THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE EFFECT OF HOT PRESTRESSING ON THE RELAXATION BEHAVIOUR OF COMPRESSION SPRINGS COILED FROM En 58A HARD DRAWN STAINLESS STEEL WIRE

by

G.E. Hale, B.Met.

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SUMMARY AND CONCLUSIONS

A programme of work has been undertaken to establish the optimum hot prestressing conditions, in terms of relaxation resistance, for helical compression springs coiled from En 58A hard drawn stainless steel wire.

These studies have suggested that hot prestressing at 450°C increases the maximum operating temperature to just below 350°C, for stresses up to 800 N/mm^2, if relaxations of approximately 10% can be tolerated. Since stainless springs of this type are currently limited to temperatures of between 280° and 300°C at stresses of up to 800 N/mm^2, these findings could be of considerable economic value to both spring makers and users alike.

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1. INTRODUCTION

Hot prestressing is becoming a fairly common operation in the spring industry, especially for low alloy valve spring materials e.g. chrome-vanadium and chrome-silicon steels. SRAMA have at various times investigated the effect of hot prestressing on both the fatigue and relaxation properties of these low alloy steels(1,2,3).

Clearly, if this technique could also be successfully applied to stainless steels then it ought to be possible to increase the maximum operating temperature for these materials. For instance, an 18/8 En 58A type stainless wire could be used at higher temperatures in preference to more exotic and thus expensive alloys. It is sometimes difficult to achieve similar tensile strengths in these latter materials to those obtained in the more common stainless qualities, and inevitably, if these strength levels are possible, the wire manufacturer is forced to use more complex drawing procedures, and this is reflected by the increased cost of the material to the spring manufacturer.

In addition, if the simpler stainless materials could be used at higher temperatures, then the spring industry would be making a small but nevertheless significant contribution to more efficient utilisation of the world's limited material and energy resources.

A theoretical investigation of the possible mechanisms responsible for the changes occurring in elastic properties and relaxation with low temperature heat treatment or hot stressing has recently been undertaken at SRAMA(4). In that paper, it was suggested that the improvements in elastic and relaxation properties may be tentatively explained by the presence of mobile dislocations which are initially pinned by fine precipitates; however, with increasing stress relieving or hot stressing temperature, these mobile dislocations break away from the precipitate particles by stress-assisted thermal activation, which then leads to plastic flow in the material. These ideas have been extended in recent work on the low temperature heat treatment of stainless steel compression springs(5). It is suggested that in hard drawn stainless steel wires, the movement of mobile dislocations is more difficult than in carbon steel wires, as the main obstacles to dislocation motion are thought to be:

a) the inherently low stacking fault energy of chromium-nickel stainless steels(6). The wide stacking fault bands therefore make cross-slip more difficult; and

b) the presence of a low carbon martensitic structure(7,8) which is thought to restrict dislocation mobility.

As mobile dislocation motion is considered to be more difficult in stainless steel wires, temperatures of 400° and 500°C are needed to obtain the optimum in elastic properties and relaxation resistance respectively for hard drawn En 58A wire, in contrast to hard drawn carbon steel wires where the optimum temperatures are 200°C and 350°C(9).

As similar mechanisms are thought to be responsible for the changes in relaxation properties which occur with LTHT or with hot prestressing, then, in stainless spring wires, the optimum hot prestressing temperature should be in the region of 450° - 500°C.

Hence a programme of work has been undertaken to investigate the effect of different prestressing temperatures on the subsequent relaxation performance of springs manufactured from hard drawn En 58A stainless steel wire. At the same time, the change in free length with prestressing temperature has also been investigated.

2. MATERIALS

2.64 mm diameter En 58A (302S25) hard drawn stainless wire to BS 2056: 1953 was used for this programme of work. The chemical composition of the wire, together with the specified composition, is given in Table A below:

TABLE A CHEMICAL COMPOSITION OF 2.64 mm DIA En 58A WIRE

Element	C	*Cr	*Ni	Mn	Si	S	P
Specified (%)	0.16 max	17.0-20.0	7.0-10.0	2.00 max	0.20 min	0.045 max	0.045 max
Actual (%)	0.05	18.3	9.05	1.60	0.55	0.023	0.022

*Note: Σ Cr + Ni $\geq$ 25.0

3. TENSILE AND TORSIONAL PROPERTY DETERMINATION

Tensile tests were carried out on the Association's vertical Amsler multi-range tensile testing machine equipped with an automatic load-extension recorder and extensometer with a 250 mm gauge length. Duplicate tests were made on the as-received wire and also on wire samples given a stress relieving treatment at 500°C for 2 hours.

Torsion testing was carried out on a horizontal multi-range Tinius-Olsen torsion testing machine using a gauge length of 100 times the wire diameter.

The torsional stress is given by:

$$\tau = \frac{16T}{\pi d^3} \qquad \text{.......... (1)}$$

where τ = shear stress (N/mm^2)

T = torque (N.mm)

and d = wire diameter (mm)

Similarly, the torsional strain can be calculated from the relationship:

$$\phi = \frac{d\theta}{2L} \qquad \dots\dots\dots\dots \; (2)$$

where ϕ = torsional strain

d = wire diameter (mm)

θ = angular deflection (radians)

and L = gauge length 100 x d (mm)

The torsional properties of the En 58A wire were similarly determined in the as-received condition and after a 500°C/2 hour LTHT.

