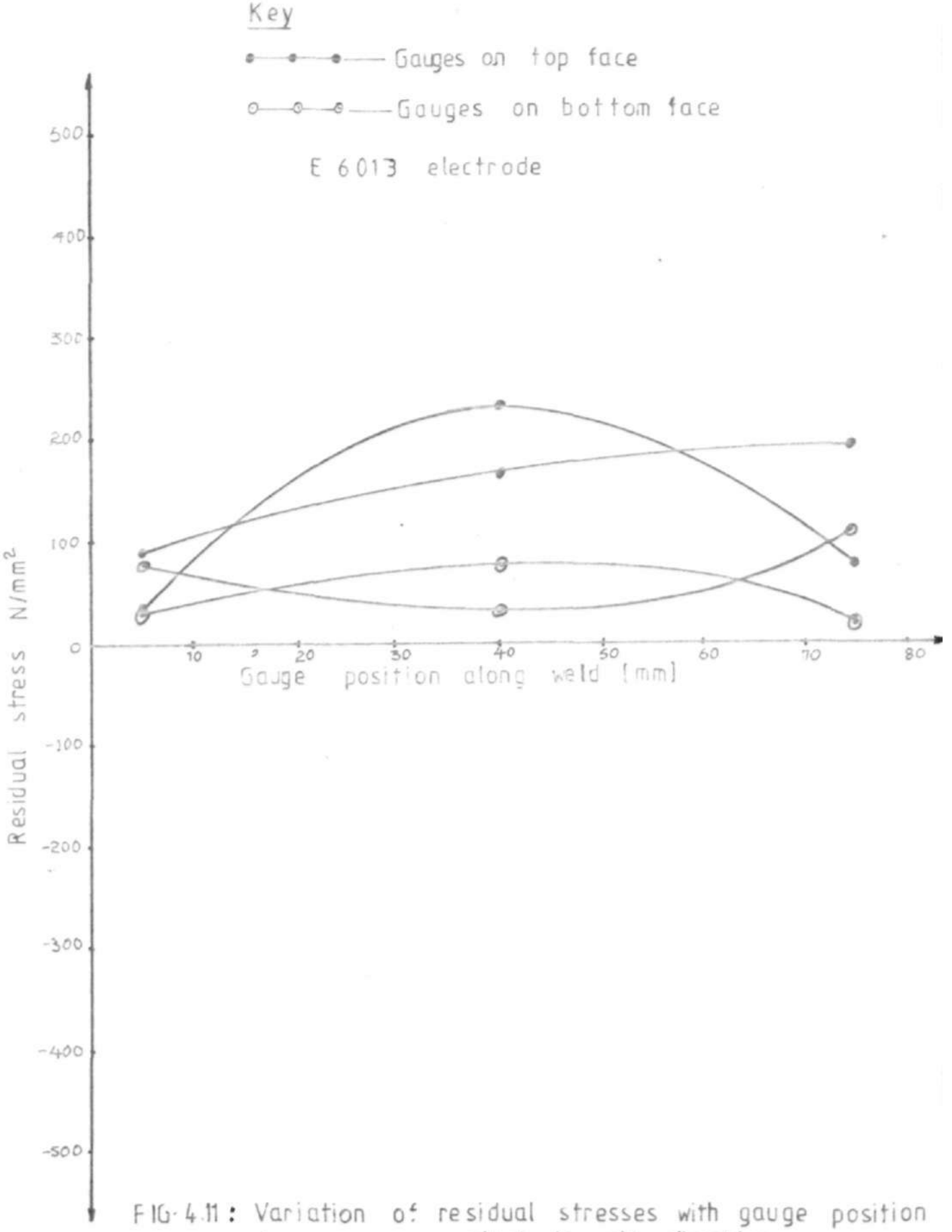



FIG-4.11 : Variation of residual stresses with gauge position for gauges parallel to weld direction.

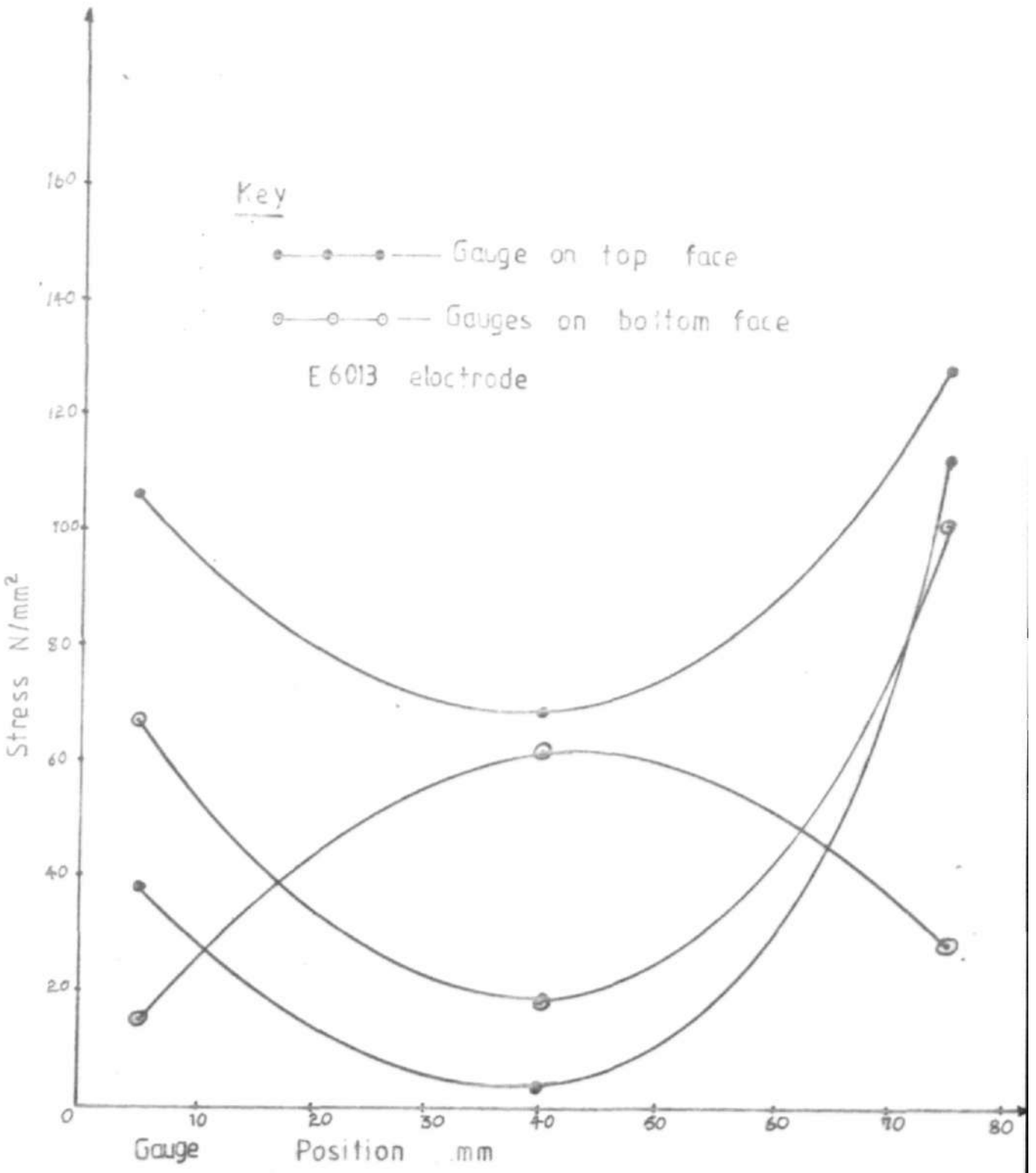



FIG 4.12: Variation of residual stresses with gauge position for gauges parallel to the weld direction.

