THE EFFECT OF AGEING AND HEAT TREATMENT ON SOME PROPERTIES OF COLD DRAWN STEEL.

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INTRODUCTION.

The cold drawing of metals is one of these ancient arts which is gradually being converted into an exact science based on firm theoretical and experimental grounds. This process is naturally slow and we are compelled to admit that there have been no epoch marking improvements on the original idea of the tapered die conceived at least 600 years ago. However, one must remember that as the process is, in essence, of fundamental simplicity, it is doubtful if it could be improved upon. The principle achievements of modern times have been the discovery of the "patenting" process and our ability to cold draw successfully, material of irregular cross-section.

There has been a distinct tendency in recent years to employ bright drawn bars - sometimes called "free cutting" when the phosphorus is high - in place of the black bars formerly procured directly from the rolling mills. The advantages of such material, drawn accurately to size and free from scale, in mass production engineering, are obvious and need not be enlarged upon here. In other commodities where a high tensile strength, accompanied by accurate finished dimensions, is essential, cold drawing, cold rolling or a combination of both often offers the most economical solution of the problem.

That there is a "mass" effect in cold drawing was first recorded by Goerens (1) who noted, although it had no doubt been appreciated by many generations of wire drawers, that the larger the cross-sectional area of a bar, the less it could be reduced in area by drawing at a single pass. Consequently it would seem that the test data accumulated on wire of small diameter cannot be directly applied to problems related to the cold drawing of wire of relatively large cross-sectional area — such material for instance as is being used so largely in automatic lathes at the present day.

It has long been recognised that internal stresses are set up in the rod by the cold drawing operation and that, while they appear to have no detrimental influence on the life of ordinary wire, "season" cracking in condenser tubes is, by many competent authorities, directly attributed to their presence. In view of the fact that such large quantities of cold drawn round steel bars are used in engineering to-day, it seems opportune that a research be conducted to investigate whether these stresses are, in practice, detrimental, and to study, in general, the effect of cold drawing on material larger in diameter than ordinary wire.

The steel investigated in the experiments to be described conformed to W3 Air Ministry Specification. Annealed steel to this specification was received from the drawers in the form of round bars about 12 feet long and ranging in diameter from approximately 15/32 inch to 5/8 inch. There were six sizes which differed by roughly 1/32 inch successively. The steel gave on analysis:-

C. 0·49%
Mn. 0·200%
Si. 0·080%
S. 0·028%
P. 0·018%

These bars after suitable treatment were cold drawn at a single pass to about 0·45 inch diameter.

The properties of this cold drawn steel when tested in tension and compression, its hardness, density, and resistance to shock on ageing up to six months after drawing have been determined. The effect of normalising at different temperatures up to 900°C on the Izod value and hardness has also been studied but as there was insufficient material the effect of the same heat treatment up to a normalising temperature of 800°C on the tensile and compressive properties has only been investigated in the case of the four lowest reductions of area in drawing. The variation in the internal stresses set up in the drawing operation with normalising temperature for the same four reductions of area in drawing, has also been determined. A microscopic examination of all heat treated specimens has been made.

Preparation of the Material for Drawing.

To ensure the initial condition of the material being as uniform as possible throughout all the tests, it was decided to re-anneal the bars under laboratory conditions. As it is essential to have no trace of scale on the bars before cold drawing, they were, therefore, "pot" annealed in a cast iron pipe 4 inch. internal diameter filled with cast iron borings to exclude or absorb any oxidising furnace gases. The end was stopped up with a clay plug, perforated to allow the escape of any enclosed gas. The annealing was performed in a semi muffle gas fired furnace which was maintained at 830 $\pm$ 10 $^{\circ}$C for $1\frac{1}{4}$ hours. The uniformity obtained by this anneal is evidenced by the consistency of the ultimate strength between members of the same series as shown in Table 2.

To assist the lubrication of the die during drawing, on the advice of Dr. Brown, it was decided to deposit a thin coat of metallic copper on the bars. In order to obtain an adherent deposit, the bars were, first of all, pickled in a 5% solution of hydrochloric acid for a few minutes and then immersed in a bath containing approximately 5% hydrochloric acid and 10% Copper Sulphate. In a few minutes a fairly adherent film was deposited and the bars were then washed in running cold water to remove excess acid and copper sulphate. To ensure further removal of acid the bars were "limed" and, lastly, placed in the furnace and allowed to cool with it from 200°C. This last operation is with a threefold object. Firstly, to drive off any acid which by some unforeseen circumstances has not been neutralised; secondly, to dry rapidly and so prevent rusting with its consequent pitting; and thirdly, which is of paramount importance, to expel any occluded hydrogen which causes a decided brittleness in the steel.(2)

All bars in each series of tests were annealed and subsequently treated together as far as possible and so it is throught that a fairly uniform starting point had been obtained.

Cold Drawing of Bars.

The drawing of the bars was performed on a Ten Ton Buckton testing machine fitted with an autographic recorder. This machine was belt driven from a line of shafting which was run at full speed during all the drawing operations. Naturally it was desirable to have this speed as nearly constant as possible throughout the whole series of experiments, but since the drawing operations have extended over two and a half years, this was scarcely attainable. However, the variation in the speed of traction actually obtained (vide Table 1) is reckoned to constitute no serious lack of uniformity. All other things being equal, the heat generated in drawing, or perhaps, more strictly, the temperature attained by the drawn rod, is probably directly proportioned to the speed of drawing. This heat has a low temperature annealing action in the material, similar in effects to aging. With the comparatively low drawing speeds necessarily employed in these experiments, this effect must have been negligible as the temperature of the bar is estimated to have never exceeded 40°C. and this maintained for a few minutes only. The "modus operandi" was to fix the die in the lower crosshead of the machine and grip the pointed end of the bar with wedge grips in the upper one. The die was now drawn down over the rod and the time to draw a 12 inch length observed on a stop-watch (for speed see Table 1). A load strain diagram was taken of the drawing operation, the load being noted at intervals and jotted down on the diagram. The mean pull for each bar was calculated from these readings. The mean of each series is given on Table 1.

The method of lubricating the die was to coat the bars with a film of ordinary white bar soap hardened by age. This procedure gives uniform lubrication conditions and approaches commercial practice. The bars were hand straightened immediately after drawing, being still in a somewhat plastic state, but probably more uniform conditions would have been obtained had a reeling machine been employed. However, as all the bars required, approximately, the same amount of straightening and were similarly treated, it is thought that the uniform conditions aimed at had been maintained.

It was observed, that, after drawing, the rod was always bent in the same direction relative to the die and this eliminates the possibility of the bending being due to falty alignement of the crossheads and shows it to be dependent on the die itself. Perhaps tilting the die suitably would remedy this bending, but the difficulty in effecting this has prevented it being tried.

The maximum length of rod possible to obtain drawn with this machine is about 21 inches.

Heat Treatment of Rods.

This was performed in an electric resistance furnace specially wound with Ni-Cr. wire, to ensure the centre portion being as uniformly heated as possible.

The normalising at 100°C. was, however, performed by immersing the specimens in boiling water. After soaking for 30 minutes at the selected temperature, the specimens were extracted and air cooled. The term "normalising" is applied advisedly to this process, but strictly speaking this term should only be used when the soaking temperature is above the upper critical point which is only attained above about 800°C. Low temperature annealing (L.T.A) or"blueing" is usually applied to this process with temperatures up to 500-600°C. and so, in order to avoid confusion of nomenclature all the graphs have been plotted to a base of "Normalising Temperature".

In the case of the Izod test pieces, however, the heating was done in a vacuum furnace, kindly loaned by Prof. Andrew of the Royal Technical College, Glasgow, in order to ensure the minimum of oxidation, as the specimens had to be formed by notching only and had been drawn to size - 0·45 inch. diameter.

Manner of Testing.

All diameters were measured with a micrometer guage, fitted with a tensioning spring and reading to 0·001 inch and to 0·0001 by estimation. Neck diameters in the tensile tests were measured with a point micrometer giving the same accuracy but were only determined to 0.001 inches, since this was reckoned to be the accuracy with which the mean diameter could be determined owing to the fracture being generally slightly ragged.

All tensile tests were carried out on a Ten Ton Buckton testing machine and were performed on the unmachined bar except in the case of the heat treated specimens which were generally polished with emery paper to remove the superficial layer of oxide, but as the diameter was never reduced by more than 0·002 inch. in this process, the specimens can be reckoned as substantially unmachined.

There are three criteria for the Elastic Limit of a material. It may be regarded as:-

1. The highest stress to which the material may be subjected in order that the loading and unloading stress - strain curves may still coincide.
2. The highest stress to which it may be subjected so that on unloading there is no permanent set.
3. The stress at which Hooke's Law ceases to hold - B. E. S. A. definition.

The stress represented by (1) is usually very low as most materials exhibit slight elastic hysteresis even under very low loads, and consequently it is probably dependent on the rate of unloading. The stress given by (2) is usually the highest, but is largely influenced by the rate of unloading, and by the elastic "after working" property of the material.

The most convenient stress to take as the Elastic Limit is that represented by (3), the value of which generally lies between (1) and (2). In these experiments, it is this value which has been determined and to avoid ambiguity of nomenclature, it is always referred to as "Limit of Proportionality".

The Limit of Proportionality was obtained by a Ewing extensometer reading to 1/12,500 inch and to 1/125,000 inch by estimation. The guage length in the tensile tests was 4 inches and in the compression tests 2 inches. The minimum load at which observations were taken was 400 lbs.

The method of determining the actual value of the limit of proportionality was to plot the load-strain curve to a large scale and then determine Young's Modulus. Knowing this and assuming Hooke's Law to hold, the theoretical strain at each load at which an extensometer reading was taken was calculated. The differences between the observed and calculated values at each load were now plotted and the load at the point of divergence from the mean, taken as the load corresponding to the limit of proportionality.

The Proof stress is generally taken as that stress which produces 0·5% permanent set. However, in cold worked material this extension is too great as it may indicate a stress in excess of the ultimate strength. To avoid this the Air Ministry recommend the proof stress of cold rolled strip to be reckoned as that stress producing 0·1% permanent set but in these experiments the permanent set was limited to 0·05%. This value was finally decided upon as in the compression tests with higher values, buckling of the specimen would perhaps occur before the proof stress could be attained. The tests appear to have been fairly successful but the values of the proof stress obtained in compression are, in most cases, lower than those obtained in tension.

Young's Modulus was calculated from the large scale load-strain diagram used in the determination of the limit of proportionality and was subsequently checked when the differences between the observed and calculated strains were plotted.

The Izod tests were performed on the full drawn diameter after milling the standard Air Ministry Specification notch. Three tests were generally performed and the average taken.

The percentage elongation was reckoned on a guage length of $4\sqrt{\text{Area of Section}}$. Four sets of guage lines were scribed, each slightly staggered and a small punch mark made on each of the lines. All measurements were made to 0·01 inch. as this was considered the accuracy with which the broken ends could be, generally, butted together and the total extension measured.

The Brinell hardness were determined using a 5 m.m. diameter ball under a 750 Kg. load, which was maintained for 15 seconds. These tests were performed on the 10 - Ton Buckton testing machine. The shape of the impression was generally slightly oval and, therefore, the spherical area was calculated from the mean of the two diameters mutually at right angles. Preliminary experiments showed that only one test need be made, but to obtain consistent readings it was found necessary to polish the surface with No. 0000 emery paper.

Some difficulty was experienced in the performance of the compression tests. In this test accurate parallelism of the compression plates is essential to ensure axial and uniform loading of the test piece.

In this instance any error would be greatly intensified by the necessity of using a comparatively slender specimen. After a review of cognate literature on this subject, the N.P.L. type of apparatus (3.) was decided upon, and manufactured to suit the present requirements. A drawing of this jig is shown in Fig.(2). The specimen used in these tests was $3\frac{1}{4}$ inches long and about 0·40 inch in diameter. In practice, this apparatus proved quite successful, but despite every precaution taken in the machining of the test pieces, the test results are not quite so regular as those obtained in the tensile tests.

The distribution of the internal stresses in the cold drawn rods was mapped out by Heyn's method. (4.) Four sets of guage points equally spaced round the circumference of the bar on a 4 inch guage length were employed. The minimum diameter to which the specimen could be machined was about 0·18 inch as below this value bending of the bar in the lathe occurred. The actual amount turned off at a time was such that a reasonable extension of the bar resulted.

RESULTS OF TESTS.

GENERAL

Table 1 gives mean values of the diameters of the different groups of bars used in the experiments before and after drawing, percentage reduction of area in drawing, load required to pull the bar through the die, nominal stress on reduced area of the bar and the work done per cubic inch of material.

Figure 3 shows typical autographic records of the cold drawing operation for each reduction of area in drawing. The vertical portions of the diagrams at either end have no definite significance. The slope at the beginning is probably dependent on some complex function of the shape of the point of the bar, the taper of the die and the reduction of area in drawing, while that at the end appears to be governed to some extent by the length of the parallel portion of the die. It will be observed from Figure 3 that in most cases the load at the commencement of the cold drawing operation is slightly greater than at any other position. This static effect might be accounted for by the material piling itself up slightly in the tapered portion of the die at the beginning of the operation.

Figure 4 shows that within the scope of the present experiments the relationship between the gross work per cubic inch of material and the reduction of area in drawing is linear. It will also be observed from the same diagram that the mean pull required to draw the bar through the die also conforms to a straight line law when plotted to a base of reduction of area in drawing. In these experiments no attempt has been made to separate the frictional work from that necessary to deform the bar. No mathematical analysis has so far been devised whereby the theoretical work can be calculated although the potential energy of cold worked steel can be determined from its electro-potential (5) and thermo-chemical properties. Further complications arise in these experiments since we are not dealing with a single phase system but one which consists of at least two components - ferrite and cementite. However, an attempt was made to determine the E. M. F. of a galvanic cell, the two electrodes of which consisted of a cold drawn and an annealed specimen. The electrolyte was a dilute solution of ferric chloride - about N/100 - but the tests were unsuccessful as parasitic currents caused by local action at the electrodes masked any difference in the electro-potential of the two specimens. The variations due to the annealed electrode could, no doubt, be eliminated by the substitution of a calomel electrode but this has not been tried.

Figure 5 shows the Maximum Stress one hour after drawing and Nominal Stress on Reduced Area plotted to a base of Reduction of Area in Drawing. Neglecting any secondary stress effects, the maximum reduction of area in drawing is attained at the point corresponding to the intersection of the above graphs. Only a slight convergence of the graphs is observed and yet some difficulty was experienced in drawing the members of series U. In several instances the bar fractured with a perfect cup and cone at the tapered portion of the rod when an attempt was made to draw it. This failure was probably due to the orientation of the lamellar pearlite at this particular point being unfavourable to the drawing operation and since Figure 5 takes no cognisance of the internal structure of the steel, naturally these failures cannot be predicted. It will be evident that any portion of the bar in which the alternate lamellae of cementite and ferrite are perpendicular to the direction of drawing, cannot withstand such drastic reductions of area in drawing as other parts where the pearlite is parallel to the axis of the bar. The former disposition of the hard cementite results in small local areas in the bar which greatly resist the radial pressure of the die and so cause excessive flow of the neighbouring ferrite with its consequent rupture. In the case of mild steel, a distinct convergence has been observed (6) but this is undoubtedly due to the excess soft and plastic ferrite.

TESTS ON ANNEALED MATERIAL.

Tables 2 - 5 give the results of tests performed on annealed test pieces selected from each of the six groups of bars. The three figures given represent the maximum, mean and minimum values and are tabulated from either three or four independent tests.

The results of the tensile tests given in Table 2 call for no particular comment except that the ductility figures for series U are rather low. The elastic tests in compression of Table 3 reveal a slightly higher limit of proportionality and stretch modulus than observed in tension. From Table 4 it will be observed that the Izod impact figure for series U is low. This test was repeated and the same result again obtained. A chemical analysis of of this group of bars revealed no abnormalities but a microscopic examination of a specimen etched in sodium picrate showed slight traces of cementite round the grain boundaries which might account for the poor impact value. The results of tests performed on heat treated members of this series revealed no particular irregularities showing that the defect was not permanent. The Brinell Hardness Number (H. 5/750) given in Table 5 prove series **U** to be the hardest.

TESTS ON AGED BARS.

Table 6 gives the results of tensile tests performed on cold drawn rods which had been aged for different periods up to six months after drawing. Table 7 gives the corresponding set of results when the material is tested in compression. Figures 10-15 show the tensile results graphically and Figures 16-18 depict the corresponding results in compression.

The hysteresis loops obtained with series W are shown in Figure 6 for the tensile tests and shown in Figure 7 for the compression tests. Figures 8 and 9 show selections from Figures 6 and 7 respectively plotted in such a way that the abscissae represent the excess of the observed over the calculated extensions as described in the method for obtaining the limit of proportionality. To each set of curves the corresponding hysteresis loop of an annealed bar is added for the sake of comparison. It will be observed that on ageing the cold drawn bar regains its elasticity, the recovery being mostly due to the straightening of the loading line. At the end of six months the hysteresis loops obtained in tension and compression are very similar to corresponding ones obtained with the annealed material.

Figure 10 shows that the Ultimate Strength generally increases with reduction of area in drawing. The bars of series U were stronger than those of series V immediately after drawing but the tensile strength of the former increased so little on ageing that when tested 28 days after drawing it proved to be inferior to that of series V which in the interval had gained about 2 tons per square.inch. The Ultimate Strength increases on ageing up to about one month after drawing but after this interval the gain is extremely small and may be reckoned to lie within the normal fluctuation of the material. The average gain was about two tons per square inch which was most noticable in the intermediate reductions of area in drawing.

It is interesting to note that this gain on ageing is not so large as that observed by Dr. Brown,[(6)] but this is attributed to the increased carbon content of the steel investigated which consequently decreased the total free ferrite - the principle ageing component. One might also predict that a steel having a carbon content in excess of the eutectoid composition would show very little ageing effect and that steels containing the same percentage of carbon and varying percentages of the deoxydiser manganese (or any other element which decreases the percentage of carbon at the eutectoid composition, e.g. Nickel) will show an ageing effect proportional to the manganese content because the amount of free ferrite will be decreased pro rata.

Figure 11 shows that the tensile limit of proportionality rises rapidly at first on ageing, but after about a month's rest there is only a relatively slight gain. The same phenomenon is observed in Figure 16 which shows the corresponding results for the compression tests plotted. In this series, however, a rather curious fall in the limit of proportionality is observed on testing after ageing for seven days. The tensile limits of proportionality are generally higher than the corresponding figures in compression which are no doubt low owing to faults in the method of determination.

The values obtained for Young's Modulus on ageing are shown for the tensile tests in Figure 12 and for the compressive tests in Figure 17. In both instances the value obtained shortly after drawing is low but seven days generally suffice for its recovery to a steady value. There appears to be no definite variation in the stretch modulus with the reduction of area in drawing but cold drawing certainly appears to lower it slightly. The value obtained in compression is generally greater than the corresponding one observed in tension.

Figure 13 gives the percentage reductions of area at fracture obtained in the tensile tests plotted to a base of "Interval between Drawing and Testing." The corresponding percentage elongations are plotted in Figure 14. In Table 6 the elongations corresponding to the bar of series Z aged one hour and the bar of series X aged 27 days are omitted since the fracture was close up to the wedge grips of the testing machine. It will be observed that the corresponding percentage reductions of area are high. In general, the ductility is decreased by ageing and with reduction of area in drawing. The general elongation is mostly affected.

The hysteresis is very great immediately after drawing as can be readily appreciated from Figure 15 which represents the effect of ageing on this property in the tensile tests and from Figure 18 which shows the corresponding variations in the compression tests. Figures 15 and 18 are not, however, strictly comparable. In the tensile tests the test piece was loaded up to the mean limit of proportionality of the annealed material corresponding to the group of bars from which the cold drawn rod was derived. When annealed bars secected from the different groups of rods are stressed up to the mean limit of proportionality of the corresponding group, the values of the hysteresis so obtained do not differ widely but when the cold drawn rods, on the other hand, are stressed up to the corresponding group limit of proportionality of the annealed material the hysteresis is found to be directly proportional to the total load on the specimen. For instance, Series W gave the highest limit of proportionality in the annealed state but when the cold drawn test pieces of this series were subjected to this stress they gave exceptionally high values for the hysteresis as will be seen in Figure 15. In the compressive tests, on the other hand, in order to investigate the effect of reduction of area in drawing on the hysteresis, all the cold drawn test pieces were loaded up to the same stress, namely the average compressive limit of proportionality of the annealed material. As will be seen from Figure 18 the severity of the pass appears to have no definite effect on the hysteresis. Although no strict comparison can be made between the two sets of results it is evident that the hysteresis obtained in the compression tests is greater than that observed in tension and again this may perhaps be due to the necessity for employing comparatively slender specimens in the former tests.

Table 8 gives the effect of ageing on the Izod value of cold drawn steel and Figure 19 shows quite distinctly that the impact value of cold drawn steel falls on ageing. It will also be observed that series W and V give the highest values. This critical reduction of area which gives the best impact values has previously been observed to occur at about the same reductions of area in drawing. In series U rather a peculiar fracture was observed. It took the form of a vee-groove extending for about an eighth of an inch down into the portion held in the vice and was consistently obtained. In some instances in series V there appeared to be a tendency to adopt this type of fracture but it was never particularly well developed.

Table 9 gives the effect of ageing on the Brinell Hardness of cold drawn steel. These results are plotted in Figure 20 which show clearly the hardening which occurs on ageing. The hardness also increases pro rata with the reduction of area in drawing.

The Effect of Heat Treatment.

The stress-strain diagrams of bars belonging to series X when tested in tension after normalising at different temperatures are shown in Figure 21. A corresponding set for the same series when tested in compression is shown in Figure 22. In general, there is a slight straightening of the loading line on heat treatment up to a normalising temperature of 400°C but this is not very apparent from these curves as the scale is too small. The occurence of the yield point after normalising at 600°C and above is caused by recrystallisation of the ferrite somewhere between 500°C and 600°C. It will be observed that normalising at 700°C gives the lowest yield point and that the material yields more sharply in tension than in compression.

Table 10 gives the effect of heat treatment on the tensile properties of cold drawn rods belonging to series Z, Y, X, and W. Table 11 gives the corresponding compressive properties. The results of Table 10 are seen plotted in Figures 23-28 and those of Table 11 appear in Figures 30-32.

Figure 23 shows that the Ultimate Strength increases on heat treatment up to a normalising temperature of 300°C or 400°C. The nett gain is usually about two tons per square inch which gives a total gain of about four tons per square inch.on ageing and heat treatment equivalent to a total increase of 7-10%. Normalising at 500°C decreases the strength slightly but above this temperature the fall is rapid up to 700°C. Since 800°C is above the upper critical point of the steel, normalising at this temperature caused a recrystallisation and refinement of the structure resulting in a marked gain in the tensile strength. The remarkably low value obtained after normalising at 700°C is due to the partial globularisation of the cementite at this temperature. It is usually accepted (7) that cold work accelerates the formation of granular pearlite and this fact is taken advantage of by the wire drawer to facilitate the drawing of refractory wire in which after a light pass the cementite is readily globularised by suitable heat treatment and the wire made amenable to further reductions.

As a matter of curiosity it was decided to check these observations with this material. With this end in view, an annealed rod of series Y was soaked for 30 minutes at 700°C and air cooled. On testing the maximum stress was found to be 31·0 tons per square inch which is lower than that obtained for any of the cold drawn test pieces after a similar heat treatment. This proves that cold drawing is not always conducive to ready globularisation of the cementite. The reason for this is not far to seek. It is well known that the effects of cold work are removed in iron and steel by annealing between 500°C and 600°C. The actual temperature of the recrystallisation of the ferrite depends on the chemical composition, the rate of heating and the amount of plastic deformation suffered by the steel. (8)

Hence, test results obtained after normalising at 600°C and 700°C will depend on the behaviour of the steel during the recrystallisation process. If marked growth of the ferrite grains occurs there will be a corresponding tendency for the pearlitic areas to coalesce and so the globularisation of the cementite will be aided. In this steel, however, no growth of the ferrite occurs but actually a refinement of the grains is observed. The nett result is, therefore, that the crystalline structure of the cold drawn steel normalised at 600°C and 700°C shows no marked difference, except for the elongated pearlite, from that of the annealed state, and, consequently, the formation of granular pearlite in each condition will follow the same physical laws.

The proof stress generally exhibits a maximum value after normalising at 400°C. That this holds good for both tensile and compressive tests can be seen from Figures 24 and 29 respectively. On normalising at 600°C and above a yield point appears which is usually very sharply defined and the proof stress corresponding to 0·05% permanent set was generally observed to coincide with it. The tensile was usually greater than the compressive proof stress and both increased with reduction of area in drawing.

The limit of proportionality shows a

a tendency to rise in sympathy with the proof stress on heat treatment but owing to the fairly delicate method of its determination, accidental variations often masked such effects. If a less accurate method of plotting the load-strain curves had been adopted perfect unison of the limit of proportionality and proof stress would have been observed and probably the former would also appear to rise with the severity of the pass. As it is, no marked variation in the limit of proportionality with reduction of area in drawing is observed. The tensile limits of proportionality are plotted in Figure 25 and those in compression appear in Figure 30.

Figure 26 shows the effect of heat treatment on the reduction of area at the fracture in tensile test. There is a slight fall in the reduction of area up to a normalising temperature of 400°C. Normalising at 500°C. causes a slight gain but above this the rise is rapid to 700°C. Normalising at 800°C. causes a sharp drop due to refinement of structure. Figure 27 shows that, on the other hand, the percentage elongation shows a tendency to rise slowly with normalising temperature up to 400°C and then more rapidly up to 700°C. or 800°C. This is most apparent in series Z, X, and W. The slight rise in the elongation up to a normalising temperature of 400°C. is probably caused by an increase in the general elongation of the test piece.

Figure 28 shows the variations in Young's Modulus in the tensile tests and Figure 31 shows the corresponding variations observed in the compression tests. Both in tension and compression there is a slight gain roughly proportional to the rise in normalising temperature. The value in compression is generally higher than the corresponding figure in tension.

In order to determine the hysteresis in both tension and compression all test pieces were loaded to a stress of 11·3 tons per square inch - the mean tensile limit of proportionality of the annealed material. As in only three instances any permanent set was observed in the tensile tests no curves have been plotted for this series of experiments. For the compression tests, however, the results are shown in Figure 32. It will be seen that the hysteresis falls to a minimum at about 400°C. normalising temperature and then rises.

Table 12 gives the effect of heat treatment on the Izod value for series Z, Y, X, W, V, and U. Figure 33 shows that there is a distinct fall in the Izod value on normalising at temperatures up to 400°C. The minimum value lies somewhere between 200°C. and 500°C. but its precise location has not been determined owing to insufficient data. Likewise any displacement of the minimum due to the severity of the reduction of area in drawing cannot be judged. Figure 34 shows that while after normalising at 100°C. series Y, X, and W, appear to give the best Izod figures, normalising at 200, 300, and 400°C. brings all the bars to approximately the same state of brittleness. The maximum observed Izod value occurs in series Z and Y when the normalising temperature is 800°C. while all the others gave a maximum at 700°C. Whether this is a function of reduction of area in drawing cannot be definitely decided at present but it appears likely. It will be observed that the Izod value of bar of series Z normalised at 700°C. is abnormally low. This test has been repeated and gave the same result, and so we may take it, that this is in some manner due to the low reduction of area in drawing. Normalising at 800°C and 900°C generally caused a lowering of the impact value due to refinement of structure causing a more uniform distribution of the carbon. The vee-groove type of fracture observed in the ageing experiments appeared in series V on heat treatment but disappeared on normalising at 400°C. and above, and in series U this same type of fracture disappeared on normalising at 600°C and above.

Table 13 gives the effect of heat treatment on the Brinell Hardness for series Z, Y, X, W, V, and U. Figures 35 and 36 show that there is at first a distinct hardening of the cold drawn material on heat treatment followed by a rapid fall. After passing through the upper critical point however, there is an increase in hardness. An initial temperature effect (9) probably causes the specimens normalised at 900°C to be harder than those heat treated at 800°C. The Brinell Hardness is remarkably constant in all bars after normalising at 900°C, as is seen in Figure 36. The maximum hardness occurs after normalising at 400°C and the minimum is generally observed after normalising at 700°C.

The Effect of Heat Treatment on the Distribution and Magnitude of the Internal Stresses.

With reference to the nomenclature adopted, Z O represents a bar of series Z aged at ordinary atmospheric temperature for at least three months before testing; Z1, Z2, etc. are bars of series Z normalised at 100°C, 200°C, etc.

The "Internal Stress" is the mean stress in a concentric ring of the unmachined cold drawn bar whose inside diameter appears opposite the tabulated stress and whose outside diameter is the one immediately preceding. The corresponding "Skin Stress" is the mean stress which existed in the same annulus just prior to its removal ~~to its removal~~ by machining.

The internal stresses are shown as ordinates plotted to a base of areas corresponding to the diameters at which the stresses are determined, so that, for equilibrium, the total positive area should be equal to the total negative area. Only one half of the bar is shown in the graphical representation of the internal and skin stresses as the distribution is symmetrical.

Tables 14-22 give the internal and skin stresses existing in bars ZO-8. Figures 37 and 38 show the internal stress results plotted from which it will be seen that no marked reduction in the internal stresses occurs until normalising at 600°C. Normalising at 600°C, 700°C and 800°C, causes practically complete release of stress. The slight changes in the length of the bars caused by the apparent release of these stresses might in general lie within the errors of observation. It will also be observed that the maximum internal tensile stress only exists at the surface of the bar after normalising at 300°C. The skin stresses for bars ZO-5 are shown in Figure 42.

Tables 23-28 give the stresses existing in bars YO-5. The internal stresses are plotted in Figure 39 and the skin stresses in Figure 43. It is observed that the maximum internal tensile stress occurs at the surface of the bar after normalising at 300°C and above. There is a slight reduction of internal stresses after normalising at 300°C and 400°C. Normalising at 500°C, however, produces a decided release of internal stresses. Heat treatment has precisely the same effect on the skin stresses as it has on the internal stresses.

In Tables 29-34 are given the stresses in bars XO-5. The internal stresses are shown graphically in Figure 40 and the skin stresses in Figure 44. The results are very similar to those obtained with series Y except that there appears to be a more uniform reduction in the stresses with increase of normalising temperature.

Tables 35-43 give internal and skin stresses for bars WO-8. The internal stresses for bars WO-5 are plotted in Figure 41 and the corresponding skin stresses are seen in Figure 45. The stresses in bars W6, 7 and 8 are not plotted as they are relatively stress free. The results call for no particular comment and are similar to those obtained in series Y and X.

Figure 46 summarises the results by showing the maximum internal tensile stresses for each series plotted to a base normalising temperature. It is generally found that normalising at temperatures up to 300°C causes no appreciable reduction in the internal stresses. Normalising at 400°C sometimes induces a slight reduction but normalising at 500°C usually causes a decided fall. Normalising at 600°C 700°C, and 800°C in the case of series Z and W caused complete release of stresses which presumably would also occur with the intermediate reductions of area in drawing. On testing the aged bars or those normalised at 100°C and 200°C the maximum internal tensile stress was never observed at the surface of the bars. This may be due to a skin effect of the drawing operation or possibly to the straightening of the bar after cold drawing causing a readjustment of the stresses. Normalising at 300°C has the curious effect of shifting the maximum internal tensile stress to the surface of the bar. This would appear to show that heat treatment at this temperature caused complete elastic recovery of the surface layers and so enabled the stresses to vary uniformly across the bar. The maximum internal stresses are found in series Y which is, no doubt, in some manner due to this particular reduction of area in drawing.

It is evident from Figure 46 that the results of tests are not very uniform. The results are probably correct to within ± 1 ton per square inch or the stresses given are correct to 10%. This accuracy is not very high for a scientific investigation but it is doubtful if it could be exceeded with the methods employed. As it is, the distributions of stress in fourteen different specimens, representing about three month's work, were determined and laid aside as practically worthless, before the present investigation was undertaken showing that the accuracy depends largely on the personal element.

