UNIVERSITY OF ROORKEE,
ROORKEE (U.P.)

Certified that the attached dissertation on DEVELOPMENT OF RESIDUAL STRESS MEASURING TECHNIQUES

was submitted by

DARSHAN KUMAR DHIMAN

and accepted for the award of Degree of Master of Engineering in

MACHINE DESIGN

vide Notification No. EX/ 71 /P-65(Degree)

dated AUGUST 6, 1965.

Dated... August 6, 1965.

7/8/65
Assistant Registrar (Exam.)

6.8.65

PSUP (R) 291 Ch. 1964—1,000

DEVELOPMENT
OF
RESIDUAL STRESS MEASURING TECHNIQUES

A dissertation submitted in partial fulfilment
of the requirements for the degree
of
MASTER OF ENGINEERING
in
MACHINE DESIGN

By
DARSHAN KUMAR DHIMAN

DEPARTMENT OF MECHANICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE
June, 1965

CERTIFICATE

Certified that the dissertation entitled "Development of Residual Stress Measuring Techniques" which is being submitted by Mr. D.K. Dhiman in partial fulfilment for the award of the Degree of Master of Engineering in Mechanical Machine Design of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other degree or Diploma.

This is further to certify that he has worked for a period of 8 months from November 1964 to June 1965 for preparing dissertation for Master of Engineering Degree at the University.

(D.V. Singh)
Associate Professor
Mechanical Engineering Department
University of Roorkee
Roorkee, U.P.

Date: July-17-1965

ACKNOWLEDGEMENT

The author expresses his deep and sincere gratitude to Dr. D.V. Singh, Associate Professor in Mechanical Engineering Department, University of Roorkee for his valuable guidance and encouragement throughout the preparation of this thesis.

The author is highly indebted to Dr. Shankar Lal, Professor and Head of the Mechanical Engineering Department University of Roorkee, for providing all the facilities for carrying out this thesis work and for the stimulating interest and benign encouragement extended by him from time to time.

Thanks are also due to Dynamics of Machine Laboratory staff particularly Mr. C.P.S. Panwar for acute interest and co-operation rendered by them during the experimentation.

(D.K. Dhiman)

TABLE OF CONTENTS

INTRODUCTION

Until recently residual stresses have been generally accepted as undesirable from a stand point of shop processing difficulties and premature service failures. This is because residual stresses were often associated with warping and distorsion after heat-treatment, crack produced in quenching or grinding, an early service failure of tools and dies, or machine parts etc. Even though built up guns employing residual stresses were first employed in America as far back as 1888, this pessimism continued because of abstract nature of residual stresses and of difficulties associated in determining their magnitude and direction. This dillusion faded away when Säch (1927) first gave his method of acuratoly determining the three dimensional residual stresses in objects of rotational symmetry in shape and stress distribution. In 1929, Föppl of Germany took one courageous step by recognising that fatigue resistance could be increased through residual stresses obtained in cold-working.

The useful application of residual stresses were first exploited for ordnance requirements. The importance of residual stresses in designing, especially the defence equipment, was so desperately recognised during the last world war that residual stresses represented the only factor of safety against failure. The attention, however, can now the oriented for employing the beneficial effects of residual stresses for peace-time applications. Before one thinks of creating any residual stress of useful sign and magnitude in any machine member, one must create easy means of measuring these stress vectors in similar machine members. Hence due attention should be given to the measurement part of it and this is the purpose of the present investigations.

CHAPTER 1

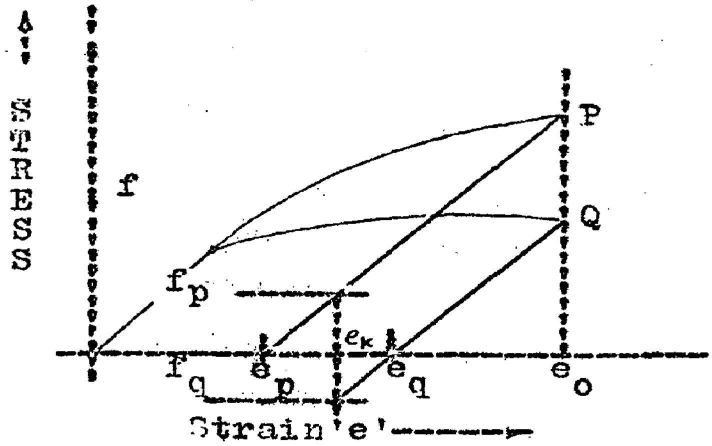
CONCEPT AND PROBABLE CAUSE OF RESIDUAL STRESSES AND THEIR CLASSIFICATION

Stress is the intensity of internal forces induced in any engineering material due to the application of external forces of varied nature and means of application. Stress distribution over a section refers to the state of stress at every point on the section. This state of stress is further identified by nine stress components, referred to the cartesian set of coordinate axes, that are necessary to define (i) magnitude, (ii) direction of stress, and (iii) orientation of the plane containing the point of interest - in fact only six out of these nine components are independent.

Broadly speaking, stress may further be recognised as (i) working-stress which persists only as long as the load causing it persists, (ii) residual stress which remains locked up in the mass of the material after the load has been removed.

The cause and mechanism of residual stress development is still a debatable question. However, it is believed to be caused by the fact that actually the engineering materials are not perfectly elastic and isotropic. It is believed that the residual stresses develop in the following manner:

An important concept, described in many volumes on material science, is the initial difference in effective yield strength among and between different regions of a polycrystaline or imperfect single crystal, ascribed to the anisotropy of crystal slip, and orientation differences in the specimen when such a specimen is loaded for example, in tension, all the grains may acquire approximately the same total strain, but those of lower effective yield-strength suffer the greater plastic elongation on removal of the load, such grains retain their neighbours in tension and in so doing are themselves compressed. The behaviour of a pair of parallel, coherent grains P and Q of different initial yield strength, is illustrated by their individual stress curves (Fig. 1.1).



(Fig. 1.1)

Let these crystals be loaded to the same total strain e_o, on unloading each grain attempts to release its elastic component of strain along the modulus slope. If each were free to do so, they would be left with the respective plastic strains e_p and e_q crystal P having the higher initial yield strength and the lower plastic elongation. Since they are coherent, they attain some intermediate strain e_k the exact position of which is determined by static equilibrium. The respective residual strains are the elastic differences $(-e_p + e_k)$ and $(-e_k + e_q)$, since e_p is less than e_k is less than e_q, these are respectively tensile and compressive. The corresponding residual stresses are :

$$f_p = E\,(\,e_k - e_p\,). \quad \text{tensile,}$$

$$f_q = E\,(\,e_q - e_k\,). \quad \text{compressive.}$$

However, a static balance must always be maintained and if these two grains alone occupied the whole cross-section, the static balance requires that

$f_p\, S_p = f_q\, S_q$, S refers to the area

i.e., $S_p(e_k - e_p) = (e_q - e_k)\,S_q$

In most of the volumes on residual stresses the authors have tried to classify these stresses on the basis of the extent of domian in which they appear in a particular metal or its alloy. Consequently these are (i) macrostresses when extending through a relatively large portion of metal and (ii) microstresses if they are confined to individual grains. The latter are sometimes called as Heyn's stresses. But as regards the most foundamental principles of applied mechanics, the stress at a point is a tensor, and A point is neither micro or macro. Hence the above statement is only a sidetrack. However, there are many other occasions when it is desired to be bilaws for the purpose of conception and clarity.

CHAPTER 2

COMMERCIAL PROCESSES EMPLOYED FOR CREATING STATE OF RESIDUAL STRESS IN METAL MACHINE MEMBERS

Like mechanical friction, residual stresses also form a necessary evil. In a case reported in literature the round shape of steel test bar changed into an oval one during tension test. This unusual behavior of the metal was believed to have been caused by residual stresses in a heavy plate from which specimen was cut out with its axis perpendicular to the direction of rolling. The plate contained high rolling stresses. In another instance, a heavy I-section girdir cracked along the web length with voilent noise without warning. The cause was again attributed to the presence of high rolling stresses. However, the presence of residual stresses in metals is not always determental; on the contrary, there is a large group of commercial products in which the stresses are brought about intensionally to improve their mechanical properties. Some of the commercial processes employed in developing the residual stress state are outlined below:

Broadly speaking, all these processes can be catagorised in four groups:

1. Processes involving thermal treatment of metals.
2. Processes involving mechanical working of metals.
3. Processes involving the changes in composition of alloys.
4. Miscellaneous process like electroplating and welding.

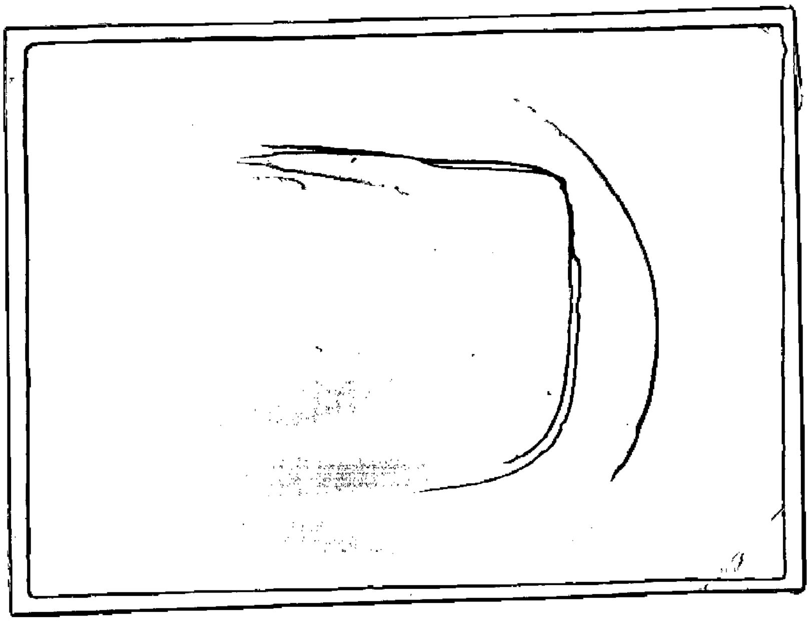


Photo of an unloaded Araldite CR/39 casting taken on Photo-elastic bench set-up. Dark patches indicate the presence off residual stresses(Bright Field).

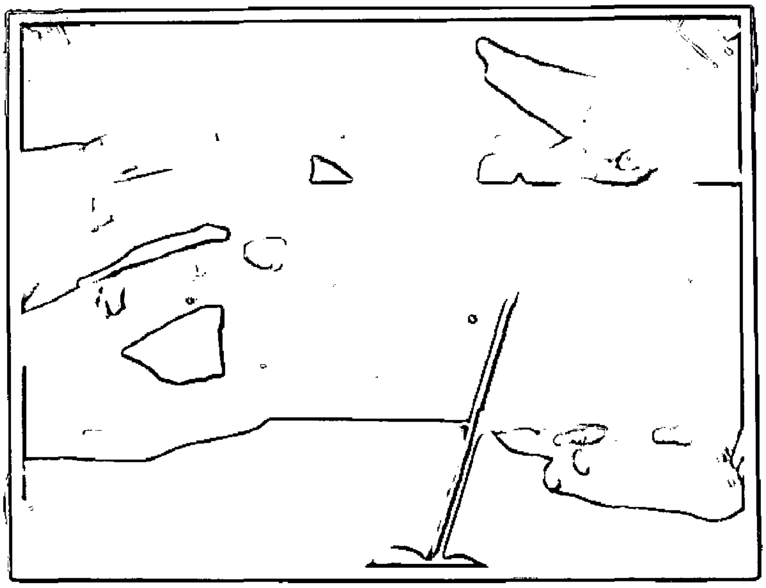


Photo shows a high carbon forged steel cylinder water quenched from red heat. The crack seen along the cylinder length is believed to have been caused due to the residual stresses induced during quenching

Thermal stresses may be developed in metal or its alloys by either heating or cooling. Treatments like quenching the heated component in some quenching media like, air, water, oil, molten metal, sand, solid materials can be utilised for producing the residual stress state. The intensity and pattern of stresses produced depend upon temperature, quenching media, component geometry, type of enclosures used if any and composition. If the component is geometrilised from molten metal, the state of stress produced depends on the rate of cooling, metal composition, the type of mold walls, the pouring temperature, etc. This method is used for preparing cast-iron specimen for the present investigations. The detailed procedure for the above and the like processes are given in any book on metal treatments.