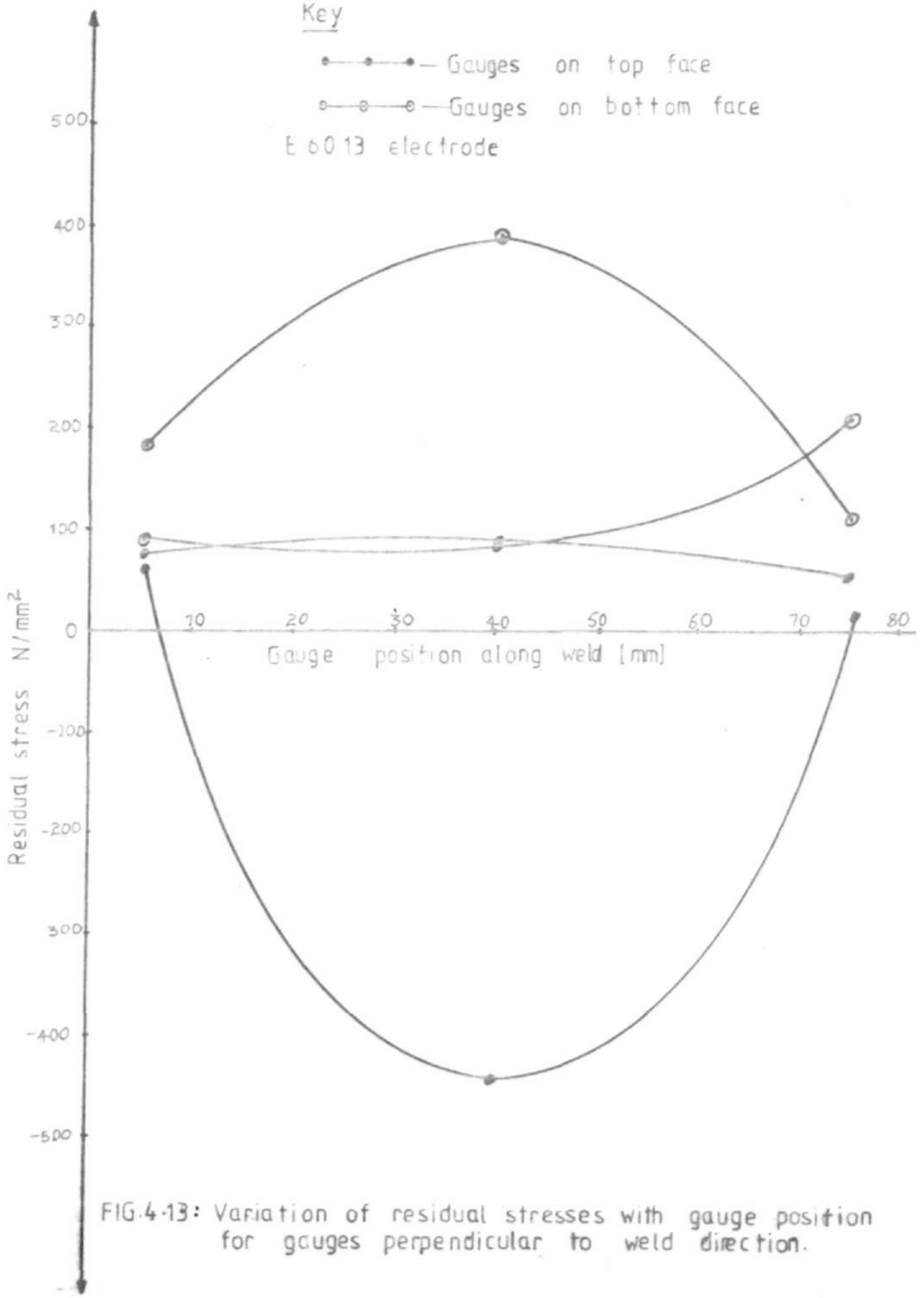



FIG.4-13: Variation of residual stresses with gauge position for gauges perpendicular to weld direction.

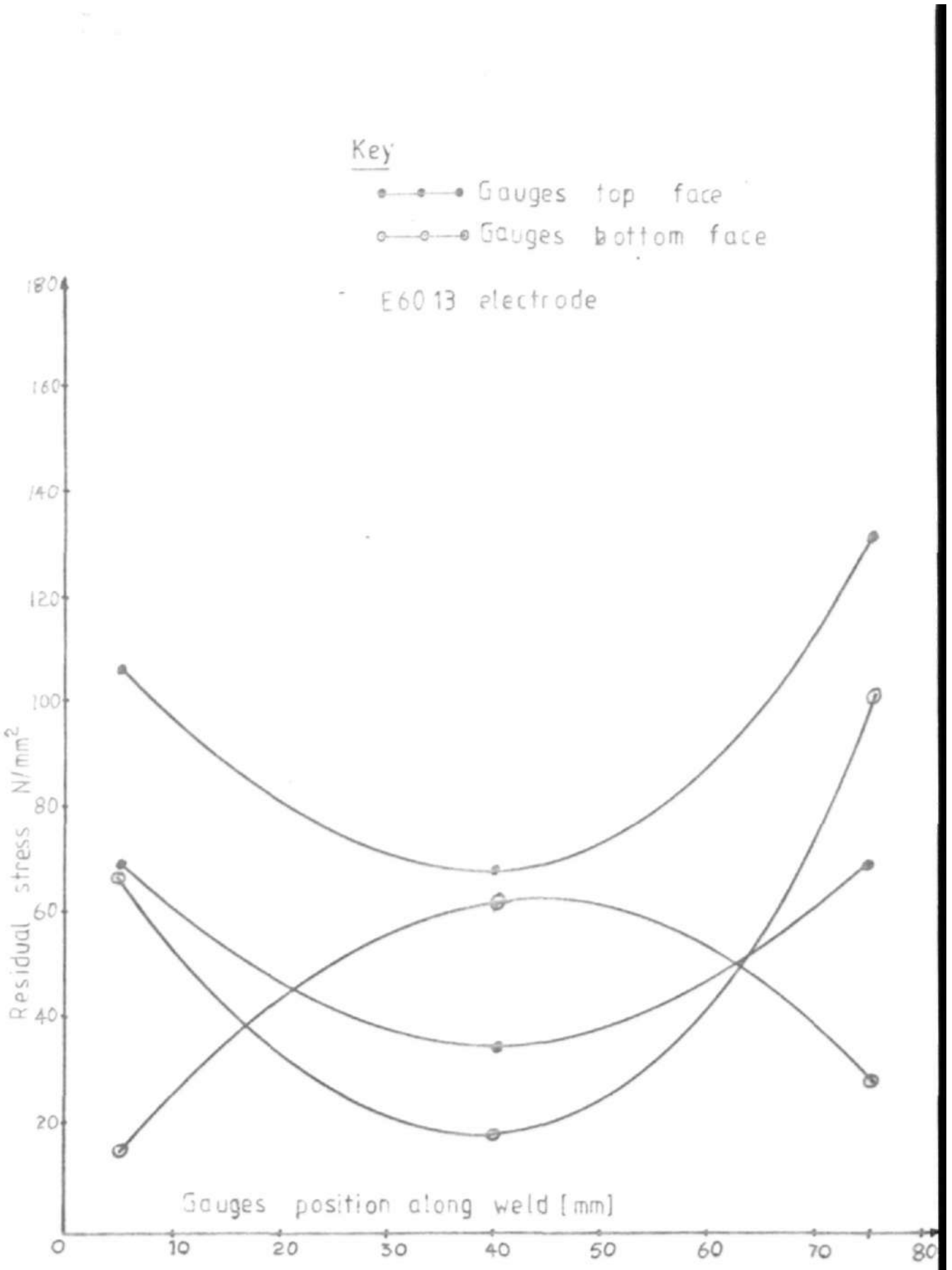



FIG. 5.14: Variation of residual stresses with gauge position for gauges perpendicular to the weld direction.

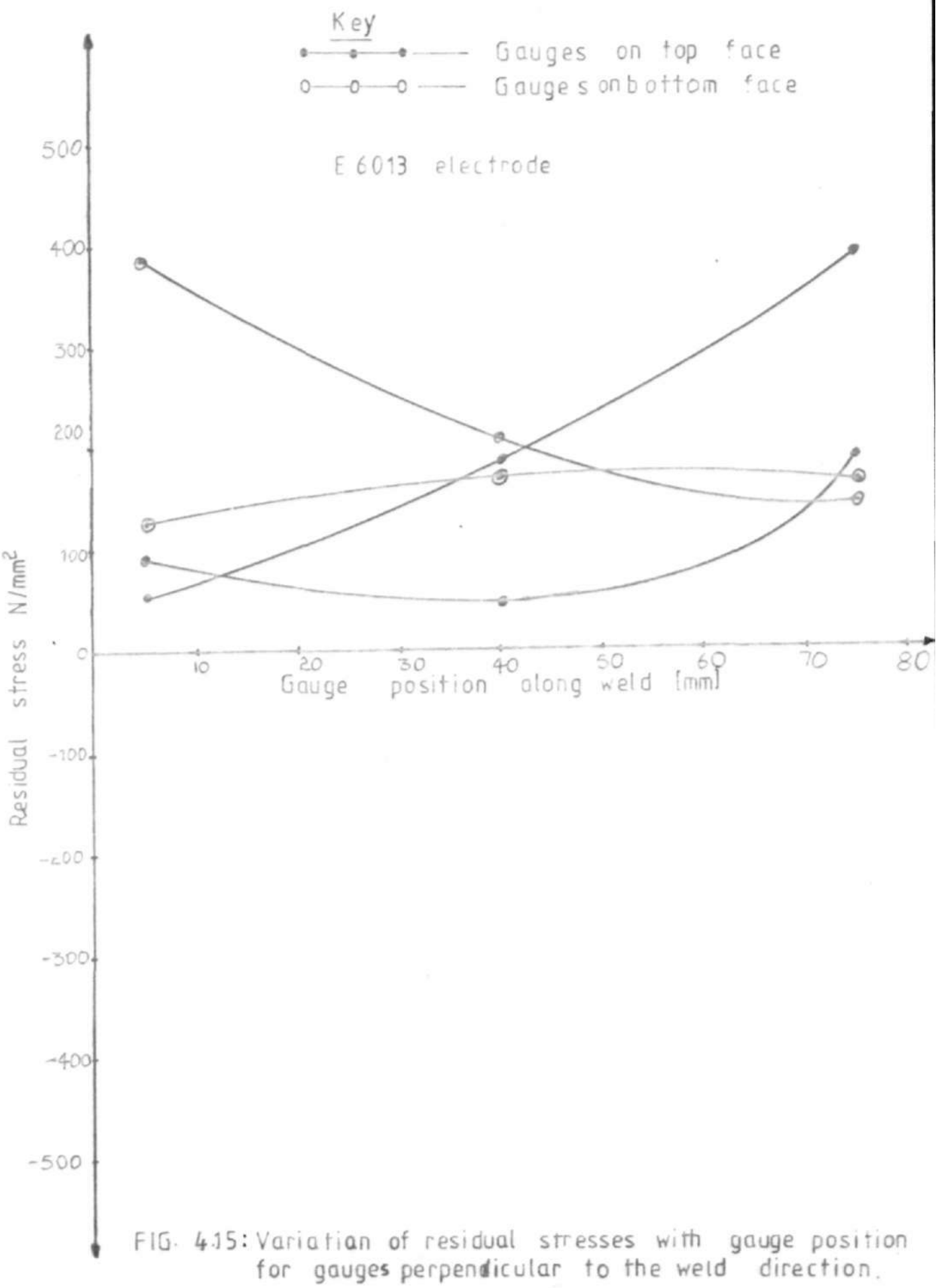



FIG. 4.15: Variation of residual stresses with gauge position for gauges perpendicular to the weld direction.

