THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE RELAXATION BEHAVIOUR OF CARBON STEEL STRIP IN BENDING

by

G.E. Hale, B.Met

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SUMMARY AND CONCLUSIONS

A simple and precise method, based on a four point bending mode, has been developed for determining the stress relaxation behaviour of strip materials. The Nikon Projection Microscope has been used as the basis for an improved measuring technique. Stress-relaxation tests on CS80 and CS90 high carbon steel strip using this new technique, gave results which were consistent and more accurate than those obtained in earlier work.

The results showed that less relaxation occurs in a nominal 0.8% plain carbon steel than in a 0.9% carbon steel at the same stress and temperature. For example, relaxation tests on CS80 and CS90 strip material over a 72-hour period resulted in relaxation values of 11.7% and 15.6% respectively, at a temperature of 125°C and a maximum initial stress of 1100 N/mm^2.

It has been demonstrated that the degree of relaxation is exponential with stress and with the reciprocal of the absolute temperature and that it is possible to derive values for the apparent thermal activation energy necessary for relaxation to occur.

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1. INTRODUCTION

Although both ferrous and non-ferrous strip materials are widely used in the spring industry, only a limited amount of work has been undertaken to determine the precise stress relaxation properties of these materials.

The objective of the present work, undertaken at SRAMA is to produce stress relaxation data for strip with statistically meaningful levels of confidence, which may be used as a basis for design criteria.

This report covers the development of a suitable test method and its subsequent application for determining the relaxation behaviour of plain carbon steel strip.

2. MATERIALS

Pre-hardened and tempered 0.25 mm high carbon steel strip was supplied to the compositions specified in BS 1449: Part 3B, in the bright polished condition and with commercially dressed edges.

Strip with nominal carbon levels of 0.80% and 0.90% was investigated; the specified and actual chemical analyses are given in Table I.

TABLE I CHEMICAL ANALYSES

Material		Compostition				
		C	Si	Mn	S	P
		Min.-Max.	Min.-Max.	Min.-Max.	Max.	Max.
CS80	Specified	0.75-0.85	0.05-0.35	0.50-0.90	0.050	0.050
	Actual	0.82	0.21	0.74	0.031	0.012
CS90	Specified	0.85-0.95	0.05-0.35	0.30-0.60	0.040	0.040
	Actual	0.88	0.16	0.48	0.022	0.013

For both qualities, a hardness of between 510 and 540 HV, which falls within the commercially used range, was selected.

3. DEVELOPMENT OF EXPERIMENTAL METHOD

3.1 Basic Principle

A major part of the current work on the stress relaxation of strip has centred round the development of an experimental procedure which is both simple and more accurate than previous methods.(1)(2)

The basic premise in measuring relaxation is the application of a specific load to give a fixed deflection. The degree of relaxation, Rel, can then be expressed as:

$$\mathrm{Rel}(\%) = \frac{W_i - W_f}{W_i} \times 100\%$$

where W_i = load required to give deflection, y

and W_f = load required to give the same deflection, y, after a period t hours at a temperature θ°C

3.2 Initial Procedure: Point Loading of Strip

The testing mode initially adopted was based on the 'change in load' theory, as described above. A test jig, similar to that used by Gohn and Arnold(1)(2) for studies of stress corrosion cracking in copper-beryllium alloys was built and its performance was evaluated.

The basic form of this test rig is illustrated by Figure 1. The jig is loaded with specimens as shown and it is relatively simple to apply any predetermined deflection by adjusting the screws, which are threaded through the cross member.

However, detailed investigation of this jig in operation indicated that the load is concentrated at one single point on the strip, rather than across its entire width, as is the normal case in a three point bend test. This would tend to produce a complex stress pattern.

3.3 Modified Procedure: Full Strip Width, Knife Edge Loading

Modifications were made to the initial jig design to overcome the inadequacy described above: a single continuous knife-edge replaced the deflecting bar and screws, so that the load was applied over the entire strip width rather than concentrated at one point. The basic format of the modified jig can be seen in Figure 2. By using a continuous knife-edge, however, only one stress could be applied to all the test strips at any one time.

The jig proved cumbersome to use in practice, as an engineer's flat plate and a dial gauge were needed to obtain the same deflection on each strip.

On closer examination it became clear that frictional effects, caused by contact between the strip and the side-member of the jig, could inhibit or restrict any relaxation which might occur. This effect would tend to increase as the applied stress increased, i.e. for larger deflections.

3.4 Pin-Board Method: Final Procedure Used

In view of the above limitations it was decided that a completely new design concept was required.

From basic bending theory, the deflection resulting from any stress can be calculated. It is then a relatively easy matter to arrange a series of pins (equivalent to the loading-points in the theory) which give this deflection. Using this premise, a pin-board jig was produced for both three and four point bending, at a number of stress levels.

Preliminary investigation suggested that the four point bending mode was most likely to produce the required degree of accuracy, as there is a uniform stress between the inner pins, in contrast to three point loading, where the maximum stress is concentrated at one point, the central pin. It is also believed that data produced for four point bending are more meaningful than for three point bending since they refer to a uniform stress situation.

The actual jig can be seen in Figure 3. Duplicate sets of pins corresponding to stress levels of approximately 20,40,60 and 80% of the tensile strength were constructed. Two specimens were tested at each stress level to obtain the smallest number of samples necessary for a correlation to the minimum acceptable degree of confidence.

The pin-board technique has several advantages over the previous jigs, including:

(a) ease of use - once the strips have been cut to size and flattened (see Experimental Procedure section below), then it is simply a matter of sliding them into position around the pins;

(b) the initial deflection can be determined accurately from the design parameters;

(c) mathematical corrections can be made to allow for the change in contact angle between the strip and the pins with increasing stress. By using these corrections it is possible to obtain more precise values for the gauge length and initial design deflection at each stress, thereby allowing more accurate determination of the actual stresses and levels of relaxation respectively (see Figure 4);

(d) with the pin-board technique, a complete series of duplicate tests can be undertaken simultaneously at all four stress levels at any one temperature. The pin-board method therefore eliminates the possibility of error resulting from variations in temperature from test to test at the various stress levels; and

(e) by using round pins, frictional effects between the strip and pin are reduced considerably, as the strip is now free to slide round the circumference of the pins.

3.5 Measuring Techniques

Relaxation values for strip materials have previously been determined by measuring the decrease in load occurring during relaxation testing. With the first two jigs, a Coats 'Comaco' cantilever-type spring load testing machine was used, which had previously been modified to give a three point bend test(3). It was realised, however, that with the very small deflections and low loads involved in this work, that the accuracy given by this form of load testing machine was not sufficient to yield meaningful results. (This is in contrast to the previous work(3), where much higher loads and, consequently, higher deflections were used.)

It became apparent therefore, that in order to obtain relaxation values for strip materials that were both reproducible and meaningful, a completely different approach to the measurement of relaxation in strip materials was required.

A technique using the Nikon Projection Microscope was developed in which the permanent deflection in the strip(H), caused by a relaxation(Rel), is measured. Since the initial deflection (y) can be determined extremely accurately from the design parameters of the pin-board, then the degree of relaxation, is given by:

$$\mathrm{Rel}(\%) = \frac{H}{Y} \times 100\% \qquad \ldots\ldots\ldots\ldots \text{(i)}$$

If the formula for four-point bending is considered:

$$Y = \frac{Wa}{24EI}(3l^2 - 4a^2) \qquad \ldots\ldots\ldots\ldots \text{(ii)}$$

where y = maximum deflection at the centre of the beam (equivalent to initial design deflection in equation (i) above)

W = applied load
E = Young's Modulus
I = Moment of Inertia
l = distance between two outer pins
a = distance between the inner and outer pins

and since it has been previously found that the elastic limits in bending for CS80 and CS90 strip, at this hardness level, are 1560 N/mm^2 and 1590 N/mm^2 respectively$^{(3)}$, then the material is stressed within its elastic range. It can thus be seen that

$$Y \propto W$$

and therefore the change in deflection can be used to measure relaxation, as in equation (i) above.

The technique is much more accurate, as the deflection can be measured to a level of 0.0025 mm (0.0001 in). To measure the final deflection, the strip was supported against a block equivalent in length to the distance between the inner pins of the pin-board jig. The arc rise from the block to the inner strip surface was then measured (see Figure 5, upper diagram).

For some of the lower stresses, the deflections were very small and could not be measured accurately using the gauge block described above. However, by using a much longer gauge block, the deflections were measurable (see Figure 5, lower diagram). Beyond the central region, the strip is depicted as straight although some very slight curvature did occur.

Mathematical relationships were derived which enabled corrections to be made to the observed experimental data to account for the change in actual gauge length, both with increasing stress and when using the longer gauge block, as described above.

Figure 4 gives details of some of the corrections which were necessary to obtain extremely accurate values for the gauge length, which increases with increasing stress, and the initial design deflection.

Between the inner and outer pins (Figure 4), the strip is depicted as being straight. Measurement of the angles, α_1 and α_2, however, showed that α_1 was consistently found to be slightly larger than α_2. Thus, the strip will have been slightly curved, a conclusion which is to be expected from the geometry of the test rig.

4. EXPERIMENTAL PROCEDURE USING PIN-BOARD JIG

4.1 Tensile Testing

The material evaluated in the present work had been used for a previous investigation and the full tensile properties of CS80 and CS90 strip, at three different hardness levels, can be found in this earlier report(4). A summary of the tensile data relevant to this report is given in Table II.

4.2 Specimen Preparation

Convenient lengths of strip were cut from the appropriate coil using tin-snips. These samples were carefully sectioned into 75 mm specimens using a DISCOTOM cut-off machine, any deformed material resulting from the cutting with the tin-snips being discarded.