4. SPRING DESIGN AND MANUFACTURE

Helical compression springs were coiled to the design given in Table B below, on a Torrington 115A single point coiling machine:

TABLE B SPRING DESIGN

Spring Parameter	Magnitude	
Wire diameter (mm)	2.64	
Mean coil diameter (mm)	22.9	
Total coils	5.5	
Active coils	3.5	
Free length after a 500°C/2 hour LTHT and cold prestressing (mm)	47.1	
Solid stress (N/mm^2)	1215	72%
R_m (as received) N/mm^2	1690	

After coiling, the springs were end-ground. (The normal practice is to end-grind after LTHT, but in this case the springs were coiled along with springs required for the SRAMA investigation into the low temperature heat treatment of stainless steel compression springs(5), which needed to be end-ground prior to LTHT so that the dimensional changes with LTHT could be measured more easily).

The springs were then stress relieved at 500°C for 2 hours in a Wild Barfield air circulating furnace. Prior to stress relief, the springs were arranged in matched pairs so that the significance of any difference in free length resulting from prestressing could be determined accurately.

At the time this work was carried out, although the optimum stress relieving temperature for maximum relaxation resistance was known to be 500°C, it had not been realised that a 30 minute treatment was as effective as a 2 hour one(5). Thus, the springs for this investigation were stress relieved at 500°C for 2 hours.

5. EXPERIMENTAL PROCEDURE

5.1 Cold Prestressing

Preliminary trials indicated that 20 scrags were required to ensure complete stability in the springs. Subsequently, sixty individually identified springs were cold prestressed to solid 20 times.

5.2 Hot Prestressing

Batches of five identified springs were held in a Wild Barfield air circulating furnace for at least five minutes to allow them to reach the required prestressing temperature. Each spring was then prestressed to solid using a parallel prestressing device operating on a scissors principle (see Figure 1). The springs were scragged solid using one load application and held in this position, at temperature, for 5 seconds, before quenching into oil while still under restraint (if the load is removed while the springs are still hot, they tend to recover some of the free length lost by the original prestressing process).

After each spring had been prestressed, the furnace lid was closed and the furnace brought back to temperature. In general, the total time a spring was in the furnace varied between 5 and 15 minutes.

Sixty springs were hot prestressed in this manner at each temperature of 300°, 400°, 450° and 500°C.

5.3 Free Length Determinations

The free length of each individual spring was measured before any prestressing operations took place.

After prestressing, the free length was remeasured on a sample of ten springs taken from the sixty springs processed at each prestressing temperature.

5.4 Relaxation Testing

5.4.1 Testing procedure

Stress-relaxation tests were carried out on springs which had been prestressed in the manner described above, using an air-circulating oven.

The relaxation tests were carried out using the standard 'nut and bolt' assembly(10,11), however, to reduce sticking friction between the washers and springs, the ends of the springs were dipped in a 'graphite-in-alcohol' suspension before bolting down.

The outside diameter of each spring was measured using vernier calipers, and individual loads for the appropriate initial torsional stress were calculated using the standard expression below:

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \text{..........} \quad (3)$$

where P = axial load (N) applied to the spring
τ = torsional stress (N/mm^2) due to a load P
d = wire diameter (mm)
D = mean coil diameter (mm)
and K = stress correction factor for curvature

$$= \frac{c + 0.2}{c-1}$$

with c = spring index = $\frac{D}{d}$

Before relaxation testing the minimum length resulting from the initial calculated load (L_o) was measured. After testing, the springs were again load tested to the same minimum length and the load (L_f) remeasured.

The % relaxation (Rel), or loss in load, which has occurred is given by:

$$\text{Rel}(\%) = \frac{(L_o - L_f)}{L_o} \times 100\% \qquad \ldots\ldots\ldots\ldots (4)$$

5.4.2 Cold prestressed springs

Springs were relaxation tested in the manner described above at temperatures of 250°, 300° and 350°C for 168 hours. Springs were tested at initial torsional stresses of 300, 600 and 800 N/mm^2, using five springs at each stress level.

5.4.3 Hot prestressed springs

In the first instance, relaxation testing was carried out at 300°C for 168 hours on springs which had been hot prestressed at 300°, 400°, 450° and 500°C.

From this work it became clear that a 300°C hot prestress did not give a particularly large decrease in % relaxation and thus testing was discontinued on springs given this hot prestressing treatment.

However, further tests were undertaken on those springs hot prestressed at 400°, 450° and 500°C, using relaxation temperatures of 350° and 400°C for 168 hours.

In all these cases, springs were tested at initial torsional stresses of 300, 600 and 800 N/mm^2, using five springs at each stress level.

6. RESULTS

6.1 Tensile and Torsional Properties

The tensile properties of the 2.64 mm dia En 58A wire in the as-received condition and after a 500°C/2 hour LTHT are given in Table I, while the corresponding torsional properties can be found in Table II.

6.2 Free Length Determinations

The decrease in mean free length on a sample of 10 springs from the 60 springs processed at each prestressing temperature is given in Table III, while a graphical representation of the data can be found in Figure 2.

6.3 Relaxation Testing

The effect of prestressing temperature on the relaxation behaviour of En 58A springs can be seen in Figures 3 to 5, while the experimental data is given in Tables IV to VI.