Heat treatment has precisely the same effect on the skin stresses as it has on the internal stresses and so requires no separate discussion. In the instances where the maximum internal tensile stresses do not exist at the surface of the bar it is generally found that the maximum skin stresses are greater than the corresponding internal stresses. The result of this is that on turning down such a bar we uncover material which is more highly stressed than the surface layers which leads us to the conclusion that in such cases it would be more important to determine the skin stresses than the actual magnitude and distribution of the internal stresses existing in the unmachined rod.

Why does he not refer to [illegible]?

<u>General Discussion and Explanation of Results.</u>

The effects of ageing and heat treatment on some of the properties of cold drawn steel have already been described and discussed from the point of view of the particular results obtained. It is now intended to discuss these results from a more general standpoint and to explain if possible the various phenomena observed.

An endeavour will first of all be made to explain the hardening of metals by cold work. The results of the present experiments cannot be reconciled with any of the current theories of hardening by cold work and none of them purport to explain the additional hardening or softening induced by ageing or mild heat treatment. The following theory explains the various phenomena observed and appears perfectly feasible in the light of recent research.

Since it is principally by the yielding of the free ferrite that low and medium carbon steels can be deformed in the cold state we shall confine ourselves at the present to its deformation only. Ferrite - α - iron - crystallises in the body centred cubic lattice[10] and plastic deformation results in slip of the crystal along the 2.1.1. trapezohedral plane - the icocitetrahedral face.[11,12.] It is universally admitted that it is the boundary condition of the cleavage planes after slipping that in some manner is the cause of the hardness. The Beilby-Rosenhain theory[13,14.] postulates the existence of amorphous metal at the cleavage planes but Tamman[15] believes that the crystal is merely fragmented.

When ferrite is subjected to an increasing load the space lattice will first of all deform elastically but there comes a point when this is no longer possible and plastic deformation follows. Just before plastic yielding, therefore, the space lattice is distorted and there is no obvious reason for supposing that after yielding it reverts to the unstressed condition. Despite the plastic deformation the whole of the crystal retains the same orientation unless twinning occurs and the atoms on either side of the cleavage planes probably no longer register to form a uniform space lattice and consequently a certain amount of distortion results. It is suggested that this distortion of the space lattice in the neighbourhood of the cleavage planes is the cause of the increase in hardness by cold work. It is shown in Appendix 2 that cold drawing causes a decrease in the density of steel which can only be explained by the supposition of a distorted lattice because if only fragmentation of the crystal occurred there is no reason to suppose, since the crystalline state gives the closest packing of the atoms, that any marked change in density would result. No doubt the density change can be explained by the amorphous cement hypothesis but modern research does not countenance the existence of such material. The idea of the distorted lattice being the cause of hardness is no new one and is given by McCance (16) as the explanation of the hardening of steel by quenching and is mentioned by Robin (17) as far back as 1911. The hardness of an amorphous substance is due to the absence of crystalline planes of weakness in it and similarly by distorting the space lattice and consequently causing interference with the free slipping of the crystals cold work generally hardens metals.

The effect of ageing is more difficult to explain but it is helpful to consider it also in the light of the density determinations. Appendix 2 shows that the density of cold drawn steel increases on ageing and the inference is that the meta-stable cold worked steel tends to revert to the crystalline condition. A corresponding softening might be predicted but this does not necessarily occur. The distorted lattice may revert to the stable crystalline condition and if, in consequence, small new crystals were formed of a different orientation from the parent grain they would greatly hinder by further slip interference the plastic deformation of the metal as a whole. This theory is in some respects similar to that given to explain the ageing of certain aluminium alloys which postulates that the increase in hardness is caused by the gradual precipitation of $Mg._2Si.$ and $Cu.Al_2$ in a very fine state of division. (18.) It is presumed that the loss of hardness due to the release of stresses in the space lattice is more than counterbalanced by the gain due to the additional slip interference of the new crystals.

Mild heat treatment by energising the atoms produces the same effects as ageing for many months at ordinary atmospheric temperature. (19.) The distorted lattice is, however, never entirely replaced by distinct crystals and this instability is removed by a complete recrystallisation of the ferrite which occurs from about 400°C to 600°C.

It is interesting to note that cold work does not always cause an increase in the hardness of metals and a further increase on ageing is not always observed.[2,20] Lead and tin appear to be anomalous in this respect, but this is due to the fact that what is called cold working in the case of iron is really hot working in their particular case. In ordinary commercial cold drawn iron and steel products ageing is often not observed as the commercial speeds of traction are generally so high that appreciable heating of the material occurs in the die and the mild heat treatment thus received is equivalent to ageing for many months.

The above theory is in general agreement with the work on tungsten crystals by Goucher[21] and Smithell Rooksby and Pitkin.[22] Since tungsten also crystallises in the body centred cubic lattice their results should be directly applicable to explain the plastic deformation of ferrite. The general effects of cold drawing and the behaviour on ageing and heat treatment of cold drawn steel appear to be reasonably explained by the suggested theory and there remains but to consider in greater detail one or two points.

In cold drawn and heat treated carbon and alloy steels Young's Modulus is practically constant and presumably bears some relationship to the space lattice of α-iron. The exceptionally low value obtained immediately after drawing is perhaps more apparent than real because if a more delicate extensometer had been employed the limit of proportionality would undoubtedly have been lower and the modulus probably correspondingly higher. The slight increase in the stretch modulus with temperature of heat treatment has been previously observed by Prof. Goodman (23) with steel to this same specification although in the sorbitic state.

That the impact figure of iron and steel is reduced by cold work and still further reduced by low temperature heat treatment is well known. (24 to 29) Investigations have also been made into the effect of deformation at these low temperatures followed by tests at atmospheric temperature and a still greater reduction in the impact figure has been observed. (27) Greaves and Jones (28) found that the elastic recovery of cold stretched steel resulted in a further reduction in the impact figure. In a later paper (29) by the same authors on tests conducted at elevated temperatures on cold rolled mild steel they show that the resistance to shock is proportionately reduced as the reduction in area by rolling is increased and that the minimum value attained is lower and occurs at a progressively lower temperature as the severity of the pass is increased. The latter results are, of course, not strictly comparable with those obtained in the present tests in which the Izod value was determined at atmospheric temperature. The present experiments are not, however, in agreement with Greaves' and Jones' general conclusion that cold work lowers the impact value in proportion to the deformation sustained since the highest values observed are obtained with the intermediate reductions of area in drawing.

In the impact tests the fracture is generally inter-granular while in the tensile tests it is usually intra-granular. By the theory put forward to explain the hardening of cold drawn steel on ageing and low temperature heat treatment the occurrence of new crystal boundaries is suggested and since with reference to the impact test they may be regarded as a source of weakness the explanation of the "blue brittleness" phenomenon in cold drawn steel logically follows.

A great deal of research work has been carried out to determine the influence of internal stresses on the "season" cracking of condenser tubes.(30.) The effect of heat treatment on the release of these stresses has also been extensively studied but in the case of cold drawn iron and steel the corresponding literature is very scanty and really apart from Heyn's contribution[4] it has received very little attention. Portevin[31], however, has studied the failure of shell cases under the combined influence of corrosion and the internal stresses induced by the shrinking on the copper band and has quantitatively estimated the stresses so produced. The raising of the elastic properties of cold drawn steel by "blueing" has generally been attributed to the release of internal stresses[32] but apart from the few figures given by Heyn there appears to be no evidence in favour of this view. Admittedly the explanation is a very plausible one but unfortunately in the present investigation a lowering of the internal stresses was not observed to coincide with the raising of the limit of proportionality or proof stress in tension on mild heat treatment.

The release of internal stresses on heat treatment appears to be governed by at least two factors.

1. If the creep stress of the material at a particular temperature is less than the maximum internal stress then heat treatment at that temperature must cause a suitable reduction in the stresses. Since the creep stress is largely influenced by the time factor so the reduction in the stresses due to this cause must increase pro rata with the time of soaking.

2. If recrystallisation of the deformed metal takes

place then a reduction in the internal stresses must occur proportional to the actual amount of recrystallisation. This recrystallisation of the metal as a whole must not be confused with the slight recrystallisation of the deformed material at the cleavage planes of the crystals.

The reduction of the internal stresses in the present experiments on heat treatment at temperatures up to 500°C is probably accounted for by a combination of reasons (1) and (2). In the light of recent research on the tensile properties of steel at elevated temperatures and a consideration of the mode of recrystallisation of the ferrite lead to the conclusion that the reduction due to cause (2) increases more rapidly with temperature than that due to cause (1). The complete release of the internal stresses on heating to 600°C and above is due to cause (2) and is confirmed by microscopic examination. (See Appendix 1).

No doubt when higher internal stresses occur than observed in this investigation mild heat treatment may reduce them appreciably but this does not necessarily prove that as a consequence a rise in the limit of proportionality will be observed. On the other hand it appears doubtful if any increase due to this cause could be detected with the extensometers usually employed. In the tensile test the stress at the surface of the test bar may exceed the limit of proportionality but appreciable plastic extension is prevented by the supporting action of the material nearer the axis. This slight plastic yielding causes a release and redistribution of the stresses which are probably being thus gradually reduced right up to the breaking load and at this point where the plastic phase predominates the internal stresses are practically zero. This effect is at present being investigated by determining the magnitude of the internal stresses in cold drawn bars after subjecting them to various amounts of cold stretching. Although an extensometer cannot detect the first sign of crystal slip and register it as the elastic limit there are various other methods (33.) and work is at present in progress to determine the nominal stress at which the first sign of plastic yielding of the surface layers can be detected. The apparatus consists of nineteen copper/ constantan thermo-couples in series which can be uniformly arranged round the test bar over a length of about $1\frac{1}{2}$ inches.

In the light of this research it does not appear likely that the internal stresses in the material investigated can be reduced appreciably by heat treatment without destroying the properties imparted to it by cold drawing, but if higher stresses were present a slight reduction might be effected without this occurring. The influence of these stresses probably cannot be detected with the extensometers generally employed. If no embrittling of the metal occurs from external influences such as the occlusion of hydrogen from acid (34.) or caustic (35.) liquors and the metal is reasonably ductile the existence of the internal stresses even of considerable magnitude will be in no way deleterious.

SUMMARY and CONCLUSION.

The Effect of Reduction of Area in Drawing.

1. When the final area is constant the gross work necessary to deform bars by cold drawing at a single pass is directly proportional to the severity of the pass.
2. The tensile strength and hardness increase pro rata with reduction of area in drawing.
3. The ductility is adversely affected with the severity of the pass.
4. The best Izod results were obtained with the intermediate reductions of area in drawing.
5. No definite relationship appears to exist between the limit of proportionality, Young's modulus and the severity of the pass.

6. From a consideration of results on heat treated specimens the proof stress increases with reduction of area in drawing.
7. The maximum internal stresses occurred in bars reduced 18.44% in area by cold drawing at a single pass.

Tests on Aged Bars.

1. Cold drawn steel is in a somewhat plastic state as it emerges from the die. A month's rest generally suffices for its elastic recovery. In this process it gains about 2 tons per square inch in tensile strength with a corresponding loss in ductility.
2. The hardness increases in sympathy with the gain in tensile strength.
3. The impact value decreases on ageing.
4. Young's modulus is low immediately after drawing but 7 days generally suffice for its recovery to a steady value.

Tests on Heat Treated Bars.

1. The elastic properties of cold drawn steel in tension

and compression are still further enhanced by suitable heat treatment. Normalising at temperatures up to 400°C causes a rise in the tensile strength, (about 2 tons per square inch) the limit of proportionality, the proof stress and the hardness. The variations in these properties on normalising above this temperature depend on the process of recrystallisation of the deformed ferrite.

2. The ductility and the Izod value are affected in the opposite direction to the above properties on heat treatment.

3. Young's modulus shows a slight increase roughly proportional to the normalising temperature.

The Effect of Heat Treatment on the Internal Stresses.

1. Normalising at temperatures up to 400°C has generally little influence on the reduction of the stresses.

2. The maximum internal tensile stress was generally only found at the surface of the bar after normalising at 300°C and above.

3. Normalising at and above 600°C causes complete release of stresses due to the recrystallisation of the ferrite.

4. In some instances it appears to be more important to determine the magnitude of the skin stresses than the actual distribution of the internal stresses in the unmachined bar.

5. With the material investigated it does not appear possible to reduce the internal stresses by heat treatment without destroying the properties imparted to it by cold work.

6. In bright drawn steel bars which only suffer a light pass in the cold drawing operation the internal stresses are not harmful unless the material is embrittled by external influences.

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A P P E N D I X.

1.

The Effect of Cold Drawing on the Micro-structure of Steel and the Changes Produced in it by Heat Treatment.

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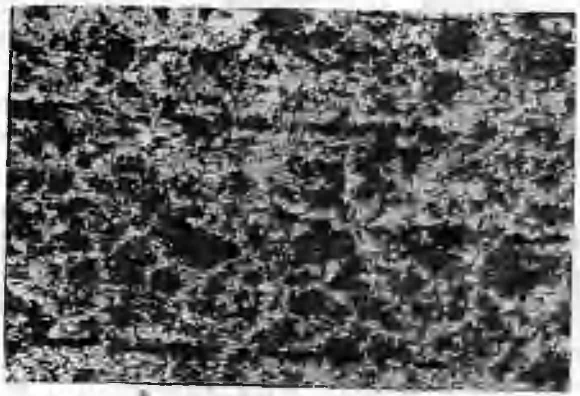
Photo-micrographs 1-6 show the effect of reduction of area in drawing on the structure of the steel investigated. The different size of crystals in the various groups of bars unfortunately sometimes masks the effect of the increasing severity of the pass but the general effect of elongating the grains in clearly shown.

Recent research work has shown that after cold drawing or rolling the crystals tend to take up a definite orientation with reference to the direction of deformation.(36.) In the case of tungsten (22.) and α-iron the orientation is such that a 1.1.0. plane lies in the direction of drawing and a 1.0.0. plane lies parallel to the surface of the wire. The other pair of 10.0 planes are symmetrically disposed, making an angle of 45° with the axis. In the light of the recent work of Smithells, Rooksby and Pitkin (22.) it would appear that with the relatively light passes adopted in this investigation this effect would not be marked and consequently by no stretch of the imagination can the hardening by cold work be attributed to the rotation of the crystals.

Photo-micrographs 7-10 show that at a low magnification there is no marked change in the crystal structure of cold drawn steel on normalising up to 700°C. Photo-micrographs 11-13 show in series Z, W and U the recrystallisation of the ferrite which occurs and the tendency for the cementite to globularise. In series Z there appears to be a more complete globularisation of the cementite but this is only apparent as the bars of this series only received a light draught and consequently the pearlitic areas were not so greatly elongated as with the higher reductions. Photo-micrograph 14 shows the granular pearlite at a high magnification. The transition from the lammelar to the granular pearlite is clearly seen. The direction of the original lammelar pearlite in the micrograph was approximately north-east and south-west.

Photo-micrograph 15 shows the crystalline structure obtained on normalising at 900°C. Grains of sorbite surrounded by free ferrite are observed. Slight grain growth is evidenced by a few large sorbite crystals. This propensity is taken advantage of in the "patenting" process when if a long fibre wire is desired this end can be attained by purposely overheating the steel and so causing excessive sorbite grain growth.

All photo-micrographs shown are of specimens etched in a 1% solution of picric acid in ethyl alcohol.



(1.)

7.74% Red^{N} in Area X 75

(2.)

18.44% Red^{N} in Area X 75

(3.)

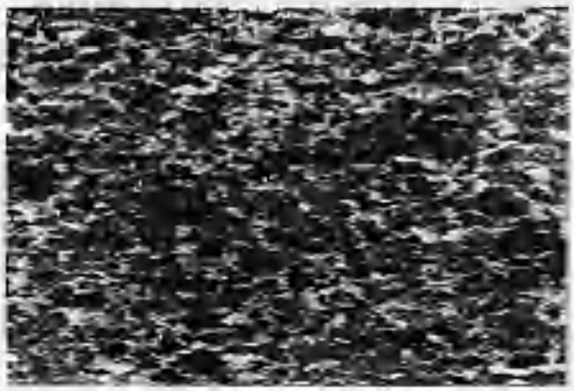
27.16% Red^{N} in Area X 75

(4.)

36.39% Red^{N} in Area X 75

(5.)

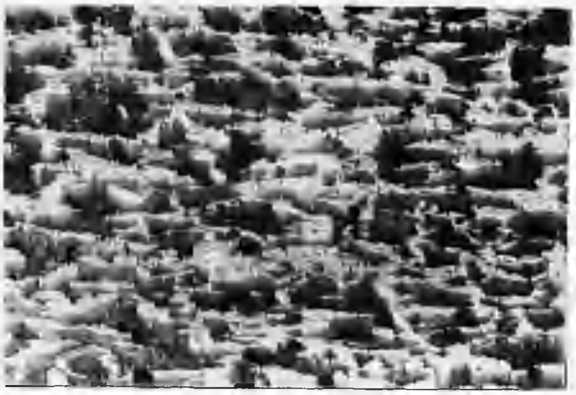
42.14% Red^{N} in Area X 75



(6.)

48.87% Red^{N} in Area X 75

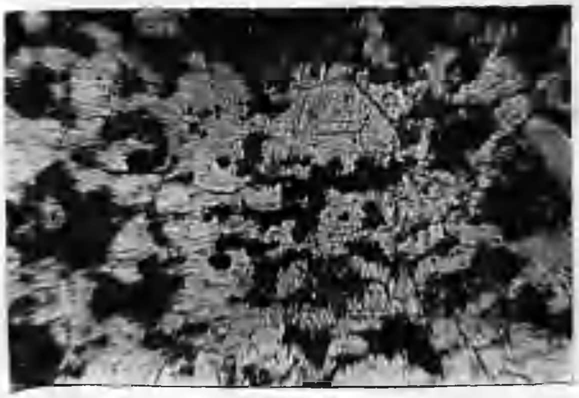
36·39% Redⁿ in Area X100
Normalised at 200°C.
(7.)



36·39% Redⁿ in Area X100
Normalised at 400°C.
(8.)

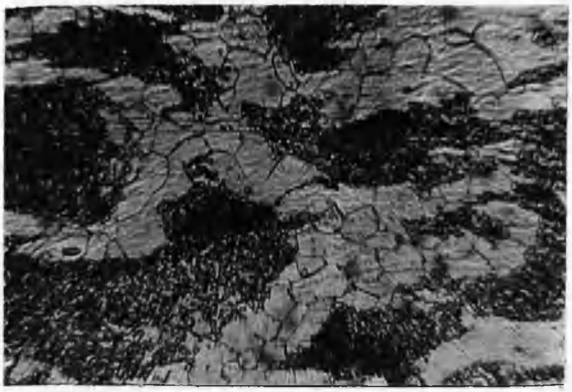
(9)
36·39% Redⁿ in Area x 100
Normalised at 600°C

(10)
36·39% Redⁿ in Area X 100
Normalised at 700°C



7·74% Redⁿ in Area x 560
Normalised at 700°C
(11.)

36·39% Redⁿ in Area. x 560
Normalised at 700°C
(12.)



(13.)

48·87% Red^n in Area × 560
Normalised at 700°C

(14.)

36·39% Red^n in Area × 1,700
Normalised at 700°C

(15.)

36·39% Red^n in Area × 100
Normalised at 900°C.

APPENDIX.

2.

The Effect of Cold Drawing on the Density of Steel and the Change Produced in it by Ageing.

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The effect of cold work on the density of iron and steel has previously been studied (7,37,38) but the effect of ageing on the density has not received much attention. Lea (39.) appears to have been about the first to conduct a scientific investigation into this matter.

Densities can be determined with considerable accuracy but the slight difference in composition of the various groups of bars might render strict comparison of the densities of the cold drawn bars invalid. To reduce this effect to a minimum an annealed bar of series V was cut into convenient lengths and the different portions machined to the diameters of bars of series Z, Y, X and W. Portions were taken from either end of the chosen length and the average density of these specimens taken as the density of the annealed material.

The bars were cold drawn at a single pass to 0·45 inch diameter and their densities determined after ageing for different periods. The method employed to determine the densities is that described by Andrew and Honeyman, (40.) except that the standard specimen was weighed before and after each weighing of the cold drawn specimens in paraffin.

The results of the investigation are given in Table 44 and are plotted in Figure 47.

It will be observed that the decrease in density is proportional to the reduction in area in drawing, and a slight rise is evident on ageing. These results are similar to those obtained by Lea.

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-----oO o-----

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TABLES.

Mark	Original Diameter Inches	Reduced Diameter Inches	Reduction of Area Per Cent	Speed of Drawing In./Min.	Max. / Mean / Min. Pull Lbs.	Nominal Stress on Reduced Area. Tons/In.^{2}	Work Done per In.^{3} of Material Tons-Ins.
Z	·4679	·4479	7·74	2·77	2,530 2,510 2,450	7·05	7·05
Y	·4986	·4501	18·44	2·84	5,600 5,540 5,460	15·54	15·54
X	·5277	·4504	27·16	2·94	7,910 7,730 7,650	21·66	21·66
W	·5649	·4507	36·39	3·20	10,720 10,640 10,590	29·78	29·78
V	·5930	·4512	42·14	3·18	12,640 12,460 12,340	34·85	34·85
U	·6319	·4518	48·87	3·45	14,600 14,510 14,430	40·40	40·40

TABLE 1

MARK	LIMIT OF PROPORTIONALITY TONS/IN²	ULTIMATE STRENGTH TONS/IN²	REDUCTION OF AREA PER CENT	ELONGATION PER CENT	HYSTERESIS INS./IN LENGTH X10⁻⁵	YOUNG'S MODULUS TONS/IN²
	10·91	35·20	59·10	36·60	—	13,390
Z	10·55	35·20	53·70	36·20	1·6	13,300
	10·20	35·20	50·10	35·80	—	13,200
	8·79	36·24	54·30	37·90	—	13,320
Y	7·79	36·10	40·90	33·90	2·0	13,290
	5·91	36·00	31·70	27·10	—	13,280
	11·81	35·63	56·60	38·30	—	13,290
X	11·78	34·53	39·23	35·13	2·4	13,180
	11·74	32·46	30·60	30·90	—	13,110
	15·99	37·69	45·90	34·50	—	13,430
W	15·53	37·64	45·90	33·50	1·8	13,320
	15·09	37·61	45·90	32·50	—	13,230
	13·06	37·41	47·10	34·10	—	13,570
V	11·67	37·31	46·17	33·47	1·4	13,450
	10·28	37·11	45·30	32·70	—	13,300
U	11·10	37·42	35·80	29·70	—	13,900
	10·47	36·90	31·53	27·77	1·6	13,800
	9·67	36·21	27·50	25·20	—	13,740

TABLE 2

SERIES	LIMIT OF PROPORTIONALITY TONS/IN.^{2}	HYSTERESIS INS./IN. LENGTH $\times 10^{-5}$	YOUNG'S MODULUS TONS/IN.^{2}
	13·05	–	13,550
Z	12·75	3·0	13,540
	12·45	–	13,530
	15·77	–	13,390
Y	13·22	3·4	13,230
	11·20	–	13,080
	13·33	–	13,740
X	12·67	2·4	13,510
	12·00	–	13,280
	10·85	–	13,960
W	10·54	3·2	13,500
	10·16	–	13,040
	13·34	–	13,860
V	12·55	2·0	13,530
	11·75	–	13,050
	12·24	–	13,600
U	11·25	2·8	13,430
	9·70	–	13,320

TABLE 3.

MARK	Z	Y	X	W	V	U
MAX.	27·8	28·4	28·8	26·0	25·8	9·5
MEAN	26·4	27·0	27·1	23·1	24·7	8·9
MIN.	24·3	24·3	25·6	21·2	22·7	7·6

TABLE 4 IZOD (FT-LBS)

SERIES	Z	Y	X	W	V	U
MAX	164	176	178	186	182	197
MEAN	161	172	168	183	179	188
MIN.	158	168	166	178	172	179

BRINELL HARDNESS NUMBER TABLE 5

Mark	Interval between Drawing and Testing	Limit of Proportionality Tons/In^2	Ultimate Strength Tons/In^2	Reduction of Area Per Cent	Elongation Per Cent	Hysteresis Ins./In. Length $\times 10^{-5}$	Young's Modulus Tons/In^2
Z	1 Hour	4·49	38·38	65·40	—	8·1	12,730
	1 Day	6·23	39·13	49·55	24·10	2·7	12,770
	7 Days	7·54	38·56	47·80	22·60	2·0	13,450
	29 "	9·37	39·37	45·60	24·10	2·8	13,140
	90 "	9·54	40·61	43·90	21·70	0	13,730
	180 "	11·88	39·28	41·20	19·30	0	13,140
Y	1 Hour	5·05	45·97	37·70	14·45	3·9	12,160
	1 Day	5·61	45·21	37·70	15·06	1·8	13,320
	7 Days	6·03	45·45	32·50	13·30	1·9	13,070
	28 "	6·31	46·34	37·10	12·60	0	13,610
	90 "	13·47	47·62	38·10	11·40	0	13,390
	180 "	13·52	47·86	36·00	10·40	0	13,950
X	1 Hour	4·60	48·67	35·80	10·90	8·6	11,920
	1 Day	6·48	48·94	35·80	10·90	7·8	12,070
	7 Days	7·15	49·44	34·20	13·25	2·8	12,980
	27 "	11·76	47·51	46·60	—	2·0	12,740
	90 "	14·31	49·50	23·30	8·10	0	13,100
	180 "	14·87	50·67	23·30	9·60	0·6	12,930
W	1 Hour	5·59	53·00	17·40	10·20	8·6	11,960
	1 Day	6·25	53·50	16·20	9·00	6·4	12,530
	7 Days	7·13	53·50	16·20	9·00	4·4	12,960
	28 "	9·88	54·20	15·40	9·60	2·6	12,800
	90 "	14·31	54·40	13·70	7·50	3·2	12,650
	186 "	16·47	55·09	13·70	7·20	3·2	12,750
V	1 Hour	5·61	55·38	15·00	9·60	5·0	12,110
	1 Day	6·51	55·49	13·30	8·40	4·8	12,270
	7 Days	9·32	55·51	14·20	9·00	2·4	12,720
	28 "	11·23	58·48	12·90	7·80	0·5	13,000
	90 "	12·63	59·27	21·00	6·60	0·4	13,020
	184 "	13·83	57·20	12·10	7·20	0·6	12,910
U	1 Hour	4·55	56·40	12·80	4·80	2·2	12,350
	1 Day	5·89	57·24	2·15	2·40	1·6	12,750
	7 Days	6·45	56·54	2·26	2·40	2·1	12,910
	28 "	13·19	56·06	2·26	1·50	0	12,940
	90 "	13·47	56·28	5·30	2·40	0	13,280
	180 "	11·79	55·85	2·01	2·40	0·8	12,860

MARK	INTERVAL BETWEEN DRAWING AND TESTING DAYS	LIMIT OF PROPORTIONALITY TONS/IN.^{2}	HYSTERESIS IN/IN. LENGTH $\times 10^{-5}$	YOUNG'S MODULUS TONS/IN.^{2}
Z	1	5·60	19·2	13,530
	4	6·27	14·0	13,310
	7	5·45	11·6	13,510
	28	8·55	5·2	13,130
	90	10·17	2·4	13,300
	180	8·83	5·2	13,200
Y	1	4·64	23·6	13,320
	4	4·88	15·6	13,200
	7	5·29	18·4	14,450
	28	8·93	6·4	13,010
	90	9·67	3·6	12,850
	180	8·84	2·4	14,220
X	1	4·28	32·0	13,190
	4	6·00	11·6	12,620
	7	5·09	7·6	13,340
	28	9·14	4·0	12,840
	90	11·40	4·8	12,660
	180	10·75	4·2	11,540
W	1	5·33	9·2	12,260
	4	6·91	9·2	12,110
	7	7·47	6·0	12,940
	28	6·90	4·8	12,720
	90	8·14	3·6	13,080
	180	10·55	4·0	12,860
V	1	4·40	17·6	12,500
	4	6·79	16·0	12,670
	7	5·67	11·2	13,000
	28	6·18	8·2	13,910
	90	10·19	5·2	12,480
	180	9·78	6·0	12,700
U	1	5·32	11·8	11,650
	4	8·72	9·2	12,500
	7	8·72	5·6	12,590
	28	8·31	6·6	13,150
	90	11·64	3·6	12,750
	180	9·70	3·2	12,810

Interval between drawing and testing	Z	Y	X	W	V	U
1 Hour	3·7	7·5	7·2	10·3	11·2	5·0
1 Day	11·3	8·2	7·0	9·2	10·7	4·8
7 Days	6·0	8·0	6·3	8·5	10·0	7·1
28 "	8·0	7·5	7·8	8·1	9·2	4·2
90 "	5·0	7·3	7·2	7·4	8·0	4·1
180 "	6·3	5·5	5·5	7·2	7·0	4·6

TABLE 8. IZOD (FT.-LBS.)

Interval between Drawing and Testing	Series					
	Z	Y	X	W	V	U
1 Day	167	194	202	218	229	230
7 Days	170	195	211	224	232	231
28 "	177	200	214	229	231	239
90 "	178	201	214	228	237	242
180 "	176	201	217	234	240	242

BRINELL HARDNESS NUMBER   TABLE 9.

Series	Normalising Temperature °C	Ultimate Strength Tons/In.^{2}	Proof Stress Tons/In.^{2}	Limit of Proportionality Tons/In.^{2}	Reduction of Area Per Cent	Elongation Per Cent	Hysteresis In./In. Length $\times 10^{-5}$	Young's Modulus Tons/In.^{2}
Z	100	40·5	28·1	12·4	45·6	23·1	0	13,380
	200	42·4	29·7	13·5	55·6	17·5	0	13,550
	300	42·9	31·6	14·0	42·4	19·4	0	13,510
	400	42·8	32·5	13·7	41·2	20·6	0	13,630
	500	41·2	30·0	13·4	45·2	24·4	0	13,520
	600	39·0	26·8	14·2	49·3	32·5	1·2	13,450
	700	34·6	25·7	15·0	57·7	33·2	0	13,580
	800	38·9	24·1	14·0	55·4	33·8	0	13,490
Y	100	48·2	33·5	13·8	38·1	12·5	0	13,420
	200	48·5	28·8	11·2	35·7	11·3	0	13,370
	300	50·0	37·9	14·4	39·0	12·5	0	13,390
	400	50·2	37·6	13·7	33·8	11·6	0	13,060
	500	48·3	37·8	15·6	38·9	18·8	0	13,470
	600	40·5	30·8	17·6	47·0	26·8	0	13,450
	700	32·7	20·4	13·4	62·0	37·5	0	13,650
	800	39·5	24·7	12·1	54·7	35·6	0	13,450
X	100	52·3	33·7	10·2	32·7	10·0	0	13,500
	200	52·2	31·8	14·8	32·8	11·9	0	13,160
	300	53·7	37·2	16·2	30·8	13·1	0	13,170
	400	53·9	40·7	16·5	31·3	13·8	0	13,240
	500	51·3	36·5	15·7	33·1	16·9	0	13,380
	600	39·1	28·8	12·3	48·7	30·7	0	13,520
	700	32·3	19·6	13·0	65·0	35·0	0·8	13,460
	800	40·2	24·5	13·9	55·6	35·6	0	13,550
W	100	54·6	32·3	13·9	17·4	6·9	0	13,170
	200	55·8	30·7	13·1	16·9	10·0	0	13,200
	300	57·0	38·5	14·5	16·2	11·2	0	13,350
	400	56·5	39·9	13·7	16·4	12·5	0	13,420
	500	54·5	35·5	13·4	19·9	15·6	0	13,520
	600	40·1	24·7	13·5	46·0	30·7	0	13,450
	700	32·9	22·4	12·6	65·6	35·6	1·6	13,740
	800	40·2	25·2	13·7	55·6	34·3	0	13,540

TABLE 10

Series	Normalising Temperature °C	Limit of Proportionality $Tons/In.^2$	Proof Stress $Tons/In.^2$	Hysteresis Ins./In. Length $\times 10^{-5}$	Young's Modulus $Tons/In.^2$
Z	100	12·0	17·8	2·4	13,600
	200	9·3	18·3	2·0	13,610
	300	10·5	19·2	2·4	13,680
	400	14·7	24·9	1·6	13,800
	500	11·6	22·8	2·0	13,810
	600	11·5	27·5	2·4	13,970
	700	11·8	19·0	4·0	13,660
	800	12·1	27·2	4·0	13,950
Y	100	11·4	18·0	2·4	13,690
	200	10·5	21·2	4·4	13,930
	300	13·6	23·6	4·4	13,730
	400	15·1	29·0	2·4	13,810
	500	14·2	27·6	1·2	13,470
	600	9·3	15·2	2·8	13,840
	700	11·8	22·4	2·6	13,920
	800	14·4	25·8	3·2	14,030
X	100	9·2	18·7	3·2	13,790
	200	11·0	20·9	3·2	14,410
	300	12·8	25·0	0·8	13,880
	400	12·0	30·0	0	13,790
	500	12·2	26·1	0·8	13,740
	600	12·0	19·9	7·2	13,530
	700	11·5	14·7	11·3	14,850
	800	10·4	15·2	3·6	14,860
W	100	10·7	20·7	7·8	13,700
	200	13·7	21·0	6·0	13,920
	300	14·7	31·0	6·0	14,110
	400	11·8	27·2	2·8	14,150
	500	11·8	23·6	3·6	14,440
	600	12·0	21·0	4·0	14,630
	700	14·1	27·0	3·6	14,100
	800	11·4	17·5	8·4	13,880

TABLE II.