To minimise any inherent twist and also to reduce any pre-existing residual stresses, the specimens were flattened in a clamped jig for 18 hours at 275°C. Prior to flattening, each strip was coated with a 'graphite-in-alcohol' suspension. The graphite had two primary functions: firstly, to reduce the coefficient of friction between the strips and, secondly, to prevent any oxide film causing adherence between the strips. Any excess graphite remaining after flattening was removed by immersing the strips in methyl alcohol for 2 hours, followed by a final rinse in acetone.

Any slight curvature remaining in the strip (due to residual stress) was almost nil, using the technique as described in Section 3.5. Over a 60 mm gauge length, the maximum deflection occurring in any of the strips was estimated to be 0.025 mm (0.001 in). This is equivalent to a stress of 1.5 N/mm^2.

Prior to relaxation testing, a 16 mm gauge length was marked on each strip so that they could be positioned accurately in the test rig.

4.3 Relaxation Testing

Relaxation tests were carried out on both the CS80 and CS90 material, at temperatures of 125, 150 and 175°C, for a period of 72 hours. Previous work has shown that all the primary relaxation occurs within the first 72 hours for carbon and low alloy steels(5)(6). The initial stress applied to the strip was varied between 300 and 1200 N/mm^2. Duplicate tests were carried out at each stress level.

4.4 Measurement of Deflection

After testing, the strips were allowed to cool to room temperature before being removed from the jig.

The permanent deflection in the strip was then measured using the Nikon Projection Microscope, as described in section 3.5.

To check if any twist occurred in the strip during testing, the deflection for both edges of each strip was measured. It was found that the variation in deflection between the two edges of any strip was insignificant compared with the variation between two samples of strip at the same stress level.

5. RESULTS

5.1 Tensile Tests

The results of the tensile tests, as described in section 4.1, are given in Table II.

5.2 Relaxation Tests

If the actual arc rise, H is known, the relaxation, Rel, is then given by:

$$\mathrm{Rel}(\%) = \frac{H}{Y} \times 100\%$$

where y = initial deflection.

Graphs relating percentage relaxation to maximum initial stress can be found as Figures 6 to 13 and the associated experimental values are given in Tables III and IV.

6. DISCUSSION

6.1 Observed Relaxation Behaviour

Over the stress range 500-1100 N/mm^2, as indicated in Table V and from Figures 9 and 13, it is evident that the CS90 strip (Fig.13) showed more relaxation than the CS80 material (Fig. 9). At the higher stresses, there is a greater proportional difference in the relaxation of CS90 compared to CS80 as the temperature decreases, e.g. 2.5% at 175^{o}C, compared with 3.9% at 125^{o}C for a stress of 1100 N/mm^2. At the lower stresses, i.e. below 500 N/mm^2, no difference in the relaxation behaviour of the two materials could be detected. The difference in the rates of relaxation between CS80 and CS90 decreased with increasing temperature, with no discernible difference being apparent at 175^{o}C (see Figures 9 and 13).

For most design purposes, the generally accepted level of relaxation is around 10%; Table VI gives the corresponding stress values ~~for~~ for each specific test temperature at this level of relaxation. It must be noted that these relaxation tests were only of 72 hours duration and, although the propriety of this time has been established for carbon and low alloy steels(5)(6), it is obviously dangerous to extrapolate relaxation values obtained after three days to longer time periods. Moreover, although 10% is the generally accepted maximum level of relaxation, for certain applications, it may be much higher than this. The maximum stress levels used in these relaxation tests were 72 and 73% of the UTS for CS80 and CS90 strip respectively. If these are equated with a 10% maximum for relaxation, then the optimum service temperature for both materials is less than 100°C.

For many flat spring applications the apparent stresses are equal to the UTS. In general, the actual stresses are of the order of 80-90% of the UTS, the remainder being advantageous residual compressive stresses resulting from the manufacturing mode and/or any built-in prestressing operations. Reference to Table II and Figures 9 and 13, indicates that plain carbon steel strip of this thickness must either be used at fairly low temperatures, approaching room temperature, for the standard type of flat spring application, or it may be used at higher temperature but in a less highly stressed situation.

6.2 Stress Dependence of Relaxation

Figures 6 to 9 show the variation of the observed relaxation behaviour with applied stress for CS80 strip, which can be compared with Figures 10 to 13, which give the equivalent stress relaxation properties of CS90 strip.

Both sets of graphs indicate that there is some form of exponential relationship between the percentage relaxation and the maximum initial stress. In fact, from current work at SRAMA(7), the relaxation behaviour of certain materials can be adequately described by the following relationship.

$$\mathrm{Rel} = \alpha e^{\beta\sigma} \qquad \text{............ (iii)}$$

where

Rel = % relaxation

σ = maximum initial stress (N/mm^2)

α and β are constants

This relationship is identical to those used in describing certain creep processes in both metals and plastics(8)(9). By rewriting equation (iii) in the form:

$$\ln \mathrm{Rel} = \ln \alpha + \beta\sigma \qquad \ldots\ldots\ldots\ldots \text{(iv)}$$

which gives a straight line relationship between ln Rel and σ, the experimental data can be fitted by a least mean squares procedure. Figures 6 to 13 are the analytical curves; the actual experimental values can be found in Table III and IV, while the values of the constants, α and β, are given in Table VII.

In Figures 6 to 8 for the CS80 material and in Figures 10 to 12 for the CS90 material, the upper 95% confidence line has been plotted, using 1.96 S_R;

where S_R = standard deviation of the residuals.

(Note: 'S' is the estimate of the standard deviation).

6.3 Temperature Dependence of Relaxation

Figures 6 to 13 show that the degree of relaxation increases as the temperature rises. A similar equation to (iii) above can be derived for the variation of relaxation with temperature at a fixed stress.

$$\mathrm{Rel} = \gamma e^{\delta/T} \qquad \ldots\ldots\ldots\ldots \text{(v)}$$

where

Rel = % relaxation
T = absolute temperature (°K)
γ and δ are constants

Analytical curves can be derived in a manner similar to the one used above, equation (v) being rewritten in the form

$$\ln \mathrm{Rel} = \ln \gamma + \delta/T \qquad \ldots\ldots\ldots\ldots \text{(vi)}$$

The magnitude of the constants, γ and δ, may then be determined by plotting ln Rel against the reciprocal of the absolute temperature and values of γ and δ can be found in Table VIII.

6.4 Apparent Activation Energy Plots

It is possible to obtain a value for the apparent thermal activation energy, Q, necessary for relaxation to occur, from the slope, $\frac{d(\ln \text{Rel})}{d(1/T)}$, taken from a plot of ln Rel versus 1/T at constant stress.

$$\text{Hence,} \quad \frac{d(\ln \text{Rel})}{d(1/T)} = -\frac{Q}{R} \qquad \ldots\ldots\ldots\ldots \text{(vii)}$$

where Q = apparent thermal activation energy ($J.mol^{-1}$)
and R = universal gas constant = 8.3 $J.mol^{-1}. {}^{o}K^{-1}$
(Note: 1eV = 96,000 $J.mol^{-1}$)

The slope of equation (vi) is 'δ'. By substitution into (vii), this gives:

$$\delta = \frac{-Q}{R} \qquad \ldots\ldots\ldots\ldots \text{(viii)}$$

The data thus derived are given in Table VIII and in Figure 14, which shows the variation of apparent activation energy with applied stress.

Obviously, there are insufficient data to draw any real conclusions from this graph. Further work is needed to establish the position of the straight line plots more accurately and also to determine whether points 1 and 2 are genuine or not. Point 2 occurs at very low stresses where the random errors in the technique may obscure the true level of relaxation and hence, have an adverse effect on the determination of the apparent activation energy at these stresses. In addition, there is a low level of correlation between ln Rel and 1/T for point 2. However, a probable trend can be seen; this indicates that as the applied stress increases the apparent activation energy decreases. Current work at SRAMA(7) tends to suggest that the above statement is likely to be correct.

6.5 Possible Explanations for the Observed Results

Consider the total amount of energy, E_T, necessary for the relaxation processes to occur as being composed of three terms, i.e.

$$E_T = I + Q + \sigma \qquad \text{............ (ix)}$$

where

I = internal strain energy resulting from dislocations, point defects etc.

Q = apparent thermal activation energy, and

σ = external strain energy in the form of applied stress.

Since the internal strain energy, I, is a basic material property and is likely to be constant for any given condition, thus, from equation (ix), it becomes clear that an increasing applied stress (σ) means that less apparent thermal activation energy (Q) is required for relaxation to occur at a given temperature.

If a least mean square procedure is adopted to find the best fit to the two lines on the apparent activation energy plot (Figure 14), then the slopes are found to be approximately equal, i.e. $-(7.7 \times 10^{-5})$ for CS80 and $-(8.7 \times 10^{-5})$ for CS90 respectively; in other words, the lines are parallel. This graph may therefore indicate a basic difference in relaxation behaviour for CS80 and CS90, although further work would be necessary to confirm this.

Since relaxation occurs by a process similar to those taking place in recovery, where recovery is here understood to be the relief of internal stresses by thermally activated processes (e.g. cross-slip), then the slopes of the apparent activation energy graphs (Figure 14) give an indication of the rate of change of recovery with temperature. As these slopes are equal then it is probable that the dynamic processes which take place during relaxation are the same.

However, the apparent activation energies, at the same applied stress, which are necessary to initiate and maintain the processes of relaxation are noticeably different. This suggests that a lower state of internal energy, (i.e. a lower dislocation density), would result in reduced recovery rates, leading to smaller amounts of stress relaxation. This hypothesis is supported by other work associated with the present studies, which has shown that lower hardness levels for a given material lead to lower levels of relaxation.

A comparison of Figures 9 and 13, together with Table V, shows that more relaxation occurs in CS90 than in CS80 for the same stress. In other words, less total energy is required in CS90 for relaxation to occur. Referring to equation (ix), the total energy, E_T, required will differ from CS90 to CS80 and, similarly, Figure 14 shows that the apparent activation energies, at the same stress, will be different. Using subscripts, in the form x_1 and x_2, to denote CS80 and CS90 respectively, equation (ix) can be rewritten for each material.