7. DISCUSSION

7.1 Chemical Composition

The chemical composition of the wire fell within the ranges specified for En 58A steel wire in BS 2056: 1953 (see Table A on page 3).

7.2 Observed Tensile and Torsional Properties of 2.64 mm dia En 58A Wire

The tensile strength of the as-drawn wire was measured at 1690 N/mm^2, which is close to the top of the specified strength range, 1390 - 1700 N/mm^2, for this wire size. Both the tensile strength and elastic properties of the wire were higher than the as-received values after a LTHT at 500°C for 2 hours (see Table I). Although the optimum lift in the elastic properties of the wire had been found to occur at 400°C, stress relieving at 500°C was necessary to obtain the maximum relaxation resistance for compression springs coiled from this wire(5).

The torsional properties of the wire were also increased by a 500°C/2 hour LTHT, as was the rigidity modulus (G) of the wire (see Table II).

7.3 Effect of Prestressing Temperature on the Free Length of En 58A Compression Springs

It was found that the free length of the springs decreased with prestressing at both ambient and higher temperatures. The magnitude of this change tended to increase as the prestressing temperature was raised (See Table III and Figure 2).

From the data obtained after prestressing at temperatures between 20^{o} and 450^{o}C, it is possible to describe the change in free length with prestressing temperature by an expression of the form:

$$\Delta = ae^{bT} \qquad \dots\dots\dots\dots (5)$$

where Δ = decrease in mean free length of the spring (mm)

T = prestressing temperature (^{o}C)

a and b are analytically determined constants

Equation (5) can be written as:

$$\ln \Delta = bT + \ln a \qquad \dots\dots\dots\dots (6)$$

By plotting $\ln \Delta$ versus prestressing temperature (in ^{o}C), the experimental data can be fitted to a straight line using a least mean squares procedure. The curve obtained has a correlation which is significant at the 99.9% level. The values of the constants, a and b, are given in Table C below. The 95% confidence band for the data has been calculated using $1.96\ S_R$ (where S_R = Standard deviation of the residuals), and this has been plotted on Figure 2, while the value of the 95% confidence increment is also given in Table C.

TABLE C ANALYTICAL CONSTANTS FOR THE EXPONENTIAL RELATIONSHIP BETWEEN THE DECREASE IN MEAN FREE LENGTH OF En 58A SPRINGS AND PRESTRESSING TEMPERATURE

Constants for $\Delta = ae^{bT}$		Increment for 95% confidence = $\pm 1.96\ S_R$
a	b	
2.37	1.9×10^{-3}	0.73

It should be noted that the scatter of the results as expressed by the standard deviation (see Table VII) is much greater for a 500°C prestress than for the other prestressing temperatures. This scatter is considered to be attributable to the increased distortion observed in those springs prestressed at 500°C. The distortion in the springs prestressed at this temperature was so great that consistent measurement of the free length was not possible, and thus the results obtained at this temperature were omitted from the mathematical analysis of the data.

It can be seen that any improvements in relaxation performance at operating temperatures higher than 450°C must be balanced against the probable increases in distortion resulting from the higher prestressing temperatures employed.

7.4 The Effect of Prestressing Temperature on the Relaxation Behaviour of En 58A Springs

The variation of relaxation with prestressing temperature at a number of initial stress levels, is illustrated in Figures 3 to 5. It should be noted that these curves have been plotted by eye and can therefore only give a tentative idea of the exact relationship between relaxation and prestressing temperature. It is clear, however, that there was a similar pattern at all three stress levels.

Relaxation decreased as the prestressing temperature rose, with the majority of the decrease occurring with prestressing temperatures above 350°C. This effect tended to be more noticeable with the higher relaxation temperature, i.e. 350°C and 400°C. A similar effect was observed for the decrease in relaxation with LTHT, where a decrease in relaxation of around 10% occurred between 350°C and 400°C, compared to 6% between 400° and 450°C(5).

At any particular prestressing temperature, relaxation was found to increase linearly with increasing stress.

7.5 Temperature Dependence of Relaxation

Figures 3 to 5 indicate that relaxation increased rapidly as the testtemperature increased, at any one particular prestressing temperature. This type of behaviour has also been observed in other spring materials(12,13,14) and it is best described by an experimental relationship of the form:

$$\text{Rel} = \alpha e^{\beta/T} \qquad \ldots\ldots\ldots\ldots (8)$$

where Rel = % relaxation

T = absolute temperature (°K)

α and β are analytically derived constants

Equation (8) can be rewritten in the form:

$$\ln \text{Rel} = \ln\alpha + \frac{\beta}{T} \qquad \ldots\ldots\ldots\ldots (9)$$

By plotting ln Rel versus the reciprocal of the absolute temperature, the experimental data can be fitted to a straight line using a least mean squares procedure. The values of the constants α and β can be determined, and these are given in Tables VIII and IX for initial stresses of 600 and 800 N/mm^2 respectively.

7.6 Suggested Improvement in Maximum Operating Temperature

On the basis of the above data, there appears to be reasonable grounds for suggesting that a hot prestress at 450°C will increase the maximum operating temperature for En 58A compression springs to just below 350°C, for stresses up to 800 N/mm^2, provided that a maximum relaxation of approximately 10% is acceptable at this stress. This is a definite improvement over the current maximum temperature of 280° - 300°C. The data suggests that a prestress at 500°C would give even lower levels of relaxation, although the springs which were prestressed at 500°C distorted much more than those at the other prestressing temperatures, as referred to in Section 7.3 above.