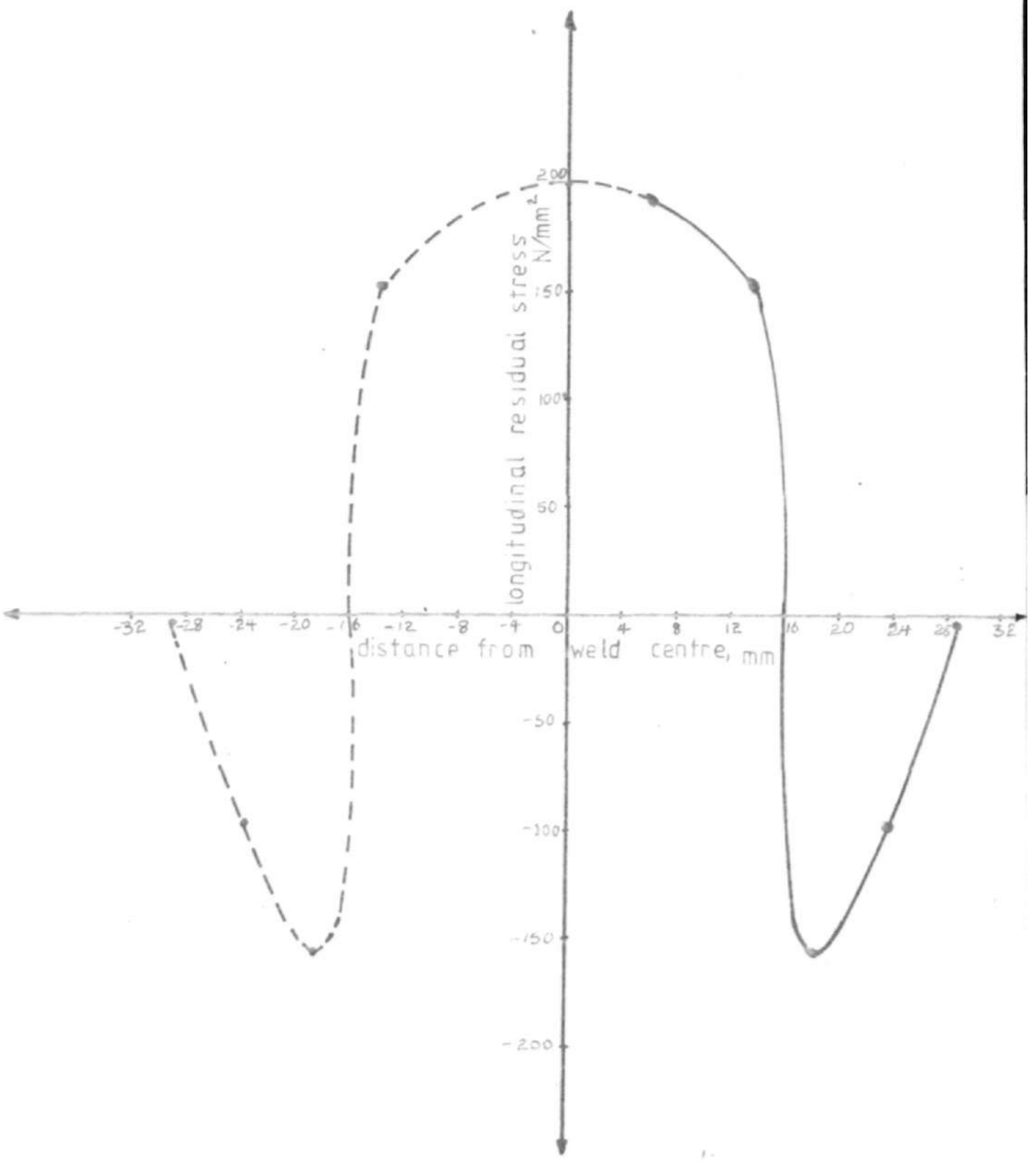



FIG.416: Distribution of longitudinal stresses along the transverse line.

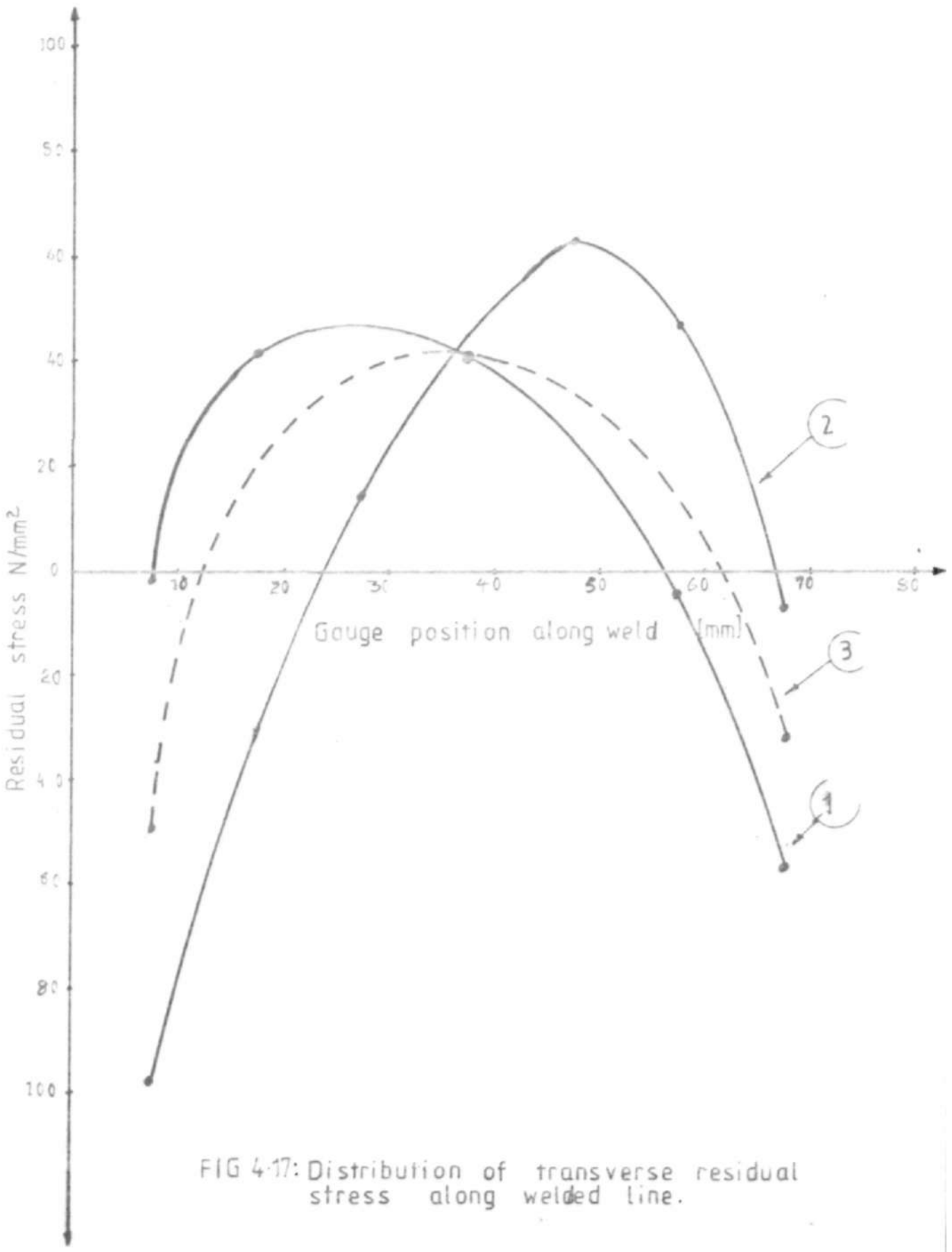



FIG 4·17: Distribution of transverse residual stress along welded line.

## 4.2. DISCUSSION

The following discussion is divided into two sections:

### 4.2.1. Joint Design

In their study on how various factors including joint design and electrode type affect residual welding stress and transverse shrinkage, Kihara and Masubuchi as reported by Masubuchi[13], showed that a single-V joint produces more stresses than the double-V joint and that the influence of the joint design on the residual stresses is large. The reasons for this were, however, not given in their work.

This investigation shows that the single-V joint produces stresses of higher magnitude in tension or compression than the double-V and squar-butt joints. This can be seen in the results presented in the pair of figures, Fig. 4.2 and Fig. 4.5, and Fig. 4.3 and Fig. 4.4, which show the stress variation with gauge position along the weld for the electrode types E6012 and E6013, respectively, the only thing varying in the set of figures being the joint design. There is an exception in Fig. 4.2 in which the double-V joint produces stresses of higher magnitude in tension than the other joints. This deviation may be due to stress raisers, such as slag inclusions playing a major role in this joint than in the other two.

Similarly the principal stresses plotted in Fig. 4.6 and Fig. 4.7 for the E6012 electrode and Fig. 4.8 and Fig. 4.9 for the E6013 electrode show the same trend.

This is to be expected since the single-V joint has a greater tendency to close when welding passes are progressively made on one side as shown in Fig. 4.18.