Hence, $E_1 = I_1 + Q_1 + \sigma_1$ .... (x)

and $E_2 = I_2 + Q_2 + \sigma_2$ .... (xi)

However, $\sigma_1 = \sigma_2$ and assuming that $I_1 \approx I_2$

then, as $Q_1 > Q_2$ (see Figure 14), it is probable that $E_1 > E_2$, and more relaxation will be seen in CS90 than in CS80 at the same stress and temperature. It is likely that the difference in relaxation arises from a difference in the fine detail of the structure. A more detailed investigation is necessary, however, to establish the actual relaxation mechanisms.

6.6 Recovery, Recrystallisation and Relaxation

The recovery process at low fractions of the melting point, say 0.4 - 0.6 T_m, is primarily concerned with reducing the number of point defects to the equilibrium value. In this temperature region, vacancies are mobile and tend to be the most important point defect. Thus, the major mechanism governing recovery is vacancy diffusion.

At even lower fractions of the melting point, below 0.4 T_m, thermally-activated cross-slip is the more predominant mechanism. In both these cases, the experimental determinations of the apparent activation energy are in close agreement with the theoretical value for the predominating mechanisms.

Relaxation is dependent on several mechanisms, including recovery, some of which are not clearly defined. The apparent activation energy resulting from these processes is analogous to that observed in recrystallisation and may be thought of as an empirical constant.

7. CONCLUSIONS

1. A technique has been developed for measuring the relaxation of strip, by bending the strip around suitably placed pins.

2. A measuring procedure, based on the Nikon Projection Microscope, has produced results which are both accurate and consistent.

3. At the same stress and temperature, the CS90 material showed more relaxation than the CS80 material.

4. To satisfy a maximum relaxation of 10%, then at the highest test stresses used, i.e. 1120 and 1190 N/mm^2 for CS90 and CS80 respectively, the maximum service temperature will be less than 100°C.

5. Relaxation was found to be exponential with both stress and the reciprocal of the absolute temperature.

6. The exponential relationship between relaxation and the reciprocal of the absolute temperature, has enabled the apparent thermal activation energy for any stress to be evaluated. It appears that the apparent thermal activation energy decreases as the applied stress increases.

8. RECOMMENDATIONS

1. The mathematical relationship and statistical techniques used to describe the relaxation processes occurring in strip, could equally be applied to all the previous relaxation data which exist.

   (a) to indicate if the above ideas hold for other materials under different conditions; and

(b) to determine the accuracy and reliability of previous work.

2. Very little reliable data are available on the relaxation properties of strip material and that which exists is of little use to designers. Further detailed work in this field is needed to remedy the situation.

3. By determining the apparent thermal activation energy necessary for relaxation to occur, it may be possible to show the mechanism for relaxation in both strip and springs is the same. If this proved to be correct, then it would be far easier to do relaxation tests on springs rather than strip and the information obtained could then be related to strip materials. Relaxation tests on a material which is available in both strip and wire form, may help to indicate if the above ideas are likely to be correct.

4. The effect of shot peening on the relaxation behaviour of high carbon steel strip should be investigated.

5. The possibility of analytical interpolation for relaxation between the experimental variables of temperature and stress suggests that it might be possible to construct a diagram relating combinations of temperature and stress to a specified level of relaxation, producing what is, in effect, an 'iso-relaxation' diagram.

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TABLE II MECHANICAL PROPERTIES OF CARBON STEEL STRIP (0.25 mm)

Quality	Hardness HV (Mean)	Tensile Strength (N/mm^2)	Proof Stress			Elongation %
			0.1% (N/mm^2)	0.2% (N/mm^2)	0.5% (N/mm^2)	
CS80	520	1640	1160	1285	1385	5
CS80	520	1670	1090	1235	1385	5
CS90	525	1520	1300	1320	1330	5
CS90	525	1550	1260	1335	1385	5

TABLE III RELAXATION DATA FOR CS80 STRIP

Applied Stress (N/mm^2)	% Relaxation at Temperatures of		
	125°C	150°C	175°C
330	5.2 4.3	4.2 4.3	5.7 5.2
640	5.4 5.2	8.4 6.9	8.1 8.4
930	10.2 9.4	12.2 12.0	14.5 14.9
1190	13.5 13.9	15.5 15.6	19.0 18.9

TABLE IV RELAXATION DATA FOR CS90 STRIP

Applied Stress (N/mm^2)	% Relaxation at Temperature of		
	125°C	150°C	175°C
300	4.0 3.7	4.6	6.0 6.0
600	5.9	6.9 6.0 7.1 6.4	10.3 11.5
870	10.9 10.4	11.3 10.6 13.8 14.8	13.7 13.8
1120	16.1 16.1	18.5 17.8 20.4 19.2	19.9 19.9

TABLE V COMPARATIVE RELAXATION VALUES FOR CS80 AND CS90 STRIP

Temperature (°C)	Material	%Relaxation at a Maximum Initial Stress of (N/mm^2)	
		500	1100
125	CS80 CS90	5.3 ±1.6 5.3 ±0.6	11.7 15.6
150	CS80 CS90	5.8 ±1.8 5.8 ±2.5	14.5 18.4
175	CS80 CS90	7.0 ±1.7 8.4 ±1.6	17.2 19.7

The associated 95% confidence band is given with the relaxation values at 500 N/mm^2

TABLE VI STRESS VALUES FOR 10% MAXIMUM RELAXATION

Temperature (°C)	Allowable Stress (N/mm^2) to Give a Maximum Relaxation of 10% (in 72 hours)	
	CS80	CS90
125	980	850
150	850	780
175	730	620

TABLE VII VALUES OF CONSTANTS FOR EXPONENTIAL STRESS-RELAXATION RELATIONSHIP

Material	Temperature (°C)	Constants for Rel = $\alpha e^{\beta\sigma}$		Increment for 95% Confidence = $\pm$ 1.96 S_R
		α	$\beta (x10^{-3})$	
CS80	125	2.8	1.3	1.6
	150	2.7	1.5	1.8
	175	3.3	1.5	1.7
CS90	125	2.2	1.8	0.6
	150	2.2	1.9	2.5
	175	4.1	1.4	1.6

TABLE VIII VALUES OF APPARENT ACTIVATION ENERGY DERIVED FROM PLOTS OF RELAXATION VERSUS RECIPROCAL TEMPERATURE, FITTED TO THE RELATIONSHIP Rel = $\gamma e^{\delta/T}$

Material	Stress (N/mm^2)	Constants for Rel = $\gamma e^{\delta/T}$		Apparent Activation Energy Q(eV)
		$\ln\gamma$ = Constant of Proportionality	δ	
CS80	330	2.6	-452	-0.04
	640	5.8	-1641	-0.14
	930	5.9	-1448	-0.12
	1190	5.5	-1146	-0.10
CS90	300	5.3	-1590	-0.14
	600	7.8	-2469	-0.21
	870	4.7	-940	-0.08
	1120.	4.8	-790	-0.07

Where Q = R.δ ($J.mol^{-1}$)
and R = Universal Gas Constant = 8.3 $J.mol^{-1}.\ {}^{o}K^{-1}$
(Note: 1 eV = 96,000 $J.mol^{-1}$)