Series	Normalising Temperature — °C								
	100	200	300	400	500	600	700	800	900
Z	5·7	2·9	3·6	5·2	8·6	10·1	10·5	27·1	26·0
Y	7·6	4·1	4·4	4·7	8·5	15·0	27·0	27·4	23·8
X	7·3	3·7	4·0	5·3	5·4	17·4	34·6	27·0	21·8
W	8·1	4·5	3·6	4·7	6·0	23·8	32·6	24·5	22·7
V	7·4	5·0	4·0	3·9	7·4	32·7	35·8	34·8	23·3
U	4·3	3·4	3·9	4·2	6·3	19·2	24·7	25·4	24·7

TABLE 12. IZOD (Ft.-Lbs.)

Series	Normalising Temperature — °C								
	100	200	300	400	500	600	700	800	900
Z	187	200	201	207	196	180	170	184	186
Y	217	220	233	234	220	191	157	171	184
X	223	224	231	244	232	189	158	185	186
W	236	250	259	263	241	200	172	187	187
V	236	253	262	265	243	220	191	169	188
U	244	244	246	259	238	224	164	192	188

TABLE 13 BRINELL HARDNESS NUMBER

Diameter In.	Internal Stress Tons/In²	Skin Stress Tons/In²
·4494		
·4327	4·5	4·5
·4202	5·4	7·5
·4044	6·8	7·6
·3846	8·4	9·8
·3635	9·8	12·3
·3433	4·3	8·9
·3230	5·7	9·5
·3040	0·15	6·6
·2841	−0·15	7·3
·2438	−1·6	2·1
·2244	−3·2	5·9
·2043	−5·4	5·6

Z0. TABLE 14.

Diameter In.	Internal Stress Tons/In²	Skin Stress Tons/In²
·4490		
·4329	3·3	3·3
·4197	11·6	13·5
·4045	10·0	10·8
·3841	12·8	14·8
·3640	12·7	16·1
·3429	5·2	10·6
·3240	6·2	12·8
·3041	3·3	11·7
·2845	1·4	11·2
·2647	−4·7	6·9
·2440	−6·5	6·1
·2239	−8·4	4·9
·2019	−10·8	3·7

Z1 TABLE 15

Diameter In.	Internal Stress Tons/In²	Skin Stress Tons/In²
·4492		
·4343	9·0	9·0
·4191	5·5	6·8
·4045	11·6	13·0
·3844	10·5	14·0
·3638	9·3	13·1
·3439	5·1	10·0
·3242	2·8	9·1
·3040	−2·0	5·4
·2841	−0·6	7·5
·2638	−6·2	3·0
·2444	−6·7	2·8
·2030	−9·3	2·1

Z2 TABLE 16

Diameter In.	Internal Stress Tons/In²	Skin Stress Tons/In²
·4487		
·4338	13·8	13·8
·4197	13·1	14·1
·4036	9·7	11·7
·3842	4·6	7·5
·3652	7·3	9·7
·3452	6·7	11·6
·3250	0·8	6·9
·3045	−0·7	6·4
·2751	−3·8	4·2
·2446	−4·9	4·0
·2190	−8·1	1·9

Z3 TABLE 17.

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.
·4488		
·4340	3·6	3·6
·4197	9·6	9·8
·3826	9·3	10·2
·3653	4·2	6·3
·3448	1·3	4·1
·3047	2·7	6·0
·2647	−0·7	4·2
·2247	−3·7	2·6
·1830	−5·1	2·1

Z4 Table 18

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
·4491		
·4343	7·7	7·7
·4178	11·8	12·4
·4003	8·5	10·0
·3850	7·0	8·0
·3448	4·8	6·2
·3050	−2·2	2·0
·2652	−1·4	3·4
·2243	−4·0	1·9
·1838	−5·1	1·5

Z5 Table 19

Diameter In.	Internal Stress Tons/In^2	Skin Stress Tons/In^2
·4496		
·4288	1·1	1·1
·3901	0·9	1·0
·3100	0·1	0·4
·2293	−0·9	−0·3
·1894	−0·4	−0·1

Z6 Table 20

Diameter In	Internal Stress Tons/In^2	Skin Stress Tons/In^2
·4490		
·4299	1·2	1·2
·3897	−0·6	−0·5
·3101	−0·9	−0·9
·2293	0·9	0·3
·1896	−0·2	−0·4

Z7 Table 21

Diameter In.	Internal Stress Tons/In^2	Skin Stress Tons/In^2
·4470		
·4096	2·0	2·0
·3289	−1·1	0·5
·2475	−1·3	−1·0
·1894	−0·0	−2·0

Z8 Table 22

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4492		
.4353	8.9	8.9
.4137	7.5	8.0
.3955	14.2	16.4
.3700	12.3	14.6
.3553	9.9	14.9
.3356	3.5	9.8
.3154	8.4	15.8
.2957	4.2	13.6
.2754	1.9	13.2
.2556	−1.5	11.1
.2356	−7.2	8.1
.2141	−9.7	6.9
.1947	−13.5	4.8

Y0 Table 23

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4500		
.4254	7.1	7.1
.3939	11.3	12.8
.3627	11.2	14.0
.3349	11.7	17.4
.3048	6.4	13.9
.2752	0.5	12.3
.2556	−6.1	8.1
.2354	−5.7	8.7
.2153	−10.0	6.0
.1945	−12.1	5.7

Y1 Table 24

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4499		
.4336	9.2	9.2
.4147	6.2	15.5
.3954	14.0	15.1
.3702	10.1	12.7
.3556	6.7	11.5
.3153	8.9	13.0
.2955	4.2	12.8
.2546	−1.0	9.0
.2349	−4.7	9.5
.1941	−10.6	5.2
.1761	−13.8	4.6

Y2 Table 25

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4491		
.4299	11.8	11.8
.3888	8.6	10.8
.3400	7.3	8.1
.3107	4.8	11.3
.2800	2.0	10.8
.2491	−3.6	7.9
.2206	−7.0	6.4
.1998	−10.8	4.3
.1794	−11.7	4.4

Y3 Table 26.

Diameter In.	Internal Stress Tons/In.²	Skin Stress Tons/In.²
·4496		
·4299	12·6	12·6
·4099	4·9	6·0
·3695	6·9	9·3
·3407	4·5	7·9
·3109	0·7	5·7
·2802	2·8	8·7
·2496	−1·1	6·9
·2202	−6·0	3·7
·1999	−6·3	4·3
·1800	−9·6	2·3

Y4 TABLE 27.

Diameter In.	Internal Stress Tons/In.²	Skin Stress Tons/In.²
·4497		
·4301	6·8	6·8
·3908	3·0	3·7
·3310	1·7	3·1
·2910	0·4	3·0
·2501	−0·7	2·8
·2090	−3·0	1·6
·1803	−3·6	1·5

Y5 TABLE 28

Diameter In.	Internal Stress Tons/In.²	Skin Stress Tons/In.²
·4500		
·4309	7·4	7·4
·4110	10·1	10·8
·3857	8·1	9·9
·3591	7·3	10·4
·3306	8·6	13·3
·3003	4·4	11·5
·2705	4·3	13·8
·2403	−2·2	10·6
·2205	−4·7	10·7
·1983	−10·8	7·2
·1806	−11·6	7·5

X0 TABLE 29.

Diameter In.	Internal Stress Tons/In.²	Skin Stress Tons/In.²
·4495		
·4306	7·5	7·5
·4100	5·8	6·6
·3853	9·7	10·8
·3605	7·1	9·8
·3307	7·4	11·6
·3007	3·5	9·8
·2707	2·3	10·7
·2405	−1·7	9·7
·2202	−3·1	10·3
·2006	−9·4	6·2
·1807	−11·2	5·5

X1 TABLE 30.

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
·4500		
·4304	7·2	7·2
·4109	5·2	5·8
·3858	9·5	10·8
·3610	6·1	8·9
·3288	7·0	10·9
·3002	6·2	12·5
·2702	1·8	10·4
·2408	0	11·3
·2196	−6·1	7·8
·2002	−9·3	6·2
·1805	−11·1	5·8

X2 Table 31.

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
·4491		
·4008	8·1	8·1
·3858	4·9	5·4
·3557	5·2	7·6
·3259	4·8	8·7
·2959	2·6	8·0
·2658	0·6	8·0
·2360	−1·1	8·0
·2058	−4·1	7·0
·1801	−7·3	6·2

X3 Table 32.

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
·4500		
·4111	7·3	7·3
·3842	4·4	5·4
·3555	1·8	4·0
·3253	2·5	5·4
·2960	0·4	5·7
·2660	0·8	5·7
·2350	0	6·4
·2053	−2·9	5·0
·1799	−4·6	4·6

X4 Table 33.

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
·4492		
·4105	5·2	5·2
·3850	1·2	2·3
·3558	1·3	1·1
·3146	0·7	2·4
·2847	−1·2	1·3
·2356	−1·4	1·4
·2049	−1·4	2·1
·1808	−3·3	1·0

X5 Table 34

DIAMETER IN.	INTERNAL STRESS TONS/IN.^{2}	SKIN STRESS TONS/IN.^{2}
·4500		
·4361	5·3	5·3
·4199	8·2	8·6
·4051	9·0	10·0
·3847	9·3	11·1
·3648	8·5	11·4
·3448	6·8	11·0
·3029	3·9	11·6
·2638	0·3	11·6
·2446	−0·9	5·2
·2242	−7·2	8·5
·2035	−9·0	7·3

W0 TABLE 35

DIAMETER IN.^{2}	INTERNAL STRESS TONS/IN.^{2}	SKIN STRESS TONS/IN.^{2}
·4498		
·4355	4·2	4·2
·4223	6·8	6·2
·3802	9·1	11·0
·3391	7·2	14·0
·3196	6·0	8·9
·2997	3·7	8·0
·2603	0·9	11·2
·2404	0·6	13·0
·2205	−4·7	9·6
·1994	−6·3	9·7

W1 TABLE 36

DIAMETER IN.	INTERNAL STRESS TONS/IN.^{2}	SKIN STRESS TONS/IN.^{2}
·4501		
·4356	4·8	4·8
·4201	5·3	5·7
·4059	7·7	8·4
·3851	10·2	11·5
·3596	9·2	12·1
·3448	7·4	10·7
·2998	3·6	9·8
·2800	0·8	8·4
·2606	0	8·2
·2200	−3·1	15·0
·1987	−7·3	6·5
·1831	−9·1	7·2

W2 TABLE 37

DIAMETER IN.	INTERNAL STRESS TONS/IN.^{2}	SKIN STRESS TONS/IN.^{2}
·4499		
·4187	11·0	11·0
·3799	6·8	8·8
·3606	9·1	8·8
·3204	4·4	9·3
·2985	2·1	8·1
·2797	1·6	9·0
·2602	−1·7	7·0
·2197	−2·3	8·3
·1994	−6·8	6·3
·1837	−7·8	6·0

W3 TABLE 38

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4503		
.4357	9.8	9.8
.4200	8.6	9.3
.4004	6.4	7.8
.3395	2.9	7.2
.3003	−0.6	5.2
.2586	−0.9	4.8
.2201	−2.3	5.0
.1823	−4.4	4.1

W4 Table 39

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4502		
.4358	5.8	5.8
.4196	3.2	3.6
.4004	3.3	4.0
.3401	1.4	4.0
.2997	−0.8	1.2
.2586	−0.8	1.9
.2179	−0.5	2.6
.1843	−2.0	2.5

W5 Table 40

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4495		
.4004	0.8	0.8
.3299	0.3	1.2
.2497	−0.4	−0.9
.1898	−0.5	0.7

W6 Table 4

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4491		
.4004	−0.9	−0.9
.3302	−0.2	−0.5
.2500	0.1	−0.4
.1900	0.7	0

W7 Table 42

Diameter In.	Internal Stress Tons/In.^{2}	Skin Stress Tons/In.^{2}
.4472		
.3992	1.3	1.3
.3301	0.1	0.5
.2499	0	0.9
.2002	−1.0	0

W8 Table 43

INTERVAL BETWEEN DRAWING AND TESTING	REDUCTION OF AREA IN DRAWING				
	6·79%	18·83%	27·50%	35·55%	41·20%
1 DAY	7·8433	7·8419	7·8394	7·8350	7·8340
5 DAYS	7·8425	7·8413	7·8390	7·8363	7·8342
12 "	7·8440	7·8416	7·8396	7·8363	7·8346
25 "	7·8440	7·8421	7·8397	7·8361	7·8355
45 "	7·8436	7·8421	7·8396	7·8361	7·8350
	ANNEALED MATERIAL ① 7·8472 ② 7·8468				

SPECIFIC GRAVITY DETERMINATIONS

TABLE 44

INTERVAL BETWEEN DRAWING AND TESTING	REDUCTION OF AREA IN DRAWING				
	6·79%	18·83%	27·50%	35·55%	41·20%
1 DAY	7·8433	7·8419	7·8394	7·8350	7·8340
5 DAYS	7·8425	7·8413	7·8390	7·8363	7·8342
12 "	7·8440	7·8416	7·8396	7·8363	7·8346
25 "	7·8440	7·8421	7·8397	7·8361	7·8355
45 "	7·8436	7·8421	7·8396	7·8361	7·8350
	ANNEALED MATERIAL ① 7·8472 ② 7·8468				

SPECIFIC GRAVITY DETERMINATIONS

TABLE 44

FIGURES.

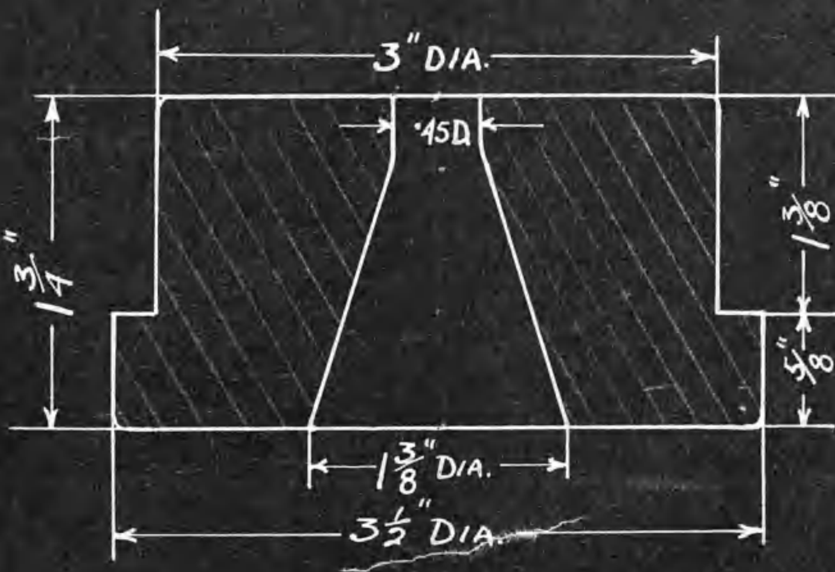


FIG. 1

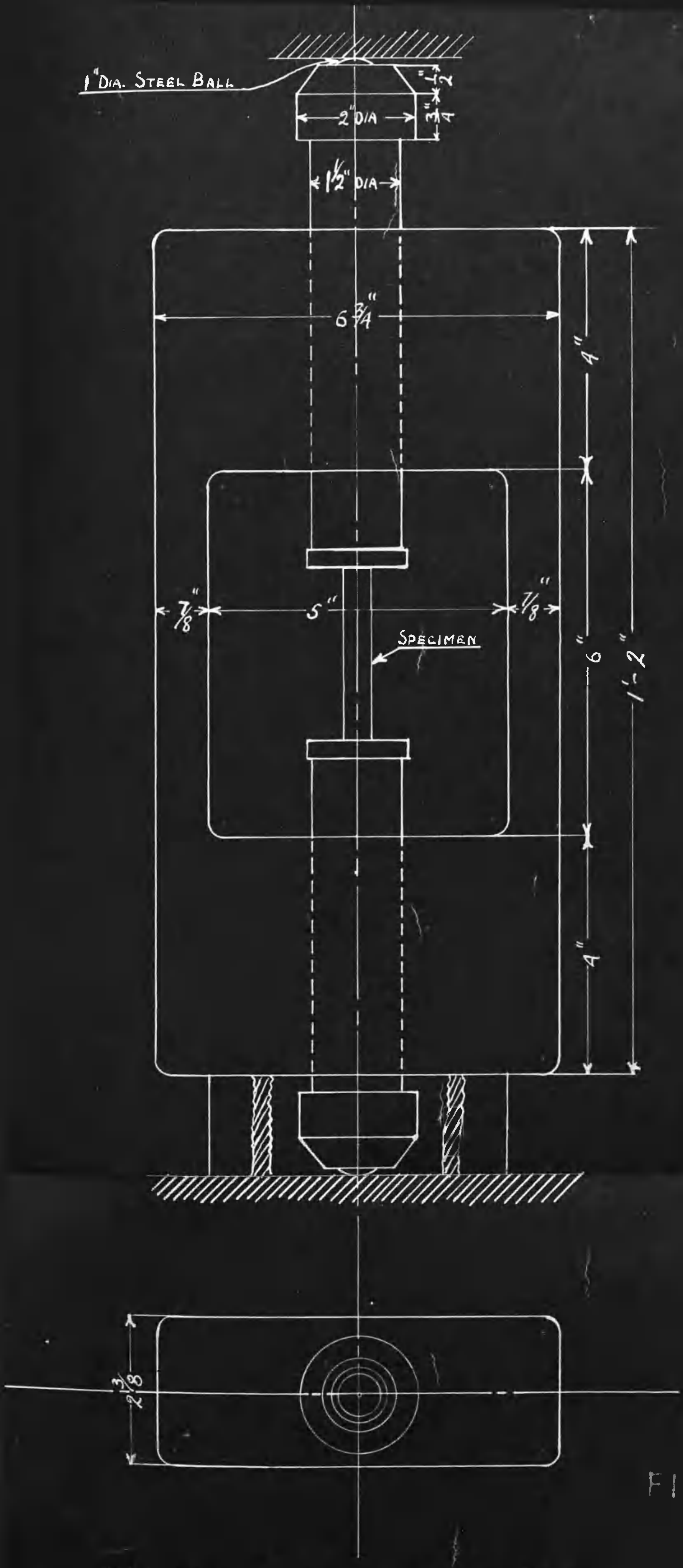


FIG. 2

N.P.L. TYPE JIG FOR COMPRESSION TESTS.

SCALE :- HALF SIZE

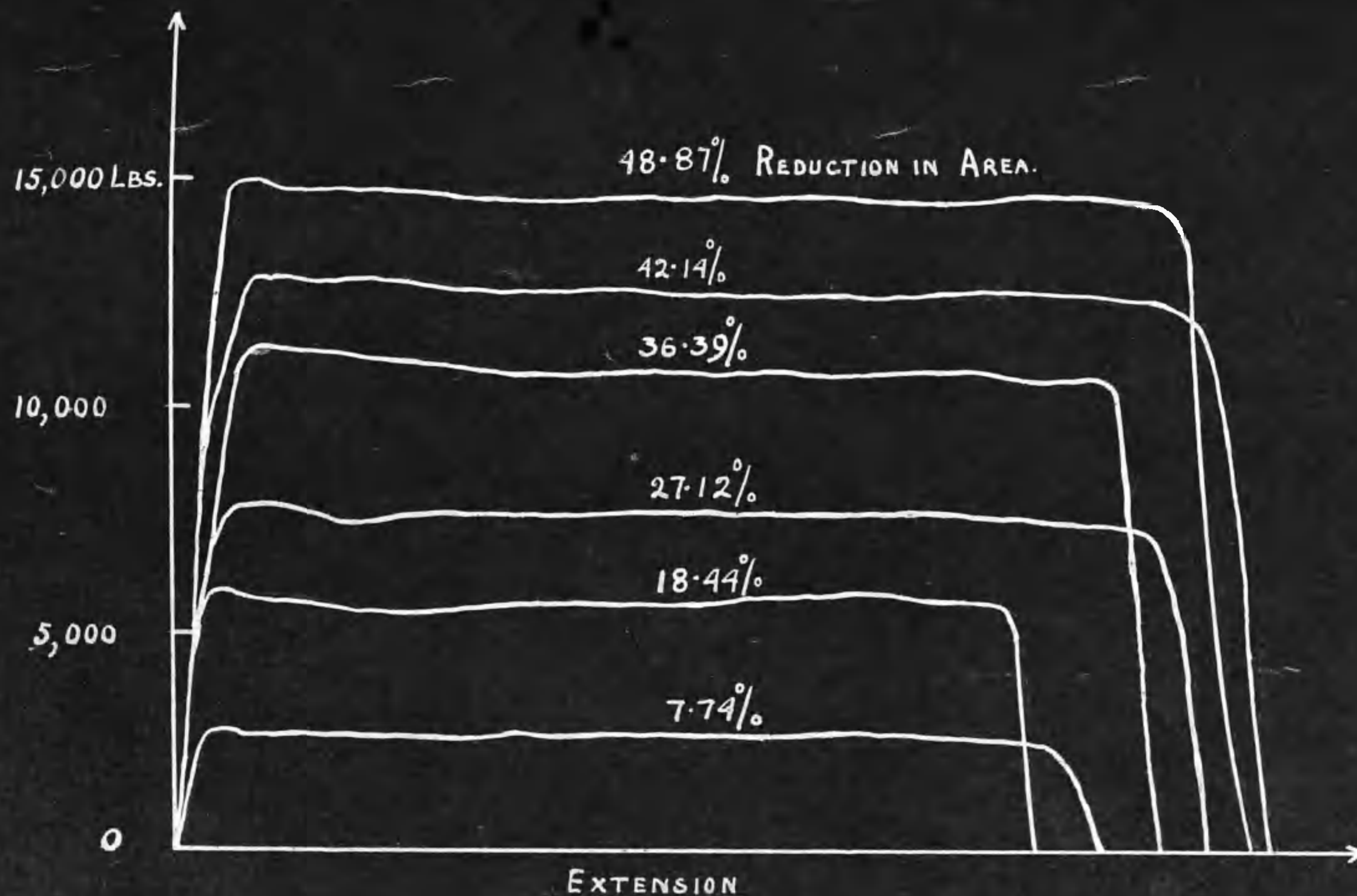

48·87% Reduction in Area.
42·14%
36·39%
27·12%
18·44%
7·74%
15,000 Lbs.
10,000
5,000
0
Extension

FIG 3.

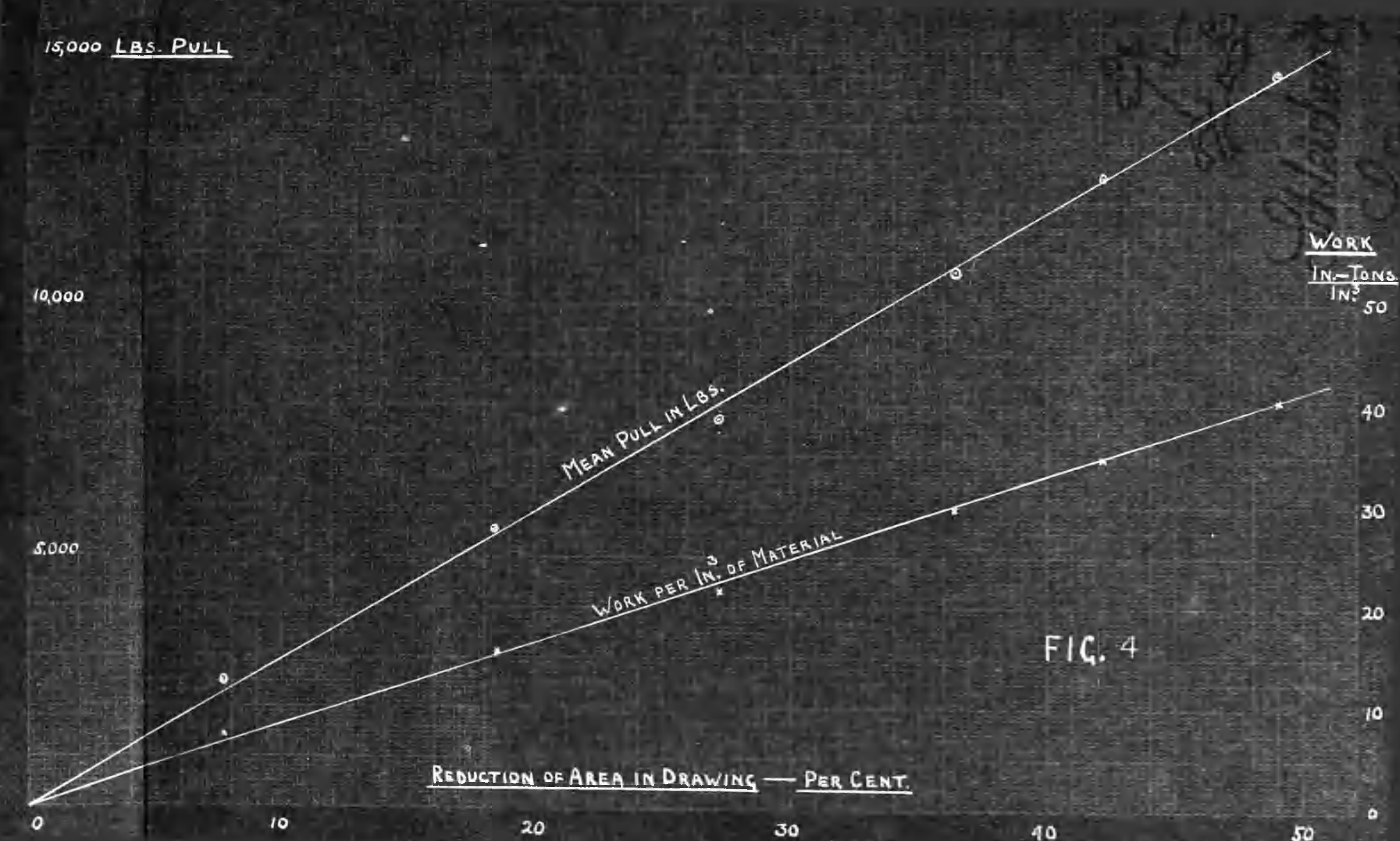

15,000 LBS. PULL
10,000
5,000
0
10
20
30
40
50
MEAN PULL IN LBS.
WORK PER IN.³ OF MATERIAL
REDUCTION OF AREA IN DRAWING — PER CENT.
WORK
IN.-TONS / IN.³
50
40
30
20
10
0

FIG. 4

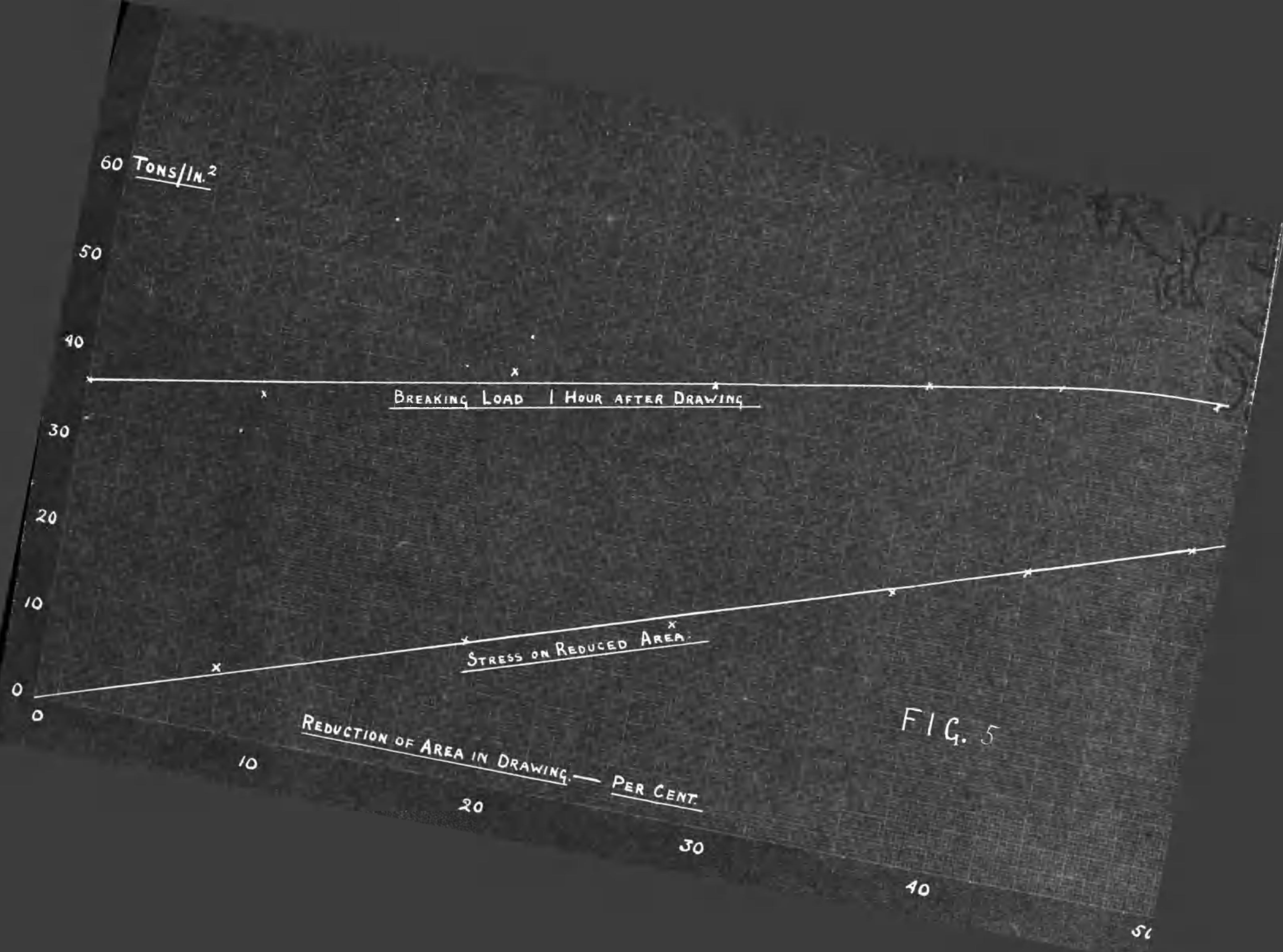
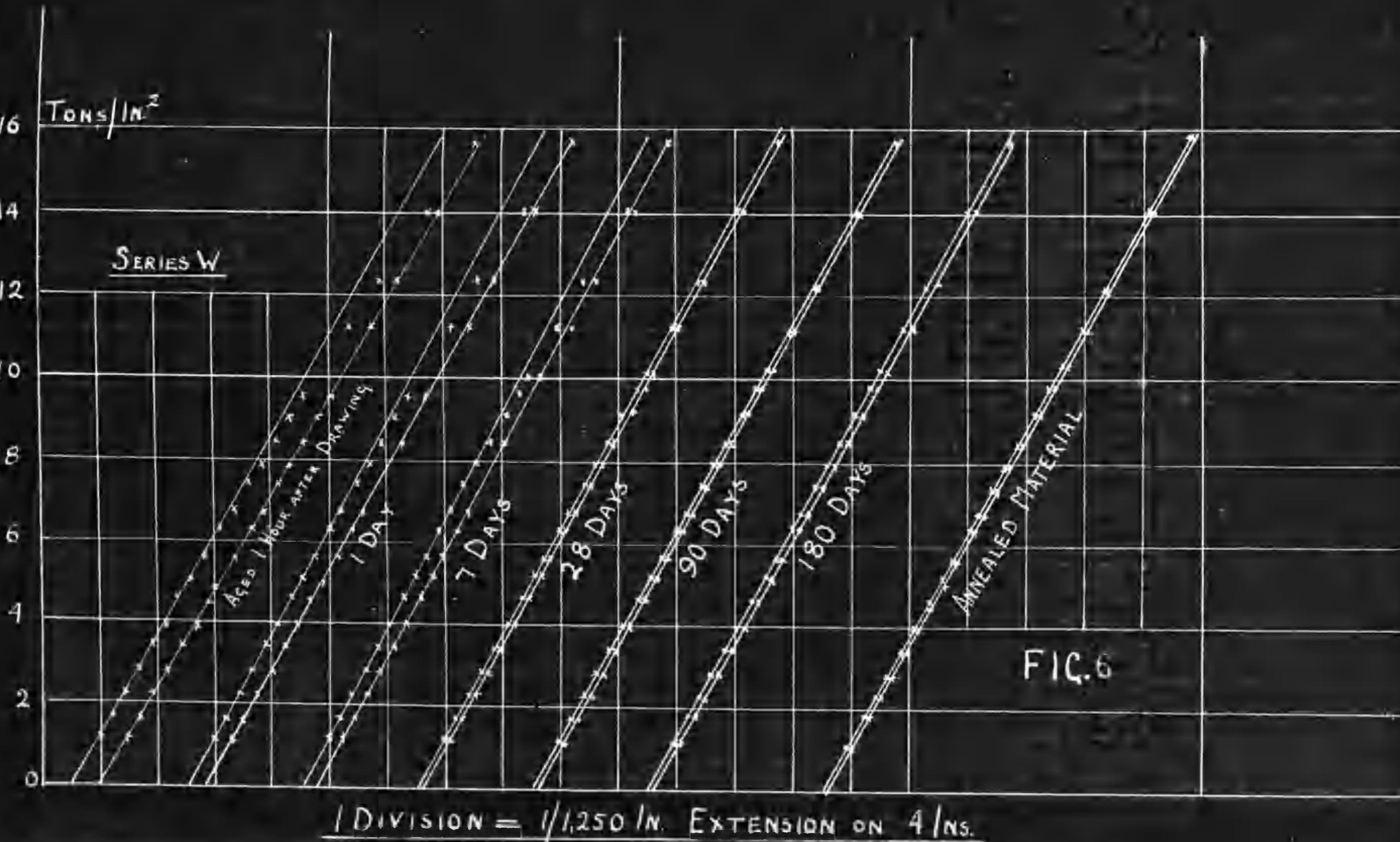

60 TONS/IN.2
50
40
30
20
10
0
BREAKING LOAD 1 HOUR AFTER DRAWING
STRESS ON REDUCED AREA.
0
10
20
30
40
REDUCTION OF AREA IN DRAWING.— PER CENT.