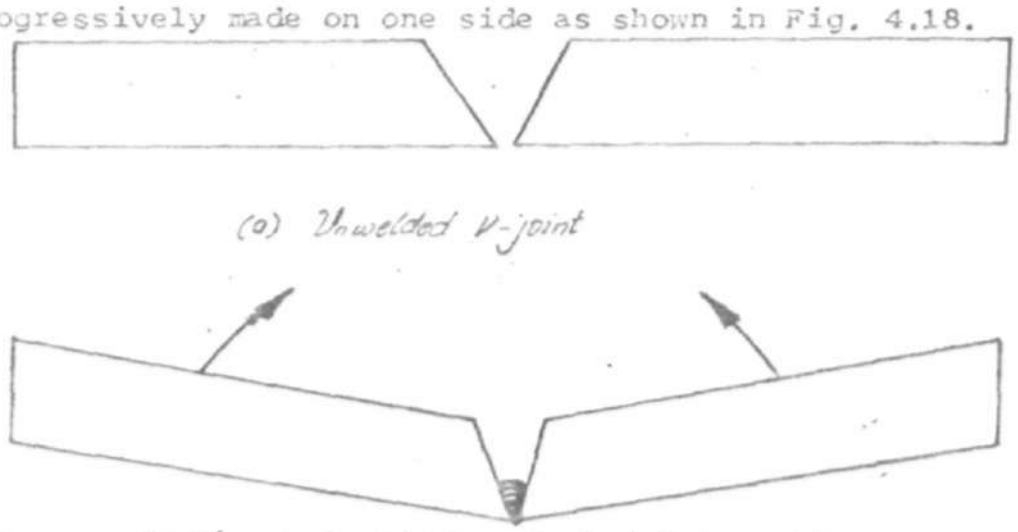



Fig. 4.18: Distortion in Unrestrained V-Joint

When the joint is restrained as in this thesis, tensile reaction stresses are set up in the joint in addition to the residual stresses due to welding. (See Fig. 2.3(b)). Also due to welding mainly on one side, the weld metal, on solidification, tends to pull up the rest of the joint as indicated by the arrows in Fig. 4.18(b).

It was further observed from the results of the present investigation that the double-V and the square-butt

joints produce stresses of comparatively the same magnitude. This is because the same number of passes were deposited on each side of the joints successively; thus providing an even pull on each side and nullifying the effect of the pass deposited previously on the other face.

The other thing that can be seen in the results discussed above, in the first batch of the specimens and that shown in Fig. 4.10 to Fig. 4.15 for the second batch of specimens is that there is lack of correlation in the stress distribution in similar specimens. For example, one would expect the double-V joint curves in Fig. 4.2 and Fig. 4.3 to remain of the same sign and magnitude; but the picture is quite different from this. The stresses in Fig. 4.2 are greater in magnitude and all tensile while the ones in Fig. 4.3 are of lower magnitude and are compressive. Similarly, the variation in the other two types of joints is not consistent. Also the results plotted on Fig. 4.10 through to Fig. 4.15 were all taken on similar specimens, but there is no correlation in the results as can be seen in the plotted graphs. The lack of correlation is due to two main reasons; viz:

(a) The gauges were placed on the weld bead. The true picture of the stresses on the weld bead is still under investigation as reported by Masubuchi[1] as the true picture is still uncertain and complicated.

(b) The superposition of residual stresses due to multilayer welding. (The welds investigated took six passes to fill).

Investigators including Kihara and Masubuchi[1] have studied how multipass welding affects residual stresses and have shown that the picture is quite complicated as shown in Fig. 4.19 below, which they could not adequately

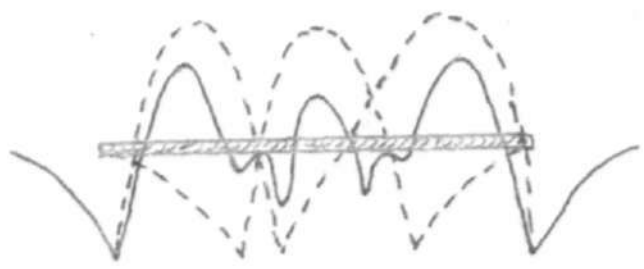


Fig. 4.19: Schematic Explanation of Complicated Stress Distribution on Welded Bead

explain. Their attempted explanation is quoted below.

> The measured value on the weld line are so scattered that it is difficult to draw a smooth curve. The scattering can be seen in the specimen welded using the block method as well as the complete multi-layer method. This complicated distribution of residual stress is probably formed during welding by the superposition of the residual stress produced by the weld of each bead.

The difficult picture is also due to partial anealing off of residual stresses in earlier passes by later ones. This too is not constant throughout the length of the weld.

Due to the above reasons no decisive conclusions have been drawn on the effect of multi-layer welding and residual stress.

There are a few readings in most of the specimens that fall above the yield point of the base metal material. The yield stress of the base metal material is 267.40 $N/mm^2$, so all the results that are above this value such as 473.50 $N/mm^2$ and 428.92 $N/mm^2$ in Table A.2 fall above the yield stress of the base metal material. As already stated earlier in Chapter 2, investigation by Masubuchi[1] and others show that the stress values are as high as the yield stress of the weld metal, which is 413.80 $N/mm^2$ in the weld metal used in this work. The values higher than this may be due to gauges fixed at edges of slag inclusion holes which will normally cause high concentration of stresses.

Hwang[14] studied the distribution of residual stresses in butt joints; his results are shown in Fig. 4.20.

The last results plotted in Fig. 4.15 and Fig. 4.17 were carried out to determine residual stress distribution in butt joints along the weld and transverse to the weld direction. More gauges were used on the base metal in these cases as can be seen in Fig. 3.5.

Figure 4.16 shows the variation of residual stress with distance from centre of the weld, that is, in the transverse direction. The solid line curve is that got from plotting the results obtained, while the dotted curve is a mirror image along the weld line of the solid curve. Both graphs were extrapolated to join on the weld line.

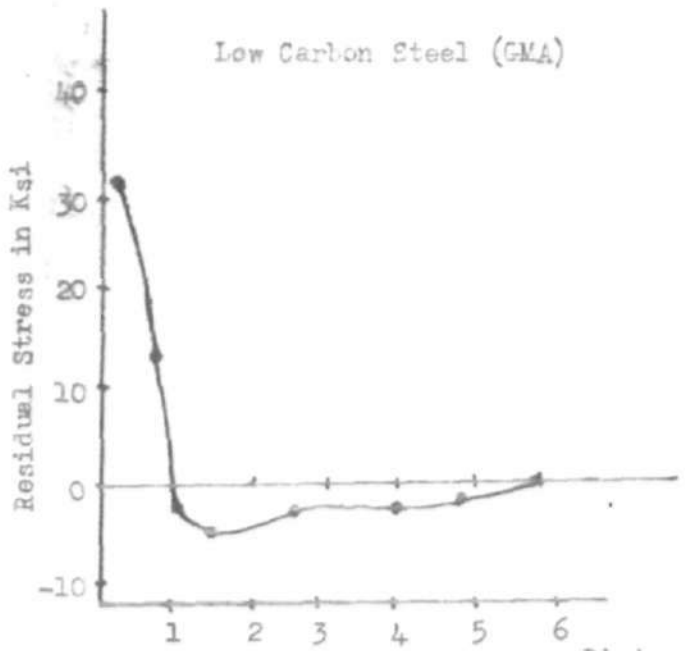



Fig. 4.20: Distribution of Residual Stress in Weldment of Low Carbon Steel After Hwang[14]

The results in Fig. 4.16 show a similar trend with Hwang's work.

Curves 1 and 2 in Fig. 4.17 represent the distribution of residual stress along the weld line, Curve 2 being on the other side of the weld line from Curve 1. Comparing this with the typical distribution of residual stresses in a butt weld as shown by Curve 1 in Fig.2.3(b), it can be seen that once again there is some resemblance. The results as shown by in Fig. 2.3 and Hwang's work shown above are usually taken on one side of the weld with the assumption that the picture on the other side of

the weld line is the same. The shift in the results shown in Fig. 4.17 may be due to a slight shift in placing the gauges which led to the unsymmetrical distribution. Taking the average value of the two curves and drawing a line of best fit between them gives Curve 3 which is closer to that shown in Fig. 2.3(c) Curve 1.

4.2.2. Electrode Type:

In the study of Kihara and Masubuchi[13] mentioned earlier, they have shown that the electrode type has a minor effect on residual welding stresses. This investigation also shows the same trend since a comparison of the pair of figures 4.2 and 4.3; 4.4 and 4.5, for principal stresses shows that, of the two types of electrodes, E6013 gave stresses of higher magnitude than E6012.

There is not much to be said about slag inclusions and weld defects in this work since they have not been investigated. Masubuchi[1] has it that weld defects in the form of porosity, slag inclusions, incomplete penetration and cracks, reduce the strength of welded structures for two main reasons. First, their presence decreases the sectional areas. Second, stress becomes concentrated around the defects.

In the welds tested, there were certainly stress concentrations in some areas as can be seen from the results as mentioned earlier.

The conclusions are outlined in the next chapter.

### 4.2.3. Difficulties Faced In The Investigation

Any work has its set-backs and difficulties, and this investigation was no exception. From the outset there was the limitation in the availability of local materials such as the base metal and weld metal to be used. The number of electrode types used was limited mainly because of the difficulty of obtaining different types for the same type of metal. The welding processes available were also limited as well as it was hard to find good skill. The lack generally of facilities such as automatic welding machines and non-destructive testing machines, has greatly limited the scope of this work.

One major difficulty faced was the lack of small strain gauges for use on the specimens. Bigger specimens would have cost more in terms of time and money. Smaller gauges have enabled one to take more readings across the face and hence one would have had a better picture of residual stress distribution. The lack of adequate literature on the subject of residual stresses was also a constraint in the work since there was no adequate theoretical basis for analysing the results.

## CHAPTER FIVE

## CONCLUSIONS

The following conclusions have been drawn from the results and discussions.

1. (a) The joint design of a butt weld has considerable influence on the residual stresses produced in the joint.