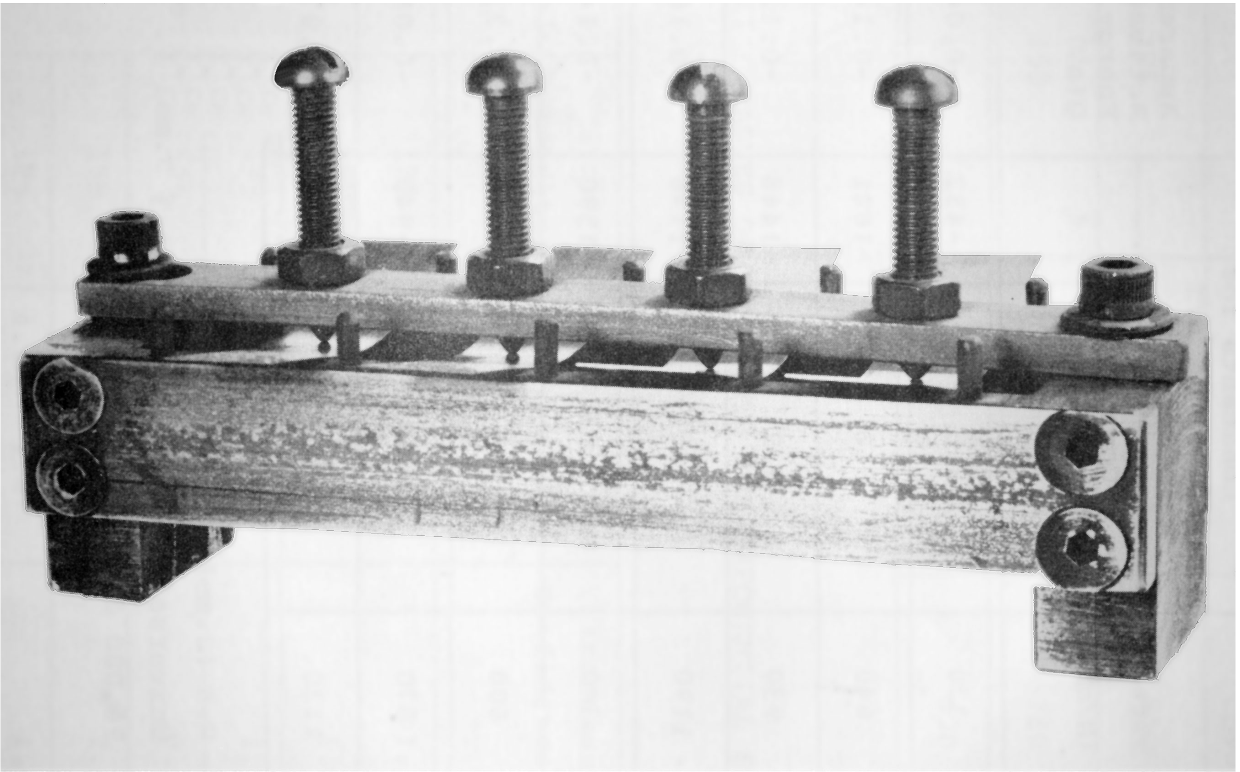


FIG. 1   Illustration of Jig used for Point Loading of Strip

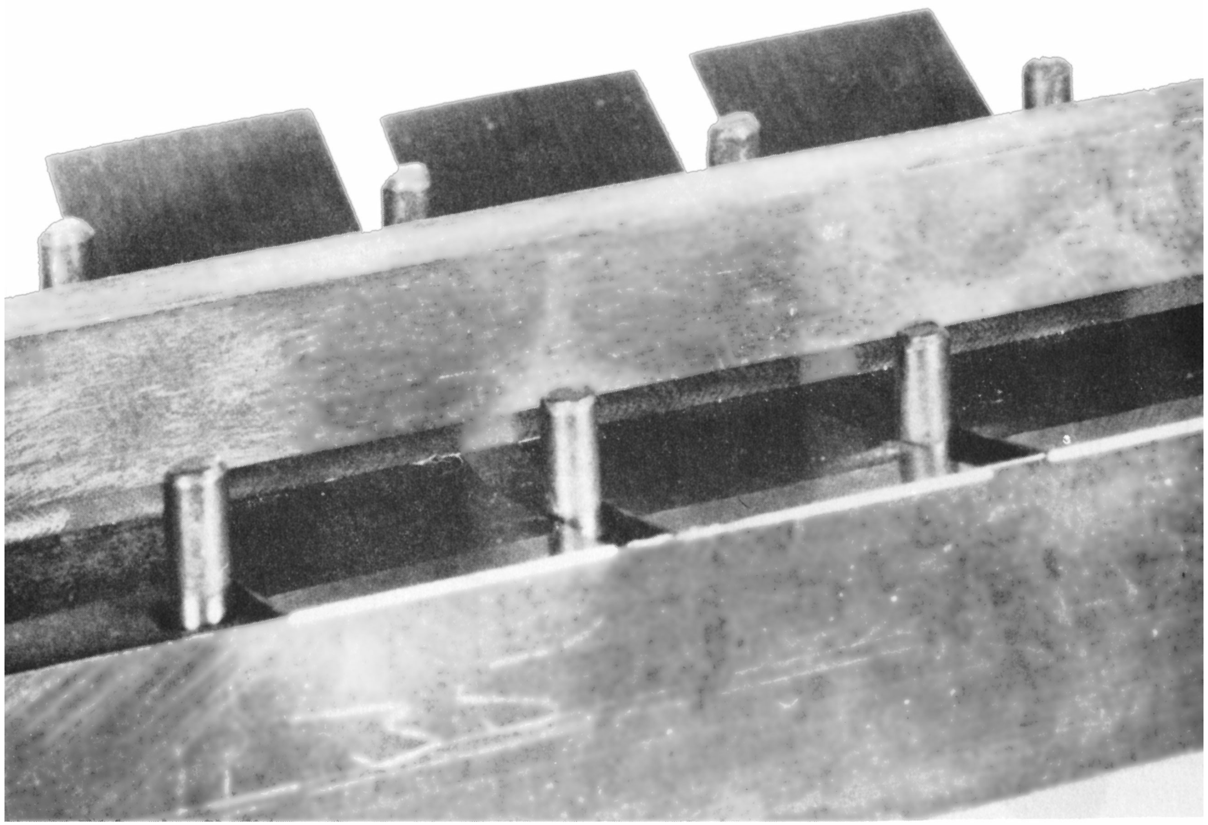


FIG. 2 Form of Jig used for Knife-edge Loading of Strip

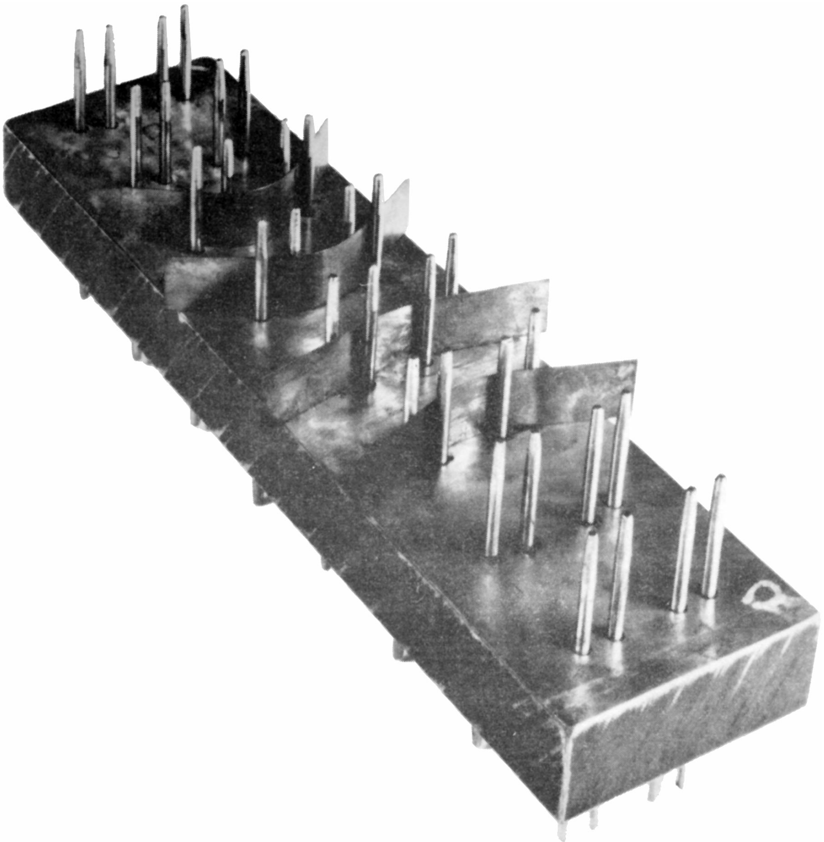


FIG. 3
Pin-board Jig Based on Four Point loading

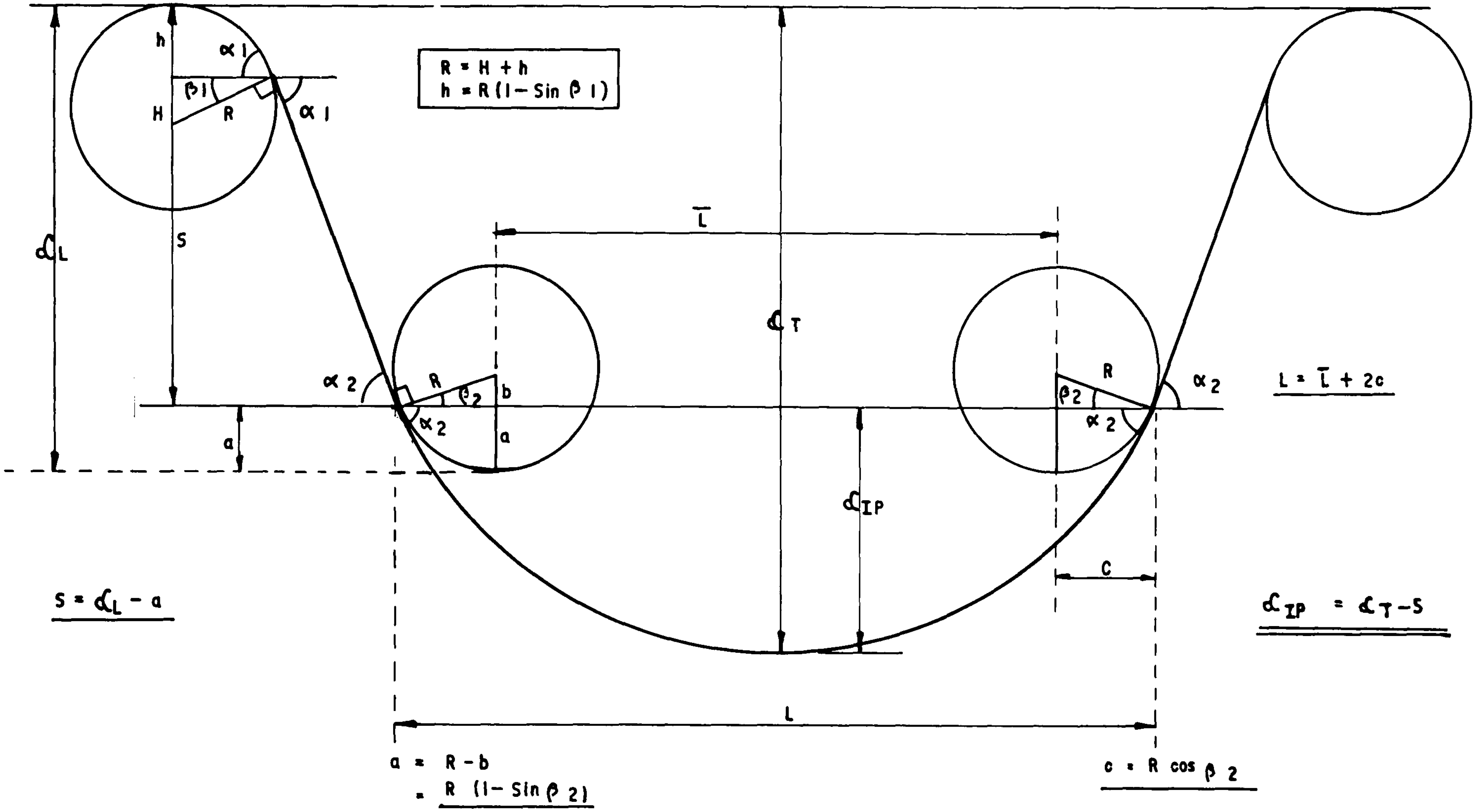
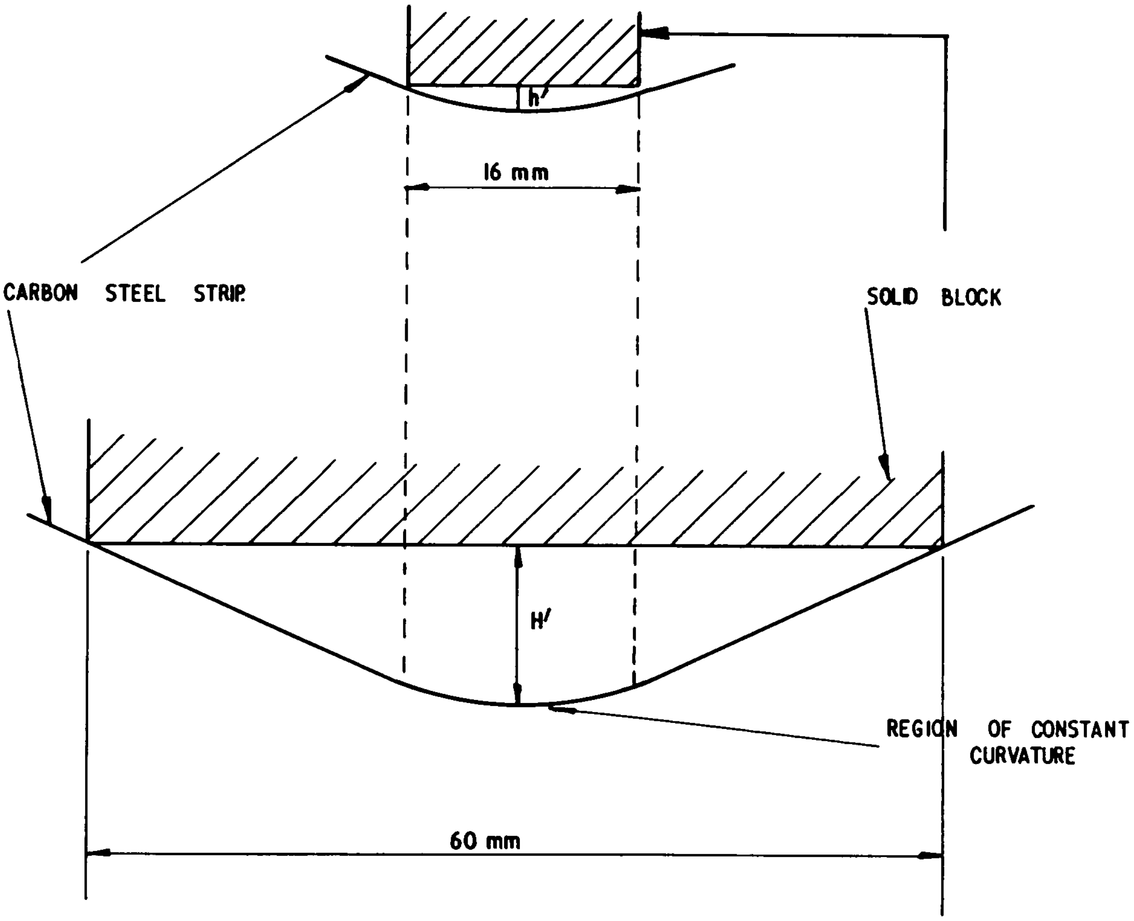