FIG. 5



Tons/In.²
Series W
16
14
12
10
8
6
4
2
0
Aged 1 Hour after Drawing
1 Day
7 Days
28 Days
90 Days
180 Days
Annealed Material
1 Division = 1/1,250 In. Extension on 4 Ins.

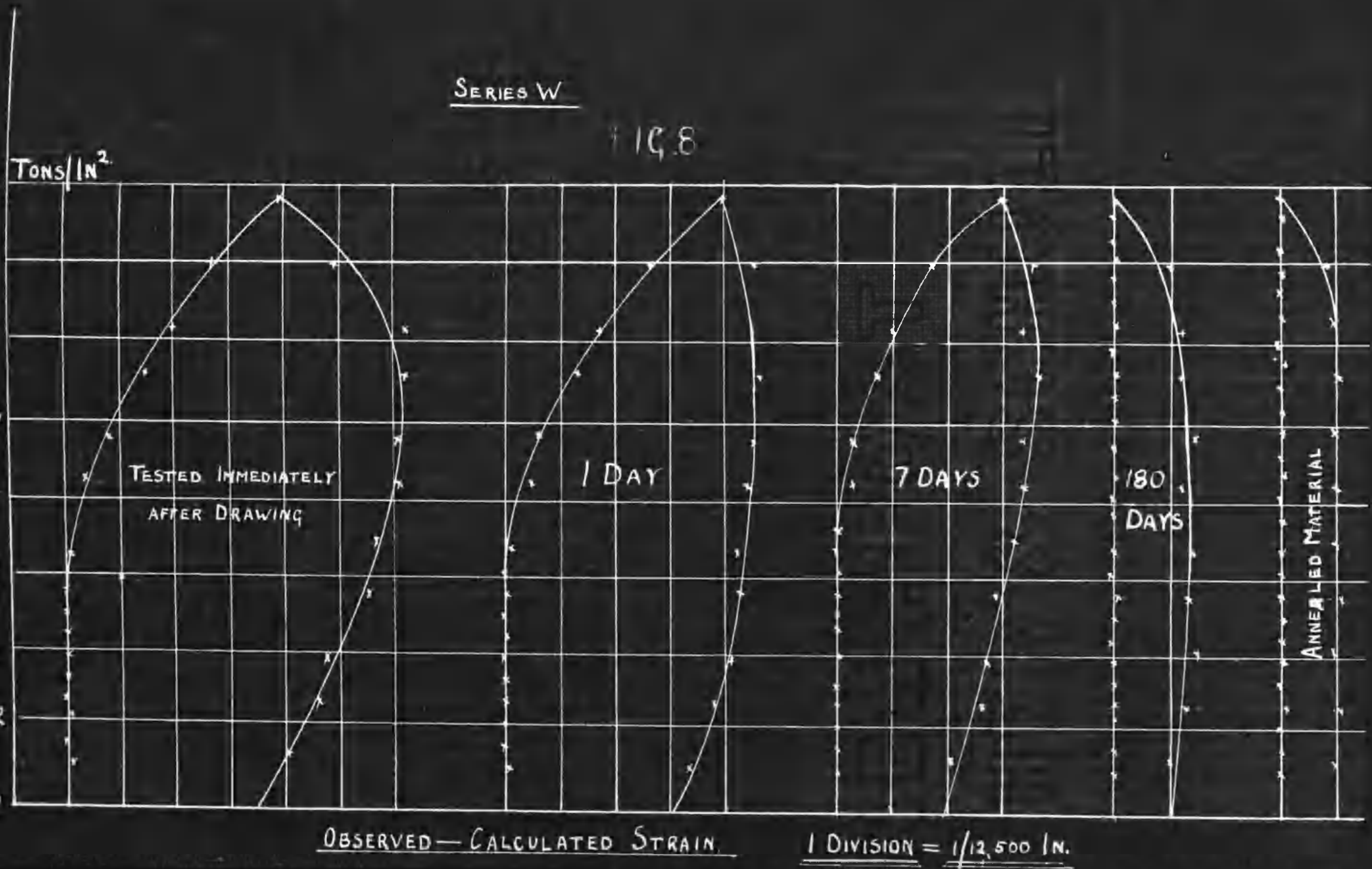
FIG. 6

FIG. 7

SERIES W
TONS/IN.^{2}
10
8
6
4
2
0
TESTED 1 DAY AFTER DRAWING
4 DAYS
7 DAYS
28 DAYS
90 DAYS
180 DAYS
ANNEALED MATERIAL
1 DIVISION = 1/1,250 EXTENSION ON 2 INS.

SERIES W

FIG. 8



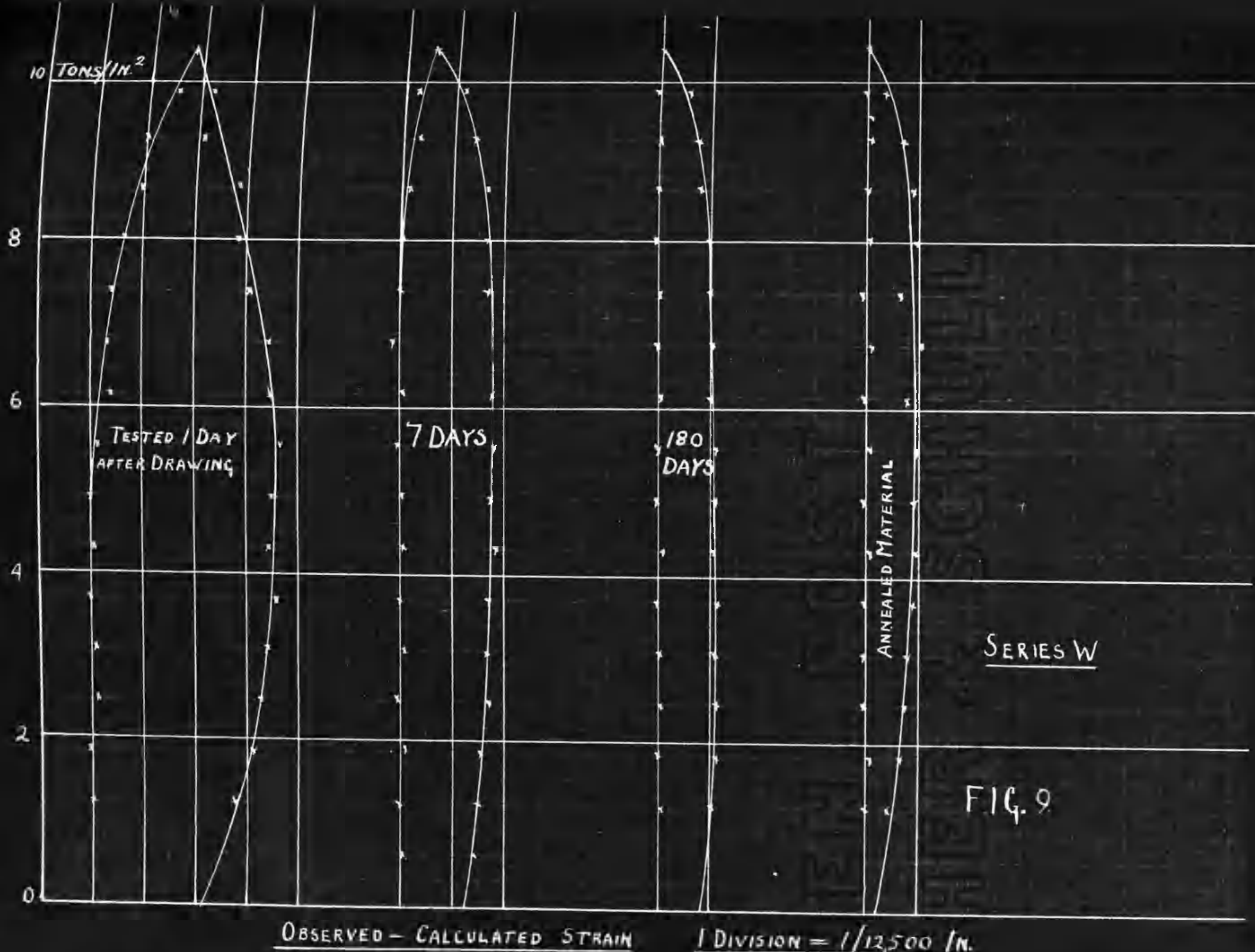
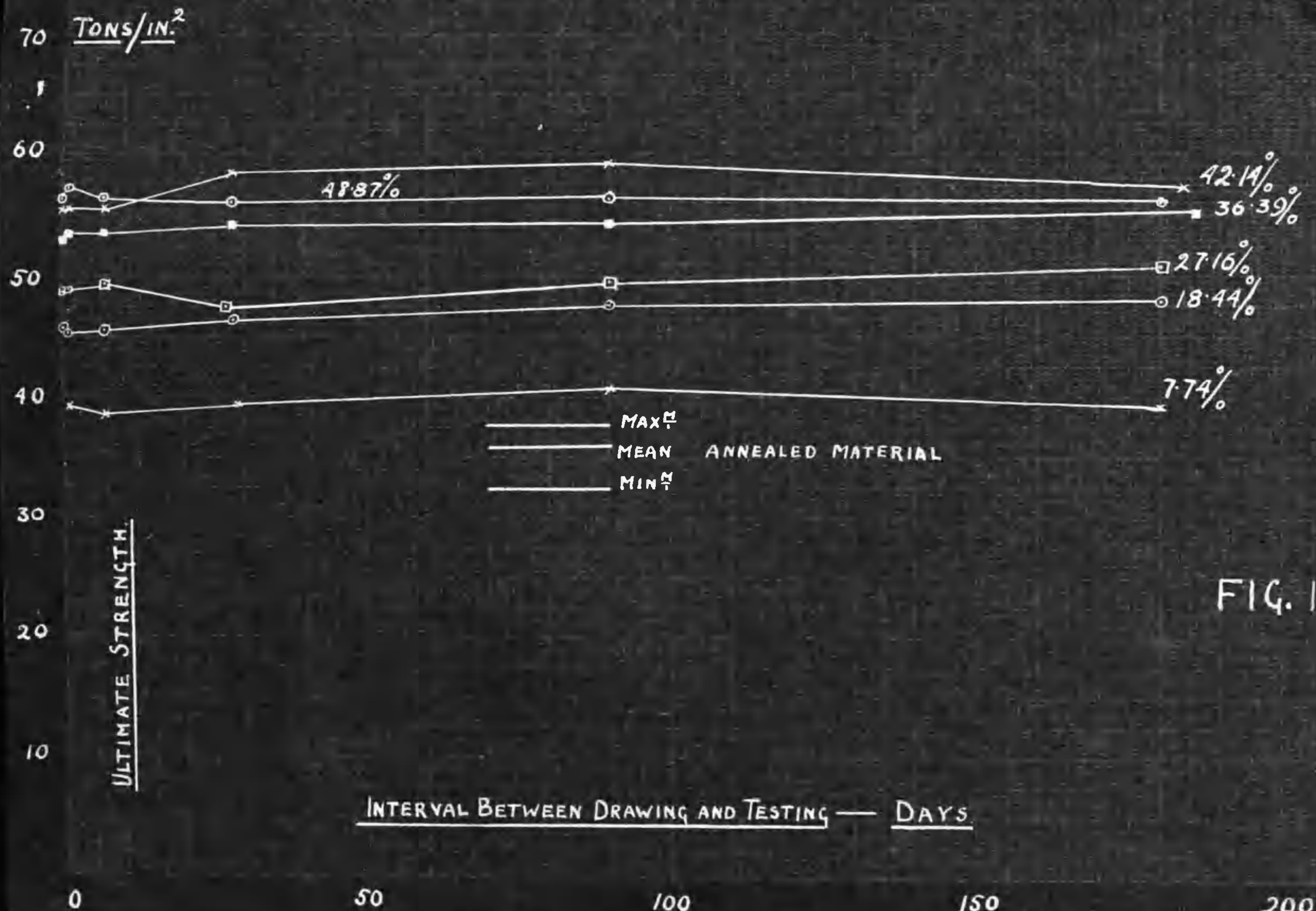
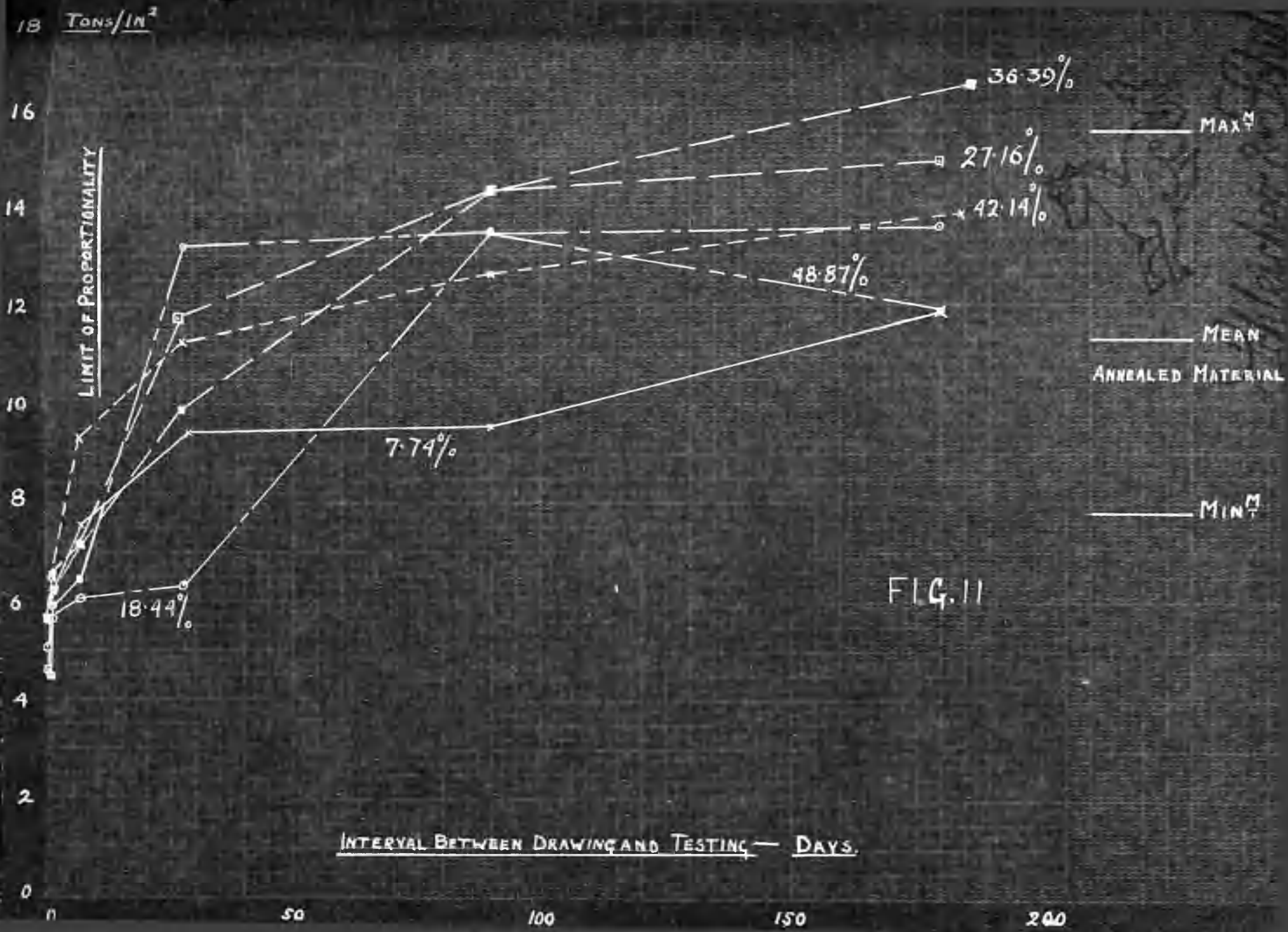

10 TONS/IN.²
8
6
4
2
0
TESTED 1 DAY AFTER DRAWING
7 DAYS
180 DAYS
ANNEALED MATERIAL
SERIES W
OBSERVED – CALCULATED STRAIN
1 DIVISION = 1/12500 IN.

FIG. 9



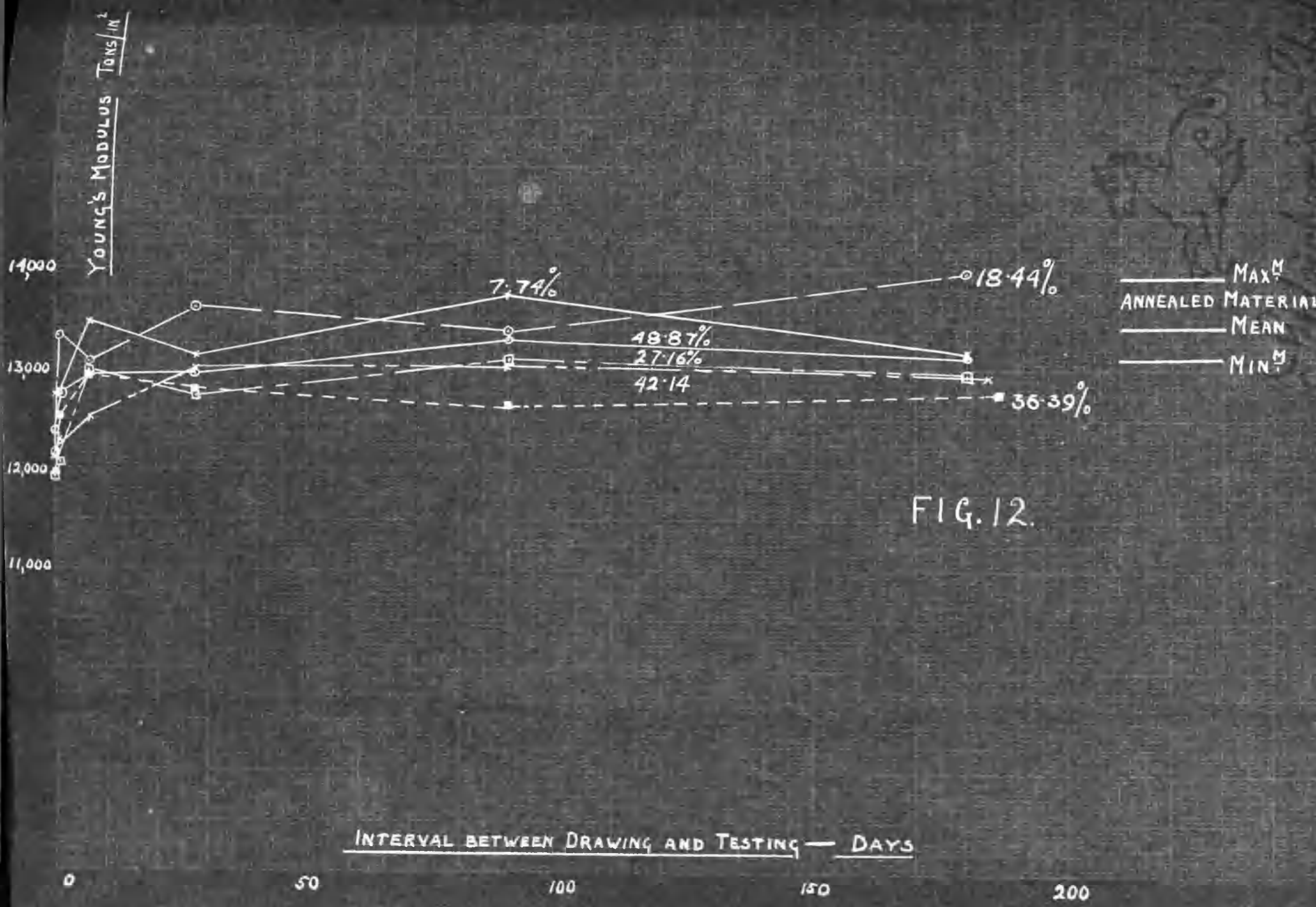
Tons/in.²
70
60
50
40
30
20
10
Ultimate Strength.
48·87%
42·14%
36·39%
27·16%
18·44%
7·74%
Maxᵐ
Mean
Minᵐ
Annealed Material
Interval Between Drawing and Testing — Days
0
50
100
150
200

FIG. 10



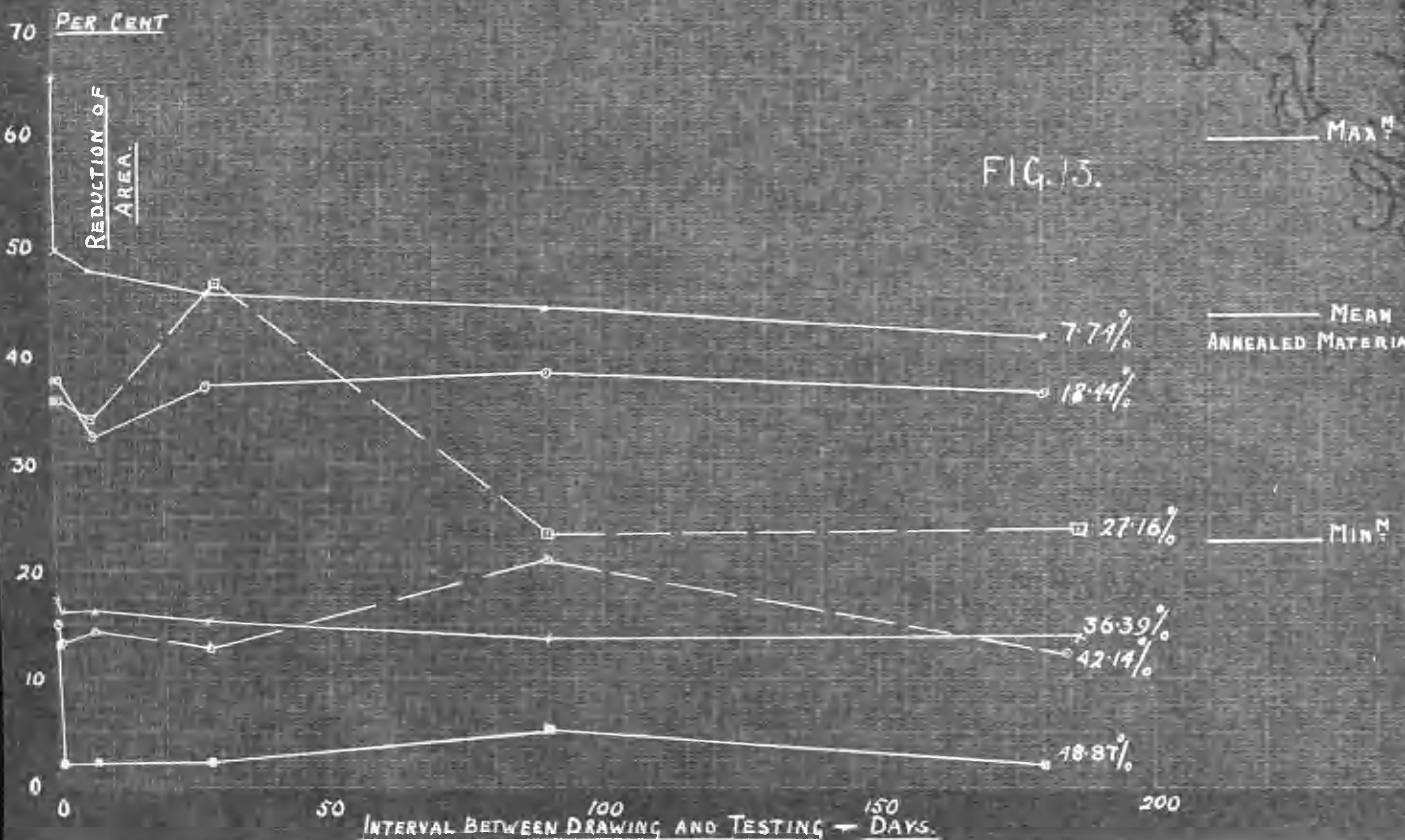
Tons/In²
Limit of Proportionality
36·39%
27·16%
42·14%
48·87%
7·74%
18·44%
Maxᴹ
Mean
Annealed Material
Minᴹ
Interval Between Drawing and Testing — Days.
0
2
4
6
8
10
12
14
16
18
0
50
100
150
200

FIG. 11



Young's Modulus Tons/in²
14,000
13,000
12,000
11,000
7.74%
18.44%
48.87%
27.16%
42.14
36.39%
Maxᴹ
Annealed Material
Mean
Minᴹ
Interval between Drawing and Testing — Days
0
50
100
150
200

FIG. 12.



PER CENT
REDUCTION OF AREA.
70
60
50
40
30
20
10
0
0
50
100
150
200
INTERVAL BETWEEN DRAWING AND TESTING — DAYS.
7·71%
18·44%
27·16%
36·39%
42·14%
48·87%
MAX^M
MEAN ANNEALED MATERIAL
MIN^M

FIG. 15.