   (b) The single-V joint produces stresses of higher magnitude than the other two - the double-V and the square-butt joints.

2. The electrode type has shown a negligible effect on the magnitude of residual stresses in welded structures.

3. The author would like to recommend the double-V joint, not only because it produces stresses of lower magnitude than the single-V joint, but also because of easy accessibility to the heart of the joint. Also the single-V joint should be avoided as much as possible.

4. This investigation has shown that residual stresses of high magnitude do exist in welded butt joints. Since this may cause premature failure at much lower stress levels than is normally expected due to internal failure resulting from residual stress, the author would like to recommend that design considerations for welded structures should take into account the original level of residual stresses present in the structure.

## CHAPTER SIX

## RECOMMENDATIONS FOR FURTHER WORK

There are various areas that if investigated will give one a better picture of not only the nature of stresses due to welding, but also their distribution, magnitude and effect on service performance of welded structures.

Welding residual stresses are as a result of complex thermal cycles produced in the weldment by the heat supplied by the welding arc. These cycles in turn cause changes in the heat-affected zone and microstructure, cause transient thermal stresses and metal movement, resulting in residual stresses and distortion in the fabricated structure. In order to analyse the problem of residual stress fully, one must start from the beginning.

The analysis can be divided into four parts:

(i) Heat Flow

(ii) Transient Thermal Strains (and Stress)

(iii) Transient Metal Movement and Distortion

(iv) Residual Stress and Distortion after Welding is completed.

If there are adequate facilities one would like to begin by investigating heat flow in welding and then follow each step onto the residual stress in the finished product. Some other possible areas of investigation that one can pursue include: varying the welding processes and seing how the stresses compare and varying the material used for the purpose of seing which ones produce greater stresses. There is also the aspect of how to effectively control distortion that arises from these stresses in

order to improve service behaviour.

If these problems are solved or at least looked into, it will go a long way in improving our welded products which have gained wide application in recent years.

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## APPENDIX A

Tables of reasings and results are shown in this appendix.

TABLE A.1: READINGS AND RESULTS FOR THE DOUBLE-V JOINT WELDED WITH E6012 ELECTRODE AT A CURRENT OF 180 AMPS AND A VOLTAGE OF 50 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ | $\sigma_1$ $N/mm^2$ | $\sigma_2$ $N/mm^2$ | Principal Angle Ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | -245 | - 52.19 | | | |
| | 2 | -677 | +144.20 | 88.37 | -188.78 | 40.56 |
| | 3 | - 85 | - 18.11 | | | |
| $G_2$ | 1 | +985 | +209.81 | | | |
| | 2 | -230 | - 48.99 | 251.13 | - 30.50 | 68.21 |
| | 3 | -260 | - 55.38 | | | |
| $G_3$ | 1 | +125 | + 26.63 | | | |
| | 2 | +192 | + 40.90 | 28.02 | -146.03 | 18.72 |
| | 3 | +697 | +148.46 | | | |
| $G_4$ | 1 | - 85 | - 18.11 | | | |
| | 2 | -182 | - 38.77 | 9.88 | -104.20 | 79.45 |
| | 3 | -225 | - 47.93 | | | |
| $G_5$ | 1 | +470 | +100.11 | | | |
| | 2 | - 30 | + 6.30 | 61.25 | -134.28 | 4.34 |
| | 3 | -710 | -181.23 | | | |
| $G_6$ | 1 | +277 | + 59.00 | | | |
| | 2 | + 85 | + 18.11 | 13.72 | -117.49 | 32.41 |
| | 3 | +618 | +131.63 | | | |

TABLE A.2: READINGS AND RESULTS FOR THE SINGLE-V JOINT WELDED WITH B6012* ELECTRODE AT A CURRENT OF 180 AMPS AND A VOLTAGE OF 50 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ | $\sigma_1$ $N/mm^2$ | $\sigma_2$ $N/mm^2$ | Principal Angle Ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | + 257 | + 54.74 | 130.81 | -102.81 | 53.61 |
| | 2 | - 635 | -135.26 | | | |
| | 3 | - 165 | - 35.15 | | | |
| $G_2$ | 1 | + 185 | + 39.41 | 55.72 | - 87.67 | 28.56 |
| | 2 | + 315 | + 67.10 | | | |
| | 3 | - 290 | - 61.77 | | | |
| $G_3$ | 1 | + 154 | + 32.80 | 156.31 | - 25.16 | 41.81 |
| | 2 | - 335 | - 71.36 | | | |
| | 3 | + 277 | + 59.00 | | | |
| $G_4$ | 1 | - 314 | - 66.88 | 152.22 | - 53.04 | 28.46 |
| | 2 | + 569 | +121.20 | | | |
| | 3 | + 640 | +136.32 | | | |
| $G_5$ | 1 | - 278 | - 59.21 | 428.92 | - 0.04 | 20.72 |
| | 2 | - 163 | - 34.72 | | | |
| | 3 | +1686 | +359.12 | | | |
| $G_6$ | 1 | - 458 | - 97.55 | 372.05 | -463.34 | 48.70 |
| | 2 | +2223 | +473.50 | | | |
| | 3 | + 158 | + 33.65 | | | |

* The electrode designation shown here is that of the American Welding Society (AWS) and each of the symbols stands for the following in B6012 electrode.

$E^x$ - designates an electrode as part of an electric circuit. The first two digits, '60' designate the minimum tensile strength in thousand Psi of the deposited metal in the as

welded condition. The third digit indicates the welding position for which the electrode is suited, viz: (1) For all positions; (2) For horizontal positions; (3) For Flat positions only. The last digit indicates the type of covering on the electrode and the type of current with which it is to be used, whether direct current or alternating current.

TABLE A.3: READINGS AND RESULTS FOR THE SQUARE-BUTT JOINT WELDED WITH E6012 ELECTRODE AT A CURRENT OF 130 AMPS AND A VOLTAGE OF 50 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ | $\sigma_1$ $N/mm^2$ | $\sigma_2$ $N/mm^2$ | Principal Angle Ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | +266 | + 56.66 | 199.47 | 96.60 | 22.69 |
| | 2 | +263 | + 56.02 | | | |
| | 3 | +707 | +180.59 | | | |
| $G_2$ | 1 | + 51 | + 10.86 | 132.53 | -160.52 | 41.89 |
| | 2 | +843 | +179.56 | | | |
| | 3 | -143 | - 30.46 | | | |
| | 1 | -320 | - 68.16 | 71.92 | -239.58 | 41.81 |
| | 2 | -674 | -143.56 | | | |
| | 3 | -231 | - 49.20 | | | |
| $G_4$ | 1 | +135 | + 28.76 | 108.58 | 58.79 | 11.43 |
| | 2 | +216 | + 46.01 | | | |
| | 3 | +415 | + 88.40 | | | |
| $G_5$ | 1 | - 6 | - 13.85 | 4.63 | -116.30 | 54.36 |
| | 2 | -533 | -113.53 | | | |
| | 3 | -302 | - 64.33 | | | |
| | 1 | +503 | +107.14 | 230.55 | 92.61 | 43.09 |
| | 2 | +111 | + 23.64 | | | |
| | 3 | +559 | +119.07 | | | |

TABLE A.4: READINGS AND RESULTS FOR THE DOUBLE-V JOINT WELDED WITH E6013 ELECTRODE AT A CURRENT OF 140 AMPS AND A VOLTAGE OF 80 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ | $\sigma_1$ $N/mm^2$ | $\sigma_2$ $N/mm^2$ | Principal Angle ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | - 590 | -125.67 | 227.56 | -448.00 | 19.53 |
| | 2 | - 687 | -146.33 | | | |
| | 3 | -1620 | -345.06 | | | |
| $G_2$ | 1 | - 200 | - 42.60 | 196.33 | -319.46 | 48.75 |
| | 2 | -1620 | -345.06 | | | |
| | 3 | - 530 | -112.89 | | | |
| $G_3$ | 1 | - 564 | -120.13 | -153.32 | -417.95 | 31.19 |
| | 2 | - 223 | - 47.50 | | | |
| | 3 | -1313 | -279.67 | | | |
| $G_4$ | 1 | -1222 | -260.29 | -174.36 | -402.87 | 56.55 |
| | 2 | - 307 | - 65.39 | | | |
| | 3 | - 675 | -143.78 | | | |
| $G_5$ | 1 | - 530 | -112.89 | -133.96 | -177.02 | 40.84 |
| | 2 | - 641 | -136.53 | | | |
| | 3 | - 492 | -104.80 | | | |
| $G_6$ | 1 | - 863 | -183.82 | -110.34 | -233.49 | 71.35 |
| | 2 | - 338 | - 72.00 | | | |
| | 3 | - 267 | - 56.87 | | | |

TABLE A.5: READINGS AND RESULTS FOR THE SINGLE-V JOINT WELDED WITH E6013 ELECTRODE AT A CURRENT OF 140 AMPS AND A VOLTAGE OF 80 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS N/mm$^2$ | $\sigma_1$ N/mm$^2$ | $\sigma_2$ N/mm$^2$ | Principal Angle Ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | +1390 | +296.07 | 394.50 | -123.09 | 26.64 |
| | 2 | +1712 | +364.66 | | | |
| | 3 | - 498 | -106.07 | | | |
| $G_2$ | 1 | + 788 | +167½84 | 199.83 | 8.01 | 20.14 |
| | 2 | + 720 | +153.36 | | | |
| | 3 | - 105 | - 22.37 | | | |
| $G_3$ | 1 | + 919 | +195.75 | 437.22 | 316.28 | 74.88 |
| | 2 | +1424 | +303.31 | | | |
| | 3 | +1557 | +331.64 | | | |
| $G_4$ | 1 | +1518 | +323.33 | 492.04 | 366.87 | 53.10 |
| | 2 | +1045 | +222.59 | | | |
| | 3 | +1305 | +277.97 | | | |
| $G_5$ | 1 | + 107 | + 22.79 | 22.23 | - 51.78 | 68.54 |
| | 2 | - 255 | - 54.32 | | | |
| | 3 | - 237 | - 50.48 | | | |
| $G_6$ | 1 | + 412 | + 87.76 | 146.23 | 84.11 | 39.91 |
| | 2 | + 565 | +120.35 | | | |
| | 3 | + 345 | + 73.49 | | | |