It might well be that if the springs were not prestressed to completely solid the distortion would be lessened. However, the elastic limit would not be raised to the same extent as occurs when prestressing solid. It would be interesting, therefore, to carry out further work at 500°C on springs prestressed almost to solid and then tested for relaxation. This might lessen the distortion, while giving a further slight improvement in relaxation resistance.

7.7 Apparent Activation Energy Determination

Recent work at SRAMA(12,13,14) has shown that a value for the apparent thermal activation energy necessary for relaxation to occur can be determined from the slope(β) of the ln Rel versus reciprocal of absolute temperature plot at a constant stress, derived from equation (9).

As the slope of the curve is given by the value of the constant (β) in equation (9), then:

$$\beta = -\frac{Q}{R} \qquad \text{..........(10)}$$

where Q = apparent thermal activation energy ($J.mol^{-1}$)

and R = universal gas constant = $8.36 J.mol^{-1}.{}^{o}K^{-1}$

(Note 1eV = $96{,}300 J.mol^{-1}$)

Values of the apparent thermal activation energy have been derived after prestressing at ambient temperature and also at temperatures of 400°, 450° and 500°C. These values can be found in Tables VIII and IX for initial torsional stresses of 600 and 800 N/mm^2 respectively. It was not possible to determine apparent activation energies at an initial torsional stress of 300 N/mm^2, as the occurrence of negative relaxation in a large number of the samples prevented their interpretation in terms of equation (9).

It has been possible to fit the limited amount of data available to expressions of the type:

$$\ln Q = A\ln T + \ln B \qquad \text{..........(11)}$$

where Q = apparent thermal activation energy (eV)

T = prestressing temperature (^{o}C)

A and B are analytically derived constants

Equation (11) can be rearranged to give:

$$Q = BT^{A} \qquad \text{..........(12)}$$

Figure 6 is a graphical representation of this expression, showing the variation of apparent thermal activation energy (Q) with prestressing temperature, at initial torsional stresses of 600 and 800 N/mm^2. The analytical constants, A and B, are given in Table D below:

TABLE D ANALYTICAL CONSTANTS FOR THE EXPONENTIAL ACTIVATION ENERGY-PRESTRESSING TEMPERATURE PLOT

Initial Torsional Stress (N/mm^2)	Constants for the Relationship $Q = BT^A$	
	A	B
600	0.31	0.17
800	0.25	0.18

As the above curves were determined from only four points, they are clearly tentative. However, in both cases, the curves give correlations which are significant at the 95% level. This indicates that the suggested expression might be correct, but more work would be needed to determine the equation of the curves more precisely.

7.8 Possible Explanation of Observed Effects of Prestressing Temperature on Relaxation

From previous work(12,13), it would seem reasonable to suggest that the apparent activation energy should increase with prestressing temperature. However, the slope of the curve (Fig. 6) tends to decrease with a rise in prestressing temperature, as the number of available mobile dislocations is decreased. This would lead to a decrease in relaxation with prestressing temperature, as seen earlier (See Figures 3 to 5).

Figure 6 also indicates that the apparent activation energy decreased with increasing initial stress. This is in agreement with previous work at SRAMA(12,13,14), where it has been suggested that the strain energy tends to vary inversely with the apparent thermal activation energy.

This work has suggested that the mechanisms responsible for changes in relaxation with LTHT or with hot prestressing are similar. These changes can be tentatively explained by the presence of mobile dislocations, which at room temperature are rendered immobile by a variety of obstacles(5), e.g. fine precipitates, type of martensite, wide stacking fault bands. Eventually, with increasing hot prestressing or LTHT temperature, it is thought that the mobile dislocations break away from the obstacles by stress-assisted thermal activation(4), which eventually leads to plastic flow in the material.

It has been shown that the maximum relaxation resistance in En 58A compression springs is obtained with similar LTHT and hot prestressing temperatures. It is possible, therefore, on the basis of theoretical considerations and work by Reynolds(16), that hot prestressing without any previous stress relieving treatment might give an equal or even lower level of relaxation. Obviously this could cause practical production difficulties, as the springs need to be stable before end-grinding, and this stability is usually imparted by the LTHT after coiling, However, by suitable jigging, it should be possible to hot prestress before end-grinding and hence give the springs the necessary stability. Further work is needed to determine if these theoretical suggestions apply in practice, and if so, considerable reductions in processing time should be possible.

CONCLUSIONS

1. By hot prestressing at 450°C, the maximum operating temperature for En 58A compression springs can be increased to just below 350°C for stresses up to 800 N/mm^2, provided that relaxation of approximately 10% can be tolerated.

2. The prestressing temperature must be distinctly higher than the operating temperature to obtain any real improvement in relaxation properties.