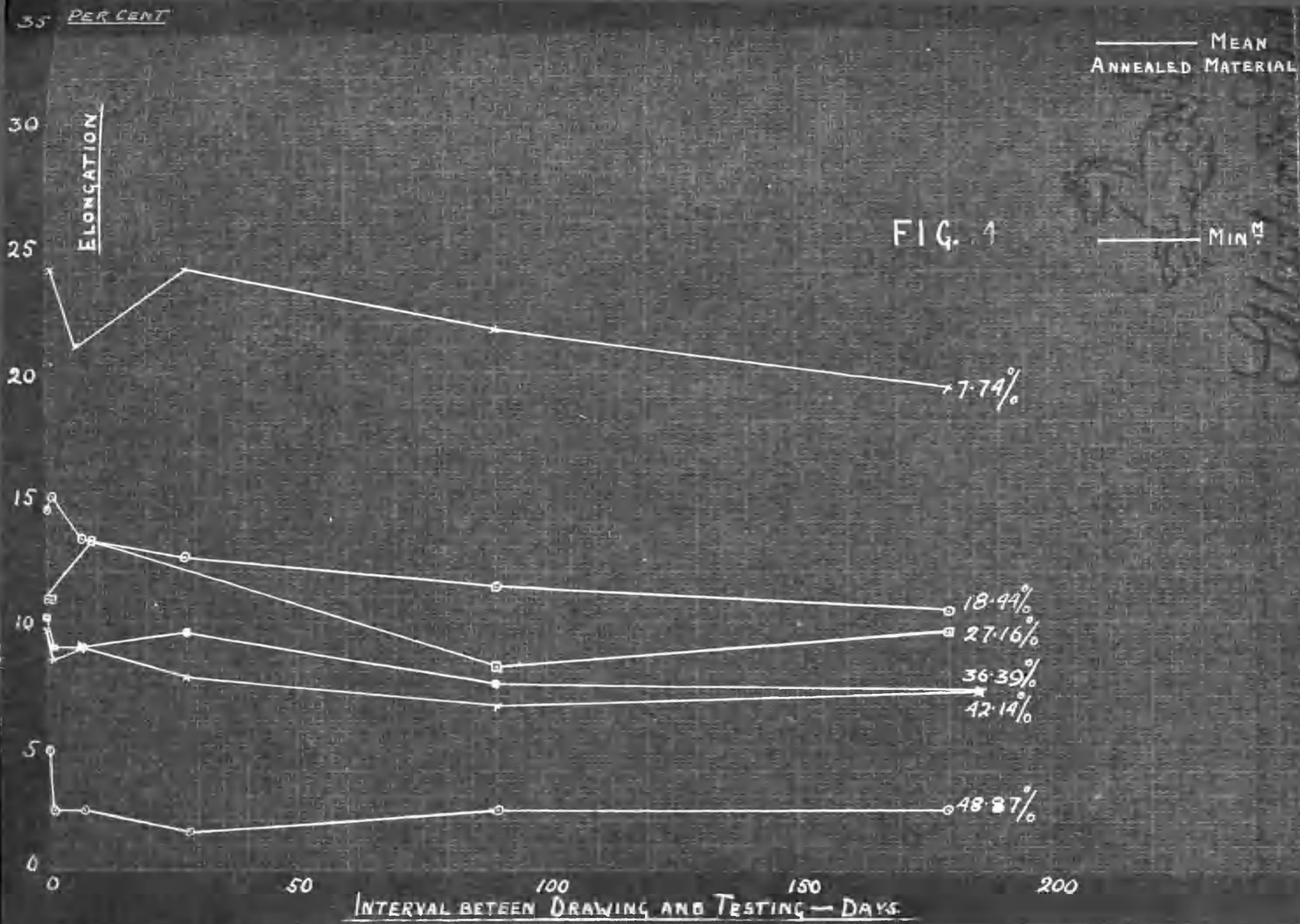

35 PER CENT
30
25
20
15
10
5
0
ELONGATION
MEAN
ANNEALED MATERIAL
MIN^{M}
7·74%
18·44%
27·16%
36·39%
42·14%
48·87%
0
50
100
150
200
INTERVAL BETEEN DRAWING AND TESTING — DAYS

FIG. 4

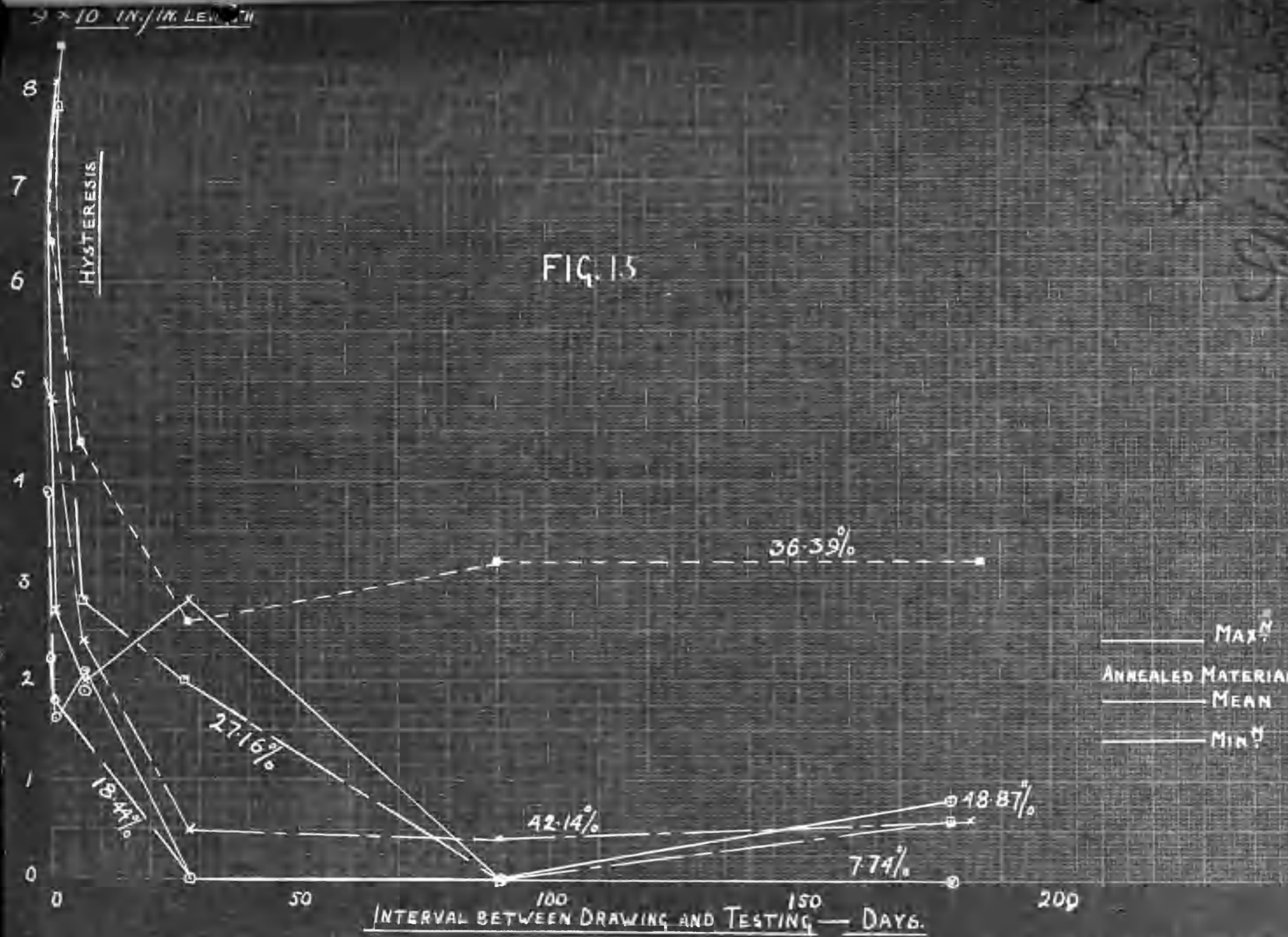
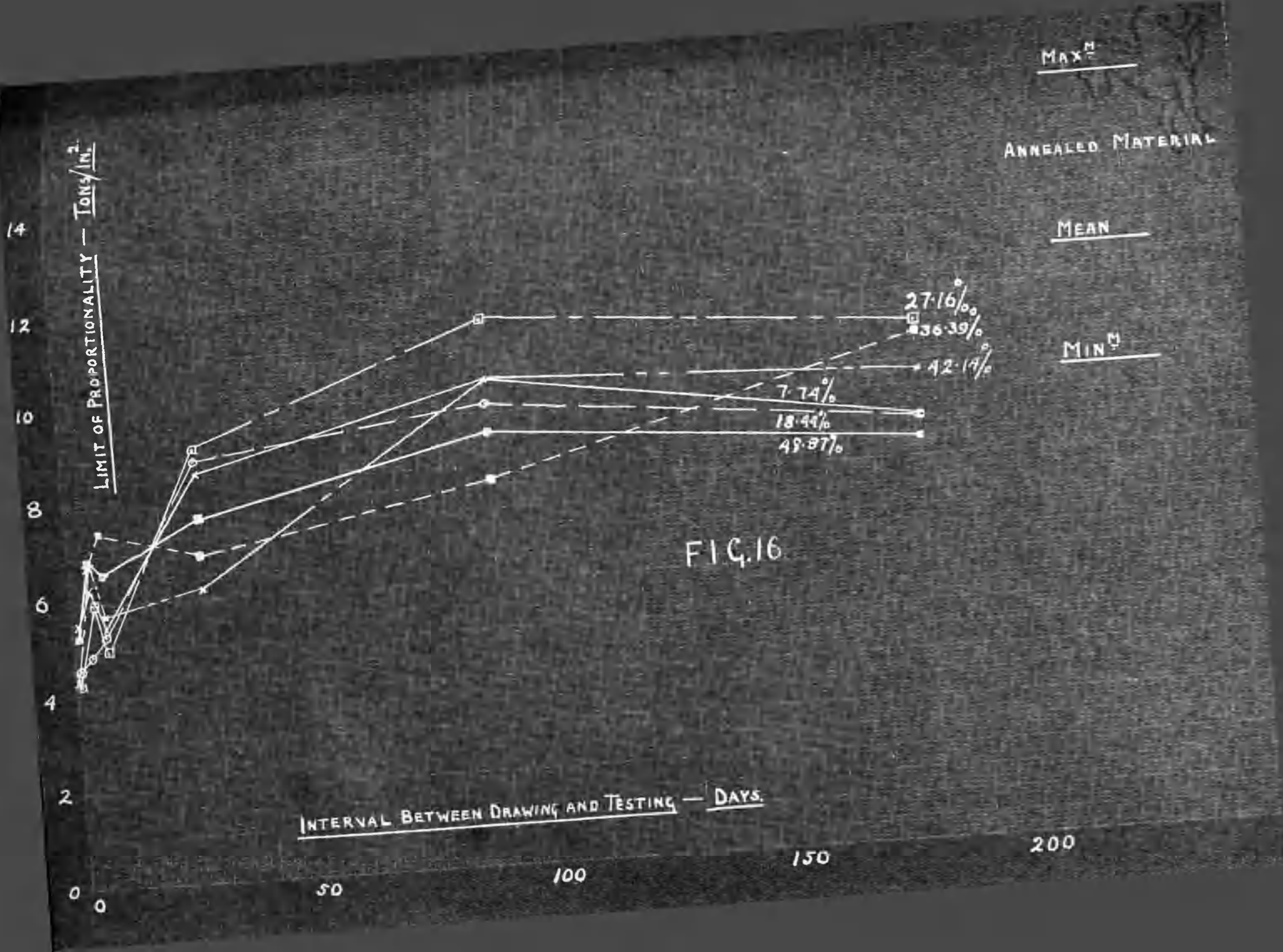


FIG. 13
9 × 10 IN./IN. LENGTH
HYSTERESIS
8
7
6
5
4
3
2
1
0
0
50
100
150
200
INTERVAL BETWEEN DRAWING AND TESTING — DAYS.
36·39%
27·16%
18·44%
42·14%
48·87%
7·74%
MAXM.
ANNEALED MATERIAL
MEAN
MINM.



MAXM.
ANNEALED MATERIAL
MEAN
MINM.
LIMIT OF PROPORTIONALITY — TONS/IN.2
14
12
10
8
6
4
2
0
0
50
100
150
200
27·16%
36·39%
42·19%
7·74%
18·44%
49·87%
INTERVAL BETWEEN DRAWING AND TESTING — DAYS.

FIG. 16

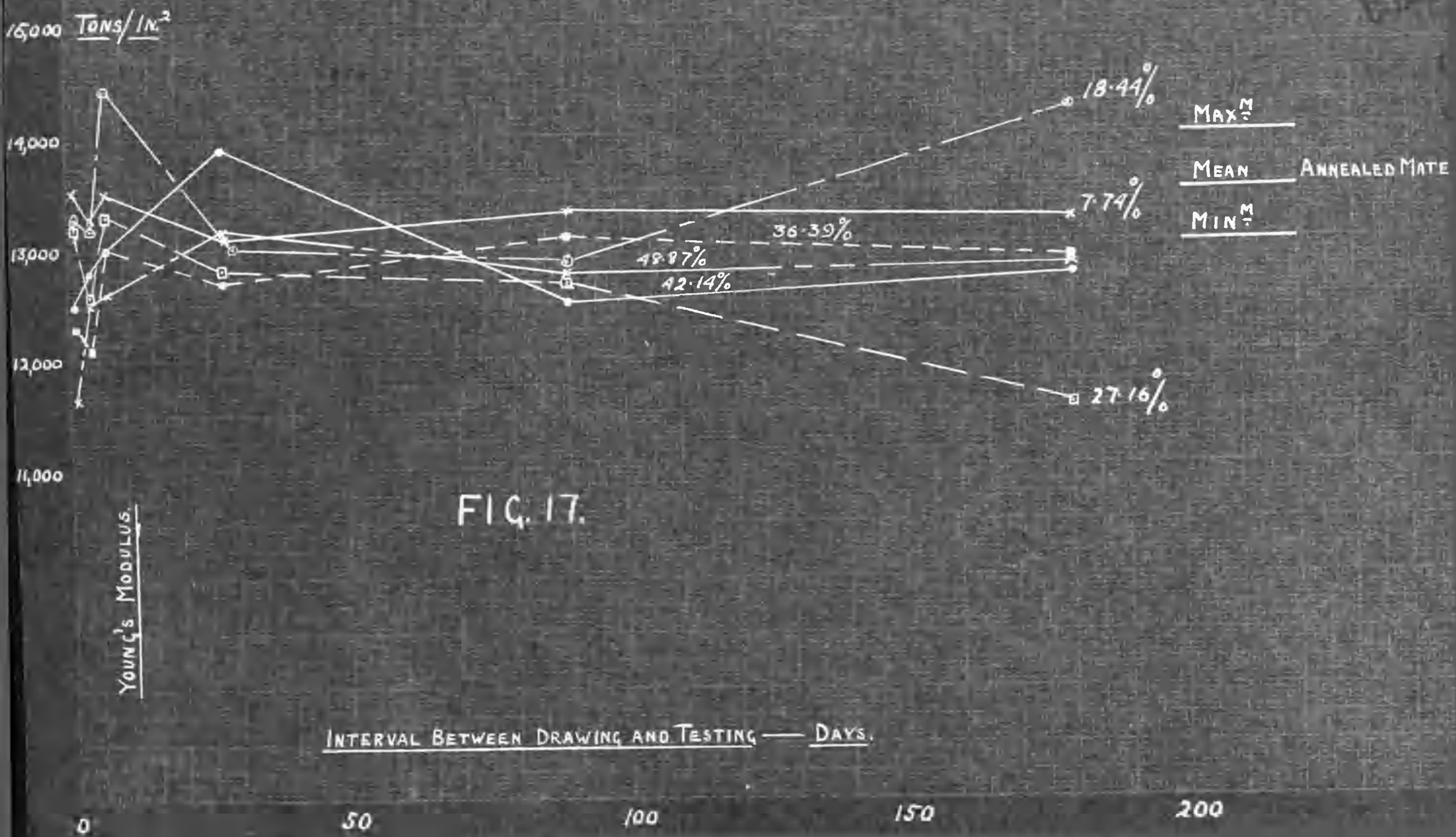
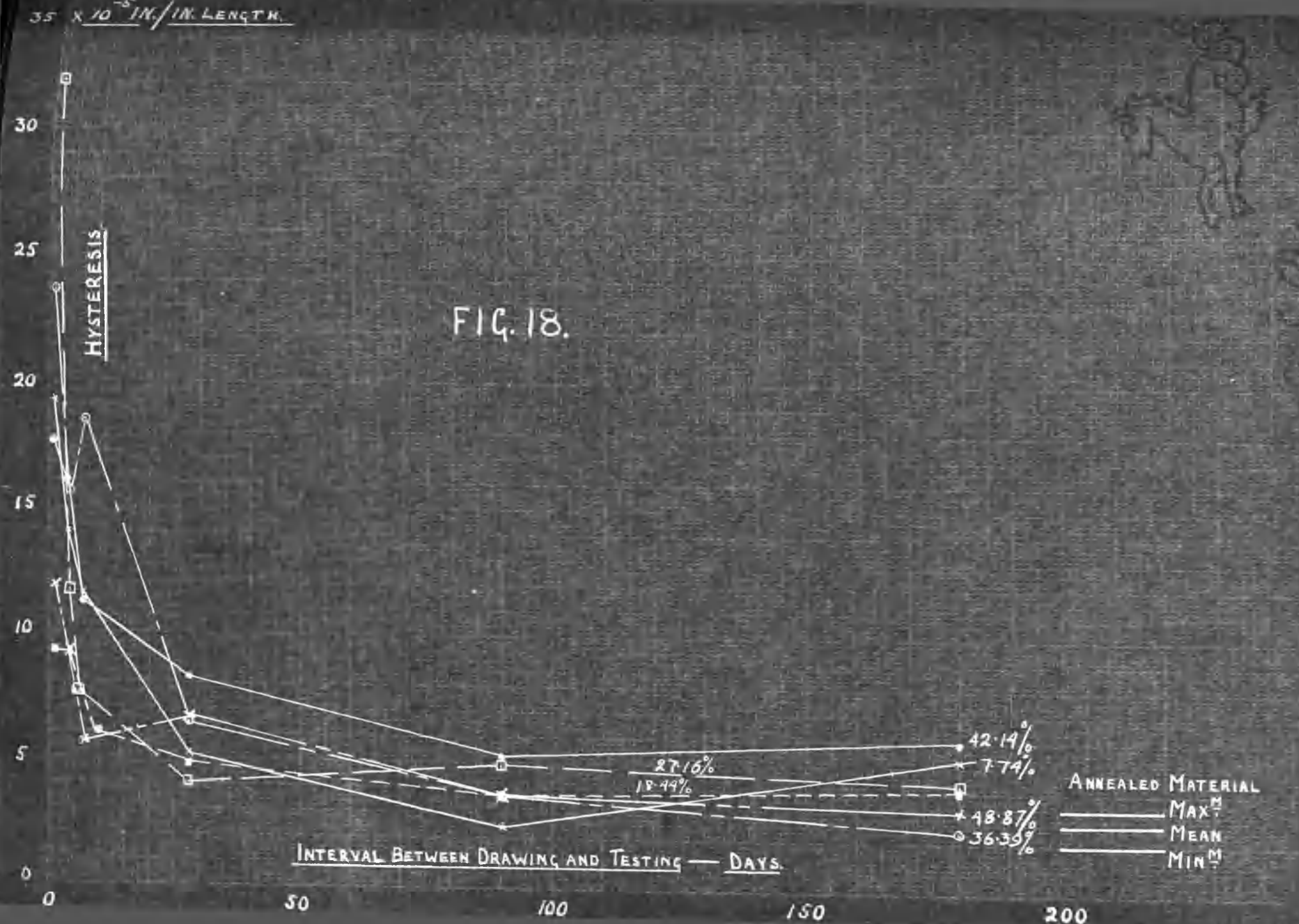

Tons/In.²
16,000
14,000
13,000
12,000
11,000
Young's Modulus.
18·44%
7·74%
36·39%
48·87%
42·14%
27·16%
Max.^m
Mean
Min.^m
Annealed Mate
Interval Between Drawing and Testing — Days.
0
50
100
150
200

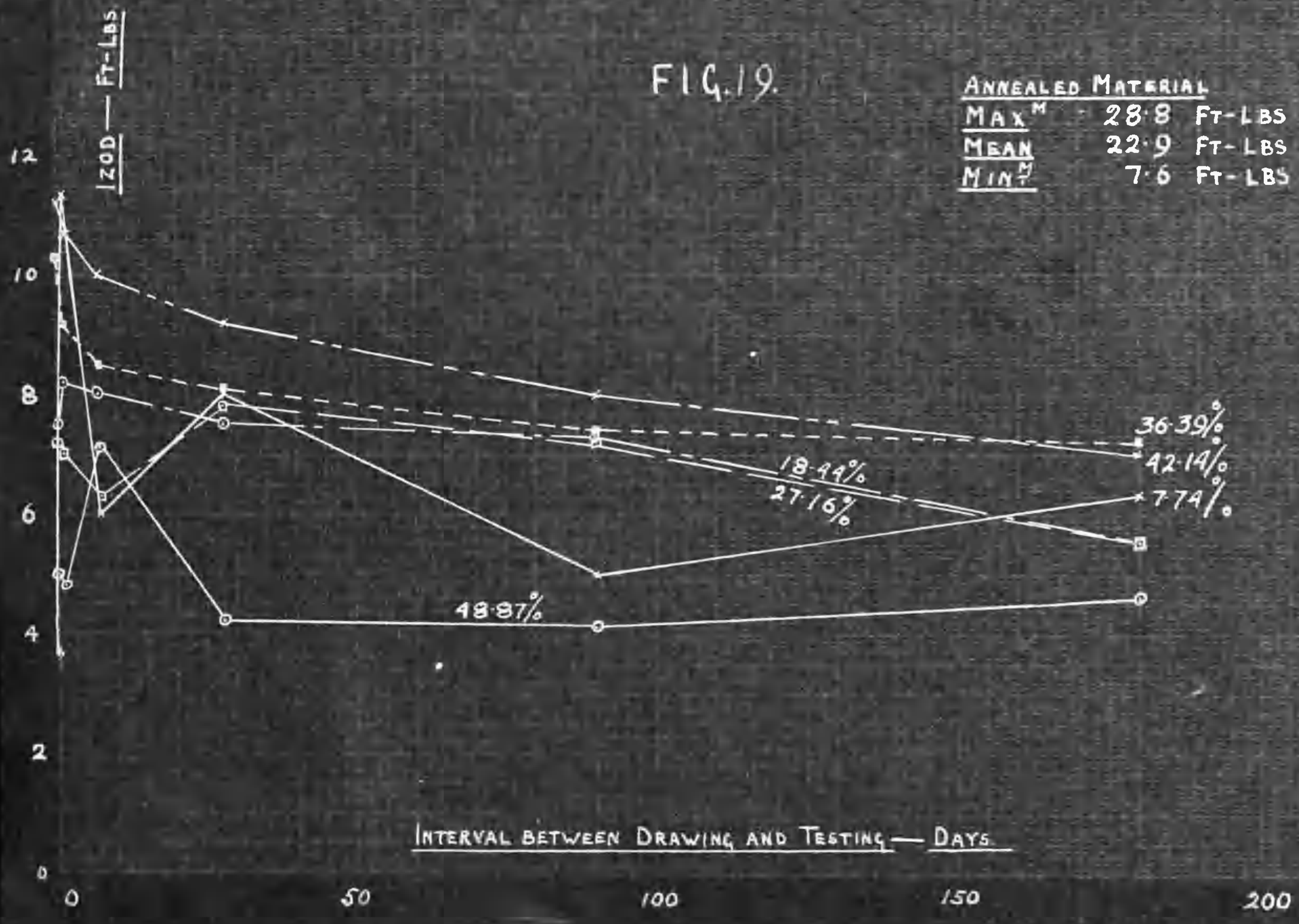
FIG. 17.



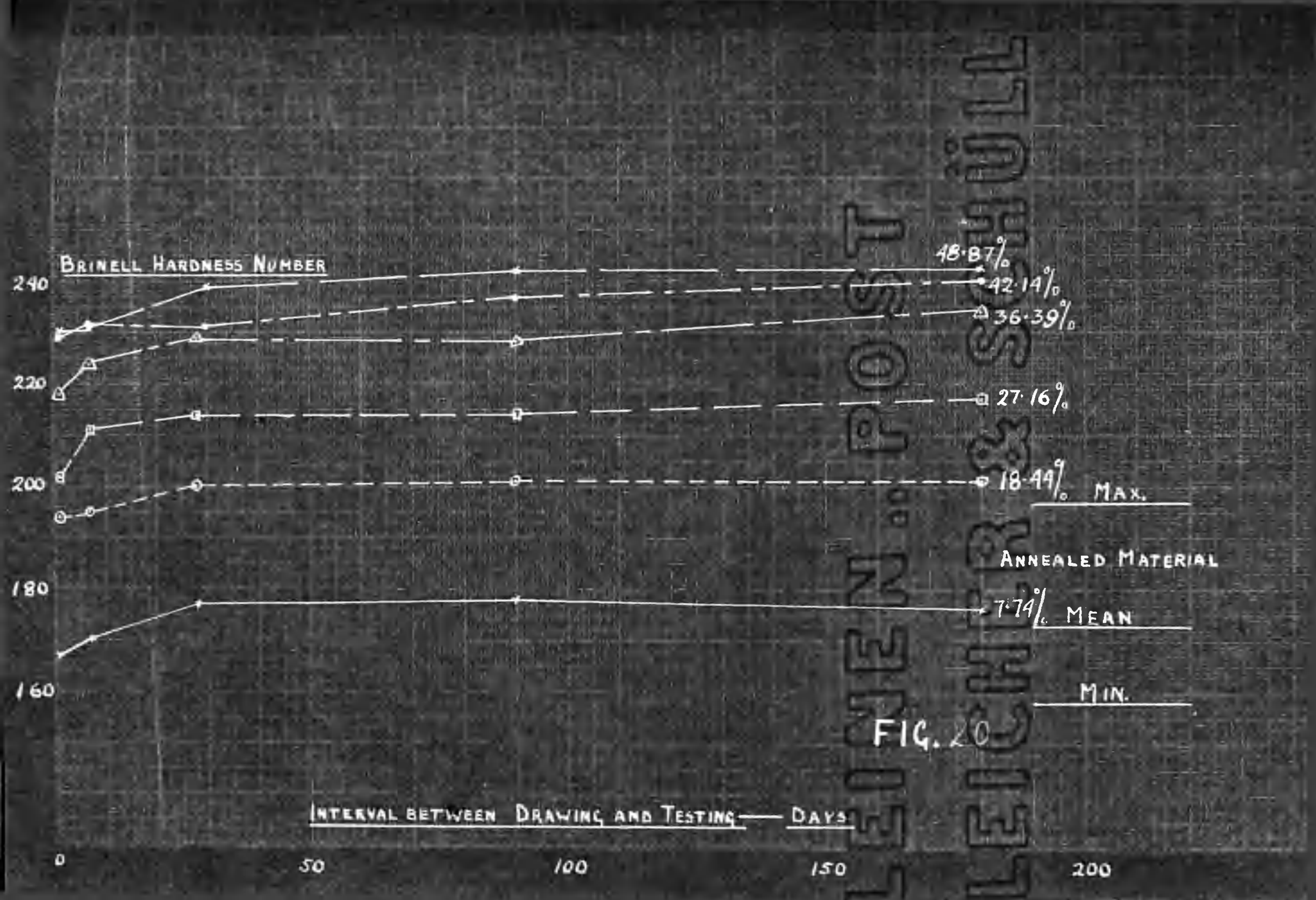
35 × 10^{-5} IN./IN. LENGTH.
HYSTERESIS
30
25
20
15
10
5
0
0
50
100
150
200
INTERVAL BETWEEN DRAWING AND TESTING — DAYS.
42·14%
7·74%
27·16%
18·44%
48·87%
36·39%
ANNEALED MATERIAL
MAX^{M}
MEAN
MIN^{M}

FIG. 18.

FIG. 19.



Annealed Material
Max^m 28·8 Ft-Lbs
Mean 22·9 Ft-Lbs
Min^m 7·6 Ft-Lbs
Izod — Ft-Lbs
36·39%
42·14%
7·74%
18·44%
27·16%
48·87%
12
10
8
6
4
2
0
0
50
100
150
200
Interval between Drawing and Testing — Days



Brinell Hardness Number
240
220
200
180
160
0
50
100
150
200
Interval between Drawing and Testing —— Days
48·87%
42·14%
36·39%
27·16%
18·44%
7·74%
Max.
Annealed Material
Mean
Min.

FIG. 20

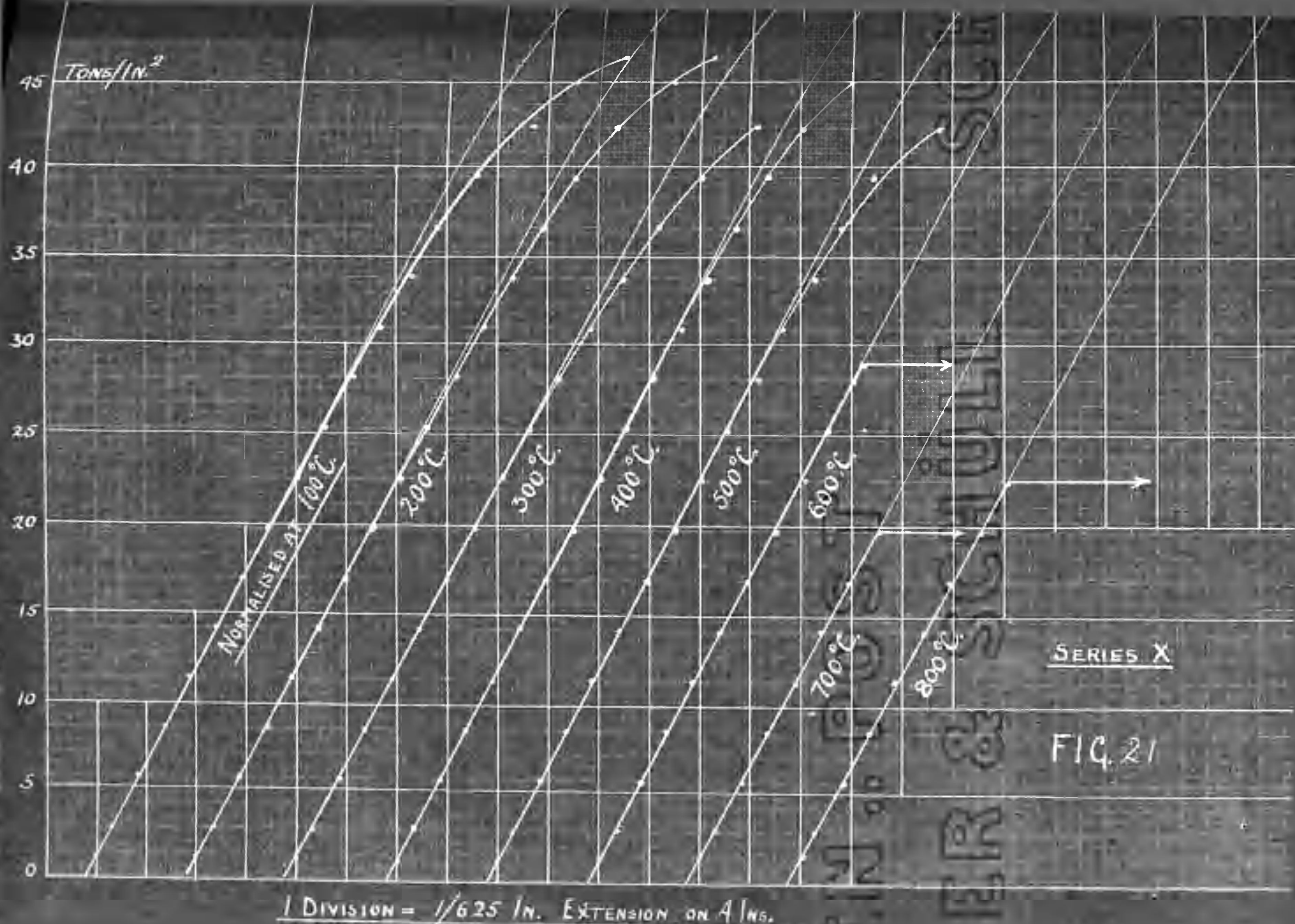
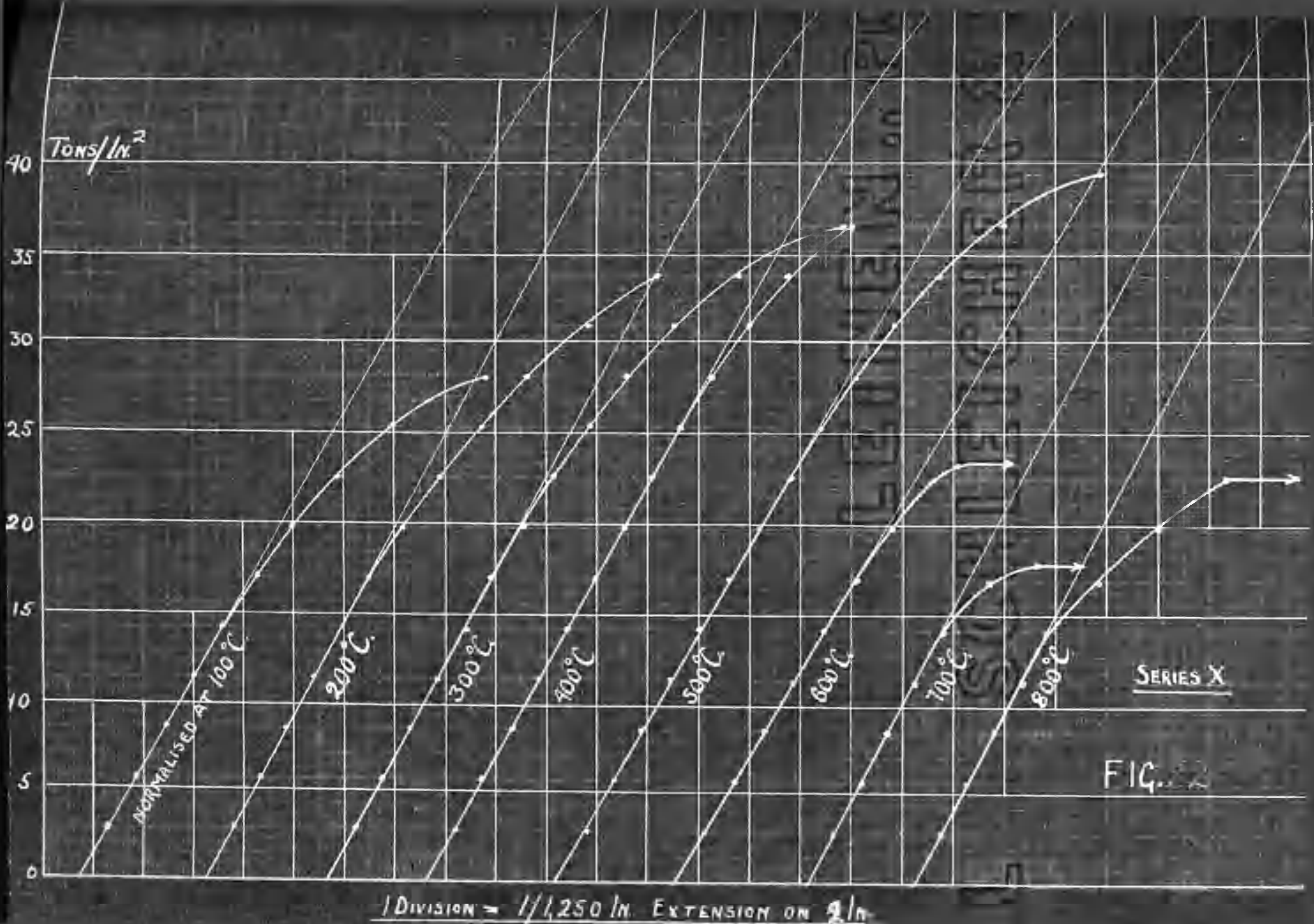
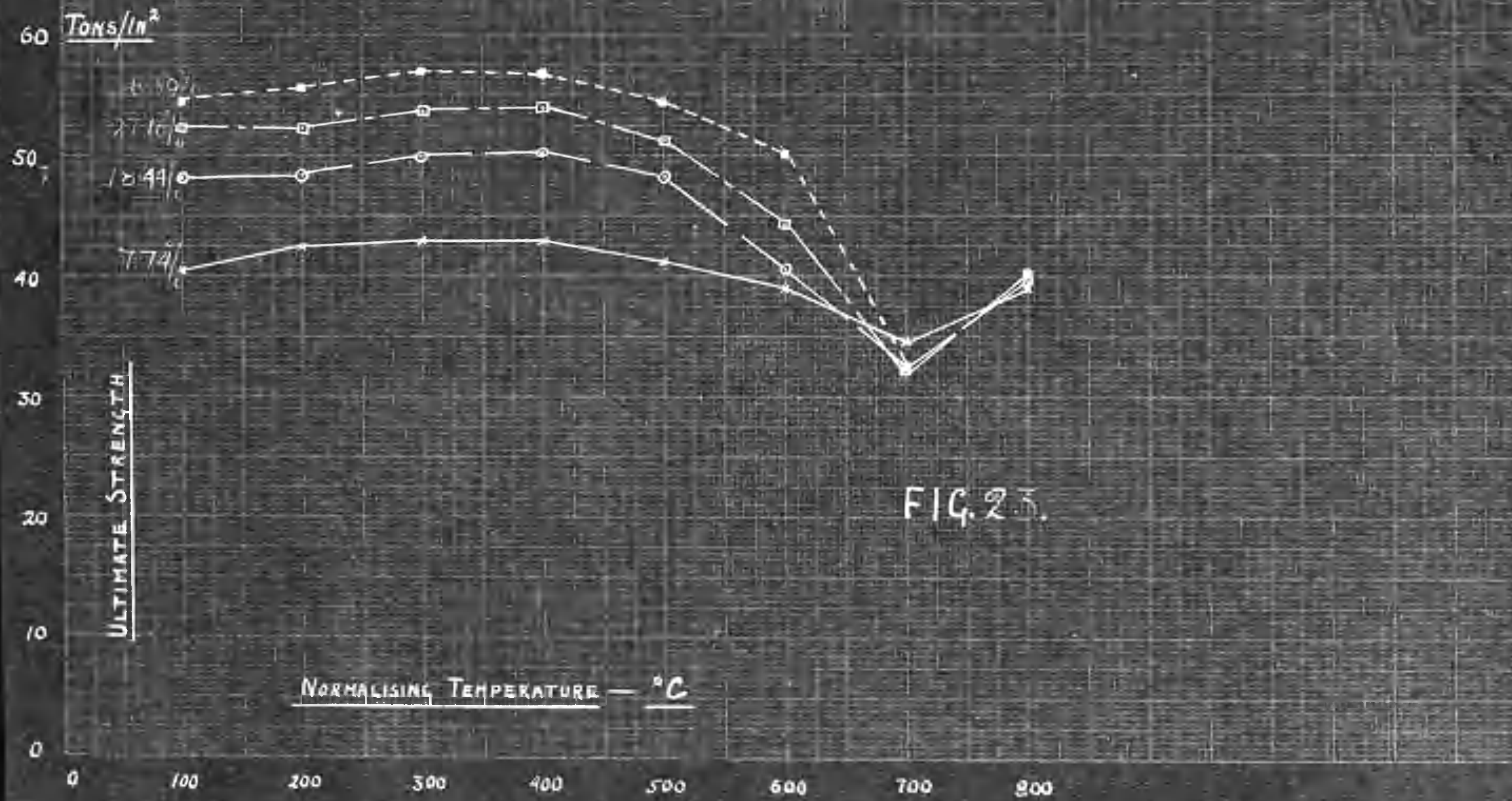

TONS/IN.^{2}
45
40
35
30
25
20
15
10
5
0
NORMALISED AT 100°C.
200°C.
300°C.
400°C.
500°C.
600°C.
700°C.
800°C.
SERIES X
1 DIVISION = 1/625 IN. EXTENSION ON 4 INS.