TABLE A.6: READINGS AND RESULTS FOR THE SQUARE-BUTT JOINT WELDED WITH E6013* ELECTRODE AT A CURRENT OF 140 AMPS AND A VOLTAGE OF 80 VOLTS

| Gauge No. | Channel | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ | $\sigma_1$ $N/mm^2$ | $\sigma_2$ $N/mm^2$ | Principal Angle Ø (deg.) |
|---|---|---|---|---|---|---|
| $G_1$ | 1 | - 978 | -208.31 | -129.33 | -251.64 | 9.71 |
| | 2 | - 750 | -159.75 | | | |
| | 3 | - 274 | - 58.36 | | | |
| $G_2$ | 1 | -1283 | -273.28 | -127.25 | -322.49 | 12.04 |
| | 2 | - 982 | -209.17 | | | |
| | 3 | - 195 | - 41.54 | | | |
| $G_3$ | 1 | - 890 | -189.57 | -255.85 | -399.88 | 32.38 |
| | 2 | - 680 | -144.84 | | | |
| | 3 | -1265 | -269.45 | | | |
| $G_4$ | 1 | - 598 | -127.37 | -122.17 | -245.41 | 45.46 |
| | 2 | - 980 | -208.74 | | | |
| | 3 | - 610 | -129.93 | | | |
| $G_5$ | 1 | -1027 | -218.75 | -136.80 | -269.12 | 13.47 |
| | 2 | - 850 | -181.05 | | | |
| | 3 | - 307 | - 65.39 | | | |
| $G_6$ | 1 | - 850 | -181.05 | -175.58 | -354.79 | 48.87 |
| | 2 | - 325 | - 69.23 | | | |
| | 3 | - 893 | -190.21 | | | |

TABLE A.7: READINGS AND RESULTS FOR DOUBLE-V JOINTS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 224 AMPS AND A VOLTAGE OF 100 VOLTS

| GAUGE NO. | CHANNEL | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ |
|---|---|---|---|
| 1 | 1 | + 129 | + 27.48 |
| | 3 | + 456 | + 97.13 |
| 2 | 1 | +1099 | +234.09 |
| | 3 | + 198 | + 42.17 |
| 3 | 1 | + 355 | + 75.62 |
| | 3 | + 880 | +187.44 |
| 4 | 1 | + 425 | + 90.53 |
| | 3 | + 275 | + 58.58 |
| 5 | 1 | + 739 | +157.41 |
| | 3 | + 880 | +187.44 |
| 6 | 1 | + 843 | +179.56 |
| | 3 | +1805 | +384.47 |
| 7 | 1 | + 357 | + 76.04 |
| | 3 | + 608 | +129.50 |
| 8 | 1 | + 120 | + 25.56 |
| | 3 | + 730 | +155.49 |
| 9 | 1 | + 500 | +106.50 |
| | 3 | + 753 | +160.39 |
| 10 | 1 | + 135 | + 28.76 |
| | 3 | +1830 | +389.79 |
| 11 | 1 | + 370 | + 78.81 |
| | 3 | + 980 | +208.74 |
| 12 | 1 | + 85 | + 18.11 |
| | 3 | + 701 | +149.31 |

TABLE A.8: READINGS AND RESULTS FOR DOUBLE-V JOINTS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 224 AMPS AND A VOLTAGE OF 100 VOLTS

| GAUGE NO. | CHANNEL | STRAIN x $10^{-5}$ | STRESS N/mm$^2$ |
|---|---|---|---|
| 1 | 1 | + 132 | + 28.12 |
| | 3 | + 354 | + 75.40 |
| 2 | 1 | + 200 | + 42.60 |
| | 3 | +2110 | +449.43 |
| 3 | 1 | + 325 | + 69.23 |
| | 3 | + 65 | + 13.85 |
| 4 | 1 | + 405 | + 86.27 |
| | 3 | + 325 | + 69.23 |
| 5 | 1 | +1365 | +290.75 |
| | 3 | + 382 | + 81.37 |
| 6 | 1 | + 615 | +131.00 |
| | 3 | + 237 | + 50.48 |
| 7 | 1 | + 60 | + 12.78 |
| | 3 | + 420 | + 89.46 |
| 8 | 1 | + 230 | + 48.99 |
| | 3 | + 410 | + 87.33 |
| 9 | 1 | + 415 | + 88.40 |
| | 3 | + 945 | +201.29 |
| 10 | 1 | + 155 | + 33.02 |
| | 3 | + 830 | +176.79 |
| 11 | 1 | + 12 | + 2.56 |
| | 3 | +1836 | +391.07 |
| 12 | 1 | + 463 | + 98.62 |
| | 3 | + 530 | +112.89 |

TABLE A.9: READINGS AND RESULTS FOR DOUBLE-V JOINTS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 224 AMPS AND A VOLTAGE OF 100 VOLTS

| GAUGE NO. | CHANNEL | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ |
|---|---|---|---|
| 1 | 1 | - 179 | - 38.13 |
| | 3 | - 325 | - 69.23 |
| 2 | 1 | - 13 | - 2.77 |
| | 3 | - 168 | - 35.78 |
| 3 | 1 | - 530 | -112.89 |
| | 3 | - 325 | - 69.23 |
| 4 | 1 | - 500 | -106.50 |
| | 3 | - 305 | - 64.97 |
| 5 | 1 | + 320 | + 68.16 |
| | 3 | -1649 | -351.24 |
| 6 | 1 | - 600 | -127.80 |
| | 3 | - 615 | -131.00 |
| 7 | 1 | - 317 | - 67.52 |
| | 3 | -1097 | -233.66 |
| 8 | 1 | - 85 | - 18.11 |
| | 3 | - 530 | -112.89 |
| 9 | 1 | - 476 | -101.39 |
| | 3 | - 667 | -142.07 |
| 10 | 1 | - 73 | - 15.55 |
| | 3 | - 986 | -210.02 |
| 11 | 1 | - 292 | - 62.20 |
| | 3 | - 704 | -149.95 |
| 12 | 1 | - 135 | - 28.76 |
| | 3 | - 431 | - 91.80 |

TABLE A.10: READINGS AND RESULTS FOR DOUBLE-V JOINTS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 224 AMPS AND A VOLTAGE OF 100 VOLTS

| GAUGE NO. | CHANNEL | STRAIN x $10^{-6}$ | STRESS N/mm$^2$ |
|---|---|---|---|
| 1 | 1 | +4020 | +856.26 |
| | 3 | +2640 | +562.32 |
| 2 | 1 | + 20 | + 4.26 |
| | 3 | -3630 | -773.19 |
| 3 | 1 | - 75 | 15.97 |
| | 3 | | |
| 4 | 1 | + 272 | 57.93 |
| | 3 | + 75 | 15.98 |
| 5 | 1 | - 325 | - 69.23 |
| | 3 | + 865 | +184.25 |
| 6 | 1 | - 235 | - 50.06 |
| | 3 | + 425 | + 90.53 |
| 7 | 1 | + 330 | + 70.29 |
| | 3 | - 590 | -125.67 |
| 8 | 1 | - 135 | - 28.76 |
| | 3 | - 550 | -117.15 |
| 9 | 1 | + 209 | + 44.52 |
| | 3 | - 370 | - 78.81 |
| 10 | 1 | - 160 | - 34.08 |
| | 3 | - 290 | - 61.77 |
| 11 | 1 | + 360 | + 76.68 |
| | 3 | - 390 | - 83.07 |
| 12 | 1 | - 339 | - 72.21 |
| | 3 | + 930 | +198.09 |

TABLE A.11: READINGS AND RESULTS FOR DOUBLE-V JOINT WELDED WITH E6013 ELECTRODE AT A CURRENT OF 170 AMPS AND A VOLTAGE OF 60 VOLTS

| GAUGE PARALLEL TO WELD NO. | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ |
|---|---|---|
| 1 | | |
| 2 | | |
| 3 | 1196 | 254.75 |
| 4 | 189 | 39.62 |
| 5 | 270 | 57.51 |
| 6 | 197 | 41.96 |
| 7 | 293 | 62.41 |
| 8 | 357 | 76.04 |
| 9 | 147 | 31.31 |
| 10 | 108 | 23.00 |
| 11 | 600 | 127.80 |
| 12 | 1005 | 214.07 |
| 13 | 405 | 86.27 |
| 14 | 897 | 191.06 |
| 15 | 145 | 30.89 |
| 16 | 60 | 12.73 |
| 17 | 1512 | 322.06 |
| 18 | 720 | 153.36 |
| 19 | -675 | -155.93 |
| 20 | -420 | - 97.02 |
| 21 | - 15 | - 3.47 |

TABLE A.12: READINGS AND RESULTS FOR DOUBLE-V JOINT WELDED WITH E6013 ELECTRODE AT A CURRENT OF 170 AMPS AND A VOLTAGE OF 30 VOLTS

| GAUGE PERPEN-DICULAR TO WELD DIREC-TION NO. | STRAIN x $10^{-6}$ | STRESS $N/mm^2$ |
|---|---|---|
| 1 | -345 | - 97.70 |
| 2 | 543 | 125.43 |
| 3 | 60 | 13.86 |
| 4 | 170 | 39.27 |
| 5 | 274 | 63.29 |
| 6 | 205 | 47.36 |
| 7 | - 33 | - 7.62 |
| 8 | - 5 | - 1.16 |
| 9 | 180 | 41.58 |
| 10 | 93 | 21.48 |
| 11 | 175 | 40.43 |
| 12 | 10 | 2.31 |
| 13 | - 20 | - 4.62 |
| 14 | -246 | - 56.83 |