There are quite a large number of mechanical processes used for producing the residual stress state. Some of these are cold rolling, cold drawing, shot-peening, grinding and the like. The discussion of these is not included here to avoid digression from the scope of this work.

Some metallurgical processes extensively exploited commercially are used for producing the state of residual stress. Usual examples are nitriding and carburizing where molecules of metal or gas are infused into the skin of another metal, altering thereby the composition of surface layers of the treated components. This gives rise to the residual state of stress.

Many a process results in creation of residual state of stress as a bi-product such as stresses induced in the base metal after electro-chemical deposition of another metal on the base metal surface. Another example is stress state produced during welding together of metal components.

With quite a large number of the above processes at our disposal, it is possible to create almost any desired pattern and intensity of residual stress in a machine member. Continous efforts are being made in this direction to achieve better results.

CHAPTER 3

RESIDUAL STRESSES Vs MECHANICAL PROPERTIES OF METAL COMPONENTS, AND THE IMPORTANCE OF RESIDUAL STRESSES IN DESIGN OF MACHINE MEMBERS

Accidents on the ground are surely less hazardous than the mid-air accidents, both from the view points of loss of property and loss of lives. Apparantly it might seem adventurous on the part of machine designers to have used smaller factors of safety in designing aeroplane components than those used in designing components of machines to be deployed on land. However, the mechanical properties of aeroplane components are estimated to a finer degree of accuracy than in the case of other machine members. To assess the mechanical properties very precisely, it must be known as to how and to what extent the working and the residual stresses affect the mechanical properties. The discussion here is limited to the study of effects of residual stress on the mechanical properties, like tensile strength, hardness creep, fatigue, dimensional stability.

Tensile Strength:

During the tension test, the specimen is assumed to be in static equilibrium at every moment. The internal stress resulting from external loading is added to any pre-existing residual stress. The total internal stress is the sum of these two components, the residual stress and the service stress. Residual stresses, if aiding an applied force, bring the material to its yield strength at a lower value of the latter and vice versa. As explained in Bauschinger effect, the previous straining has a 'hardening' effect in that it raises the yield strength for subsequent loading in the same direction and a softening effect for the reverse direction.

Hardness:

In atomic dimensions, hardness can be regarded as movement of dislocations. The motion of a dislocation may be promoted by a residual (shear) stress of one sign and impeded by the other. If a residual stress varies in sign over a region of the order of distance that dislocations move, it has a hardening effect. This is what happens in precipitation hardening also commonly known as age hardening.

Creep:

Deformation due to creep is a sum of elastic and plastic strains. Creep is a rate process occuring gradually and dependent on temperature. It may be thought of as diffusion under stress and residual strain energy is believed to activate this diffusion. Hence in the initial stages, it promotes creep, but the effect gets diluted as the intensity of residual strain energy decays.

Fatigue:

Presence of compressive residual stresses in the surface layers of a component subject to cyclic straining enhances fatigue life. This is because the initial cracks leading to fatigue failure are held to originate in the surface zone as a result of the tensile part of cycle straining, and the compressive residual stresses in the surface layers get subtrated from the tensile stresses imposed by the applied load. The maximum tensile stress actually attained is thereby reduced. This statement may be viewed to be statistically true because of our unawareness of the precise mechanism of fatigue failure.

Dimensional Stability:

The generation and relaxation of residual stresses may result in dimensional changes. This is one of the most undesirable manifestations because it enhances dimensional instability of a machine member whenever its stress pattern is distrubed to from a new static equilibrium. However, this principle provides the basis for most accurate method of determining residual stress distribution. Machining of residually stressed components presents odd problems. Cold drawn bars are to be carefully machined in steps of very shallow cuts in order to avoid sudden cracks and/or exceedingly large deformations occuring due to the original stress pattern being disturbed due to metal removal following the machining operations.

Component geometry goes a long way in deciding the stress distribution to which the component is subjected. After the geometry is decided, it pays to avoid failure at locations of stress concentration, which occur so commonly in engineering design. One of the possible solutions is to induce, at these locations, a residual stress of favourable sign so that the effective service stress is held below the material yield strength.

In the language of design the obvious cause of a structural failure is the fact that the effective stresses imposed on the member by service loads are greater than its strength. A general procedure for examining these failures is to check the balance between the stress and strength, that is, to re-evaluate the loads, the stresses and strength in the failed part. So far as the evaluation of stresses is concerned, all the stresses, whatever they are caused by, must be taken into account. As the residual stresses have a far reaching effect on the mechanical properties of any machine member, these stresses must be precisely evaluated. Since the present design demands are becoming more and more exacting, care should be exercised to minimize the factor of ignorance and in so doing the beneficial effects of residual stresses should be fully exploited because this would help to improve the existing designs in all fields of industry.

CHAPTER 4

THEORY OF ANALYSIS

While the presence of residual stresses in metals can be revealed by several methods, accurate measurement of their magnitude is extremely difficult and only possible in exceptional cases. Since residual stresses form an internally balanced system of stress and are produced by mutual interaction of various elements of the strained body, the sub-division of the body into parts will cause an imbalance and partial relaxation of stress in each part, because strain due to residual stresses is of elastic nature, giving rise to measurable dimensional changes.

The problem in measuring residual stress is to reveal and measure these strains. The general method, therefore, embodies a reversal of the process by which the strains are produced, that is, remove portions of the specimen in layers of small thickness and observe the resulting dimensional changes produced in the remaining stock. The following method is developed for round bars or tubes, wherein material from the centre of cylindrical rod is progressively removed and the circumferential and longitudinal strains in the remaining stock are measured. The method was originally developed by Mesnager and simplified by Sächs. The following assumptions are made:

1. The stress distribution is symmetric about the axis of the specimen and is constant along the length of specimen.

2. Removal of a layer of material is accompained by an equal change in longitudinal stress at all similar points of the cross-section.

Although this might seem to be very restrictive but most cold forming operations performed on cylindrical rods or tubes, such as sinking, extruding, or drawing, result in such a symmetrical residual stress pattern. Uniform axial quenching, carburizing, or nitriding of cylindrical tubes or rods also result in a symmetrical stress distribution about the longitudinal axis. The stress distribution remains relatively constant along the length of the specimen.

In analysing a solid cylindrical rod, the first bore is essentially performed by using a drill.

Let, A_o = original cross-sectional area of solid cylinder.

A_b = area of bored out portion of cylinder

$A = A_o - A_b$ = Net cross-sectional area of cylindrical tube after each removal.

e = Strain liberated, due to metal removal, and appearing on the remaining stock.

f_r = Stress relieved from the remaining cylindrical tube, after the bore is performed, allowing the dimensional changes to appear on its external surface.

f = average stress that exists in the removed material.

E = Young's modulus of elasticity of the material.

F_{skin} = force in the tube after the bore has been performed.

F_{core} = force in the removed inner portion.

For static balance

$$F_{core} = F_{skin} \qquad (1)$$

Now
$$f_r = Ee \qquad (2)$$

$$F_{skin} = (A_o - A_b) \cdot f_r \qquad (3)$$

combining (2) and (3), we obtain

$$F_{skin} = (A_o - A_b) \cdot E \cdot e \qquad (4)$$

Also
$$F_{core} = f \cdot A_b \qquad (5)$$

Substituting (4) and (5) in (1), we get

$$f \cdot A_b = (A_o - A_b)\ E \cdot e$$

or
$$f = \frac{(A_o - A_b) \cdot E \cdot e}{A_b} \qquad (6)$$

The order of removals is characterized by subscripting f and e, so that

$$f_1 = \frac{(A_o - A_b) \cdot E \cdot e_1}{A_b} \qquad (7)$$

gives the stress in the material removed during first removal. Let the metal removals be of differential order dA_b, liberating differential strain de, then equation (7) gets modified as under:

$$f_1 = A_1 E \cdot \frac{de_1}{dA_b} \qquad (8)$$

The actual stress that existed in the second removal, before the removals started is given by the following equation,

$$f_2 = A_2 E \cdot \frac{de_2}{dA_{b\,2}} - E \cdot de_1 \qquad (9)$$

where, dA_{b2} refers to the net cross-sectional area of concentric tube drilled out during second removal. Thus the stress that existed in n^{th} removal is given by

$$f_n = \frac{A_n \cdot E \cdot de_n}{dA_{bn}} - E\,(de_1 + de_2 + \ldots \ldots + de_{(n-1)}) \qquad (10)$$

Equation (10) is further modified to get

$$f_n = E\,(A_n \frac{de_n}{dA_{bn}} - e_{(n-1)}) \qquad (11)$$

where, $e_{(n-1)}$ means the total strain after (n-1) removals and de_n stands for strain liberated during the n^{th} removal only.

The above would apply only to cases of unidirectional stress field. But this is rarely the case. The most general case would be a three dimensional stress field. The quation (11) is modified in the wake of generalization by measuring strain e_L in longitudinal direction, strain e_T in tengential direction, while strain in the radial direction of the cylinder can be arrived at with the help of e_L and e_T. If μ be the Poisson's ratio of the material, e_L and e_T can be assembled into parameters P and θ, so that

$$P = e_L + \mu e_T$$

$$\theta = e_T + \mu e_L$$

The introduction of these parameters for expressing the strains was proposed by Sächs and has greatly simplified the analysis. The three stresses f_L , f_T , f_R (longitudinal, tangential, and radial respectively) are then expressed as follows:

$$f_L = \frac{E}{1-\mu^2}\left[(A_o - A_{bn})\frac{dP_n}{dA_{bn}} - P_{(n-1)}\right]$$

$$f_T = \frac{E}{1-\mu^2}\left[(A_o - A_{bn})\frac{d\theta_n}{dA_{bn}} - \frac{A_o + A_{b(n-1)}}{2A_{b(n-1)}}\theta_{(n-1)}\right]$$

$$f_R = \frac{E}{1-\mu^2}\left[(A_o - A_{bn})\frac{\theta_n}{A_{bn}}\right] \qquad (12)$$

(the similarity between equations (11) and (12) is evident since the first term inside the brackets on the right hand side of the equations, is the stress relieved by the n^{th} bore and the second term the stress relieved by all previous boring)

CHAPTER 5

DESCRIPTION OF TEST PROCEDURE

Stress is almost invariably calculated indirectly after the strains have been actually measured in nearly all techniques of stress measurements save photoelasticity, photostress coat, and stress-gage methods. This orthodox principle is utilized in the course of present investigations and strains liberated due to the release of residual stresses are measured by the help of strain gauges.