3. The magnitude of the decrease in free length of En 58A compression springs with prestressing appears to increase exponentially as the prestressing temperature rises, for prestressing temperatures between 20° and 450°C

4. Relaxation has a linear relationship with stress, for springs coiled from En 58A hard drawn wire.

5. Relaxation is related exponentially to the reciprocal of the absolute temperature for En 58A stainless steel springs.

6. The exponential relationship between relaxation and the reciprocal of the absolute temperature has enabled the apparent thermal activation energy to be evaluated, at initial stresses of 600 and 800 N/mm^2. It appears that the apparent thermal activation energy decreases as the applied stress increases.

7. The apparent thermal activation energy appears to vary as a simple power relationship with the prestressing temperature (in °C).

8. It is suggested that the improvements in relaxation properties and elastic properties with LTHT and/or hot prestressing can be explained by similar mechanisms, based on the interaction of mobile dislocations with a variety of obstacles in the structure.

9. RECOMMENDATIONS FOR FUTURE WORK

1. Further work at other prestressing temperatures would be useful for a variety of reasons:

   a) to establish the relaxation-prestressing temperature curves more precisely;

b) to obtain a better estimate of the maximum operating temperature for the stresses investigated;

c) to determine more precisely if the apparent activation energy for relaxation does vary as a simple power relationship with the prestressing temperature (in °C).

2. It is possible that if the springs were not prestressed completely solid, distortion might be reduced. Higher prestressing temperatures could then be used, with the possibility of a further slight improvement in relaxation resistance. It is suggested that further work is carried out to investigate these ideas.

3. The effect of hot prestressing on the subsequent fatigue performance of both unpeened and shot peened En 58A compression springs should be investigated.

4. The relaxation behaviour of springs which have been coiled, hot prestressed and end-ground should be studied and compared to the normal route of coil, LTHT, end-grind and hot prestress.

5. Further studies aimed at understanding the basic physical metallurgy involved in relaxation processes should be carried out.

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TABLE I TENSILE PROPERTIES OF 2.64 mm En 58A WIRE

Material Condition	R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)	Elongation % A (on a 2" gauge length)	Reduction in Area % Z
		R_p 0.2	R_p 0.1	R_p 0.05			
As-received	1690	1525	1335	1115	705	3.1	38
	1690	1525	1390	1205	715	3.1	38
500°C 2 hours LTHT	1750	1560	1390	1220	770	-	42
	1740	1560	1405	1240	710	-	42

TABLE II TORSIONAL PROPERTIES OF 2.64 mm En 58A WIRE

Material Condition	Ultimate Shear Strength (N/mm^2)	Torsional Proof Stresses (N/mm^2)		Limit of Proportionality (N/mm^2)	Twists to failure	G (N/mm^2) x 10^4
		0.2%	0.1%			
As-received	1250	790	670	455	5	6.6
	1250	780	665	450	5	6.6
500°C 2 hours LTHT	-	940	840	540	-	7.2
	1330*	910	815	540	-	7.2

* Unbroken

TABLE III DECREASE IN FREE LENGTH WITH PRESTRESSING TEMPERATURE

Decrease in Free Length (mm) after Cold Prestressing at 20°C	Decrease in Free Length (mm) after Prestressing at Temperatures of:			
	300°C	400°C	450°C	500°C
2.650	3.575	4.225	6.350	6.300
2.650	4.825	5.425	5.400	5.950
2.100	4.475	5.525	5.575	6.675
2.850	4.000	5.025	5.875	7.450
2.025	4.250	5.025	5.525	9.125
2.425	3.500	5.050	5.875	7.600
2.450	4.450	5.875	5.350	7.800
2.500	4.425	5.325	5.650	7.400
2.650	4.300	5.250	5.375	8.450
2.575	4.000	5.325	6.475	7.850

Note: The values shown are the mean of two measurements on each spring.

TABLE IV RELAXATION DATA AT AN INITIAL STRESS OF 300 N/mm^2, AFTER PRESTRESSING AT VARIOUS TEMPERATURES

Prestressing Condition	% Relaxation at an Initial Stress of 300 N/mm^2, after 168 hours at Temperatures of:			
	250°C	300°C	350°C	400°C
20°C 20 Prestresses	-0.6	1.3	9.6	-
	-0.1	1.4	8.0	
	-0.4	2.0	8.8	
	-0.6	1.5	8.8	
	-1.1	2.2	9.4	
300°C 1 Prestress for 5 secs	-	1.6	-	-
		2.2		
		1.1		
		2.1		
		1.7		
400°C 1 Prestress for 5 secs	-	-0.5	7.9	22.3
		-0.7	7.2	22.5
		-1.1	6.7	23.1
		-0.9	7.0	21.9
		-1.2	7.2	21.5
450°C 1 Prestress for 5 secs	-	-3.4	4.5	21.2
		-3.8	6.5	17.9
		-3.8	5.5	16.4
		-3.8	4.9	20.2
		-3.3	4.7	20.2
500°C 1 Prestress for 5 secs	-	-5.7	-4.5	11.3
		-6.3	-4.6	10.0
		-5.2	-3.4	11.3
		-6.6	-5.1	10.3
			-4.8	