FIG. 4 ACCURATE GAUGE LENGTH AND INITIAL DEFLECTION DETERMINATION IN FOUR-POINT BENDING.



WHERE h′ AND H′ ARE THE MAXIMUM DEFLECTIONS FOR THE 16 mm AND 60 mm BLOCKS RESPECTIVELY.

FIG. 5 GAUGE BLOCKS USED FOR THE MEASUREMENT OF THE PERMANENT DEFLECTION IN THE STRIP

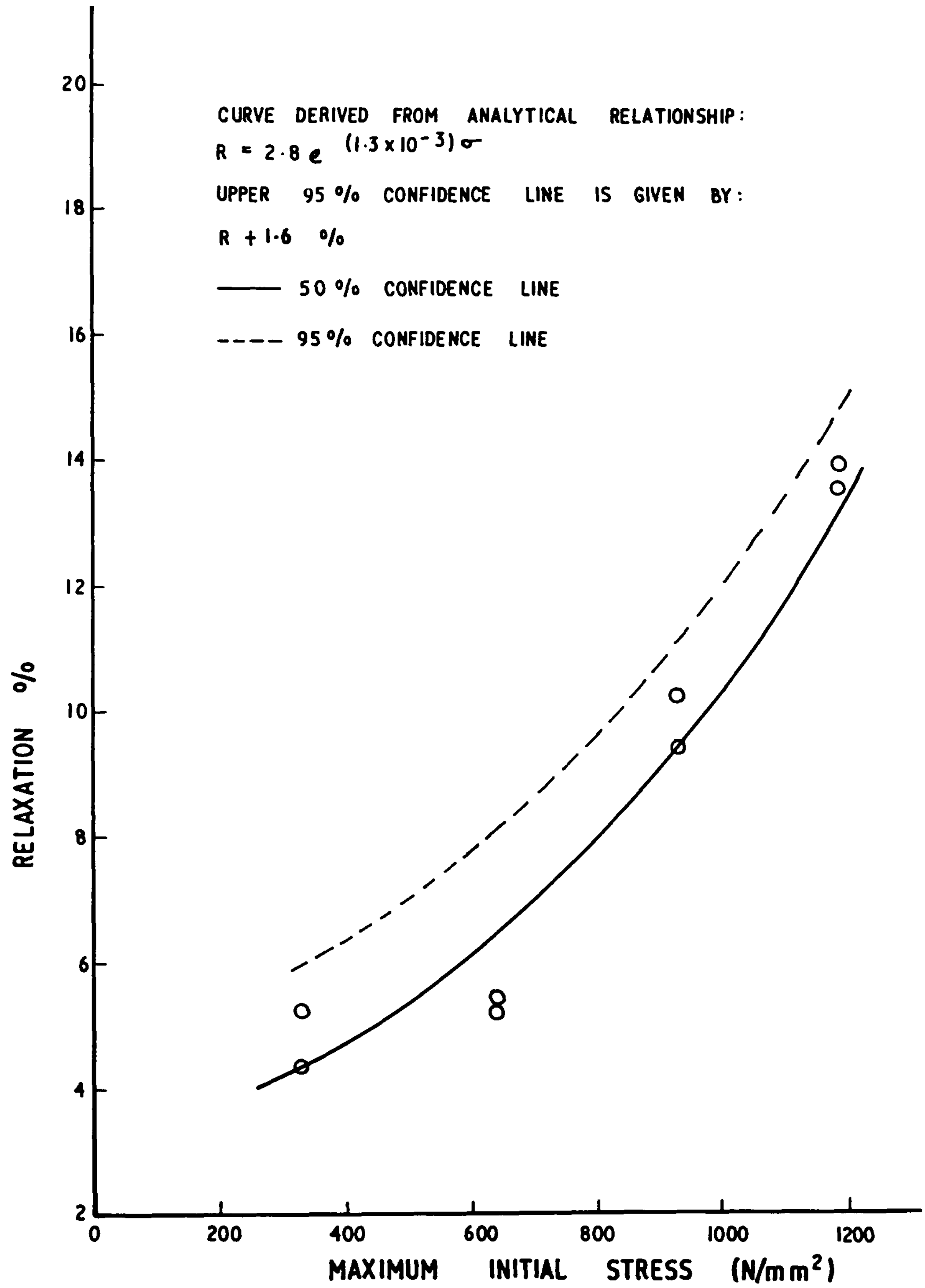


FIG. 6 STRESS RELAXATION OF 0·25 mm CS 80 STRIP AT 125°C (72 HOURS.)