TABLE A.13: STRESSES PARALLEL TO WELD DIRECTION IN SPECIMENS WELDED WITH ELECTRODE E6012, AT A A CURRENT OF 180 AMPS AND VOLTAGE OF 50 VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V $N/mm^2$ | SINGLE-V $N/mm^2$ | SQUARE-BUTT $N/mm^2$ |
|---|---|---|---|
| 1 | - 50.19 | +54.74 | + 56,66 |
| 2 | +209.19 | +39.41 | + 10.86 |
| 3 | + 26.63 | +32.80 | - 68.16 |
| 4 | - 18.11 | -66.88 | + 28.76 |
| 5 | +100.11 | -59.21 | - 13.85 |
| 6 | + 54.00 | -97.55 | +107.14 |

TABLE A.14: STRESSES PARALLEL TO THE WELD DIRECTION IN SPECIMENS WELDED WITH E6012 ELECTRODE AT A CURRENT OF 140 AMPS AND A VOLTAGE OF 80 VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V $N/mm^2$ | SINGLE-V $N/mm^2$ | SQUARE-BUTT $N/mm^2$ |
|---|---|---|---|
| 1 | -125.67 | +296.07 | -208.31 |
| 2 | - 42.60 | +167.84 | -273.28 |
| 3 | -120.13 | -195.75 | -189.57 |
| 4 | -260.29 | +323.33 | -127.87 |
| 5 | -112.89 | + 22.79 | -218.75 |
| 6 | -183.82 | + 87.76 | -181.05 |

TABLE A.15: STRESSES PERPENDICULAR TO THE WELD DIRECTION IN SPECIMENS WELDED WITH E6012 ELECTRODE AT A CURRENT OF 180 AMPS AND VOLTAGE OF 50 VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V $N/mm^2$ | SINGLE-V $N/mm^2$ | SQUARE-BUTT $N/mm^2$ |
|---|---|---|---|
| 1 | - 18.11 | - 35.15 | +150.59 |
| 2 | - 55.38 | - 61.77 | - 30.46 |
| 3 | +148.46 | + 59.00 | - 49.20 |
| 4 | - 47.93 | +136.32 | + 88.40 |
| 5 | -151.23 | +349.12 | - 64.33 |
| 6 | +131.63 | + 33.65 | +119.07 |

TABLE A.16: STRESSES PERPENDICULAR TO THE WELD DIRECTION IN SPECIMENS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 140 AMPS AND VOLTAGE OF 80 VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V $N/mm^2$ | SINGLE-V $N/mm^2$ | SQUARE-BUTT $N/mm^2$ |
|---|---|---|---|
| 1 | -345.06 | -106.07 | - 58.26 |
| 2 | -112.89 | - 22.37 | - 41.54 |
| 3 | -279.67 | +331.64 | -269.45 |
| 4 | -143.78 | +277.97 | -129.93 |
| 5 | -104.80 | - 50.48 | -65.39 |
| 6 | - 56.87 | + 73.49 | -190.21 |

TABLE A.17: STRESSES AT 45° TO THE WELD DIRECTION IN SPECIMENS WELDED WITH E6012 ELECTRODE AT A CURRENT OF 180 AMPS AND VOLTAGE OF 50 VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V $N/mm^2$ | SINGLE-V $N/mm^2$ | SQUARE-BUTT $N/mm^2$ |
|---|---|---|---|
| 1 | +144.20 | -135.26 | + 56.02 |
| 2 | -48.99 | + 67.10 | +179.56 |
| 3 | +40.90 | - 71.36 | -143.56 |
| 4 | -138.77 | +121.20 | + 46.01 |
| 5 | - 6.39 | - 34.74 | -113.53 |
| 6 | +18.11 | +473.50 | + 23.64 |

TABLE A.18: STRESSES AT 45° TO THE WELD DIRECTION IN SPECIMENS WELDED WITH E6013 ELECTRODE AT A CURRENT OF 140 AMPS AND VOLTAGE OF 80VOLTS

| JOINT DESIGN / GAUGE NO. | DOUBLE-V | SINGLE-V | SQUARE-BUTT |
|---|---|---|---|
| 1 | -146.33 | +364.66 | -139.75 |
| 2 | -345.06 | +153.36 | -209.17 |
| 3 | - 47.50 | +303.34 | -144.84 |
| 4 | - 65.39 | -229.59 | -208.74 |
| 5 | -136.53 | - 54.32 | -181.25 |
| 6 | - 72.00 | +120.35 | - 69.23 |

## APPENDIX B

(a) Determination Of The Yield Stress Of The Mild Steel Material

A tensometer was used to determine the yield stress and ultimate stress of the mild steel material used in this work.

A mild steel specimen of 5 mm diameter made of the same material as the material of the specimen was inserted in the tensometer and the load-extension curve traced out on a graph sheet. The specimen was then removed and the curve for the rigid member traced out and used in correcting the curve of the specimen. The corrected curve is shown in Fig. B.1.

From Fig. B.1, the yield load and maximum load were read off and from these loads the yield stress and ultimate stress were calculated.

Diameter of specimen = 5.00 mm

Yield Load = 5.25 kN.

Cross-sectional area = $\frac{\pi.(5)^2}{4}$

= 19.635 $mm^2$

$\therefore$ Yield load = $\frac{5.25 \times 10^3}{19.635}$

= $\underline{267.38}$ $N/mm^2$

and Ultimate Stress = $\frac{7.75 \times 10^3}{19.635}$

= $\underline{394.70}$ $N/mm^2$

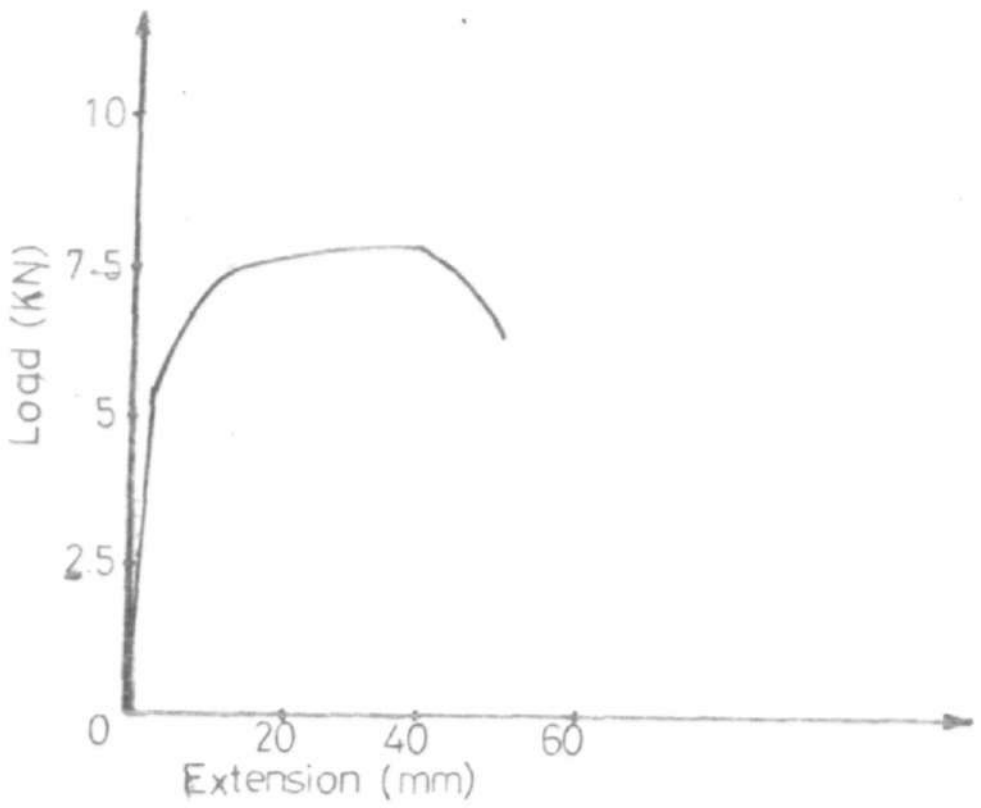



FIG. B1: Load vs. extension

(b) Determination Of Young's Modulus And Poisson's Ratio

In order to determine the above constants, a bar of rectangular cross-section made of the same material as the test specimen was loaded using a 50 tonne Denison testing machine. Gauges were fixed at the middle portion of the specimen in the longitudinal and transverse directions and connected to a strain meter, The specimen was then loaded in 400 N increments up to 2 kN and the readings on the channels of the strain meter recorded are shown in Table B.1 below.

TABLE B.1: VALUES OF LOAD AND READING ON METER CHANNELS

| LOAD (kN) | READING ON CHANNEL 1($\mu e$) | READING ON CHANNEL 2($\mu \varepsilon 2$) |
|---|---|---|
| 0 | - | - |
| 4 | 80 | - 25 |
| 8 | 200 | - 52 |
| 12 | 350 | - 78 |
| 16 | 400 | -106 |
| 20 | 465 | -136 |

Graphs of load versus readings on Channel 1 and Channel 2 were plotted in Figs. B.2 and B.3, and the gradients of the curves were obtained and from these, the material constants were calculated.

Specimen dimensions:-

Width = 31.22 mm

Thickness = 6.45 mm.