Solid cylindrical test pieces of even but not very smooth surface prepared by casting from pig iron and in lengths three times the diameter were used for experimental investigation. The surfaces of the test specimens were prepared carefully for mounting the strain rosettes. For marking reference lines each specimen is positioned on V-blocks placed on a surface plate. The steel pointer of a marking block is moved along the specimen surface by bodily sliding the marking block back and forth on the surface plate and holding the specimen securely at the same time on V-blocks thereby inscribing on the surface a faintly visible line parallel to the specimen axis to represent its longitudinal direction. Next a circumferential line is inscribed by rotating the specimen in V-blocks and against a rigid end sport while

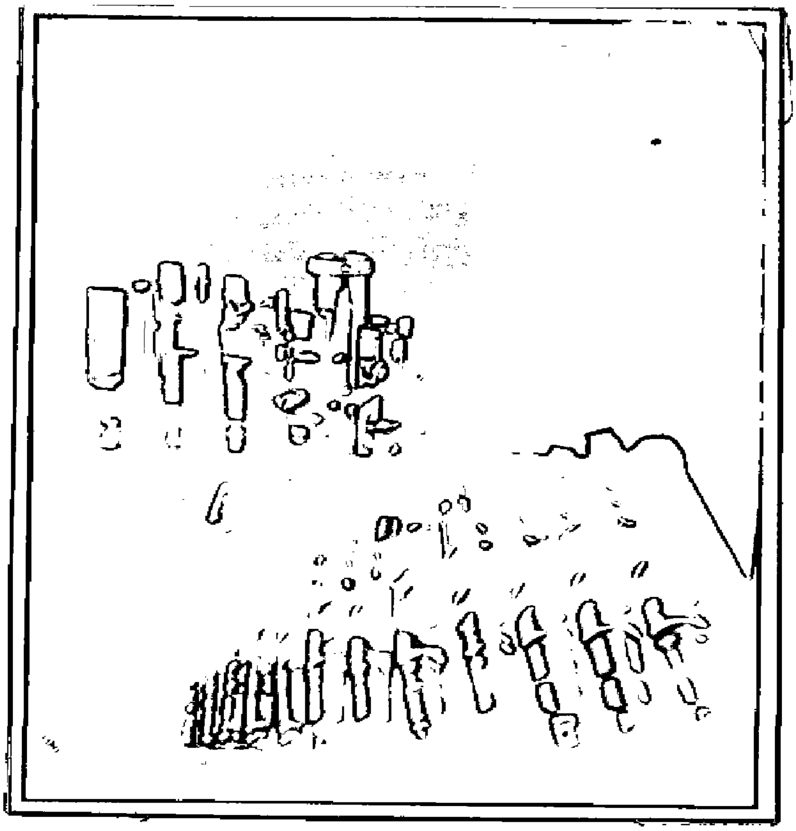


Photo showing (top to bottom) the test-specimen, the series of hand reamers, and the series of twist drills employed for metal removals.

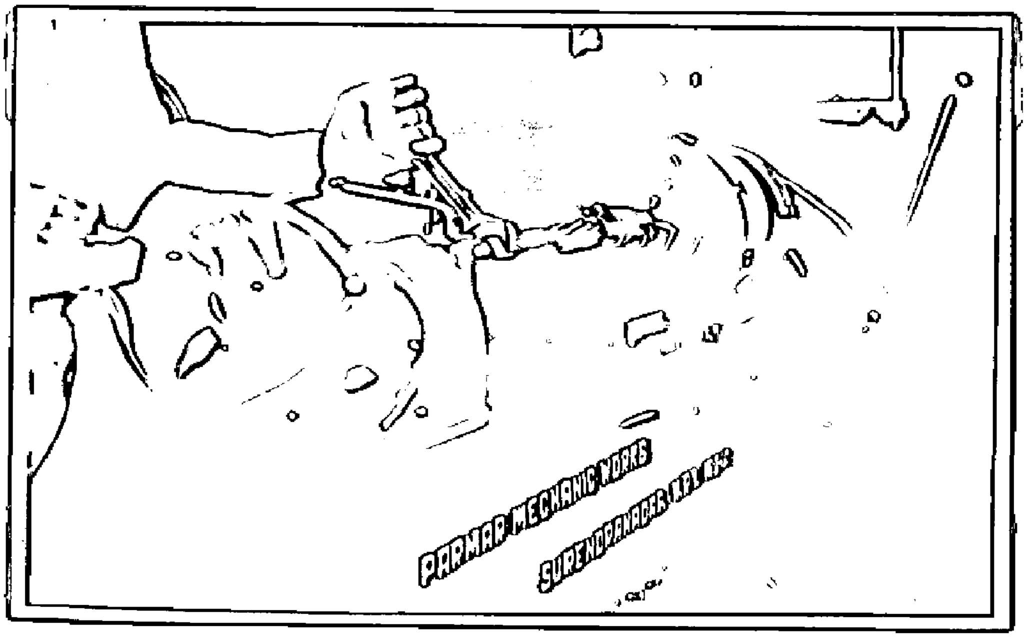
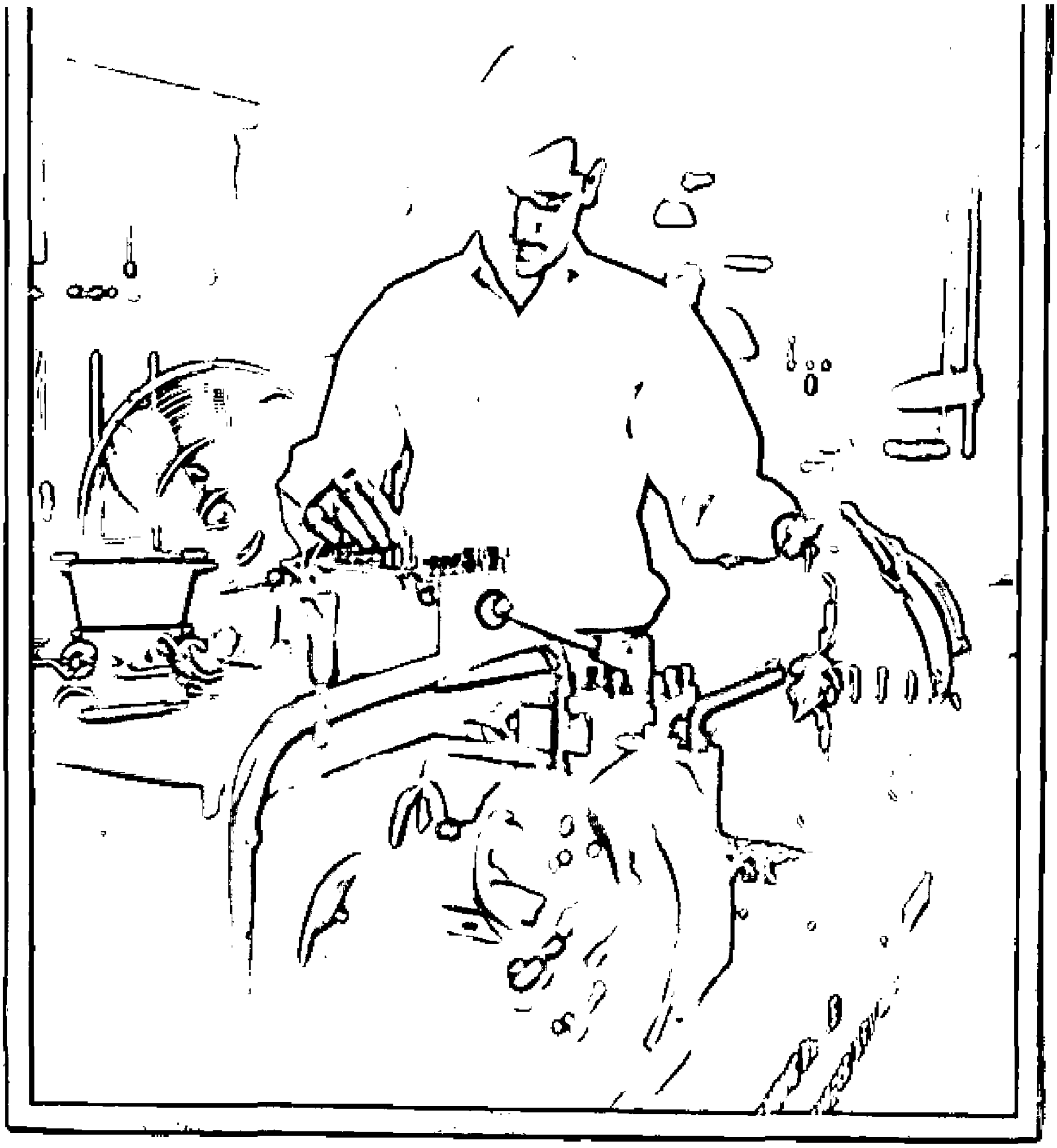


Photo showing the reaming operation in progress.



Strain gage readings being taken after the specimen has cooled down to room temperature.

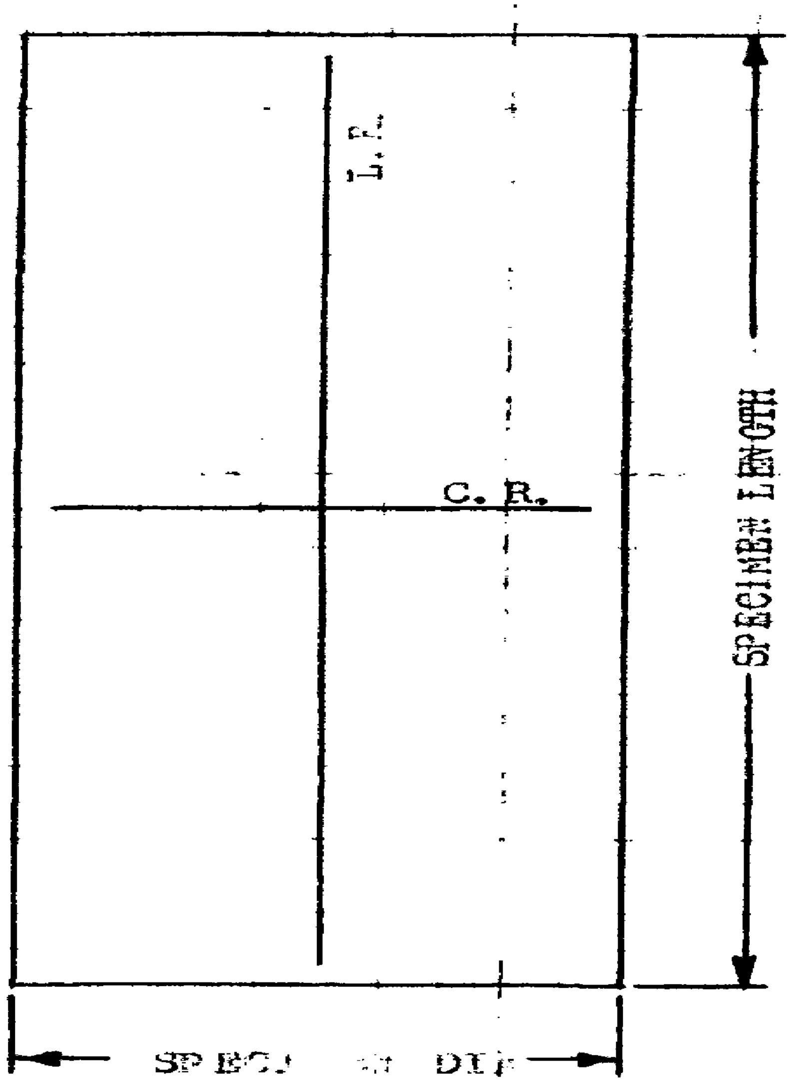
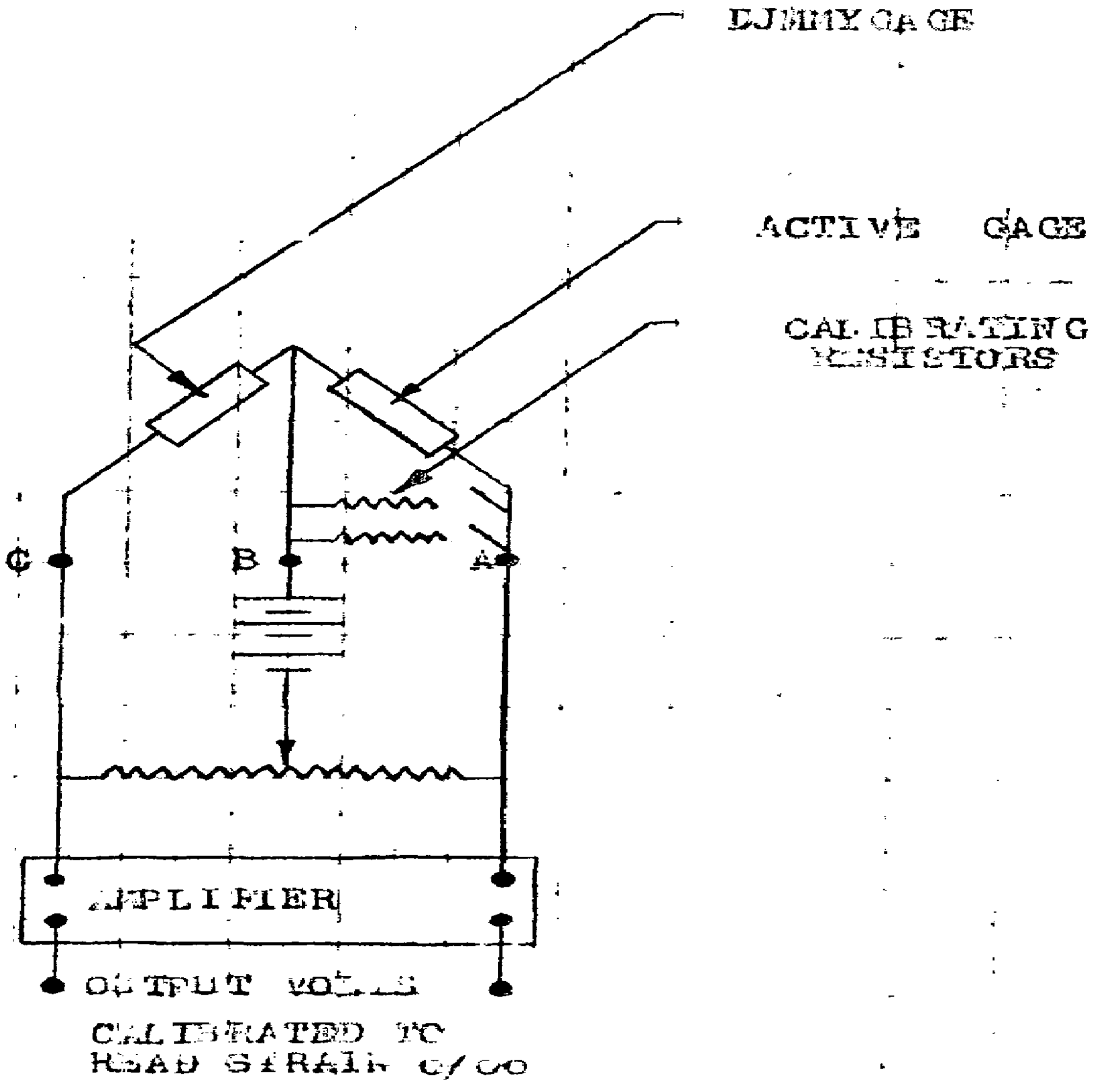