FIG. 21

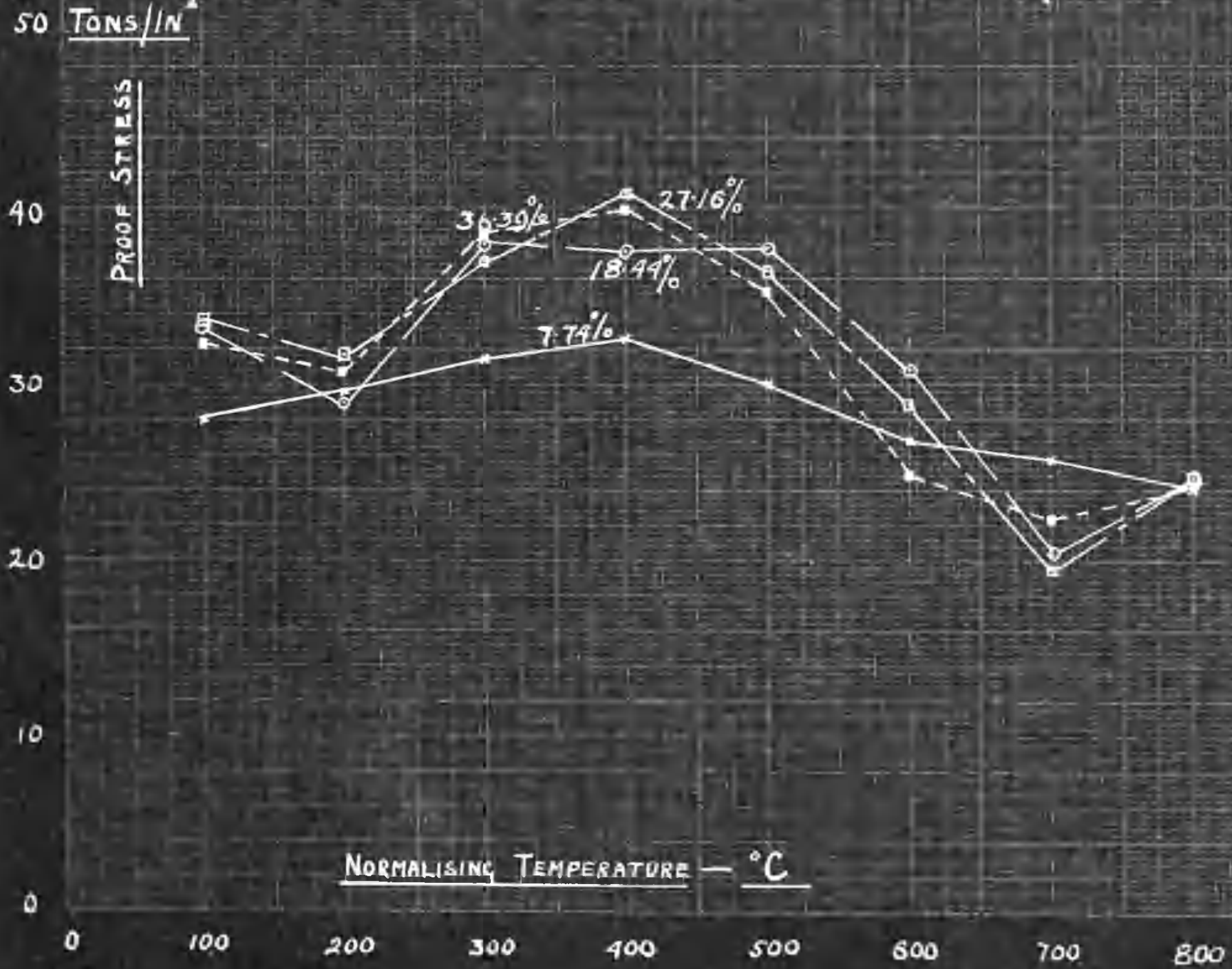

Tons/In.²
0
5
10
15
20
25
30
35
40
Normalised at 100°C.
200°C.
300°C.
400°C.
500°C.
600°C.
700°C.
800°C.
Series X
FIG.
1 Division = 1/1,250 In. Extension on 2 In.



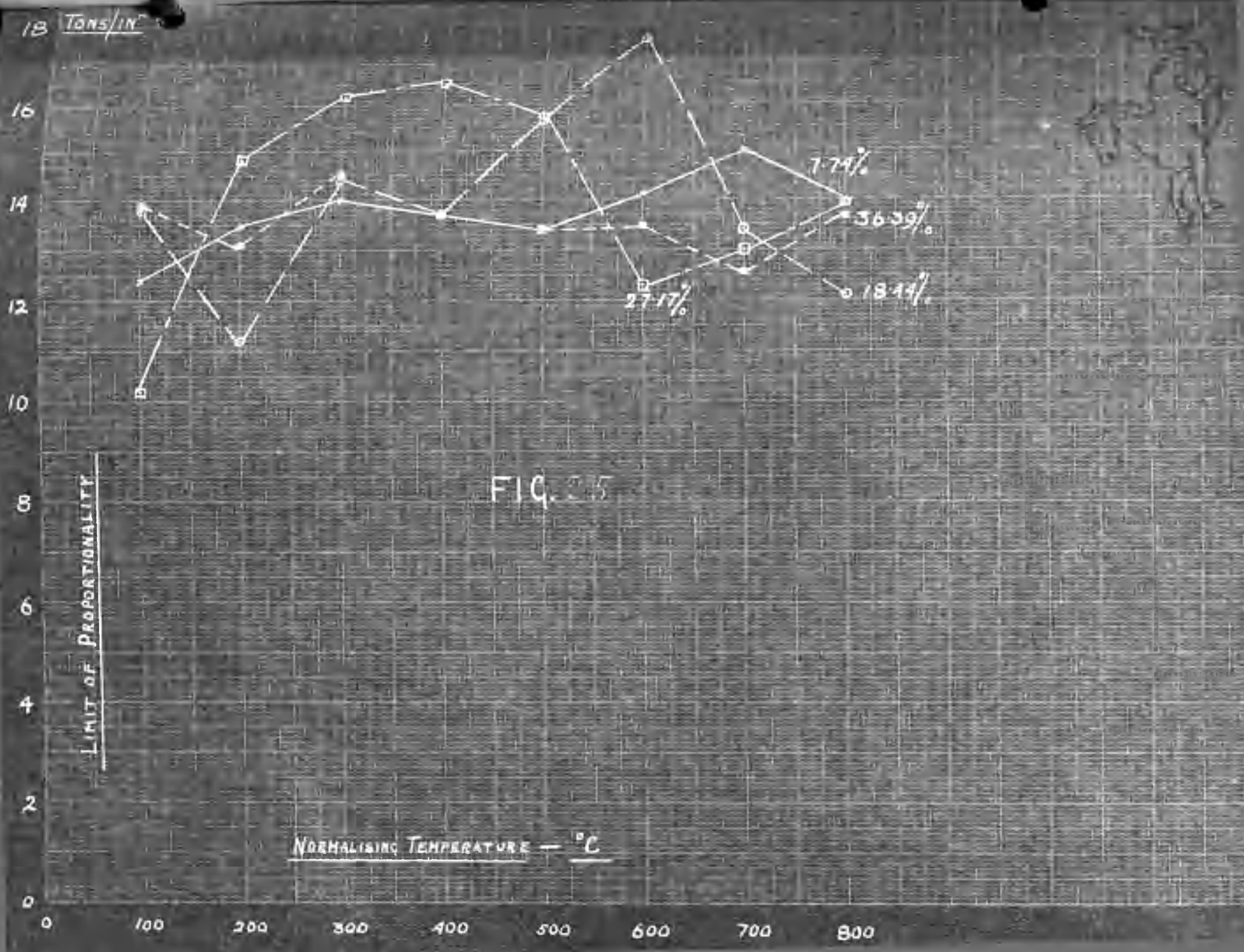
TONS/IN²
37.10%
18.44%
7.74%
ULTIMATE STRENGTH
NORMALISING TEMPERATURE — °C
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800

FIG. 23.

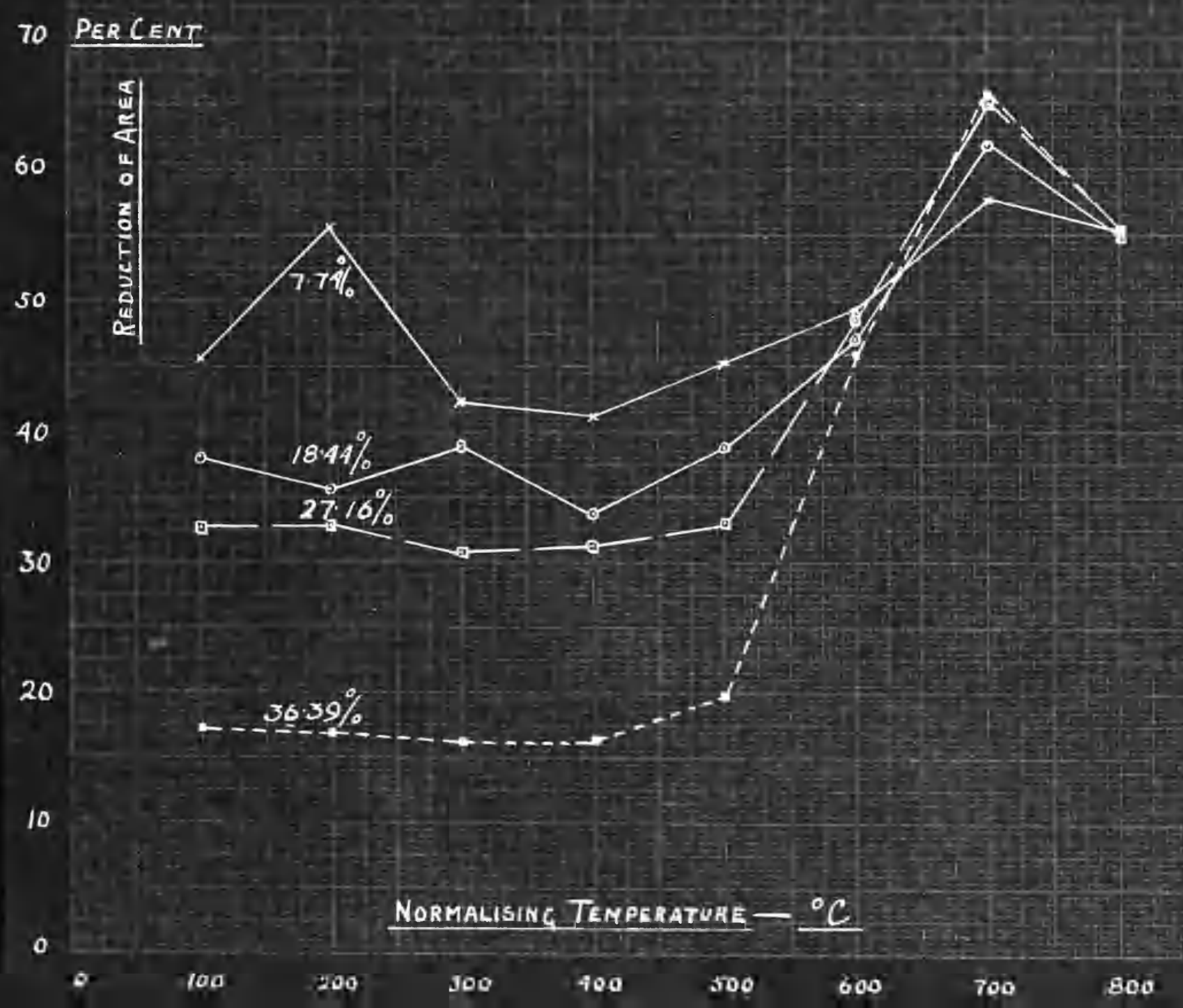
FIG. 24



Tons/in²
Proof Stress
50
40
30
20
10
0
36·39%
27·16%
18·44%
7·74%
Normalising Temperature — °C
0
100
200
300
400
500
600
700
800



18 TONS/IN²
16
14
12
10
8
6
4
2
0
LIMIT OF PROPORTIONALITY
7·74%
36·39%
18·44%
27·17%
FIG.
NORMALISING TEMPERATURE — °C
0
100
200
300
400
500
600
700
800



PER CENT
REDUCTION OF AREA
70
60
50
40
30
20
10
0
7·74%
18·44%
27·16%
36·39%
NORMALISING TEMPERATURE — °C
100
200
300
400
500
600
700
800

FIG. 26.

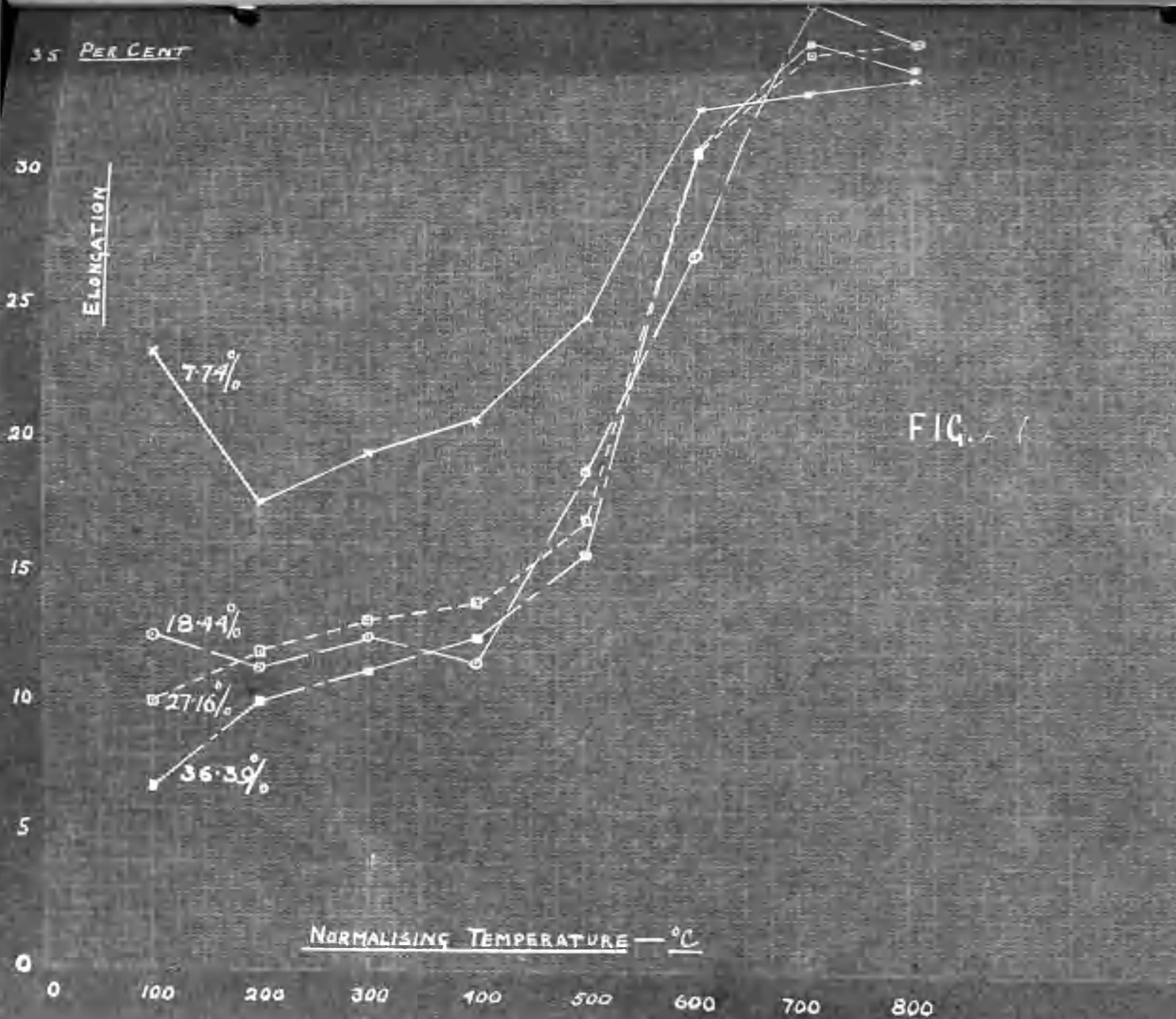
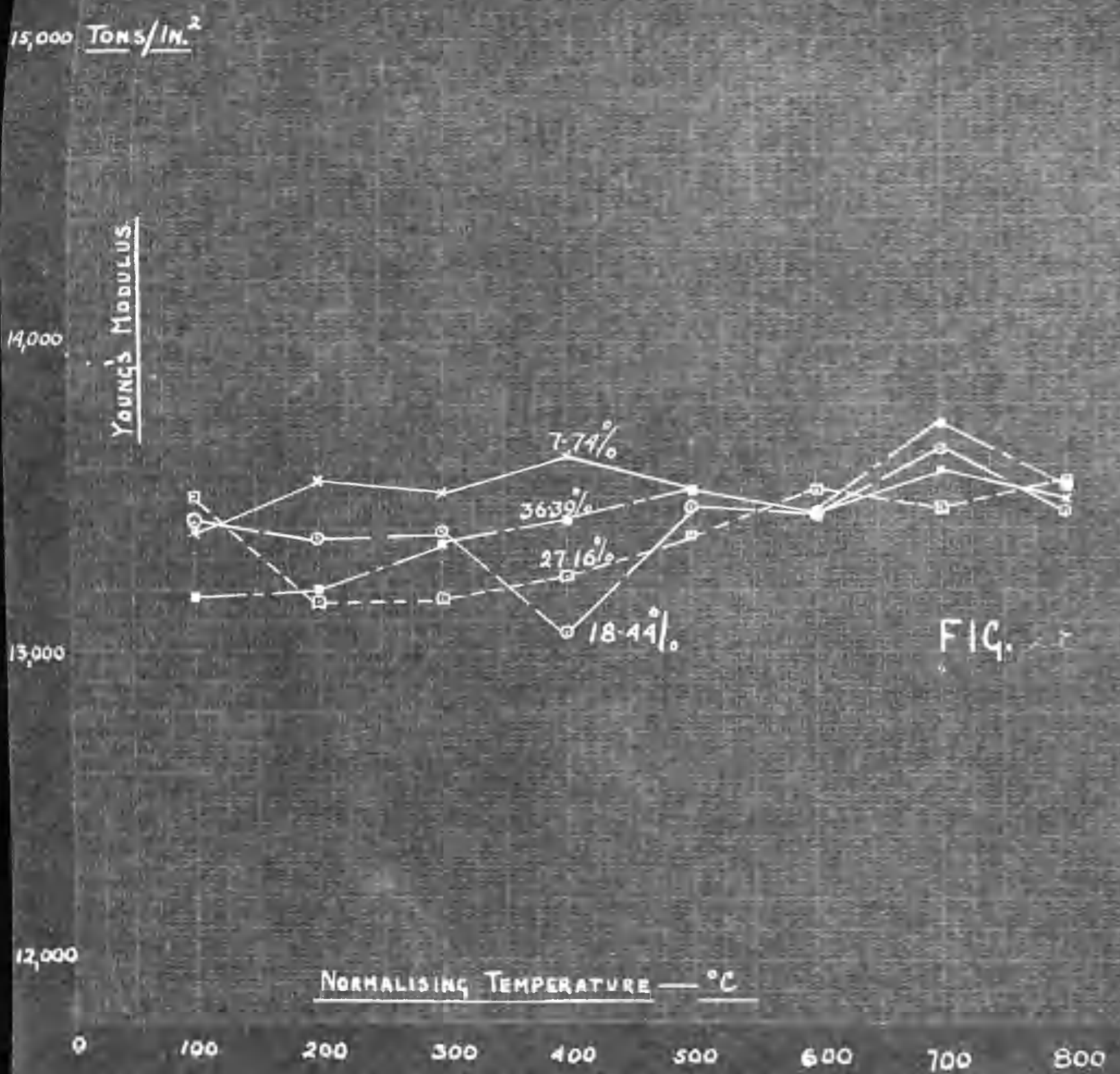

PER CENT
ELONGATION
35
30
25
20
15
10
5
0
7·74%
18·44%
27·16%
36·39%
0
100
200
300
400
500
600
700
800
NORMALISING TEMPERATURE — °C

FIG. 1



15,000 Tons/In.²
14,000
13,000
12,000
Young's Modulus
7·74%
36·39%
27·16%
18·44%
Normalising Temperature — °C
0
100
200
300
400
500
600
700
800

FIG.

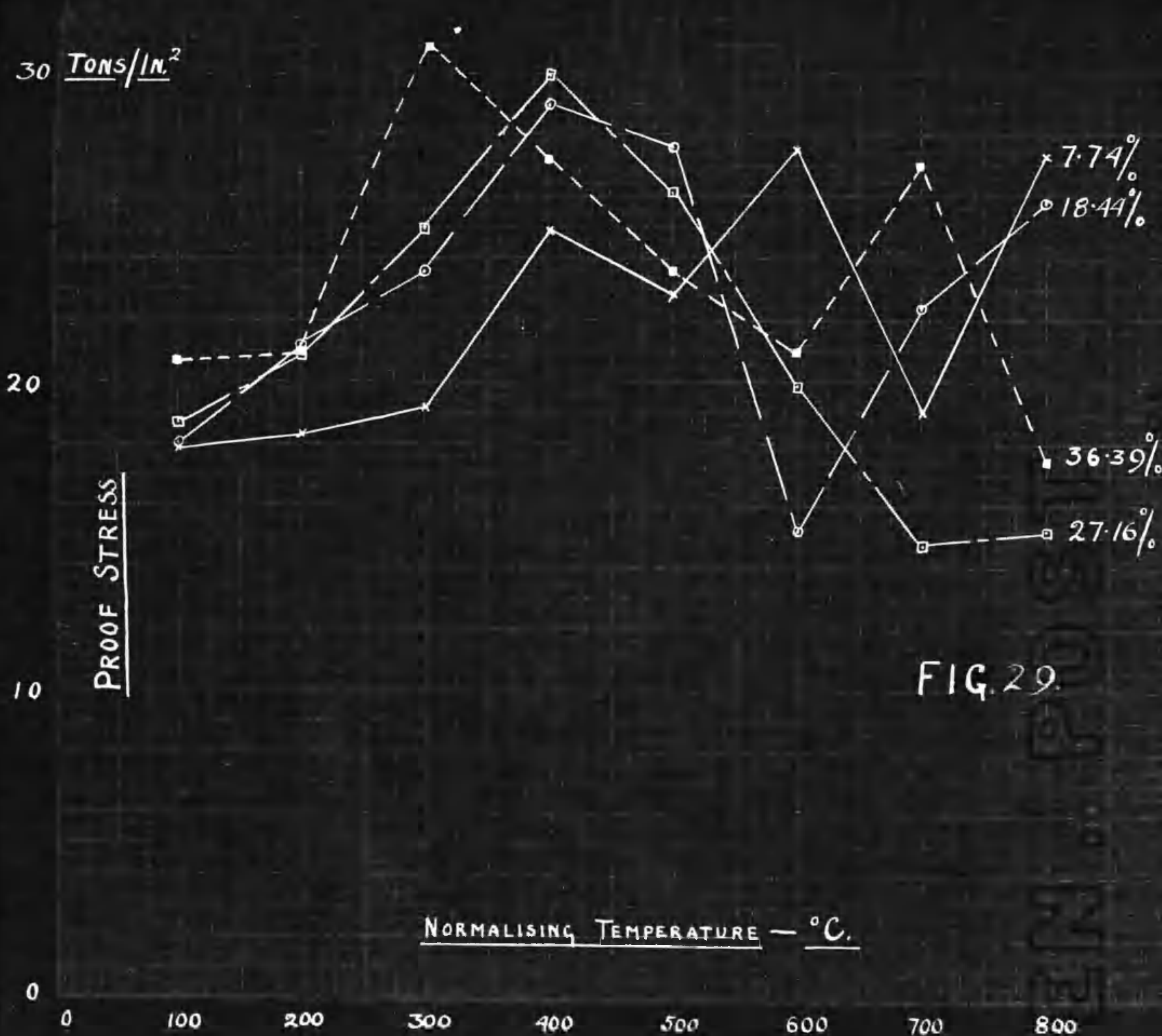

30 TONS/IN.^{2}
20
10
0
PROOF STRESS
0
100
200
300
400
500
600
700
800
NORMALISING TEMPERATURE — °C.
7·74%
18·44%
36·39%
27·16%

FIG. 29.