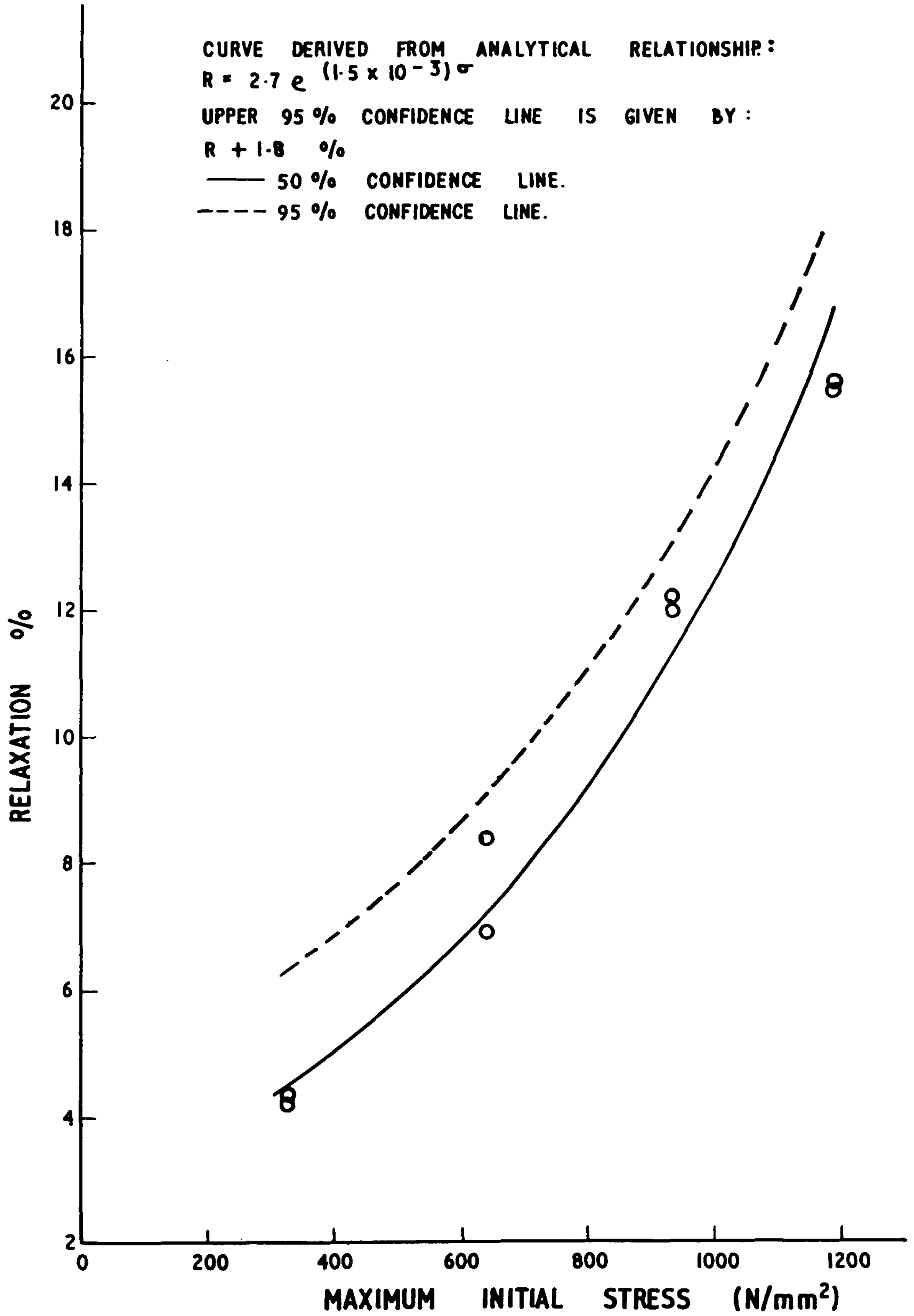


FIG. 7 STRESS RELAXATION OF 0·25 mm CS 80 STRIP AT 150°C (72 HOURS)

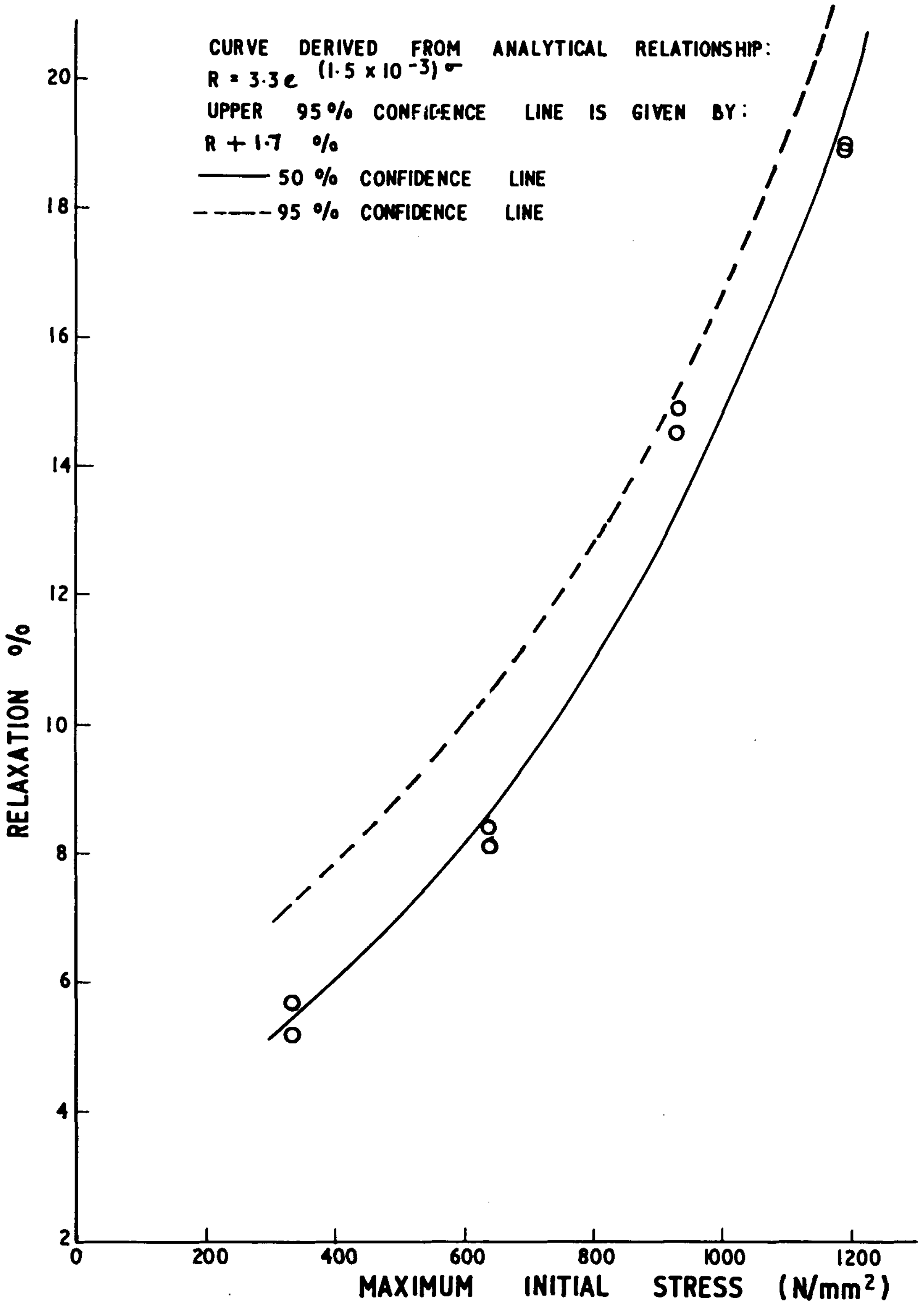


FIG. 8 STRESS RELAXATION OF 0·25 mm CS 80 STRIP AT 175° C (72 HOURS)

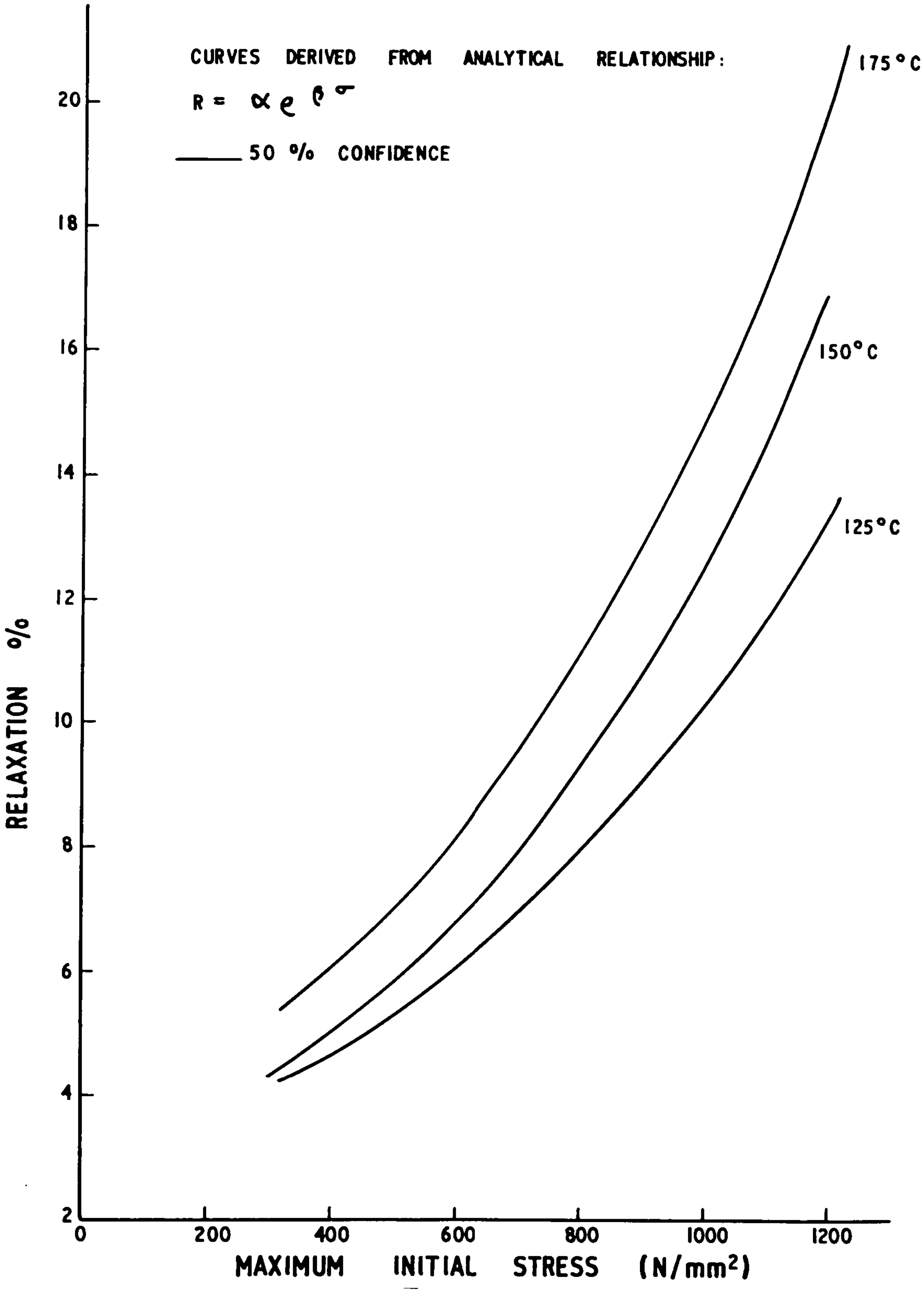


FIG. 9 STRESS RELAXATION PROPERTIES OF CS 80 STRIP.