FIG. 6.1 SHOWING THE REFERENCE LINES

C.R. : circumferential reference line
L.R. : longitudinal reference line

holding fast the steel pointer of the marking block against the specimen surface mid-length. This line represents the circumferential direction of the test piece. The two lines, fig. 5.1, taken together represent a convenient reference for fixing a rectangular strain rosette. The rectangular rosette is mounted so that the reference lines run midway and parallel to the gage leads. This practically ensures that the strains are measured in longitudinal and circumferential directions. The continuity and resistance of each gage is checked by using a multimeter. The gage leads are soldered by 1½" long leads which in turn are connected to plug-holders. Care is taken to use strain gages from one single lot. A dumy gauge is mounted on a similar specimen to compensate for the effects of atmospheric changes.

The test piece is held concentrically at one end in a four jaw lathe chuck and rotated at the lowest lathe speed available. The specimen is now drilled and reamed in steps of one eighth of an inch on diameter starting from 3/8" reamer till the specimen is reduced to a hollow tube of 1/16" wall thickness. Each drilling operation is performed in steps of small lengths to avoid over-heating of the specimen. After performing each bore, time is allowed for the specimen to cool down to room temperature. The strain measurements are made by using a strain gauge bridge amplifier which directly reads the strain in %$_o$.



D. C. BRIDGE AMPLIFIER
(FIG. 5. 3)

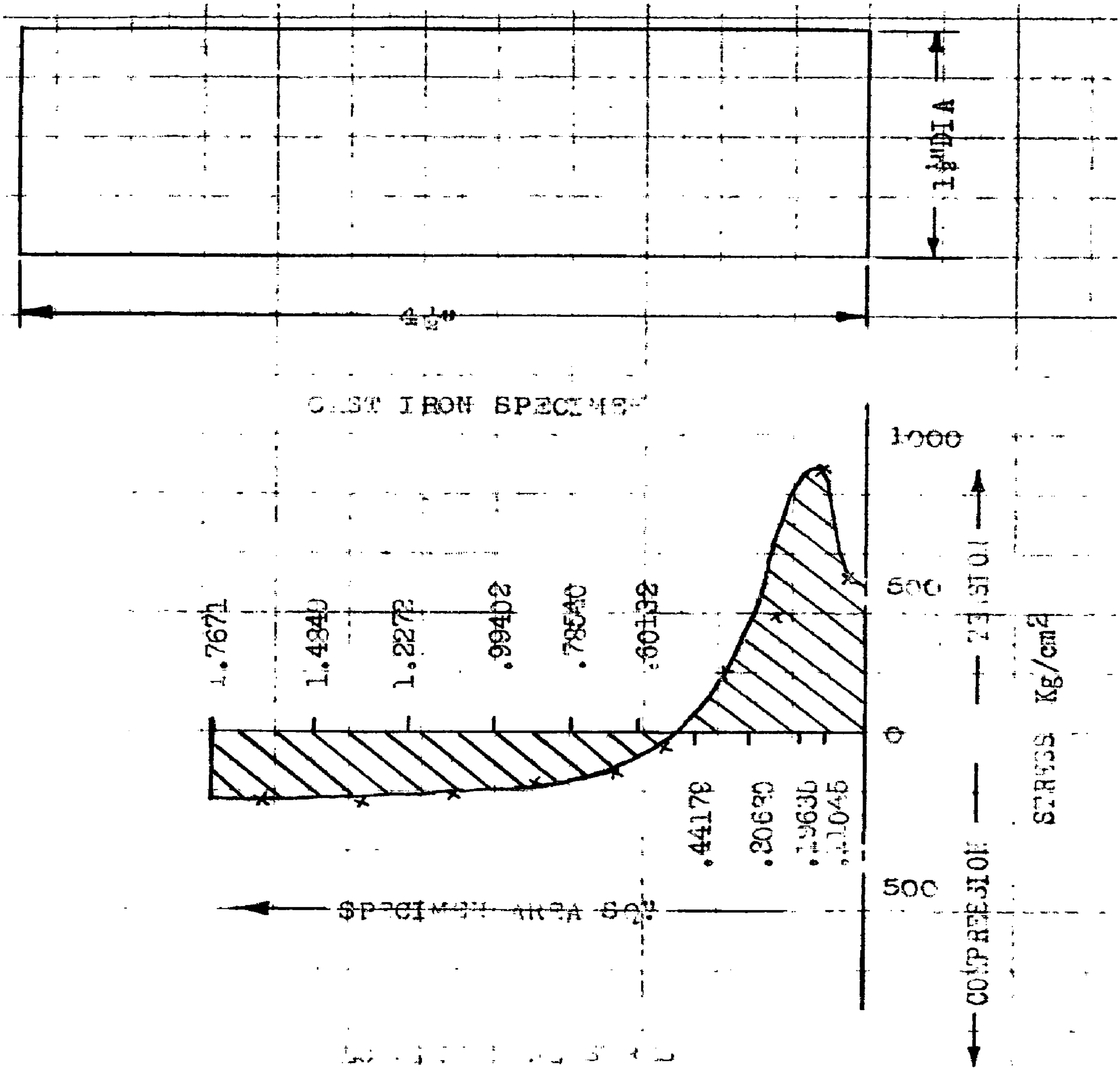
The schematic of bridge amplifier are made as shown in the fig. 5.2. The process is repeated for each test piece.

CHAPTER 6

OBSERVATIONS AND RESULTS
SAMPLE CALCULATIONS DISCUSSION OF RESULTS

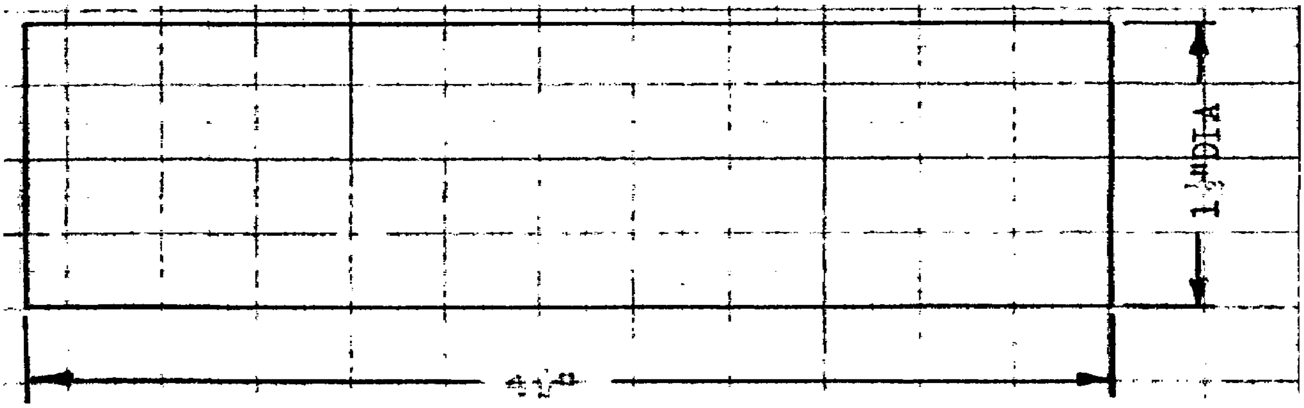
SPECIMEN No. 1

S.No.	STRAIN GAGE READING $^0/_{00}$				STRESS Kg/cm^2		
	LONGITUDINAL		CIRCUMFERENCIAL		$E = 1x10^6$ Kg/cm^2 ; $\mu = .22$		
	RANGE SWITCH	POTENTIOMETER	RANGE SWITCH	POTENTIOMETER	LONGITUDINAL	CIRCUMFERENCIAL	RADIAL
0	16	1.650	14	1.683	-	-	-
1	16	1.620	14	1.665	-510	-369	-370
2	16	1.575	14	1.635	-911	-409	-517
3	16	1.535	14	1.607	-393	-128	-483
4	16	1.5070	14	1.588	-214	-141	-379
5	16	1.475	14	1.581	35	249	-272
6	16	1.450	14	1.592	146	335	-166
7	16	1.437	14	1.610	188	221	-93
8	16	1.428	14	1.630	211	208	-45
9	16	1.438	14	1.655	249	154	14
10	-	-	-	-	227	81	0