TABLE V RELAXATION DATA AT AN INITIAL STRESS OF 600 N/mm^2, AFTER PRESTRESSING AT VARIOUS TEMPERATURES

Prestressing Condition	% Relaxation at an Initial Stress of 600 N/mm^2, after 168 hours at Temperatures of:			
	250°C	300°C	350°C	400°C
20°C 20 Prestresses	2.7	6.1	11.8	-
	3.3	6.6	13.3	
	3.5	6.2	14.7	
	2.0	5.4	10.9	
	3.2	5.4	13.3	
300°C 1 Prestress for 5 secs	-	3.2	-	-
		4.5		
		3.7		
		2.3		
		3.1		
400°C 1 Prestress for 5 secs	-	0.7	12.4	29.2
		3.0	11.2	29.1
		2.0	11.3	32.5
		1.5	12.0	29.2
		1.2	11.3	29.4
450°C 1 Prestress for 5 secs	-	1.2	10.6	28.7
		1.6	9.1	29.1
		0.1	9.9	26.5
		1.2	9.4	27.9
		0.1	9.8	28.0
500°C 1 Prestress for 5 secs	-	2.5	6.5	25.8
		1.0	6.4	23.4
		1.0	6.5	26.5
		1.4	6.7	28.8
		1.3	6.9	22.5

TABLE VI RELAXATION DATA AT AN INITIAL STRESS OF 800 N/mm^2, AFTER PRESTRESSING AT VARIOUS TEMPERATURES

Prestressing Condition	% Relaxation at an Initial Stress of 800 N/mm^2, after 168 hours at Temperatures of:			
	250°C	300°C	350°C	400°C
20°C 20 Prestresses	4.4	8.2	16.1	-
	4.8	8.7	15.2	
	4.4	7.3	18.2	
	4.2	8.6	16.6	
	5.1	7.3	16.6	
300°C 1 Prestress for 5 secs	-	5.4	-	-
		5.1		
		5.8		
		6.3		
		5.2		
400°C 1 Prestress for 5 secs	-	2.4	14.7	33.5
		4.3	14.6	33.7
		5.4	15.0	34.0
		4.2	13.8	35.4
		5.0	14.9	34.5
450°C 1 Prestress for 5 secs	-	3.1	12.8	32.3
		3.1	12.2	34.6
		3.2	12.8	33.2
		2.4	12.5	30.2
		2.7	14.1	33.5
500°C 1 Prestress for 5 secs	-	1.6	9.2	31.5
		2.4	7.1	26.1
		3.0	8.7	27.3
		2.6	8.2	28.3
		1.8	7.6	29.0

TABLE VII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON FREE LENGTH MEASUREMENTS

Prestressing Condition	Mean Value $\bar{A}$ (mm)	Std Dev S_A	't'*	Comments
Cold Prestressed at 20°C	2.49	0.26	30.78	Differences all significant at the 99.9% level
300°C	4.18	0.41	31.87	
400°C	5.20	0.43	38.10	
450°C	5.74	0.40	45.56	
500°C	7.46	0.96	24.59	

Where A = (Free length before prestressing)

− (Free length after prestressing)

* Total number of pairs in each case = 10

TABLE VIII VALUES OF APPARENT ACTIVATION ENERGY DERIVED FROM PLOTS OF RELAXATION VERSUS RECIPROCAL OF ABSOLUTE TEMPERATURE, AT AN INITIAL STRESS OF 600 N/mm^2

Prestressing Temperature (°C)	Analytical Constants for the relationship: $Rel = \alpha e^{\beta/T}$		Apparent Activation Energy Q (eV)
	$\ln\alpha$ = constant of proportionality	β	
20	10.3	-4821	-0.42
400	20.8	-11613	-1.01
450	27.3	-15931	-1.38
500	20.0	-11291	-0.98

where Q = $R.\beta$ ($J.mol^{-1}$)

and R = Universal Gas Constant = 8.36 $J.mol^{-1}.{}^{o}K^{-1}$

(Note 1 eV = 96,300 $J.mol^{-1}$)

TABLE IX VALUES OF APPARENT ACTIVATION ENERGY DERIVED FROM PLOTS OF RELAXATION VERSUS RECIPROCAL OF ABSOLUTE TEMPERATURE, AT AN INITIAL STRESS OF 800 N/mm^2

Prestressing Temperature (°C)	Analytical Constants for the relationship: $Rel = \alpha e^{\beta/T}$		Apparent Activation Energy Q (eV)
	$\ln\alpha$ = constant of proportionality	β	
20	9.5	-4211	-0.37
400	15.8	-8199	-0.71
450	17.5	-9406	-0.82
500	17.9	-9811	-0.85

where Q = $R.\beta$ ($J.mol^{-1}$)

and R = Universal Gas Constant = 8.36 $J.mol^{-1}.{}^{o}K^{-1}$

(Note: 1 eV = 96,300 $J.mol^{-1}$)