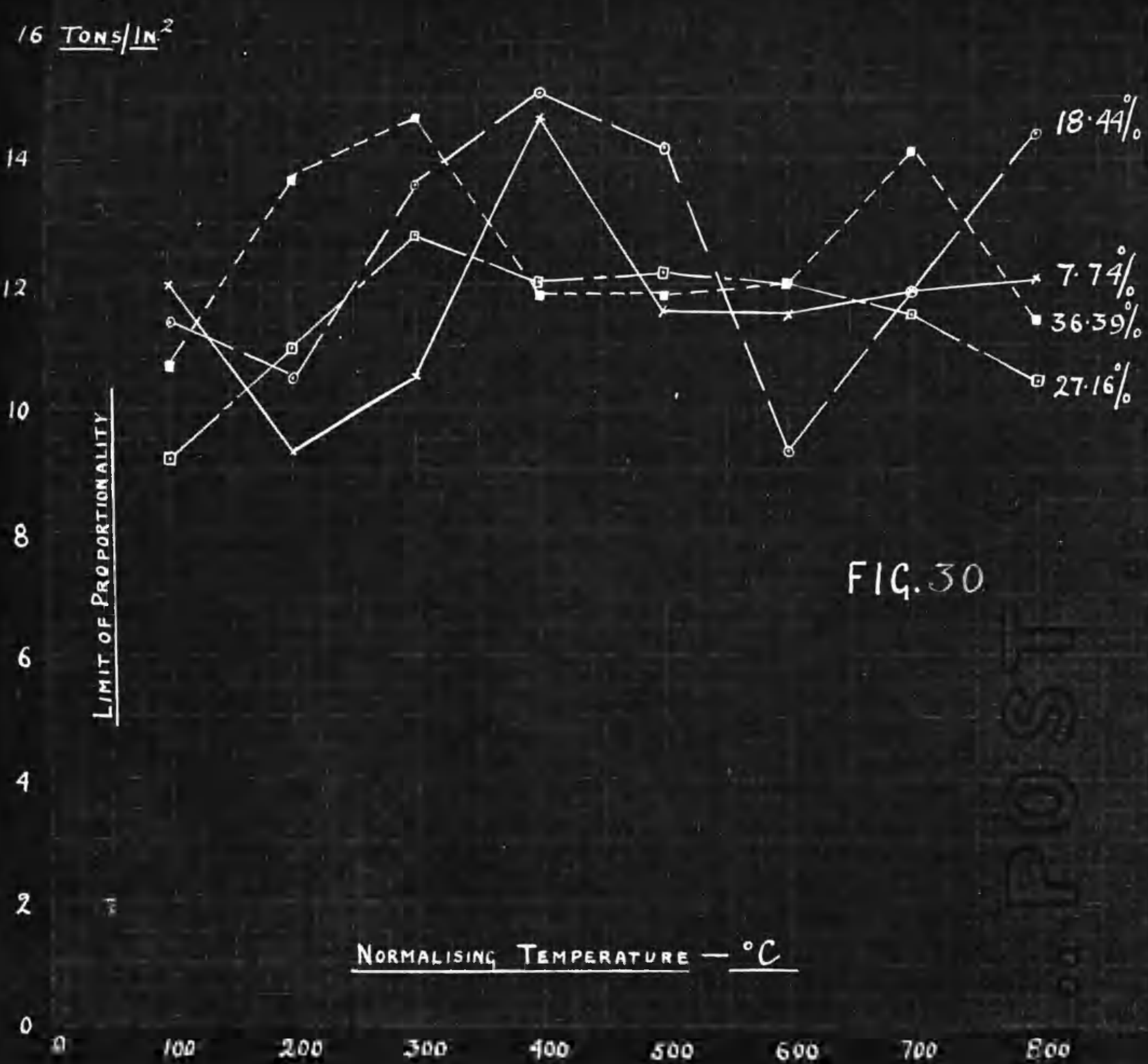

16 TONS/IN.²
14
12
10
8
6
4
2
0
LIMIT OF PROPORTIONALITY
18·44%
7·74%
36·39%
27·16%
NORMALISING TEMPERATURE — °C
0
100
200
300
400
500
600
700
800

FIG. 30

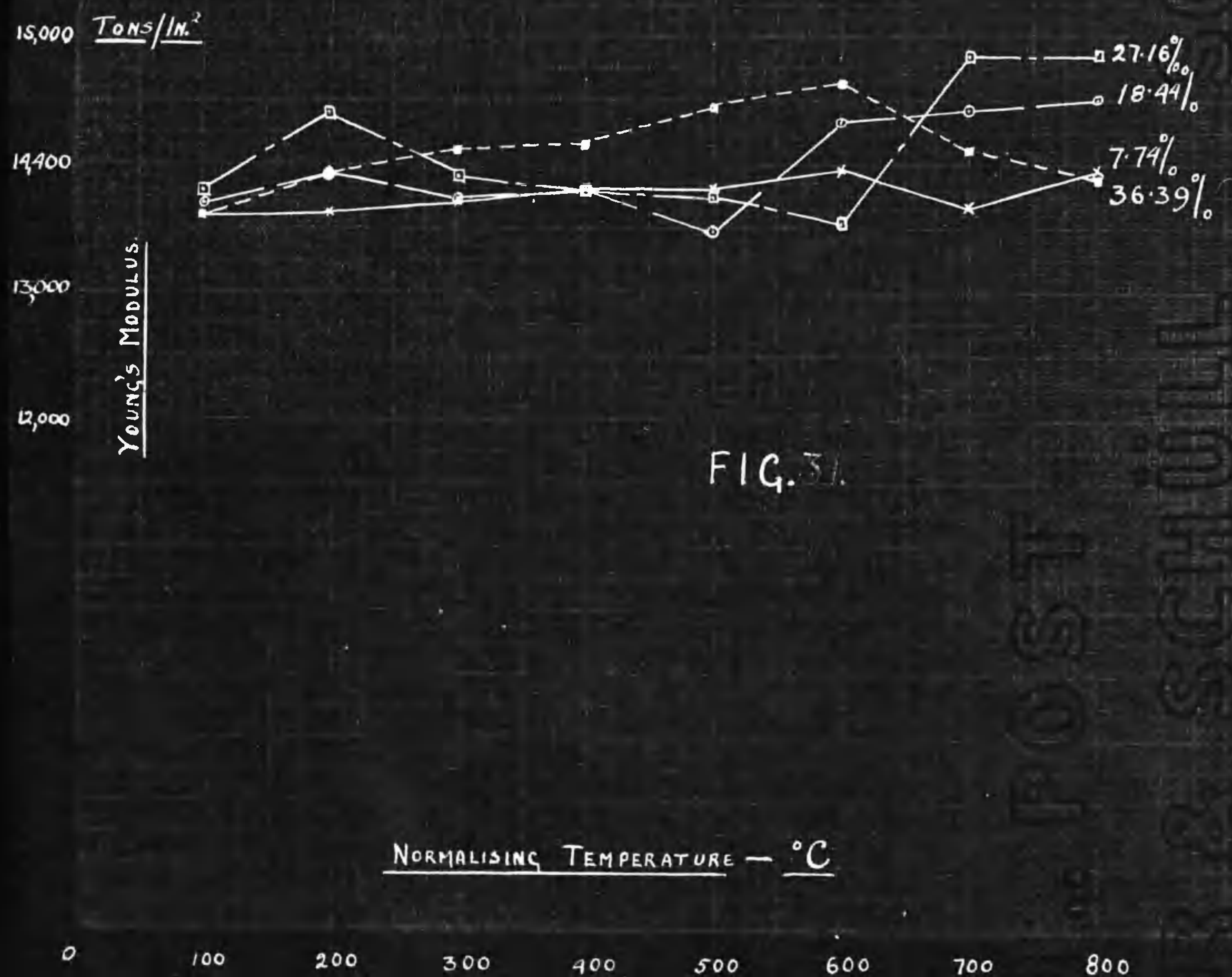
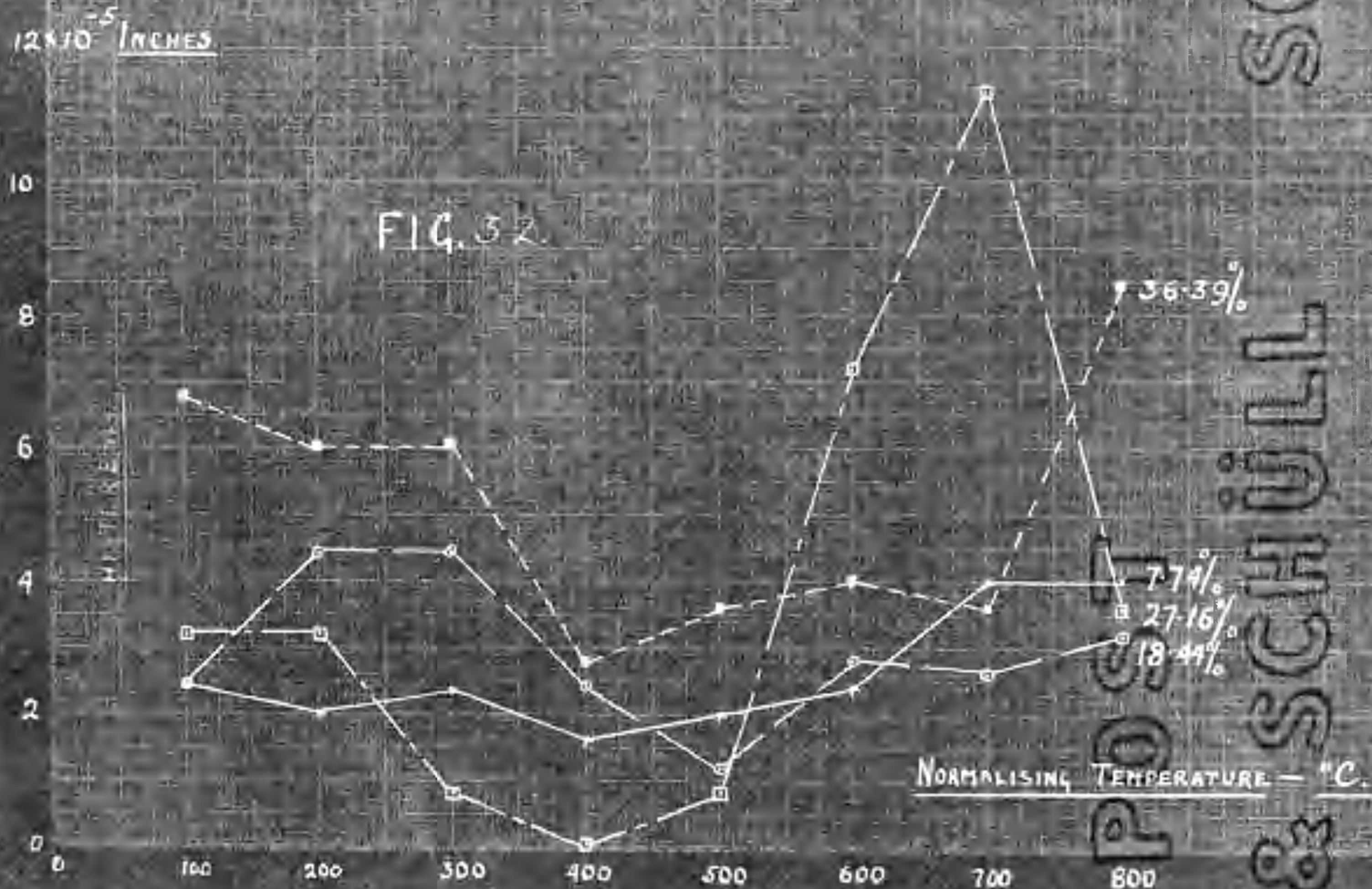
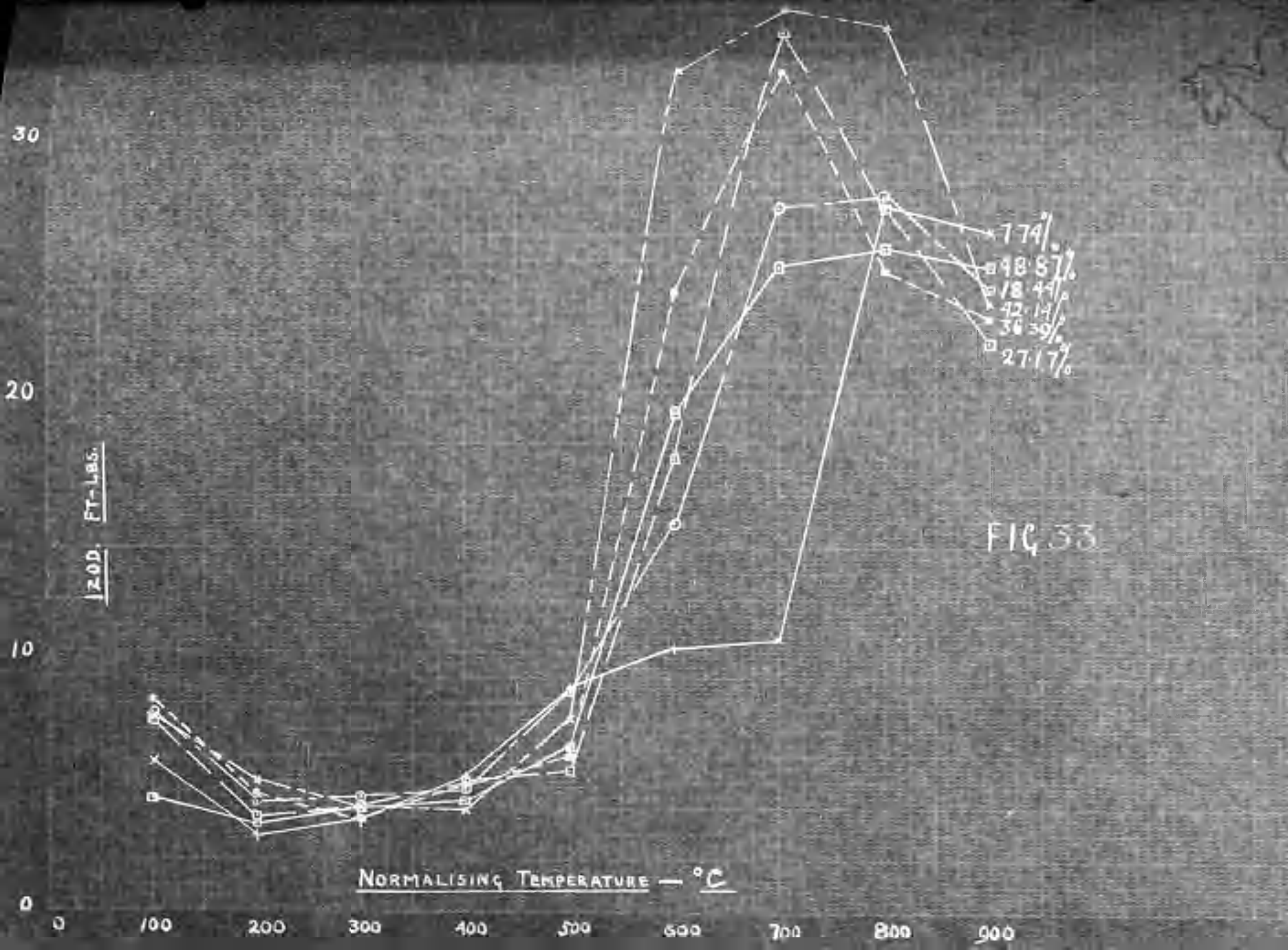

15,000
14,400
13,000
12,000
TONS/IN.²
YOUNG'S MODULUS
27·16%
18·44%
7·74%
36·39%
NORMALISING TEMPERATURE — °C
0
100
200
300
400
500
600
700
800

FIG. 3[illegible]



12×10^-5 INCHES
HYSTERESIS
36·39%
7·74%
27·16%
18·44%
NORMALISING TEMPERATURE — °C.
0
2
4
6
8
10
100
200
300
400
500
600
700
800

FIG. 32.



30
20
10
0
IZOD. FT-LBS.
0
100
200
300
400
500
600
700
800
900
NORMALISING TEMPERATURE — °C
7.74%
98.87%
18.44%
42.14%
36.39%
27.17%

FIG. 33

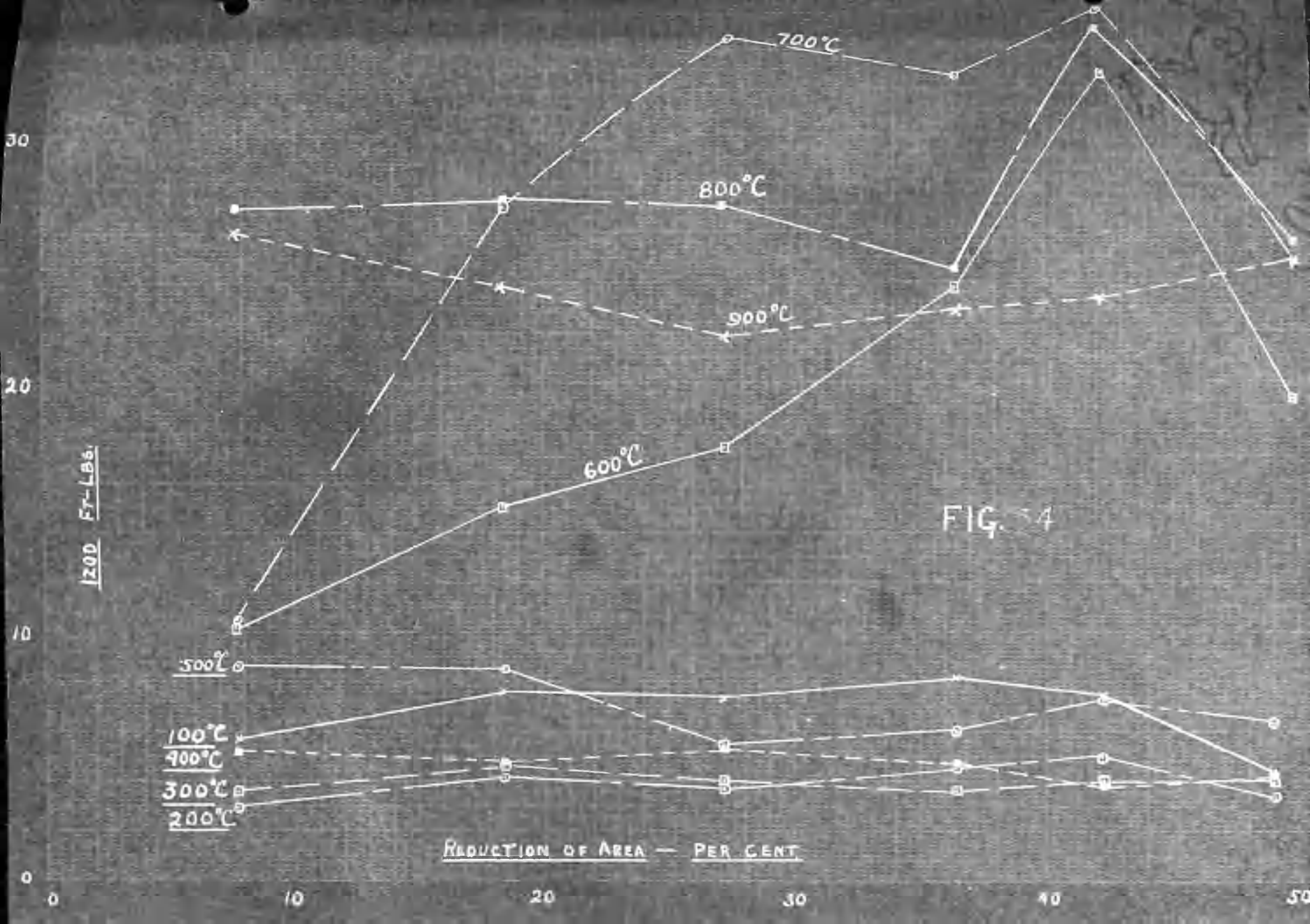

700°C
800°C
900°C
600°C
500°C
100°C
400°C
300°C
200°C
1200 FT-LBS.
REDUCTION OF AREA — PER CENT
0
10
20
30
40
50

FIG. 54

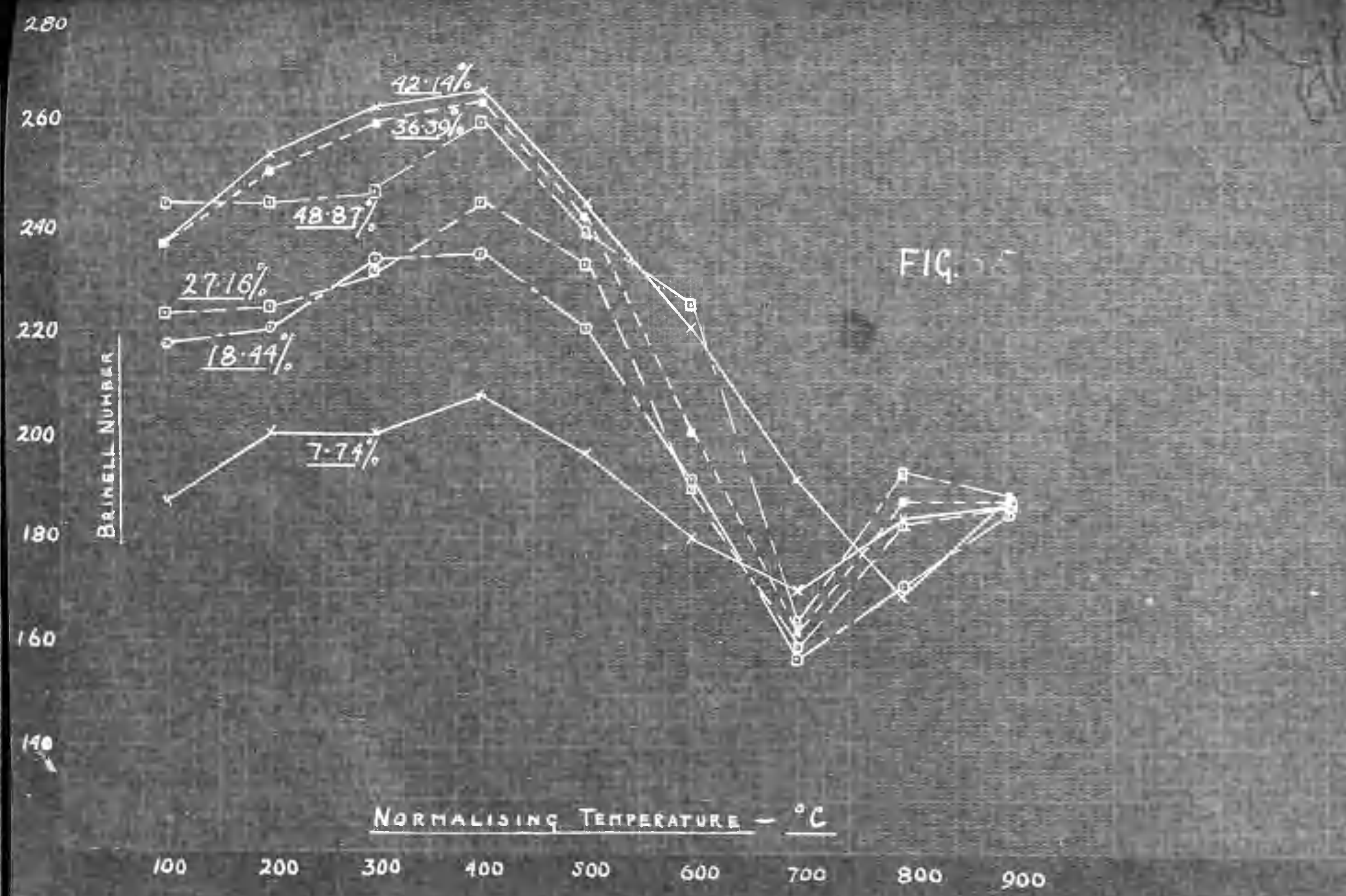
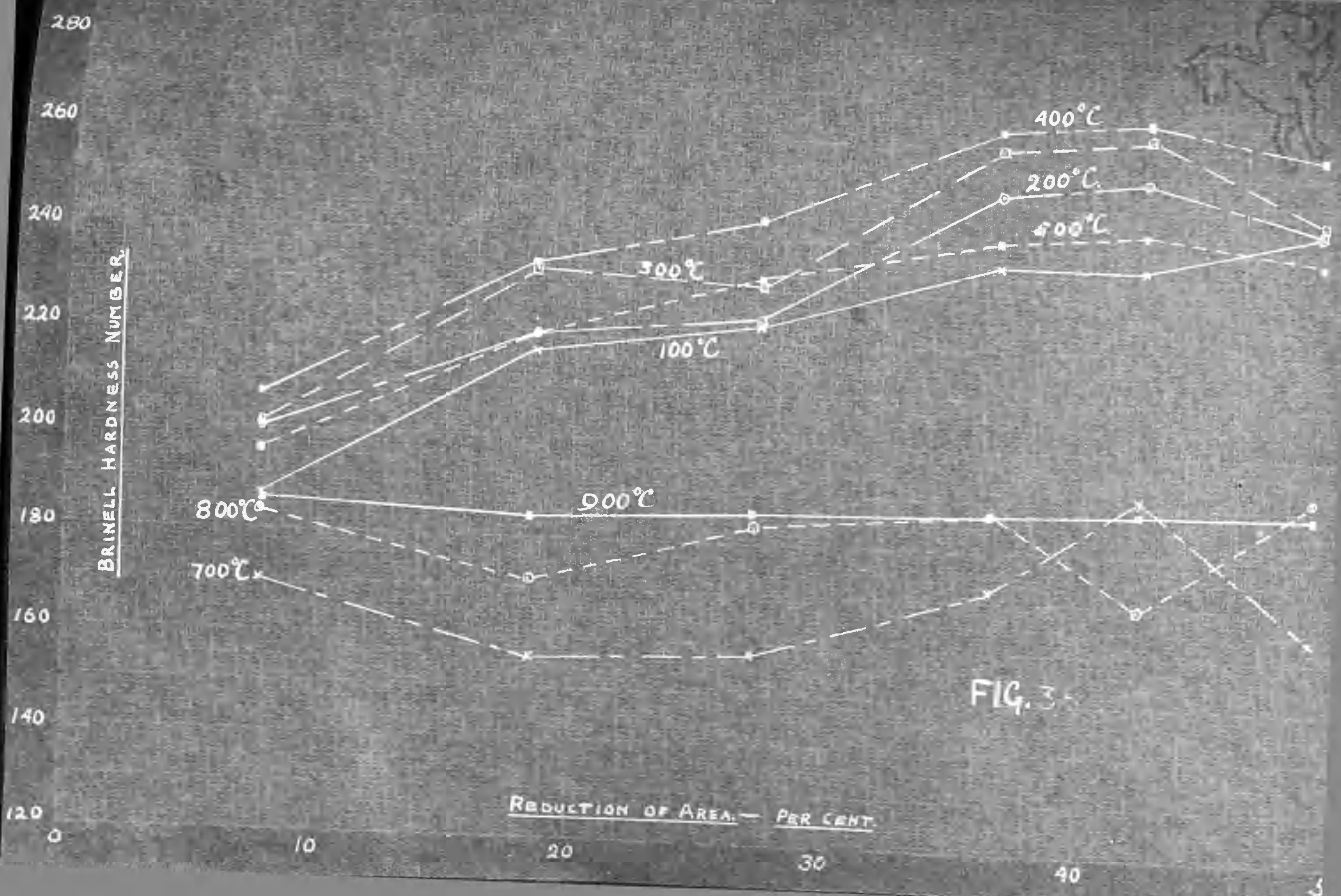

280
260
240
220
200
180
160
140
BRINELL NUMBER
42·14%
36·39%
48·87%
27·16%
18·44%
7·74%
100
200
300
400
500
600
700
800
900
NORMALISING TEMPERATURE – °C

FIG.



BRINELL HARDNESS NUMBER.
280
260
240
220
200
180
160
140
120
0
10
20
30
40
400°C
200°C
500°C
300°C
100°C
900°C
800°C
700°C
REDUCTION OF AREA. — PER CENT.

FIG. 3.

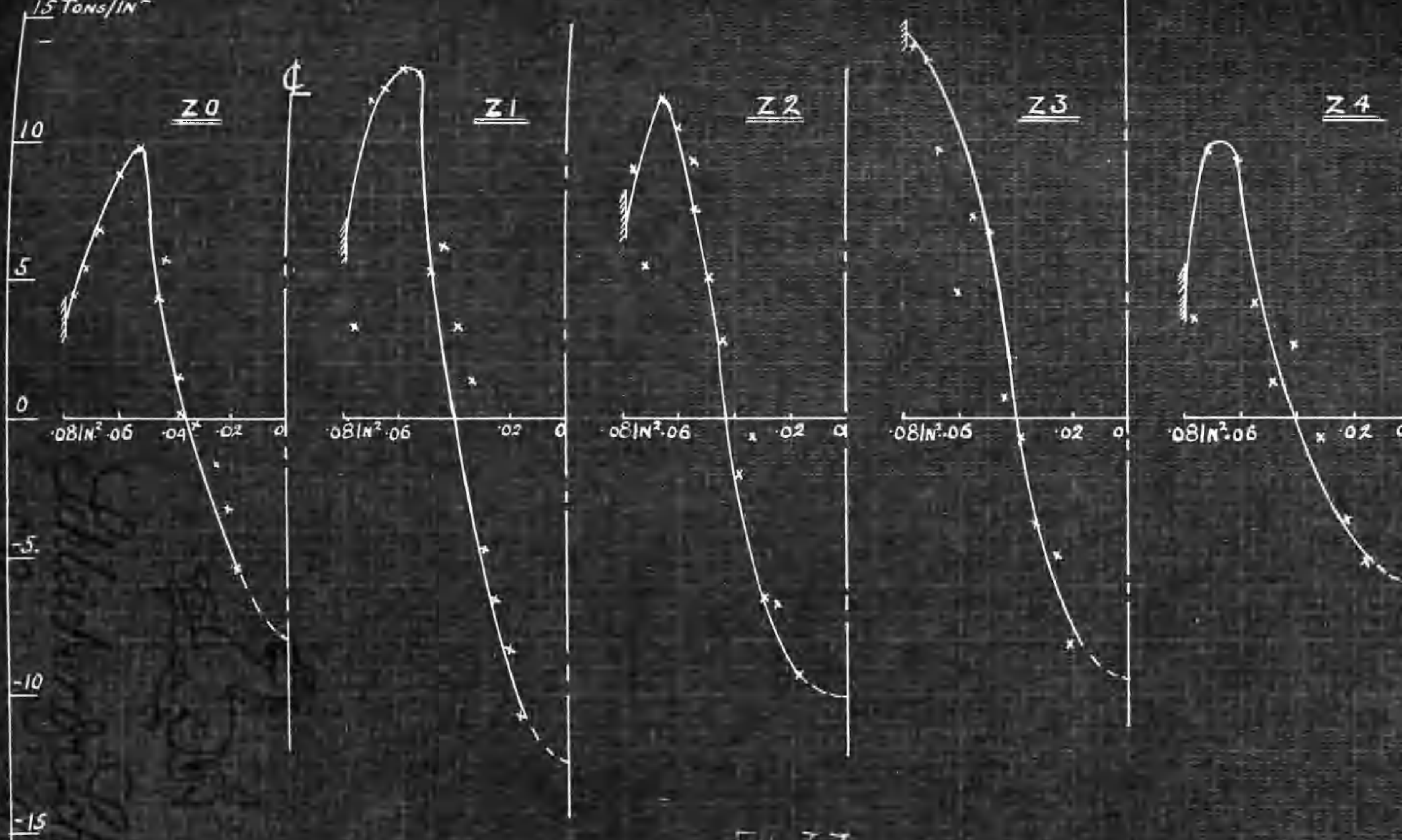
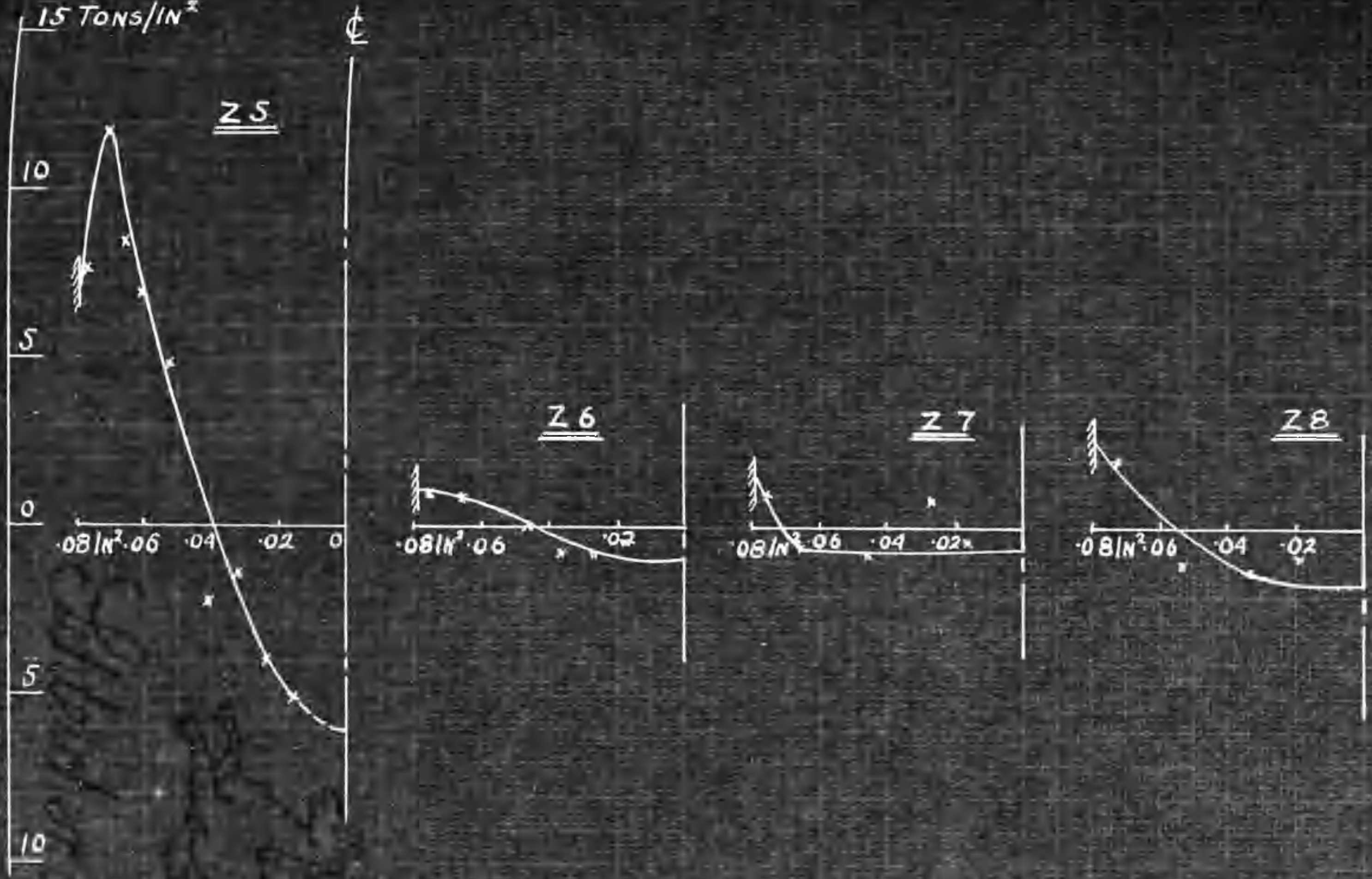


FIG. 37



15 TONS/IN²
℄
Z 5
10
5
0
5
10
·08 IN²·06
·04
·02
0
Z 6
·08 IN²·06
·02
Z 7
·08 IN²·06
·04
·02
Z 8
·08 IN²·06
·04
·02

FIG.38.