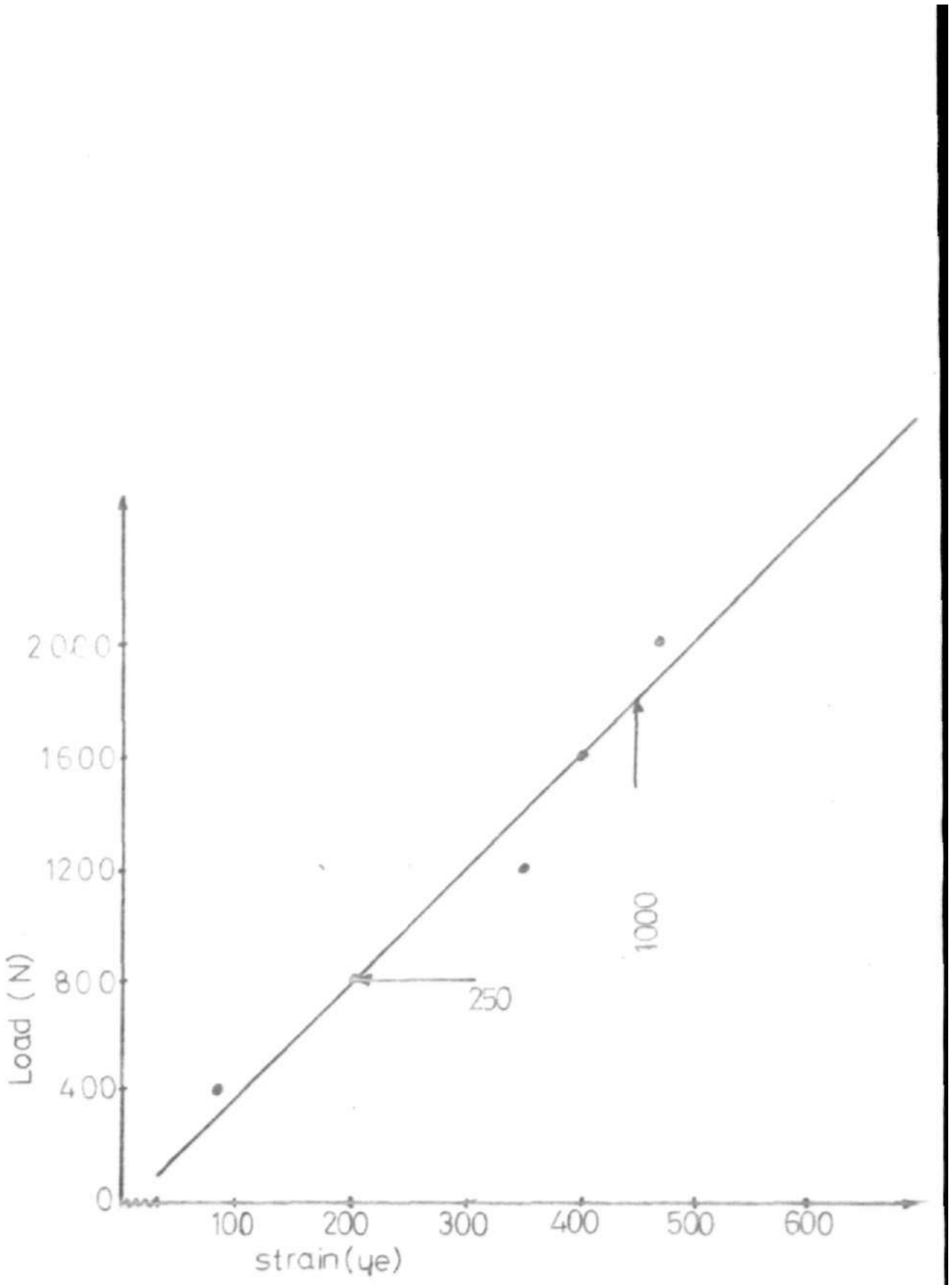



FIG. B2: Variation of Load with Strain on channel 1

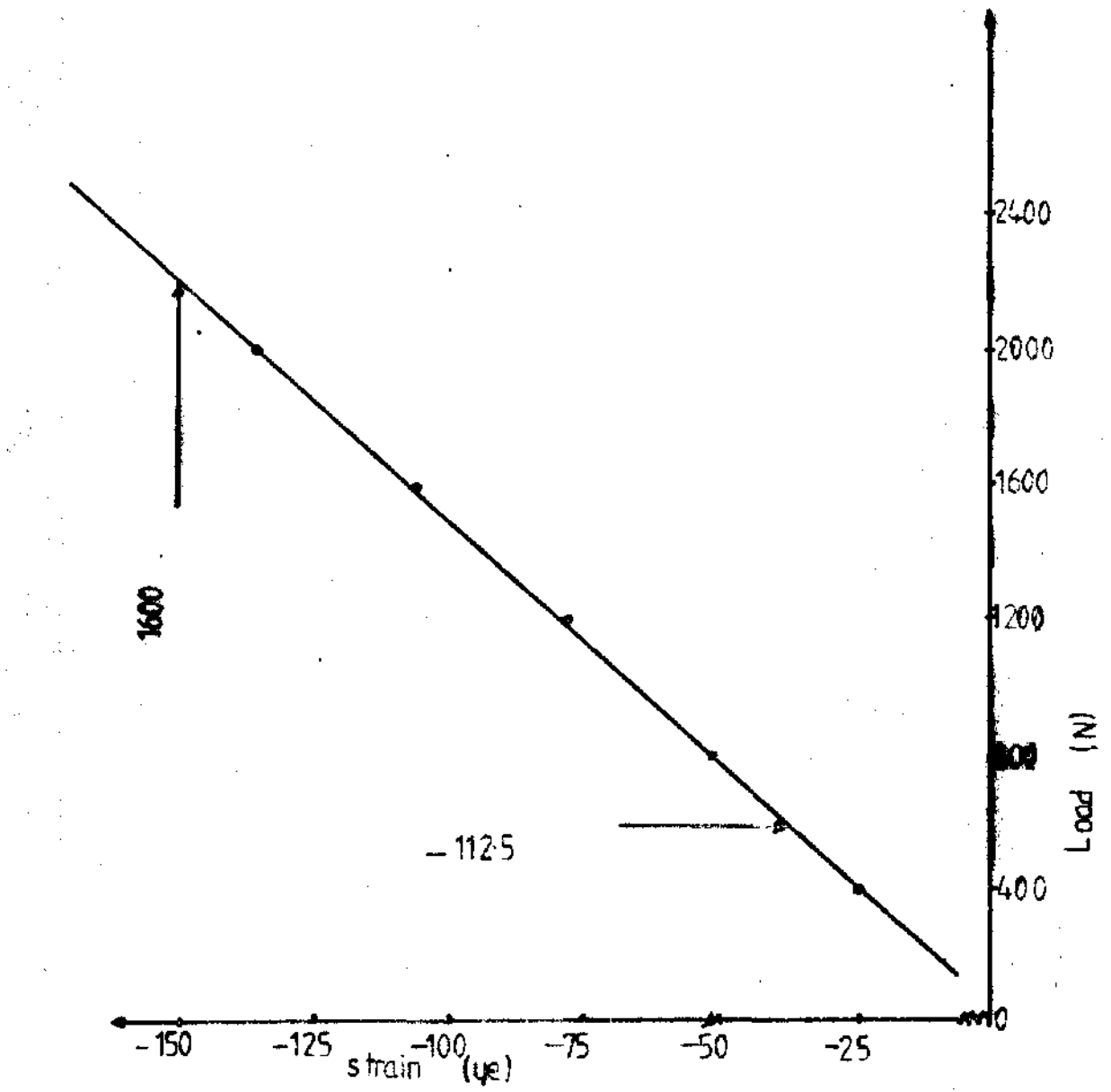



FIG-B3: Variation of Load with Strain on channel 2

Gradient $M_L$ of Fig. B.2 is given by

$$M_L = \frac{1800 - 800}{450 - 200}$$

$$= \frac{1000}{250 \times 10^{-6}}$$

$$= 4.00 \times 10^{6} \text{ N/Unit strain.}$$

Gradient $M_W$ of Fig. B.3 is given by

$$M_W = \frac{2200 - 600}{150 - 37.5}$$

$$= - \frac{1600}{112.5 \times 10^{-6}}$$

$$= - 1.422 \times 10^{7} \text{ N/Unit strain.}$$

Calculations:-

Poisson's Ratio: .

$$\nu = - \frac{e_W}{e_L}$$

from the graphs the slopes are:

$$M_W = \frac{\text{Load } P}{e_W} \quad \text{and} \quad M_L = \frac{\text{Load } P}{e_L}$$

$$\therefore e_W = \frac{P}{M_W} \quad \text{and} \quad e_L = \frac{P}{M_L}$$

Hence, $\nu = - \frac{e_W}{e_L} = - \frac{P}{M_W} \cdot \frac{M_L}{P}$

$$= - \frac{M_L}{M_W}$$

Substituting:-

$$\nu = - \frac{4.00 \times 10^{6}}{1.422 \times 10^{7}}$$

$$= \underline{0.281}$$

Young's Modulus:-

The axial stress, is given by

$$\sigma = \frac{\text{Maximum Load Applied}}{\text{Cross-Sectional Area}}$$

$$= \frac{20000}{31.22 \times 6.45}$$

$$= 99.3 \text{ N/mm}^2$$

The Maximum Measured, $e_L$, is $4.65 \times 10^{-4}$

$$\therefore \text{ Young's Modulus, } E = \frac{\sigma}{e_{Lmax}}$$

$$= \frac{99.3}{4.65 \times 10^{-4}}$$

$$= 2.13 \times 10^5 \text{ N/mm}^2$$