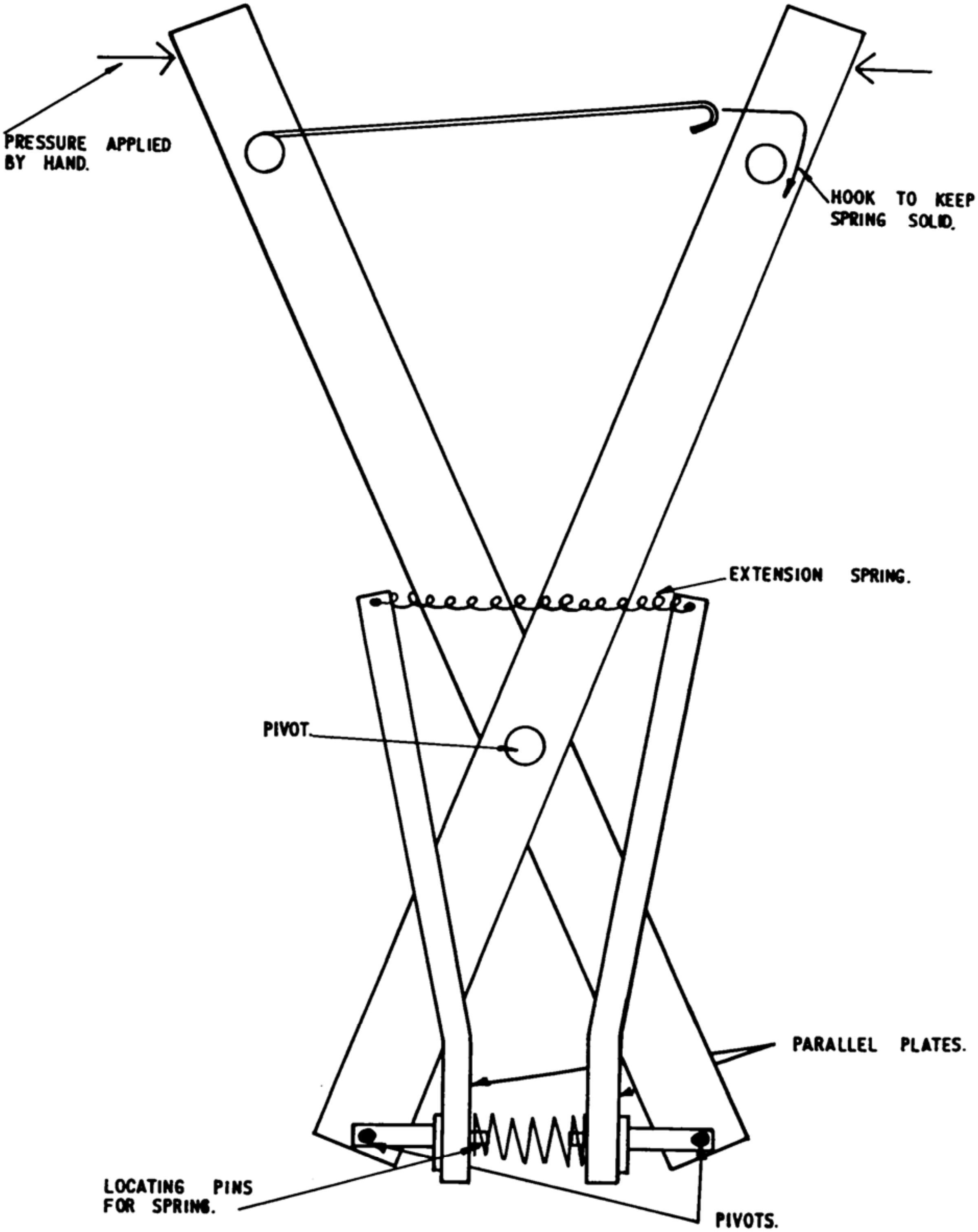

FIG. I. HOT PRESTRESSING DEVICE.