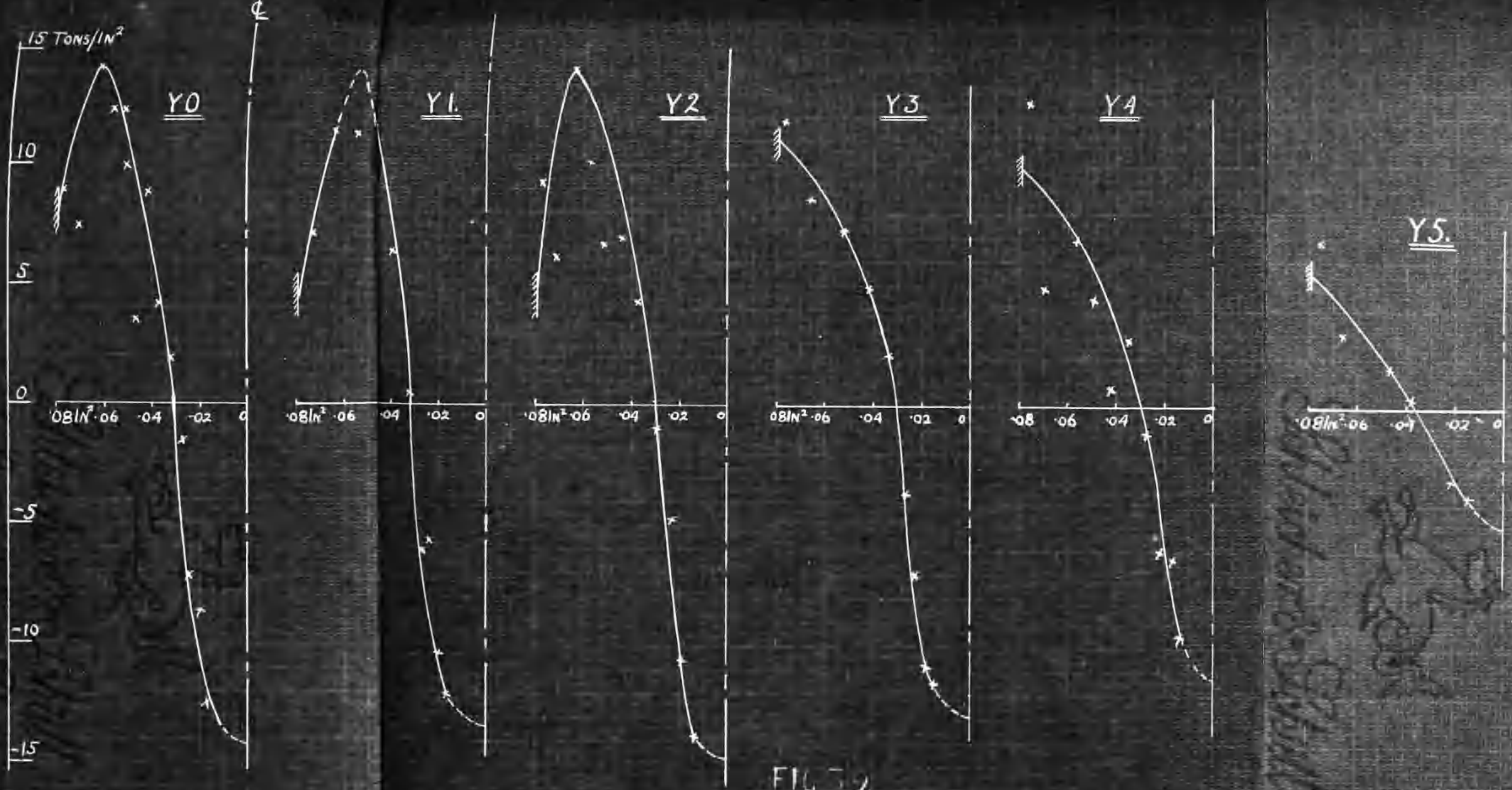


FIG. 52.

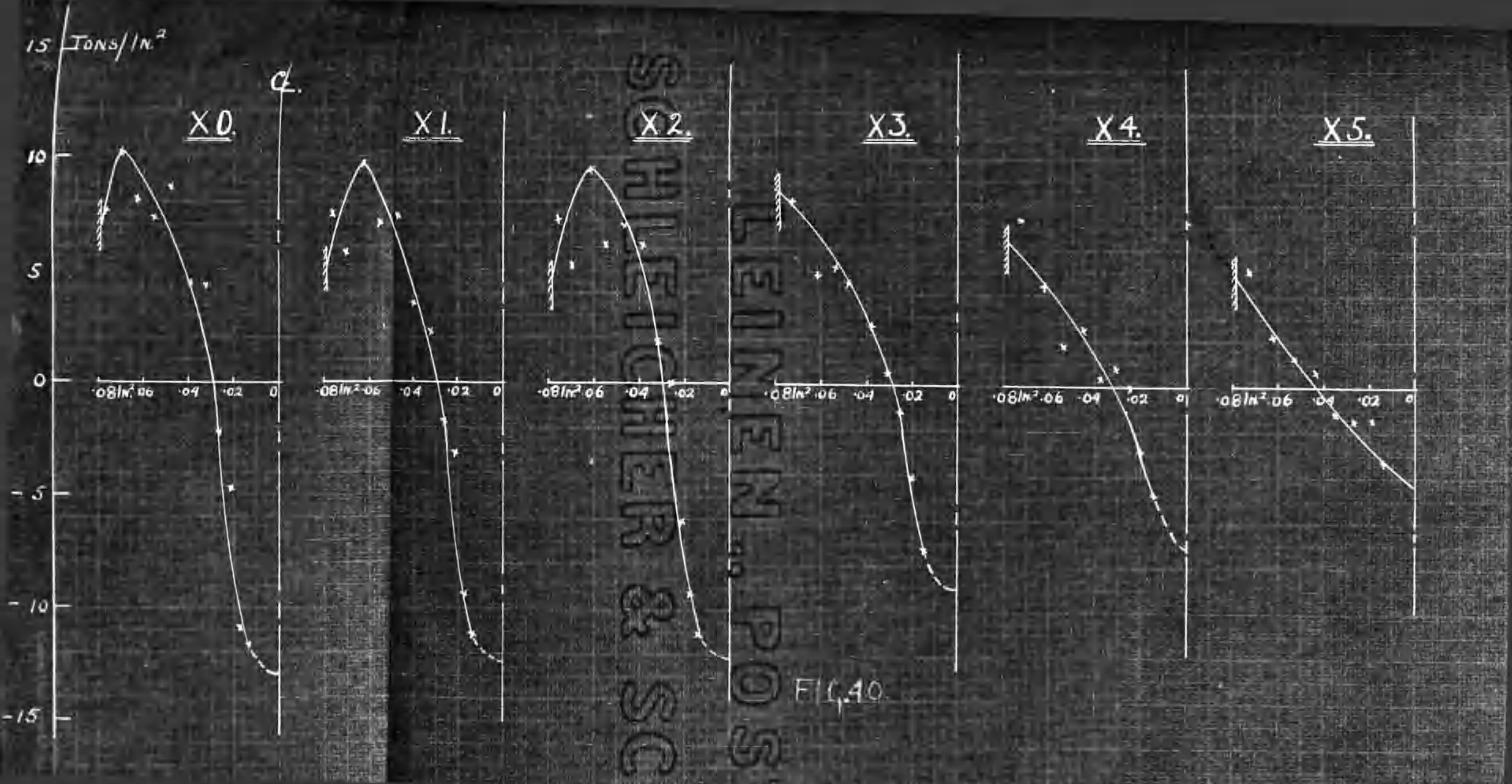


FIG. 40.

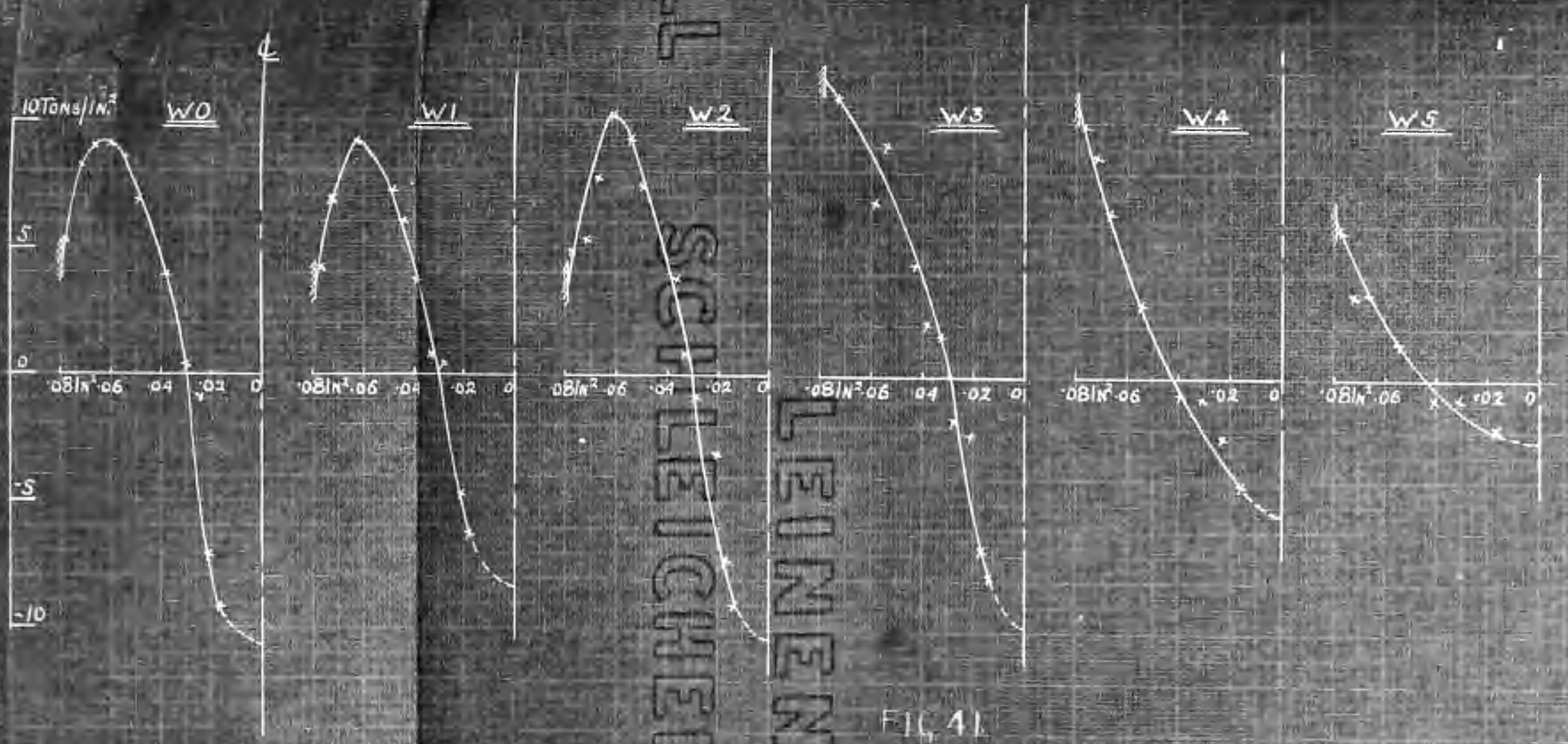


FIG. 41.

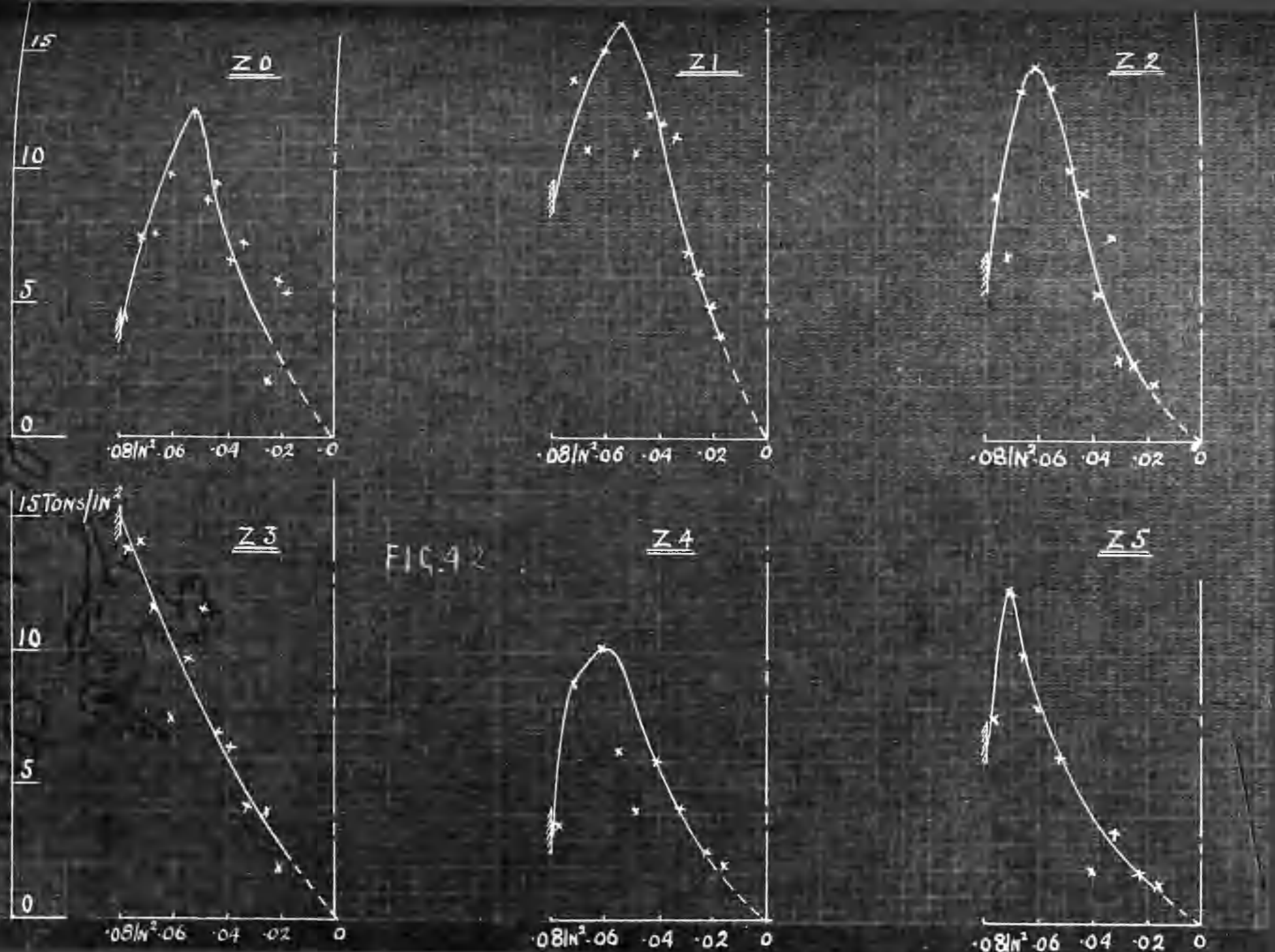

15
10
5
0
Z0
·08 IN² ·06
·04
·02
·0
Z1
·08 IN² ·06
·04
·02
0
Z2
·08 IN² ·06
·04
·02
0
15 TONS/IN²
10
5
0
Z3
·08 IN² ·06
·04
·02
0
Z4
·08 IN² ·06
·04
·2
0
Z5
·08 IN² ·06
·04
·2
0

FIG. 42

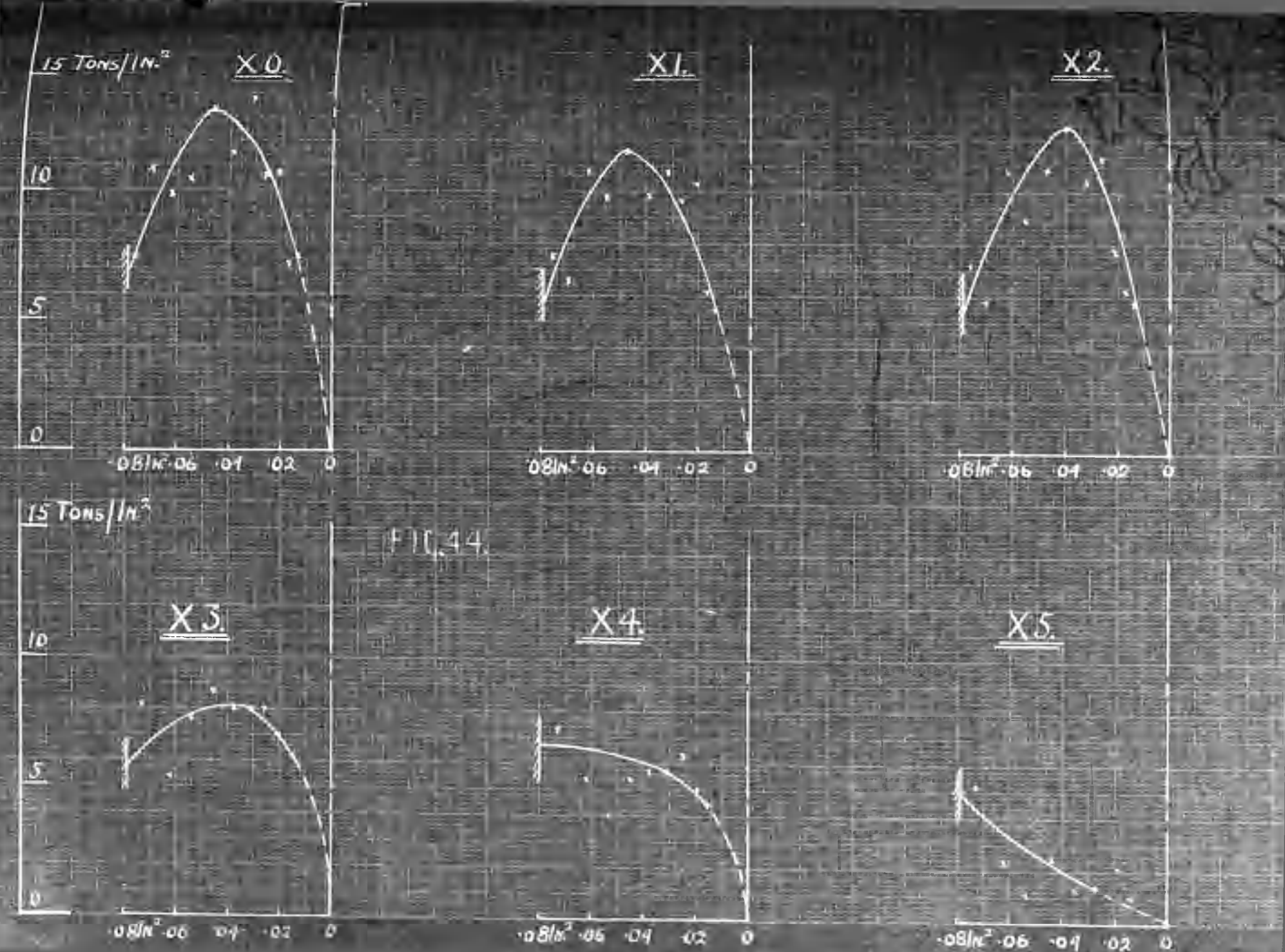
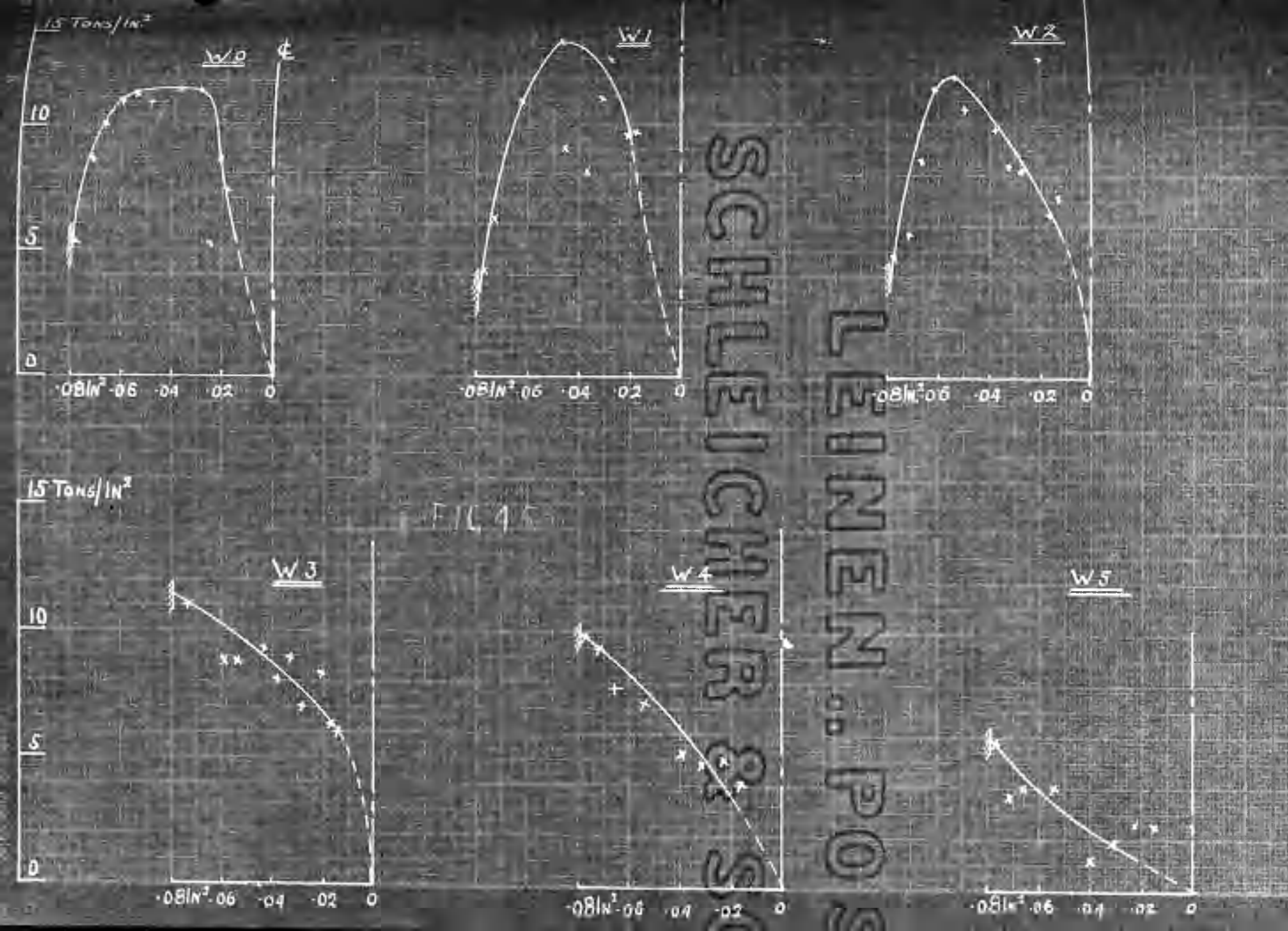
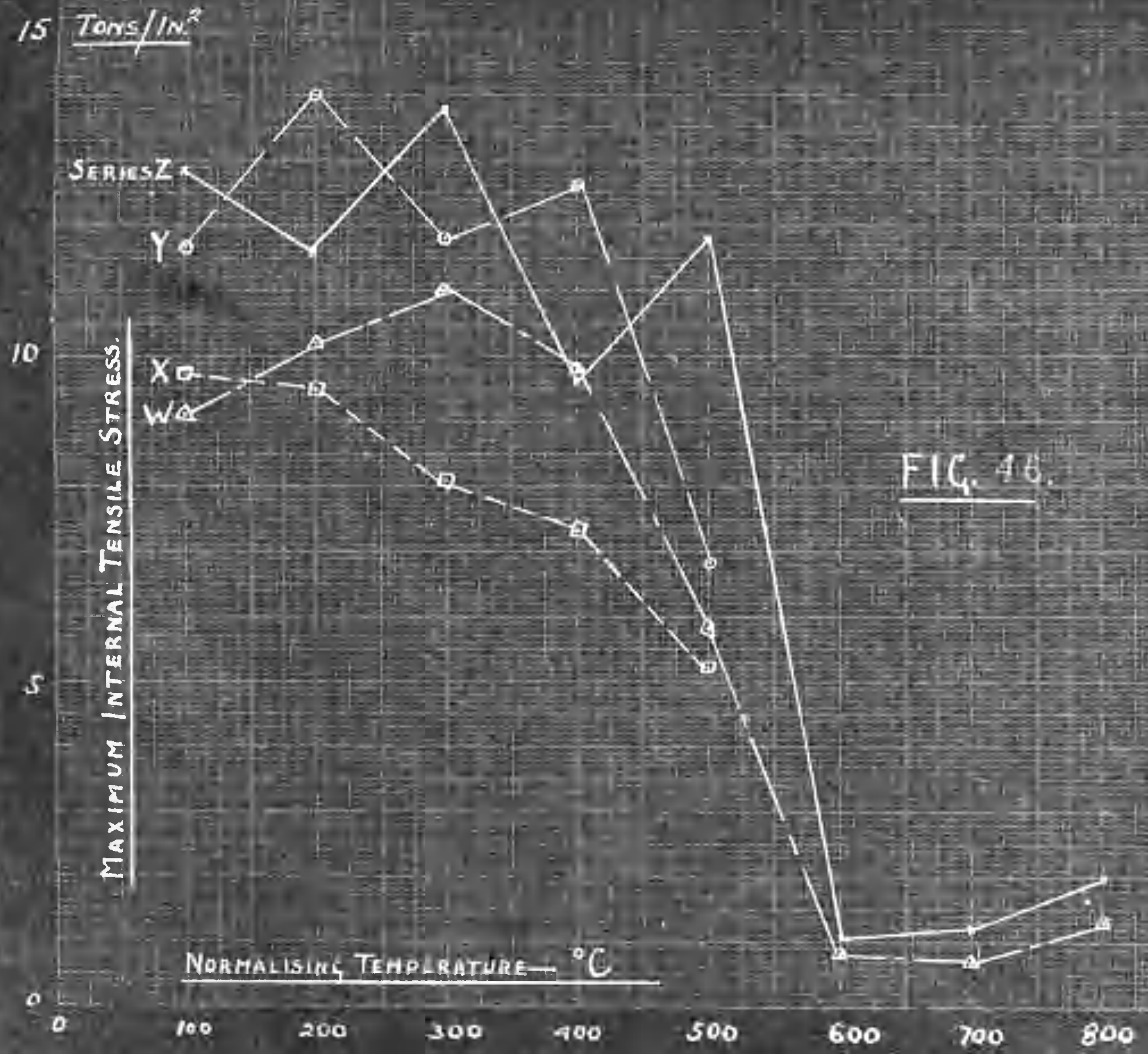

15 TONS/IN.²
X 0.
10
5
0
·08 IN.² ·06 ·04 ·02 0
X 1.
·08 IN.² ·06 ·04 ·02 0
X 2.
·08 IN.² ·06 ·04 ·02 0
15 TONS/IN.²
X 3.
10
5
0
·08 IN.² ·06 ·04 ·02 0
X 4.
·08 IN.² ·06 ·04 ·02 0
X 5.
·08 IN.² ·06 ·04 ·02 0

FIG. 44.

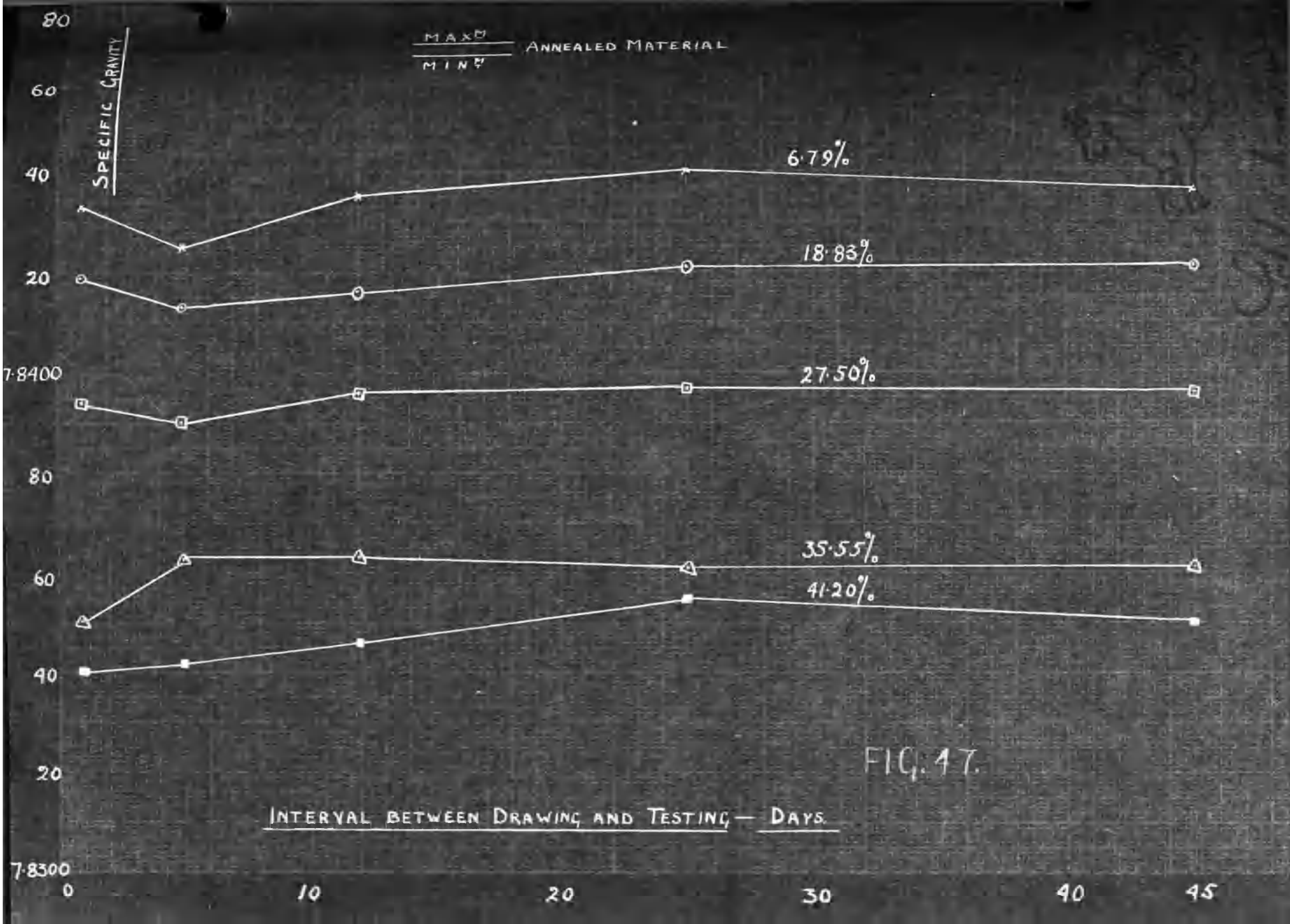


15 TONS/IN²
10
5
0
W0
·08IN² ·06 ·04 ·02 0
W1
·08IN² ·06 ·04 ·02 0
W2
·08IN² ·06 ·04 ·02 0
15 TONS/IN²
10
5
0
W3
·08IN² ·06 ·04 ·02 0
W4
·08IN² ·06 ·04 ·02 0
W5
·08IN² ·06 ·04 ·02 0



15
Tons/In.^{2}
Series Z
Y
X
W
10
5
0
Maximum Internal Tensile Stress.
Normalising Templrature — °C
0
100
200
300
400
500
600
700
800

FIG. 46.



MAXM / MINM ANNEALED MATERIAL
SPECIFIC GRAVITY
80
60
40
20
7·8400
80
60
40
20
7·8300
6·79%
18·83%
27·50%
35·55%
41·20%
0
10
20
30
40
45
INTERVAL BETWEEN DRAWING AND TESTING — DAYS.

FIG. 47.