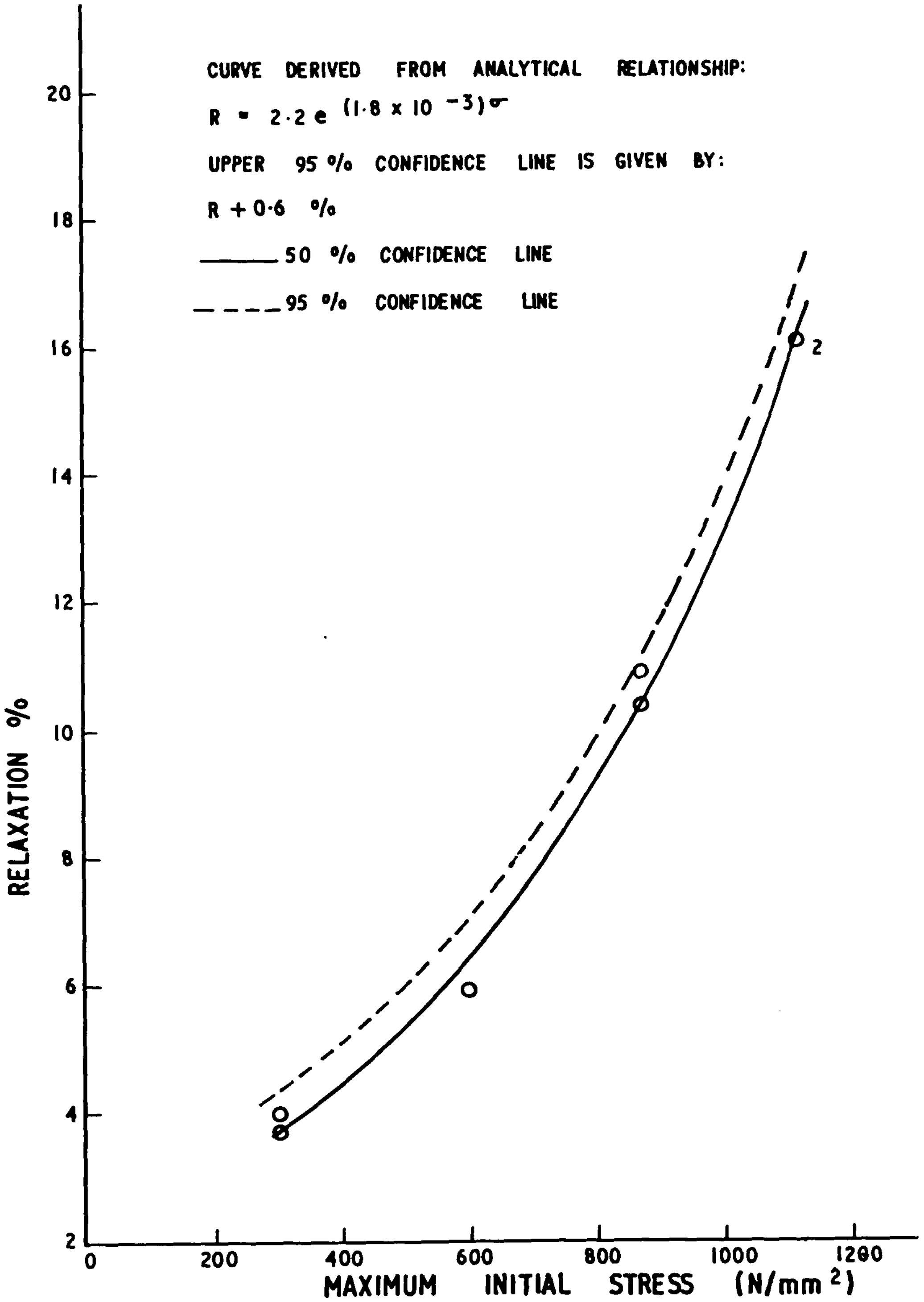


FIG. 10 STRESS RELAXATION OF 0·25 mm CS 90 STRIP AT 125° C (72 HOURS)

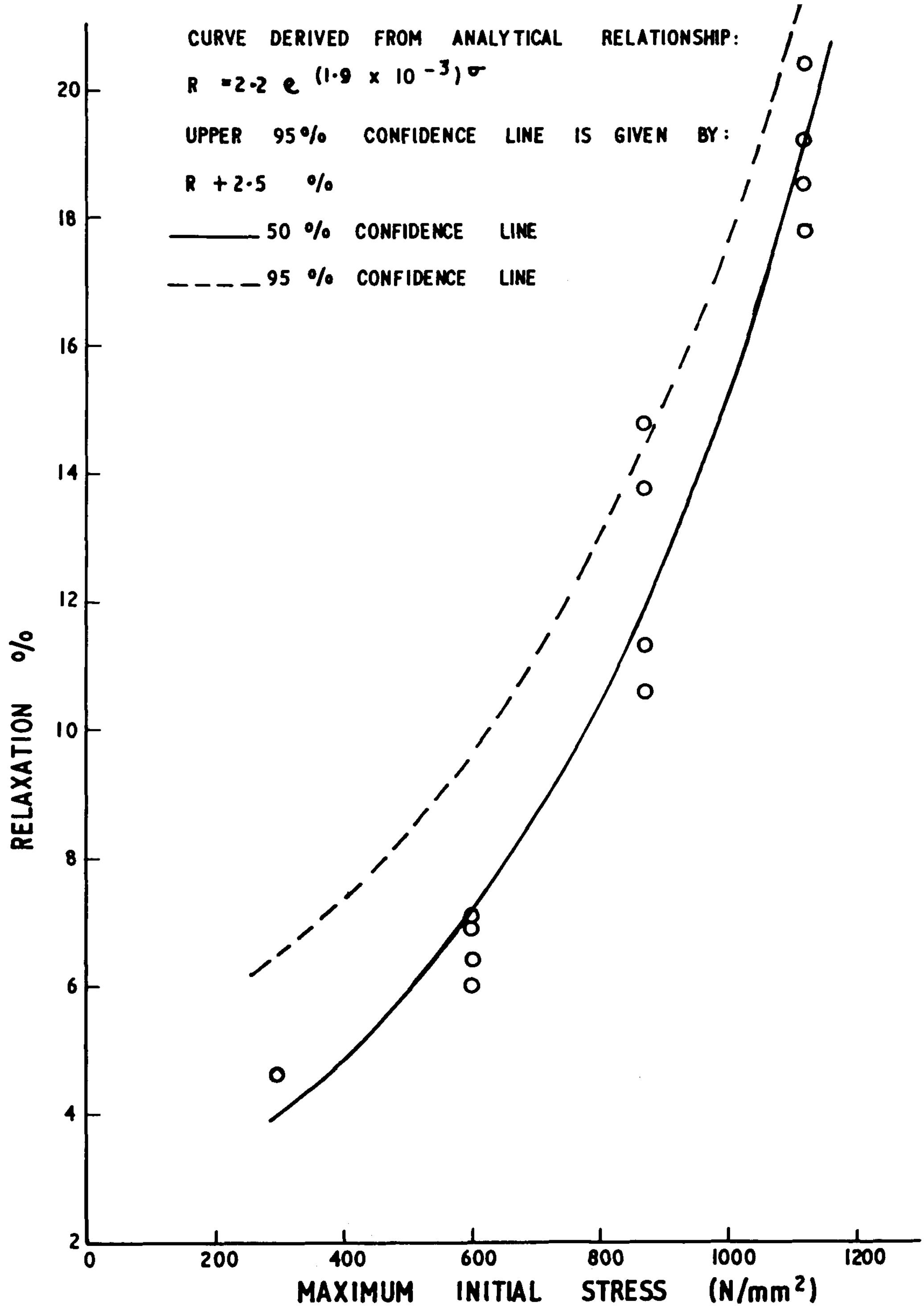


FIG. 11 STRESS RELAXATION OF 0·25 mm CS 90 STRIP AT 150°C (72 HOURS.)