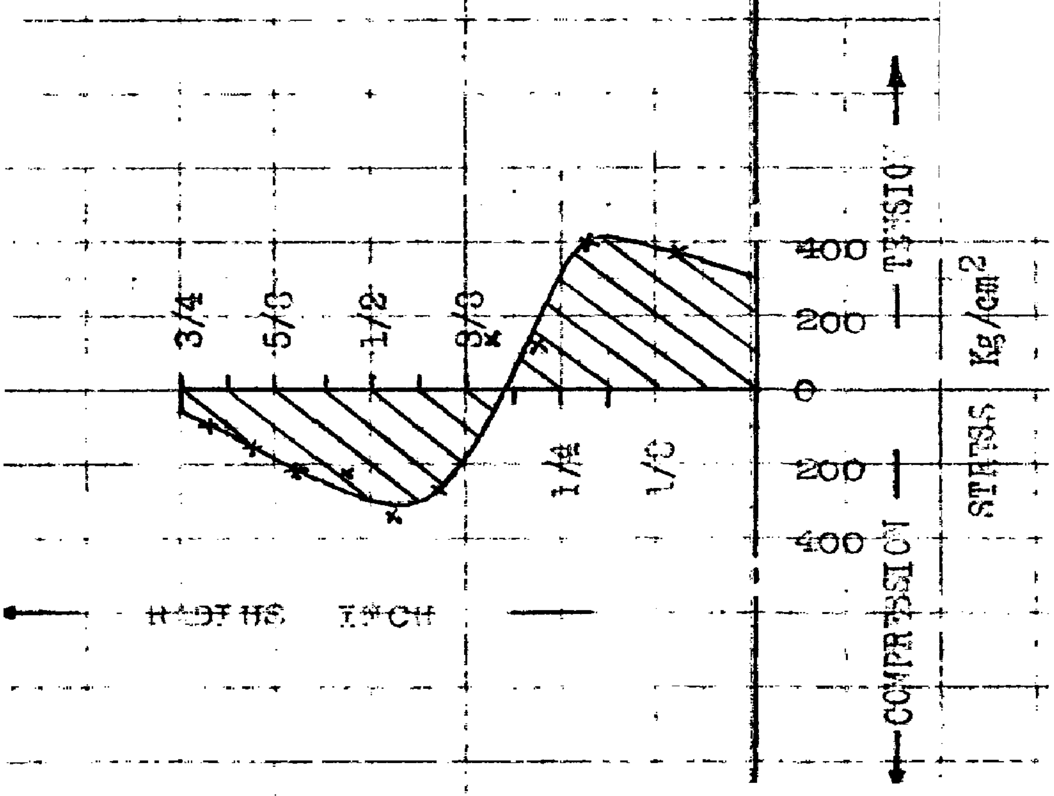


[illegible] STRESS
vs.
CROSS-SECTIONAL AREA

[illegible]



CAST IRON SPECIMEN

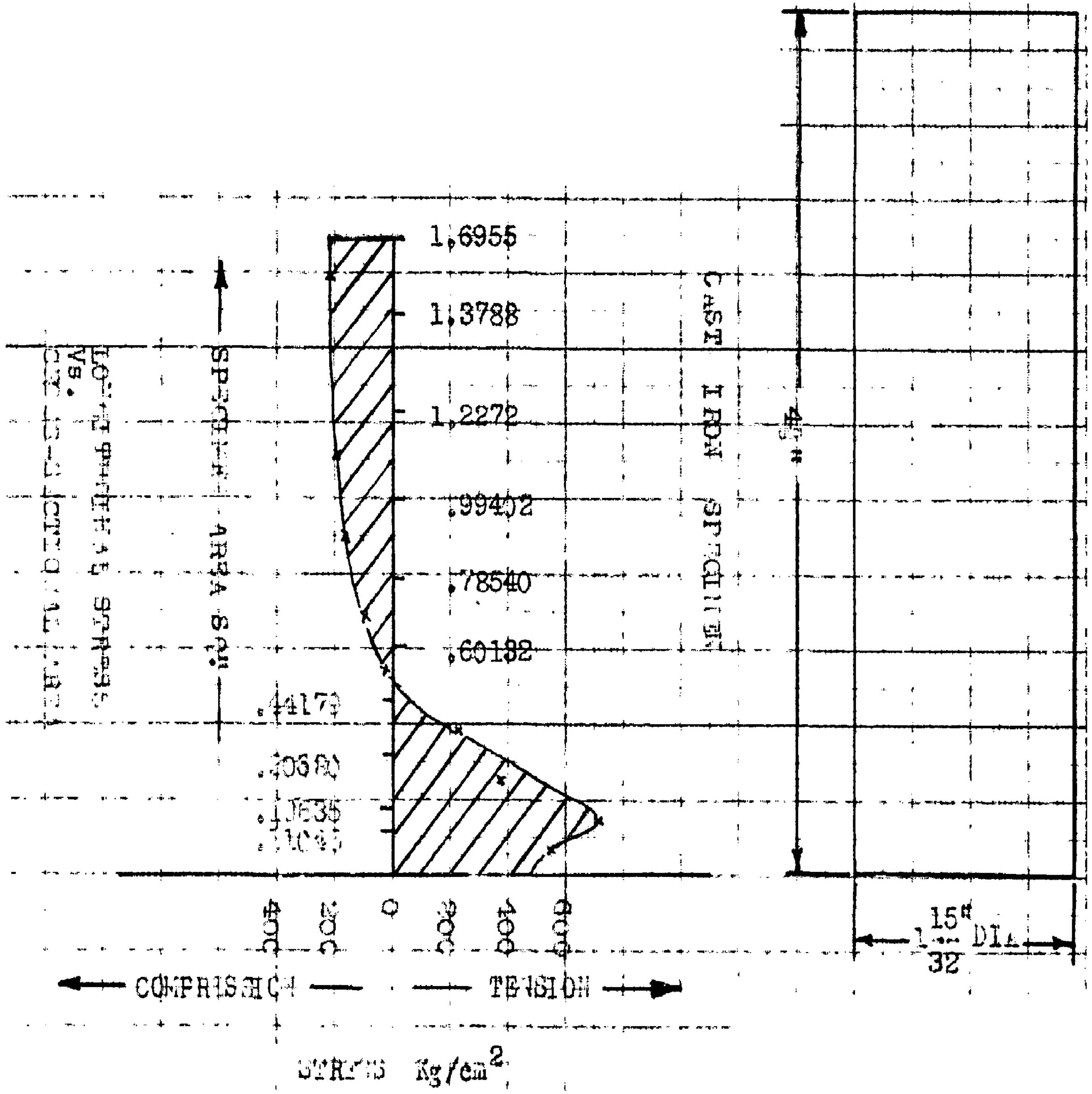


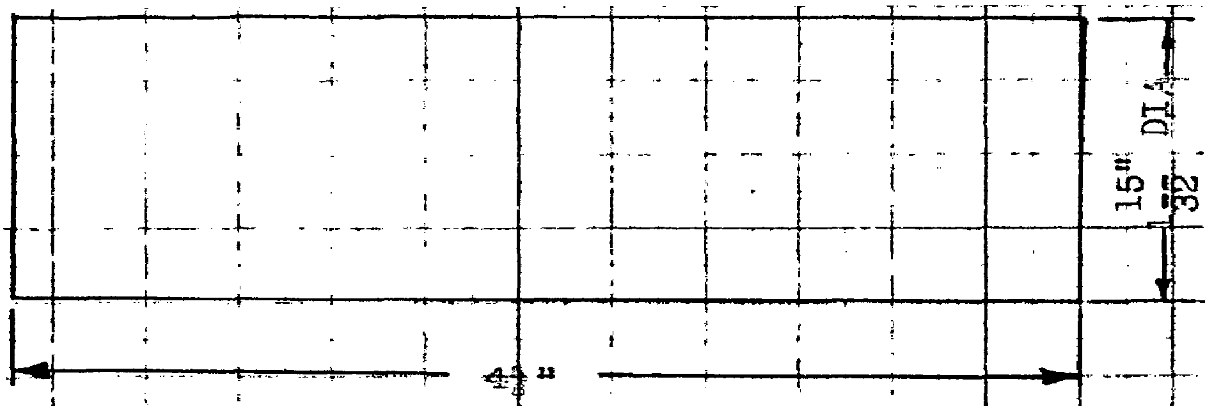
TANGENTIAL STRESS
Vs.
RADIUS

SPECIMEN No.1

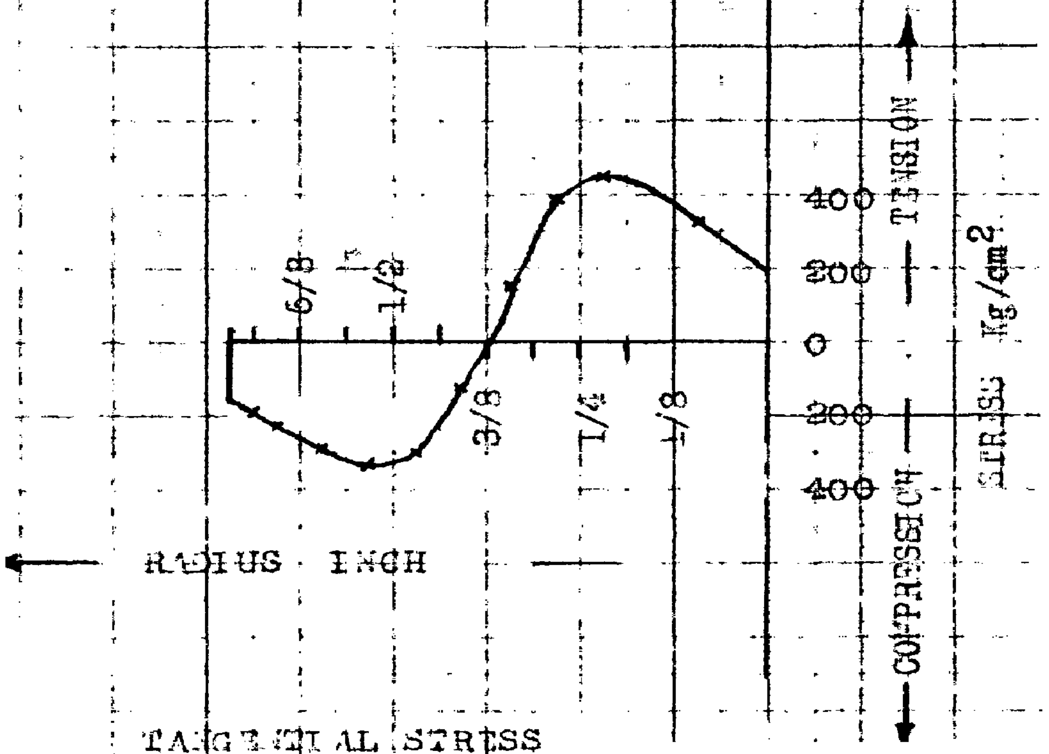
S.No.	STRAIN GAGE READING $^0/_{00}$				STRESS Kg/cm^2		
	LONGITUDINAL		CIRCUMFERENCIAL		E = 1x10^6 Kg/cm^2; ν = .22		
	RANGE SWITCH	POTENTIOMETER	RANGE SWITCH	POTENTIOMETER	LONGITUDINAL	CIRCUMFERENCIAL	RADIAL
0	13	1.150	13	1.485	-	-	-
1	13	1.115	13	1.470	-550	-326	-328
2	13	1.075	13	1.450	-737	-450	-888
3	13	1.045	13	1.422	-370	-394	-1080
4	13	1.010	13	1.407	-237	-155	-1010
5	13	0.991	13	1.427	24	118	-637
6	13	0.974	13	1.466	98	299	- 26
7	13	0.963	13	1.511	156	328	- 51
8	13	0.953	13	1.560	185	289	64
9	13	0.957	13	1.604	209	230	18
10	-	-	-	-	221	196	0

SPECIMEN No.2


CAST IRON SPECIMEN
4⅝"
1 15/32" DIA
1.6955
1.3788
1.2272
.99402
.78540
.60182
.4417
.3068
.1635
.1043
SPECIMEN AREA SQ"
400
200
0
200
400
600
COMPRESSION — — TENSION
STRESS Kg/cm²
LONGITUDINAL STRESS
Vs.
CROSS-SECTIONAL AREA



CAST IRON SPECIMEN

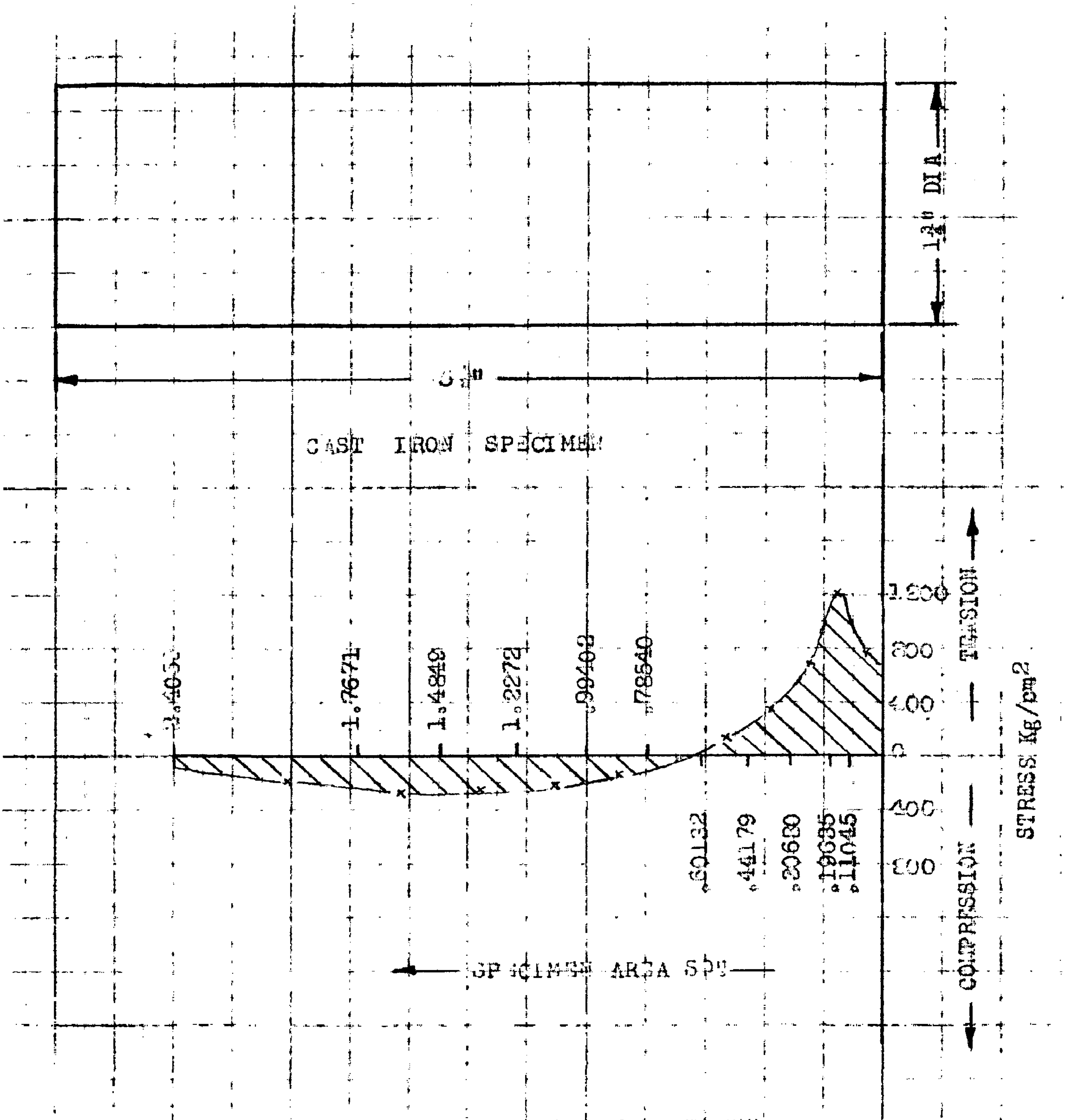


TANGENTIAL STRESS σ_θ, RADIUS

SPECIMEN No.2

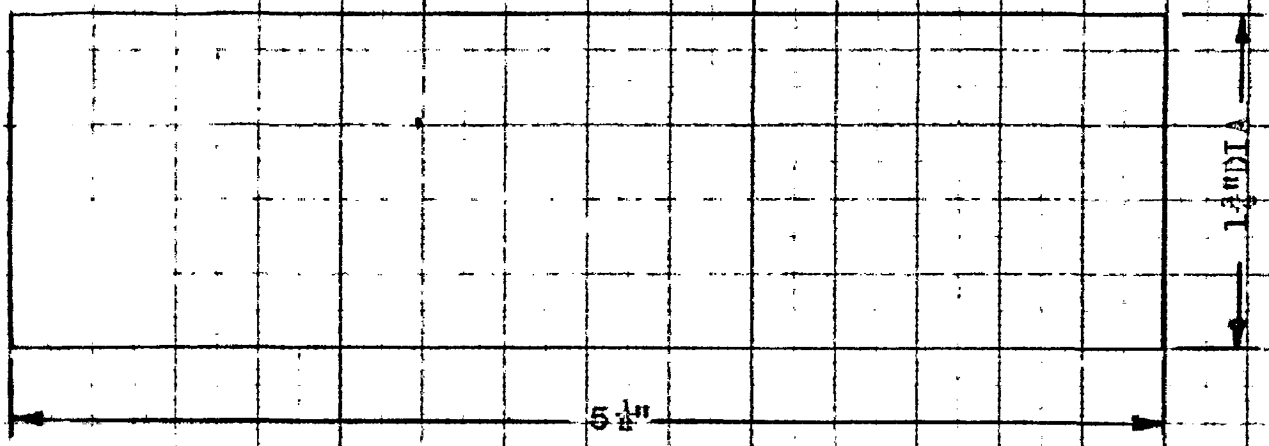
S.No.	STRAIN GAGE READING $^{0}/_{00}$				STRESS Kg/cm^2		
	LONGITUDINAL		CIRCUMFERENCIAL		E = 1x10^6 Kg/cm^2; μ = .22		
	RANGE SWITCH	POTENTIOMETER	RANGE SWITCH	POTENTIOMETER	LONGITUDINAL	CIRCUMFERENCIAL	RADIAL
0	15	1.319	15	1.295	-	-	-
1	15	1.286	15	1.275	-776	-566	-566
2	15	1.244	15	1.244	-1223	-749	-1740
3	15	1.209	15	1.217	-689	-210	-1940
4	15	1.180	15	1.199	-351	99	-1860
5	15	1.154	15	1.196	-142	309	-1820
6	15	1.133	15	1.201	12	439	-1180
7	15	1.115	15	1.212	121	422	-750
8	15	1.110	15	1.229	216	398	-505
9	15	1.112	15	1.251	249	354	-325
10	15	1.125	15	1.280	260	207	-130
11	-	-	-	-	197	68	0