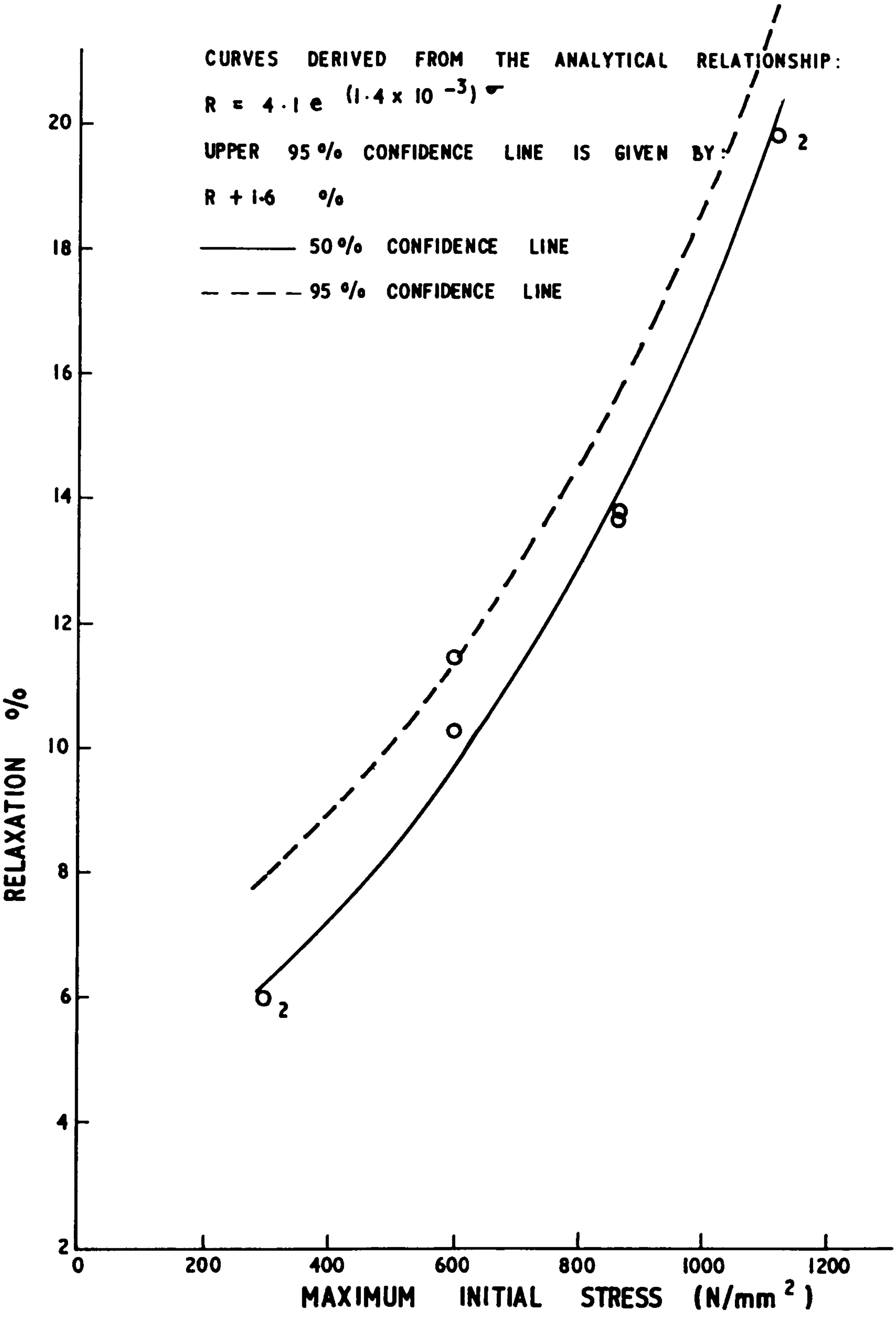


FIG. 12 STRESS RELAXATION OF 0·25 mm CS 90 STRIP AT 175°C (72 HOURS)

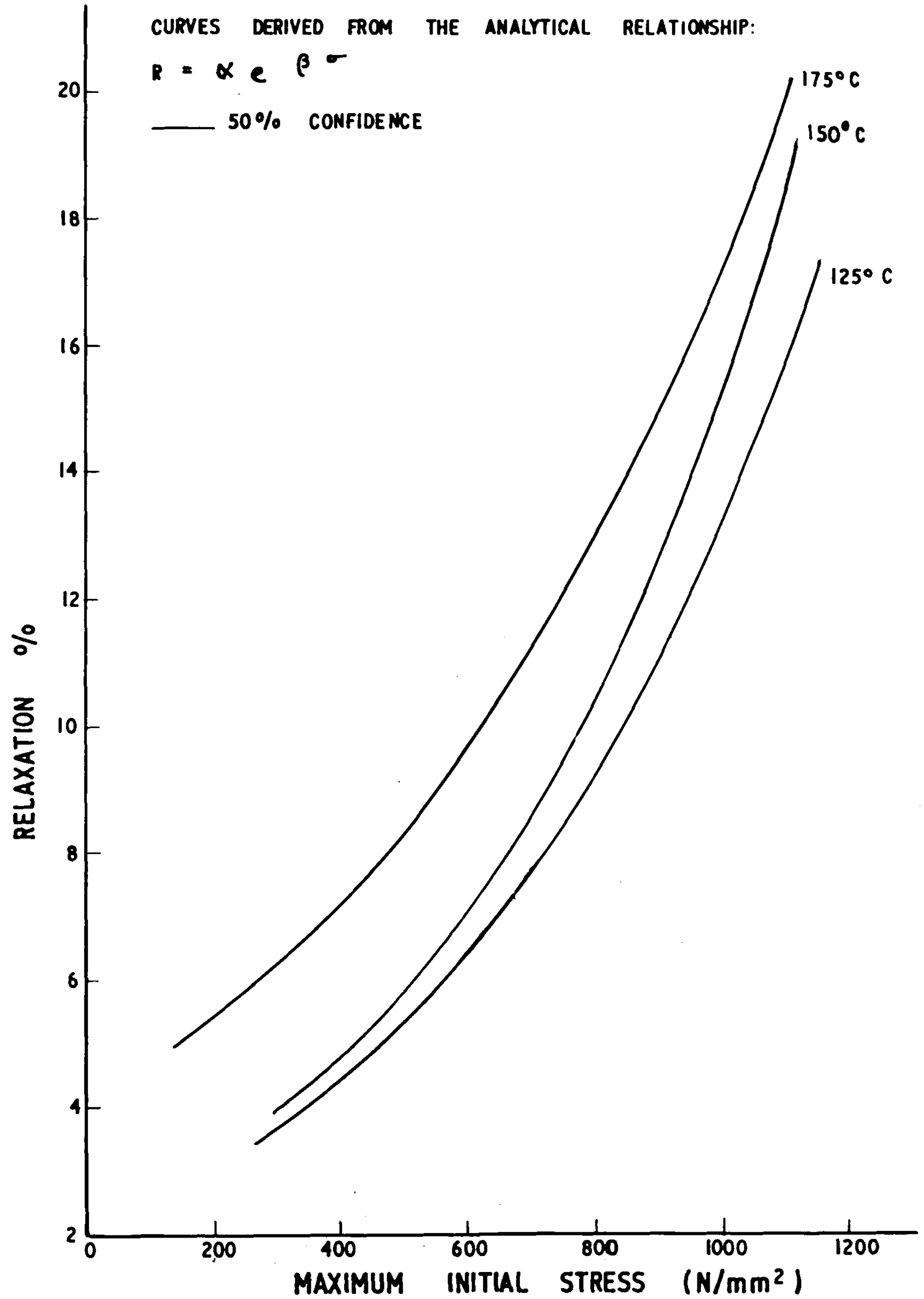


FIG. 13 STRESS - RELAXATION PROPERTIES OF CS 90 STRIP.

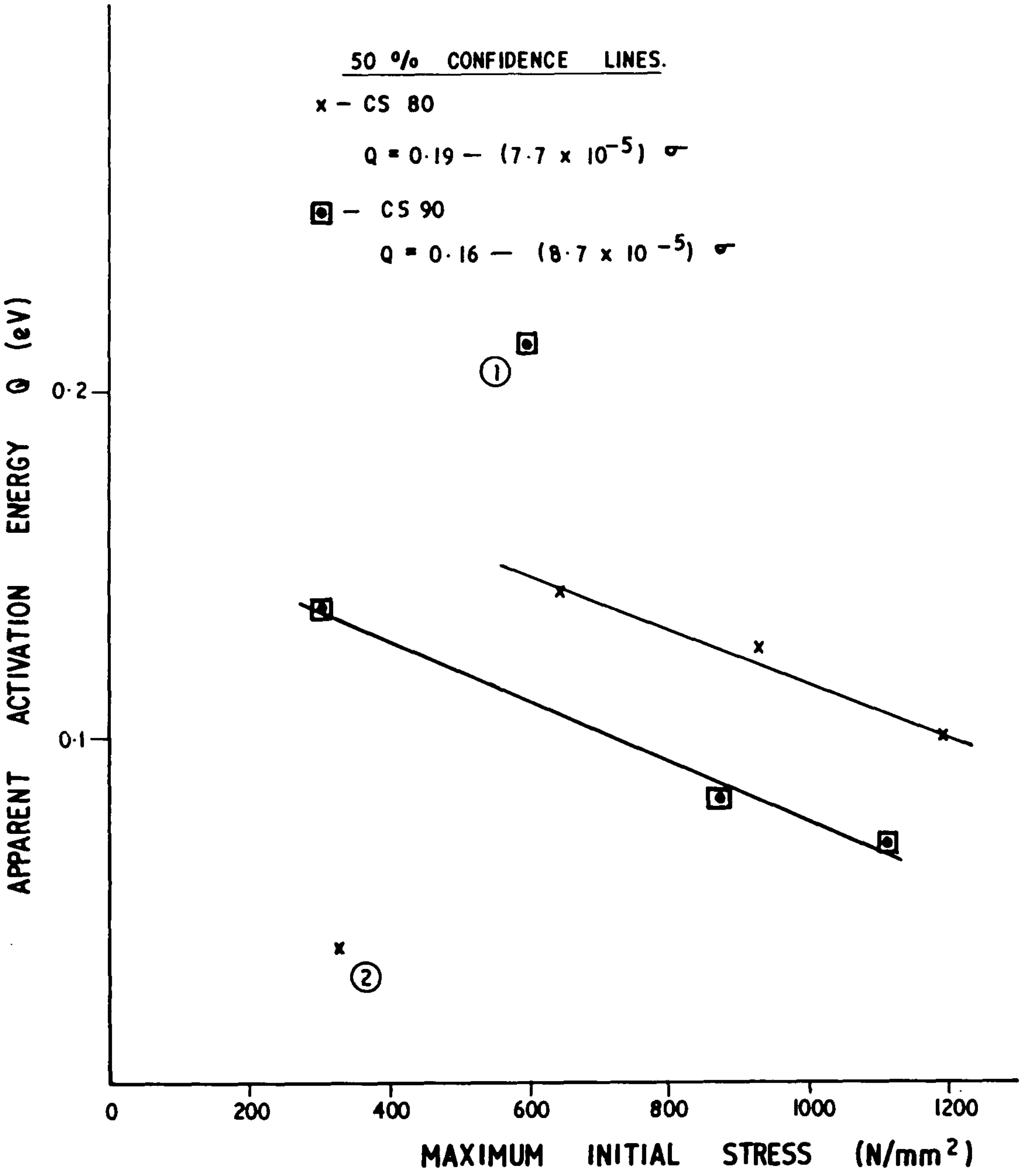


FIG. 14 VARIATION OF APPARENT ACTIVATION ENERGY FOR RELAXATION WITH APPLIED STRESS.