SPECIMEN No.3

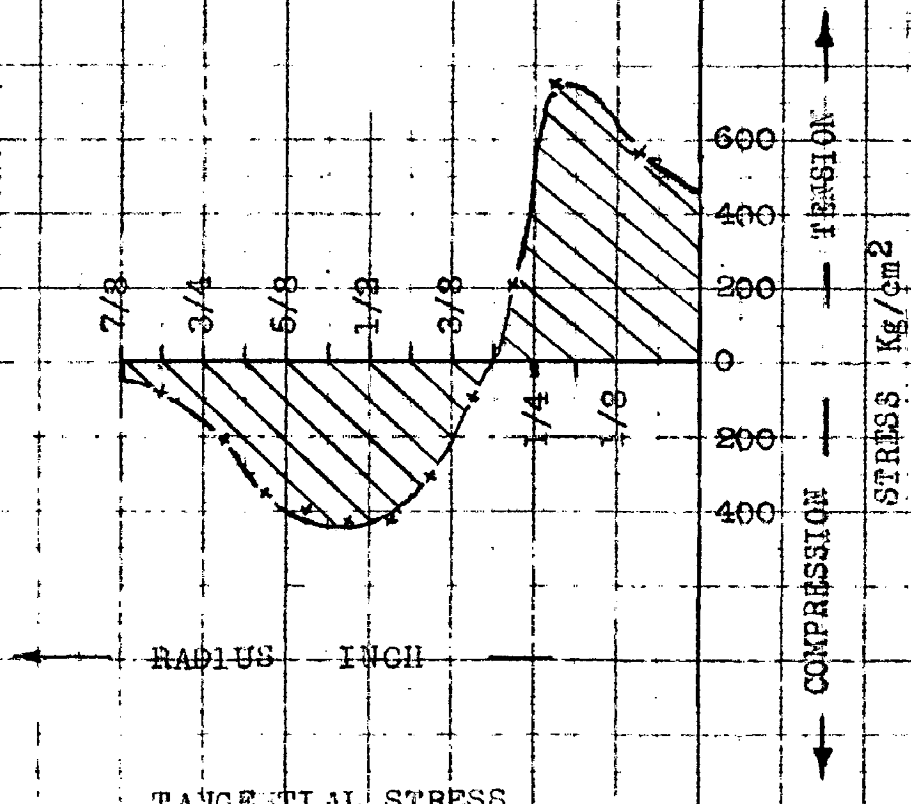


LONGITUDINAL STRESS
Vs.
CROSS-SECTIONAL AREA

SPECIMEN No.3



CAST IRON SPECIMEN

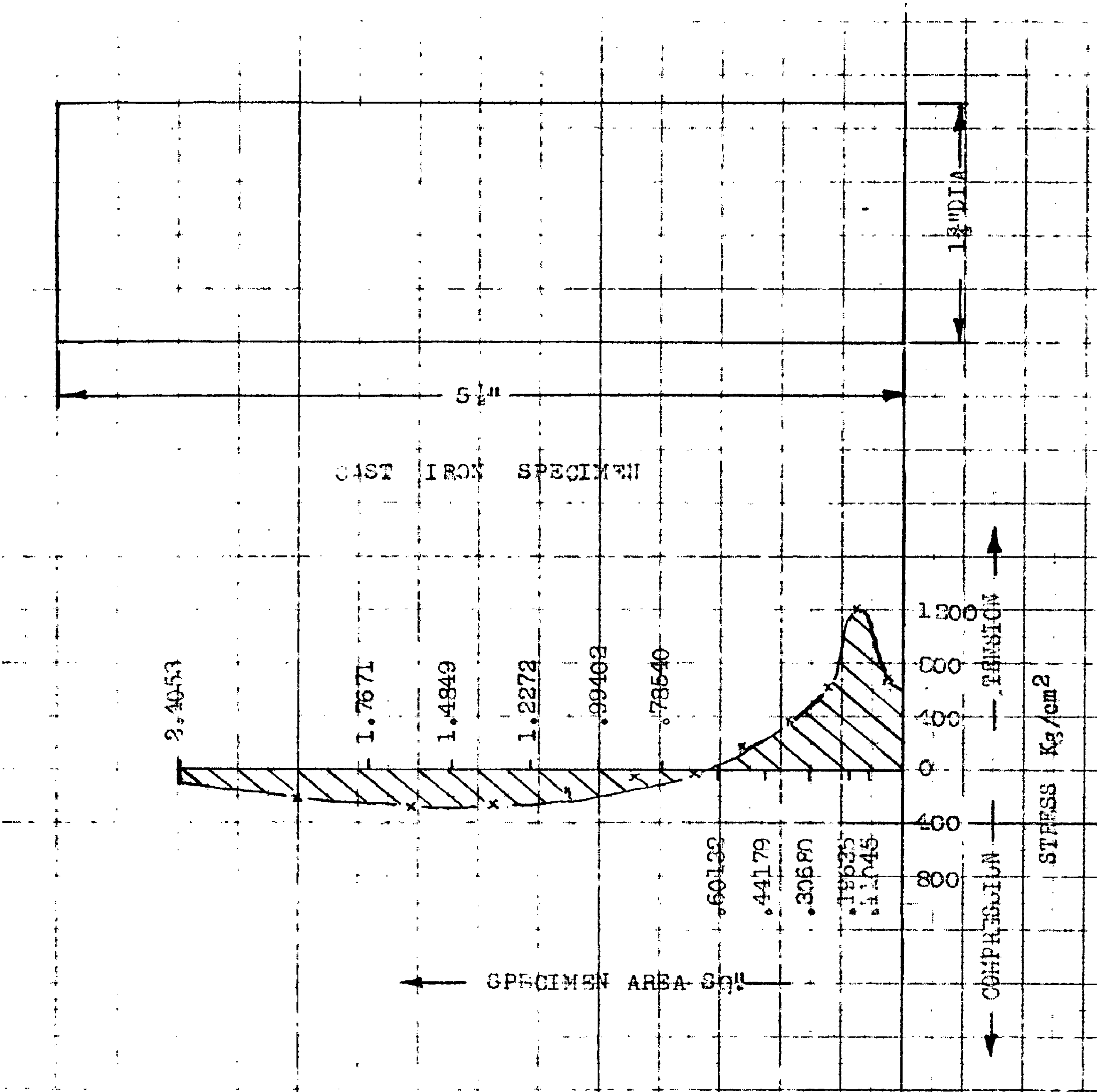


TANGENTIAL STRESS
Vs.
RADIUS

SPECIMEN No. 2

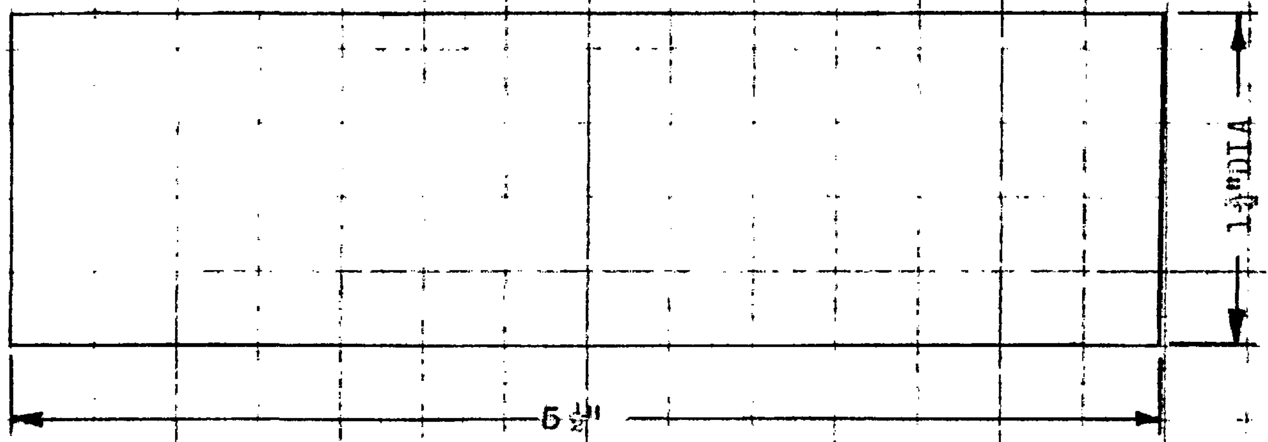
Sl.No.	STRAIN GAGE READING $^{0}/_{00}$				STRESS Kg/cm^2		
	LONGITUDINAL		CIRCUMFERENCIAL		$E = 1 \times 10^6$ Kg/cm^2; μ =.22		
	RANGE SWITCH	POTENTIOMETER	RANGE SWITCH	POTENTIOMETER	LONGITUDINAL	CIRCUMFERENCIAL	RADIAL
0	15	0.858	14	1.175	-	-	-
1	15	0.829	14	1.157	-684	-506	-506
2	15	0.789	14	1.125	-1177	-775	-730
3	15	0.767	14	1.098	-639	-199	-667
4	15	0.737	14	1.079	-377	167	-551
5	15	0.709	14	1.075	-174	287	-404
6	15	0.689	14	1.079	12	436	-208
7	15	0.671	14	1.089	53	416	-184
8	15	0.657	14	1.107	138	376	-109
9	15	0.658	14	1.125	248	245	- 58
10	15	0.670	14	1.155	260	270	- 22
11	-	-	-	-	210	72	0

SPECIMEN No.4

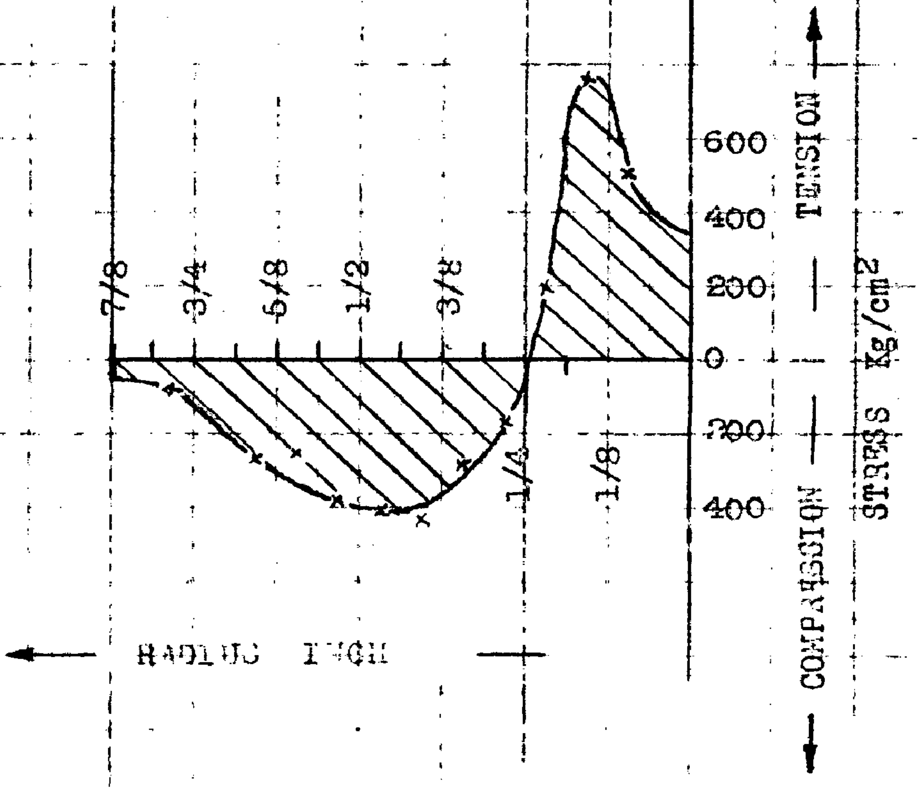


LONGITUDINAL STRESS
Vs.
CROSS-SECTIONAL AREA

SPECIMEN No. 4



CAST IRON SPECIMEN



TANGENTIAL STRESS

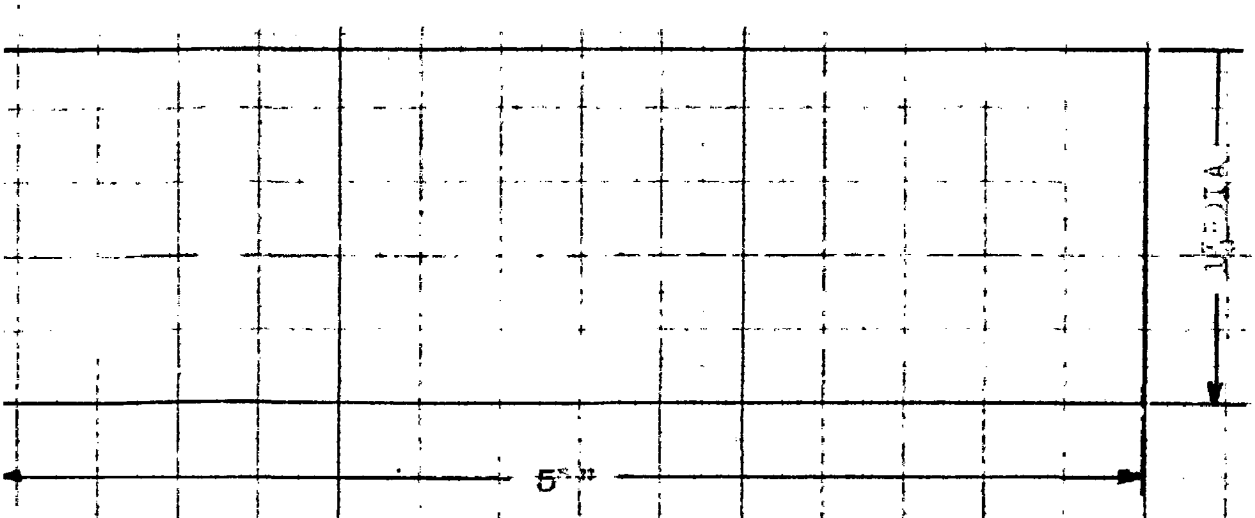
V.

RADIUS

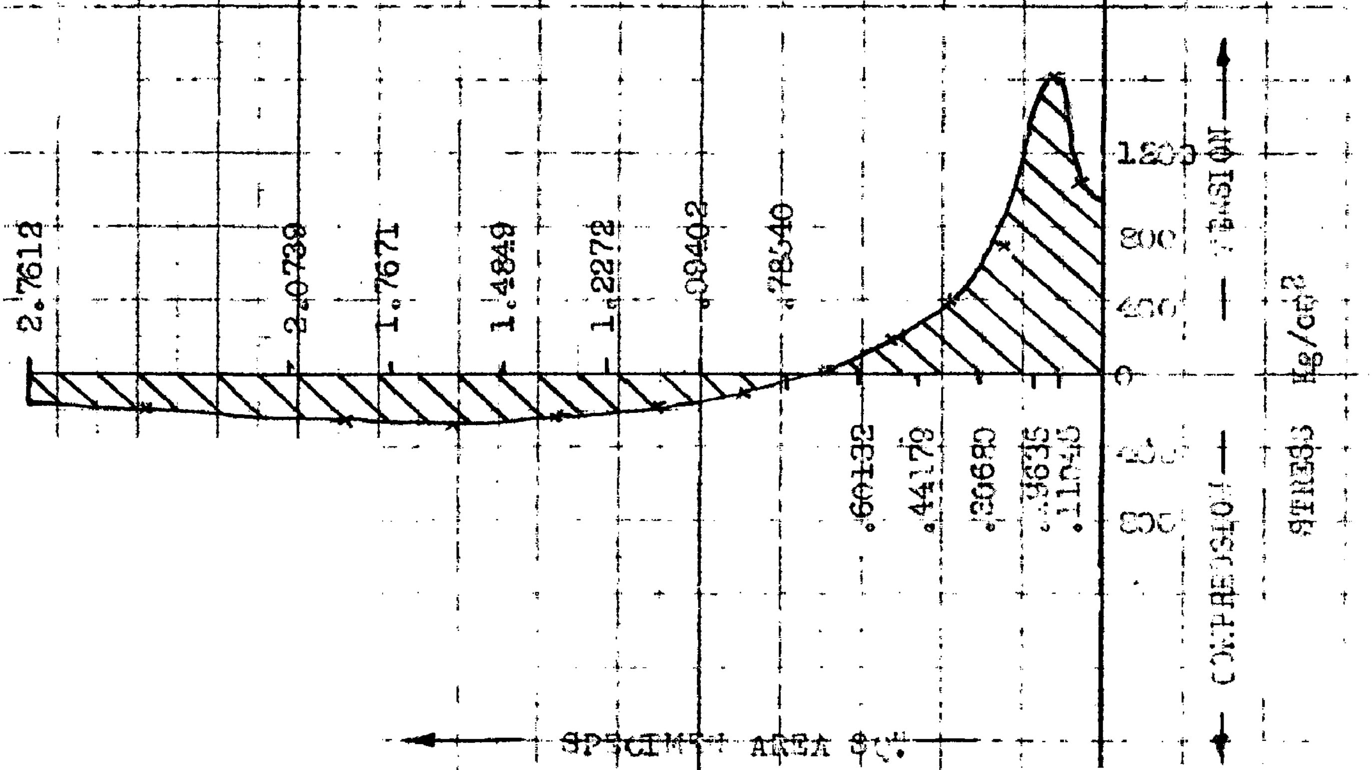
SPECIMEN No.4

S.No.	STRAIN GAGE READING $^0/_{00}$				STRESS Kg/cm^2		
	LONGITUDINAL		CIRCUMFERENCIAL		E = 1x10^6 Kg/cm^2; μ =.22		
	RANGE SWITCH	POTENTIOMETER	RANGE SWITCH	POTENTIOMETER	LONGITUDINAL	CIRCUMFERENCIAL	RADIAL
0	14	1.405	16	1.134	-	-	-
1	14	1.365	16	1.115	-1060	-557	-657
2	14	1.317	16	1.086	-1616	-818	-750
3	14	1.287	16	1.064	-681	-226	-782
4	14	1.261	16	1.048	-379	-135	-616
5	14	1.241	16	1.047	-191	354	-442
6	14	1.225	16	1.041	-3	339	-333
7	14	1.213	16	1.047	110	398	-230
8	14	1.205	16	1.057	173	389	-152
9	14	1.203	16	1.076	236	387	-88
10	14	1.211	16	1.100	265	337	-43
11	14	1.224	16	1.130	245	172	-15
12	-	-	-	-	182	52	0

SPECIMEN No.5

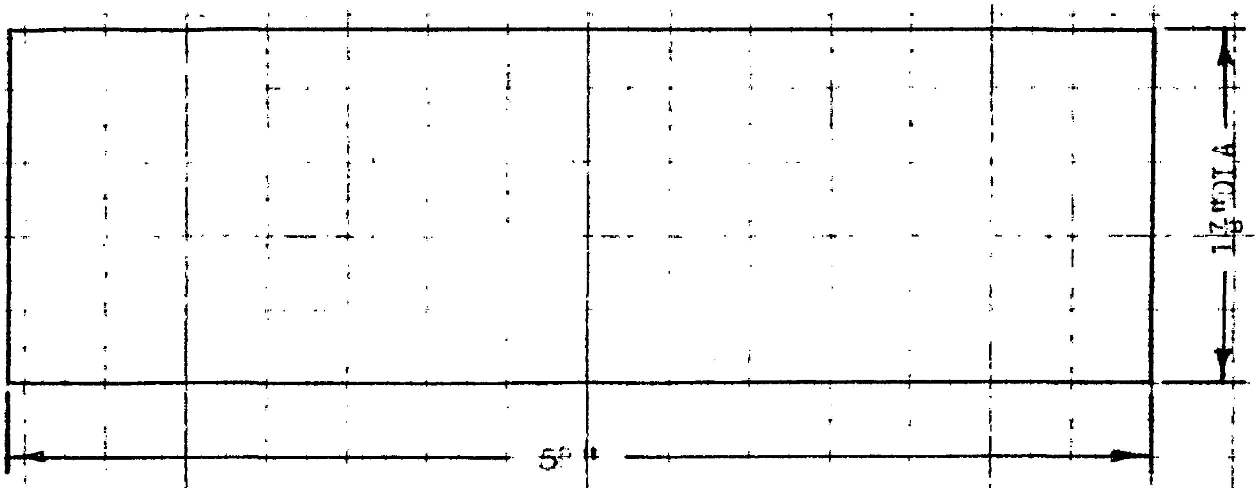


CAST IRON SPECIMEN

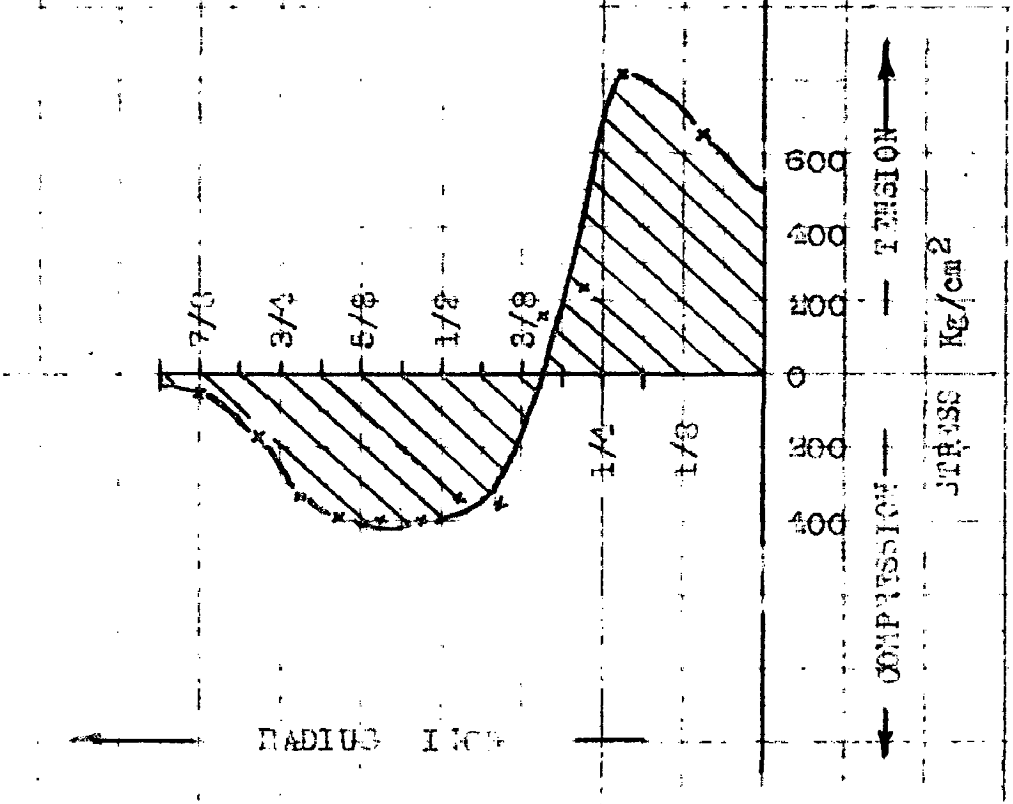


LONGITUDINAL STRESS
Vs.
CROSS-SECTIONAL AREA

SPECIMEN No.5



CAST IRON SPECIMEN



[illegible] vs.

RADIUS

SPECIMEN No.5

Sample calculations

For demonstrating the method of evaluating the residual stress relieved in any single removal a random observation say (3) of specimen No.1 for longitudinal strain may be picked up. In this case the following guiding steps will provide the general procedure.

The differential longitudinal strain liberated during the 2nd removal alone, $dL_3 = (16 + 1.535) - (16 + 1.575) = -.028$

The total longitudinal strain liberated after the first two removals are performed,

$L_2 = (16 + 1.650) - (16 + 1.575) = -.075$

The differential tangential strain liberated during the 3rd removal alone,

$dT_3 = (14 + 1.607) - (14 + 1.635) = -.028$

The total tangential strain liberated after the first two removals are performed,

$T_2 = (14 + 1.635) - (14 + 1.683) = -.048$

Now $P_2 = L_2 + \mu T_2 = -.075 + .22 \times (-.048) = -.08556$

& $dP_3 = dL_3 + \mu dT_3 = -.028 + .22 \times (-.028) = -.03416$

$(A_o - A_{b3}) = (1.7671 - .30680) = 1.4603$

$dA_{b3} = .11045$

These values may now be substituted in the following equation to obtain the longitudinal stress that existed in the third layer alone

$$f_{L3} = \frac{E}{1-\mu^2}\left[(A_o - A_{b3})\frac{dP_3}{dA_{b3}} - P_2\right]$$

$$= 1 \times 10^{6} \left[1.4603 \times \frac{(-.03416)}{.11045} - (-.08556) \right] \times 10^{-3}$$

$$= -393 \text{ Kg/cm}^{2}$$

The negative sign should not be understood for a compressive stress. Here this stands for a tensile stress because removals of tensile strain from the core of the cylindrical specimen will release an equivalent compressive strain from the case which is picked up by the strain gages.

Discussion of results

The shape of the curves drawn is strikingly similar for any one kind of stress distribution. The stress pattern can therefore be generalised for any particular manufacturing process. The stress distribution in 'the core' is tensile while that in 'the case' is compressive. The peak intensity of the former being higher in the present case. The results are checked to establish the conditions of stress equilibrium as given below.

The force equilibrium requires that

(a) the sum of longitudinal stresses over the cross-sectional area must be zero. This is checked by plotting longitudinal stress against bore area. The area under the tensile stress should then equal the area under compressive stress. The deviation for each specimen is as follows:

$$\frac{(\text{area under tensile stress curve} - \text{area under comp. stress curve})}{\frac{1}{2}(\text{area under tensile stress curve} + \text{area under comp. stress curve}} \times 100 = \%\ \text{deviation}$$

for specimen No.1, % deviation = 5.3

for specimen No.2, % deviation 9.1

for specimen No.3, % deviation = 6.5

for specimen No.4, % deviation [illegible].9

for specimen No.5, % deviation = 0.9

(b) The sum of the tangential stress over the diametrical section of the cylinder must be zero. This is checked by plotting tangential stress against bore radius. The area under tensile stress must then equal the area under the compressive stress. The deviation for each specimen is as follows.

$$\frac{(\text{area under tensile curve} - \text{area under comp. stress curve})}{\frac{1}{2}(\text{area under tensile curve} - \text{area under comp. stress curve})} \times 100 = \%\ \text{deviation}$$

for specimen No.1, % deviation = 15.2

for specimen No.2, % deviation = 16.0

for specimen No.3, % deviation = 12.2

for specimen No.4, % deviation 19.0

for specimen No.5, % deviation = 15.3

(c) The radial stress is zero at the surface and is equal to the tangential stress at the centre of the cylinder

The biggest single factor that might be held responsible for the deviations given above may be stresses induced due to the mechanical working of the material during metal removals. This may shift the zero stress line parallel to itself. Some error might also have been caused due to the temperature compentation not being ideal. Keeping in view these limitations the deviation in the results can be deemed to be well within the permissible limits.

CHAPTER 7

RESIDUAL STRESSES IN GUN-BARRELS AND SCOPE OF FURTHER WORK

A soldier's performance on the front line depends on the number of effective shots his gun is capable of firing accurately. The design of barrels has therefore, to be very exacting, which means that the significant stress induced in any part of barrel should be well below its significant strength. A larger factor of safety would overcome the difficulty but this will make the gun heavier. Lighter barrell can be produced employing favourable residual stresses which will provide the necessary factor of safety. This is achieved by including compressive residual stresses by shot peaning the exposed surface.

To provide a check, the residual stresses should be measured both in magnitude and sign. The method described in this treatise may be applied in principle i.e., removing thin layers of uniform thickness (to maintain the rotational symmetry of the barrel) from within (or outside) the barrel and observe the resulting strains appearing on the remaining stock. This may be achieved by pickling the surface layers in steps by means of some corrosive agent like 5 - 20% Nitric acid without disturbing the original residual stress pattern. Pickling is necessitated because gun barrels have too hard a surface to be machined by using conventional cutting tools.

Apart from this, residual stresses can also be measured in flats, slabs, and in-fact in any machine component by employing the above technique in principle. Residual stresses in gun barrels can also be found by x-ray defraction technique.

Irrespective of the method used for measuring these abstract stresses, the designer of tomorrow may be able to think of better designs if he learns to harness the vital effects of residual stresses to his requirements, and in so doing he will contribute to the ceaseless effort of mäking machine design a more exacting science.

BIBLIOGRAPHY

1. Experimental Stress Analysis, Vol. XV, No.2 December, 1957, pp. 53-56.
2. Hand-book of Experimental Stress Analysis M. HETE N,Y, 1, pp. 460-468.
3. Residual Stress Measurements, A.S.M. Oct. 1951.
4. Residual Stresses in Metals and Metal Construction by OsGood 1954.
5. An Introduction to Experimental Stress Analysis by George Hamor Lee, 1956.
6. Experimental Stress Analysis, Vol. 2 No. 1, 1944 pp. 147.
7. Symposium on Internal Stresses in Metals and Alloys 'The Institute of Metals London, 1948, Evaluation of Residual Stresses by K. Heindlhofer.
8. Prevention of the failure of Metals under repeated Stress by Battelle.
9. Principles of Experimental Stress Analysis by Mark B. Moore, pp. 38-52, 62-68 and 84-91.
10. S.E.S.A. Manual on Experimental Stress Analysis.
11. Lectures and Laboratory Exercises on Strain Gage Techniques.
12. "Laboratory Manual of Applied Instrumentation" by Suresh Chandra & A.B.L. Agarwal.