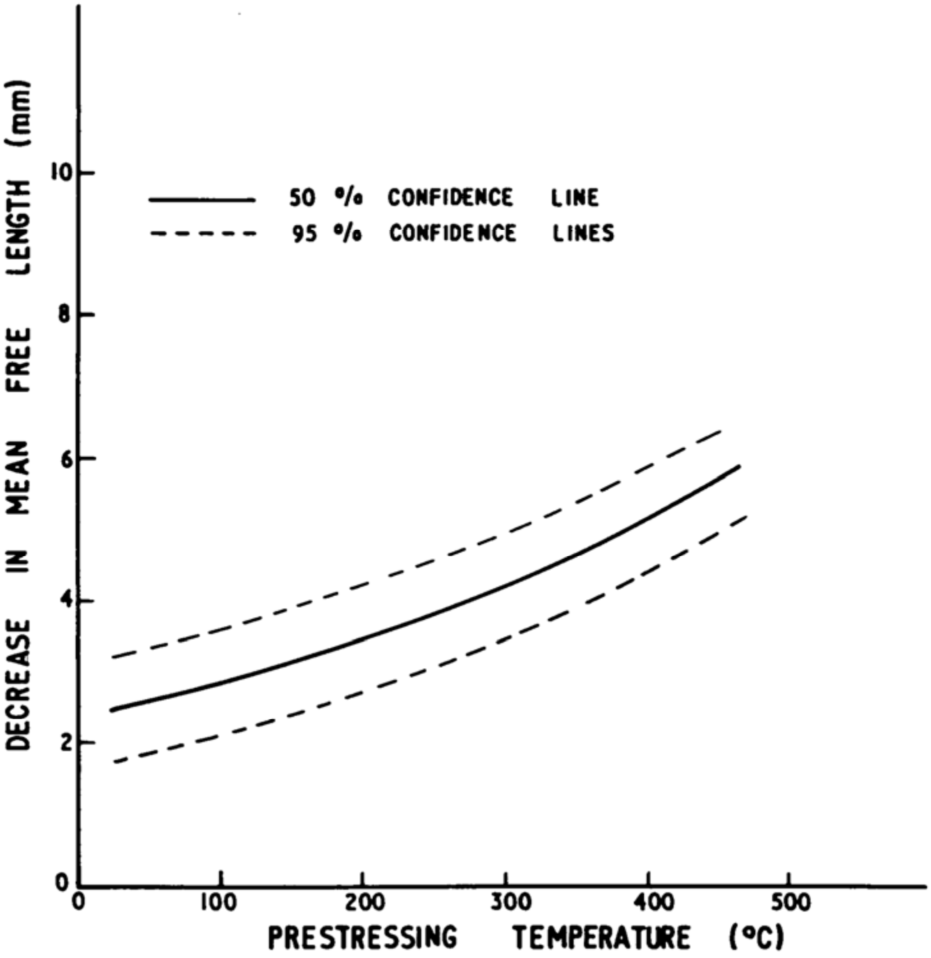

FIG. 2 THE EFFECT OF PRESTRESSING TEMPERATURE ON THE MEAN FREE LENGTH OF EN 58 A SPRINGS.

NOTE :- ORIGINAL MEAN FREE LENGTH BEFORE PRESTRESSING = 49·65 mm.

∴ THEORETICAL SOLID STRESS BEFORE PRESTRESSING = 1310 N/mm^2

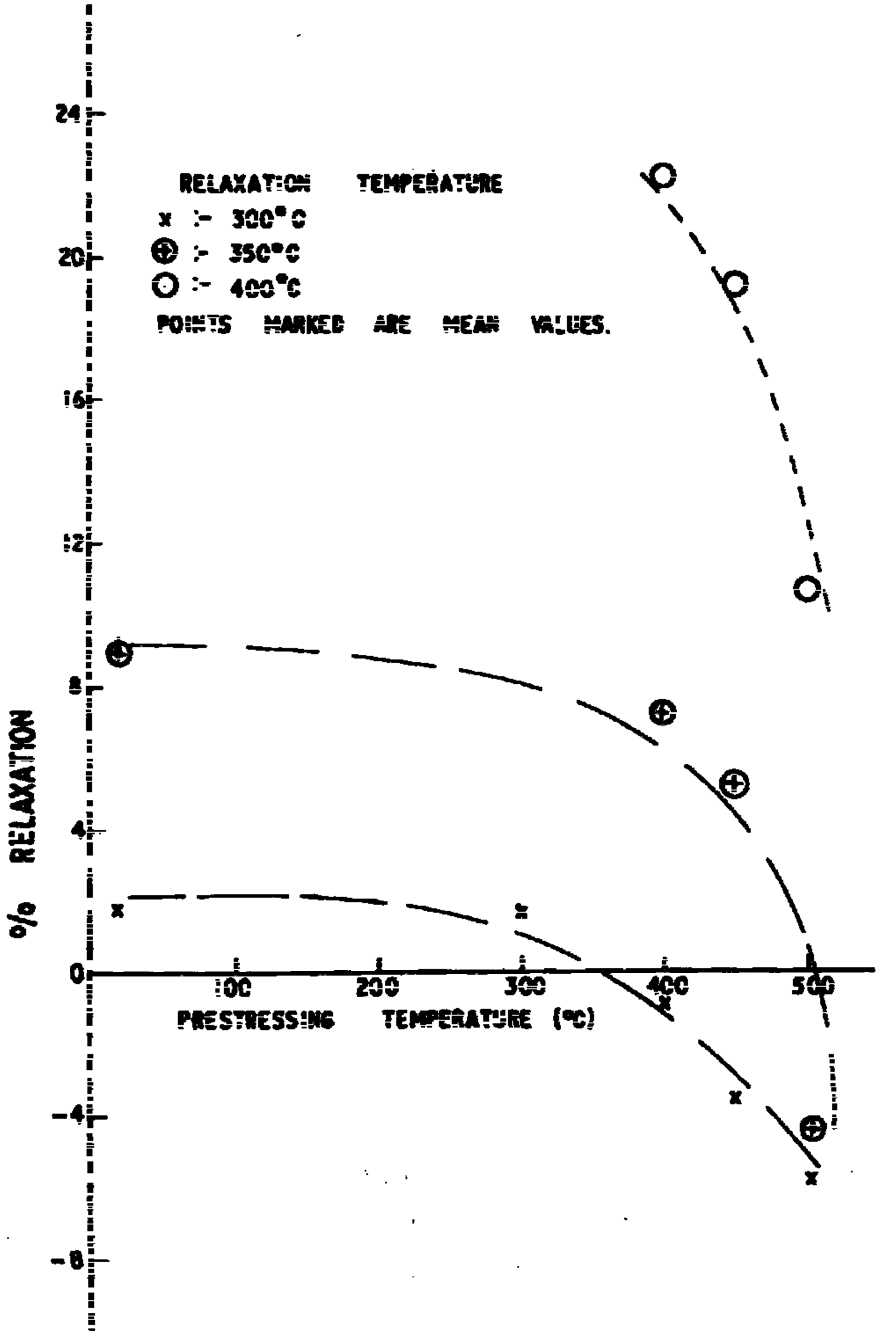

FIG. 3 VARIATION OF RELAXATION (AFTER 168 HOURS) WITH PRESTRESSING TEMPERATURE AT AN INITIAL STRESS OF 300 N/mm²

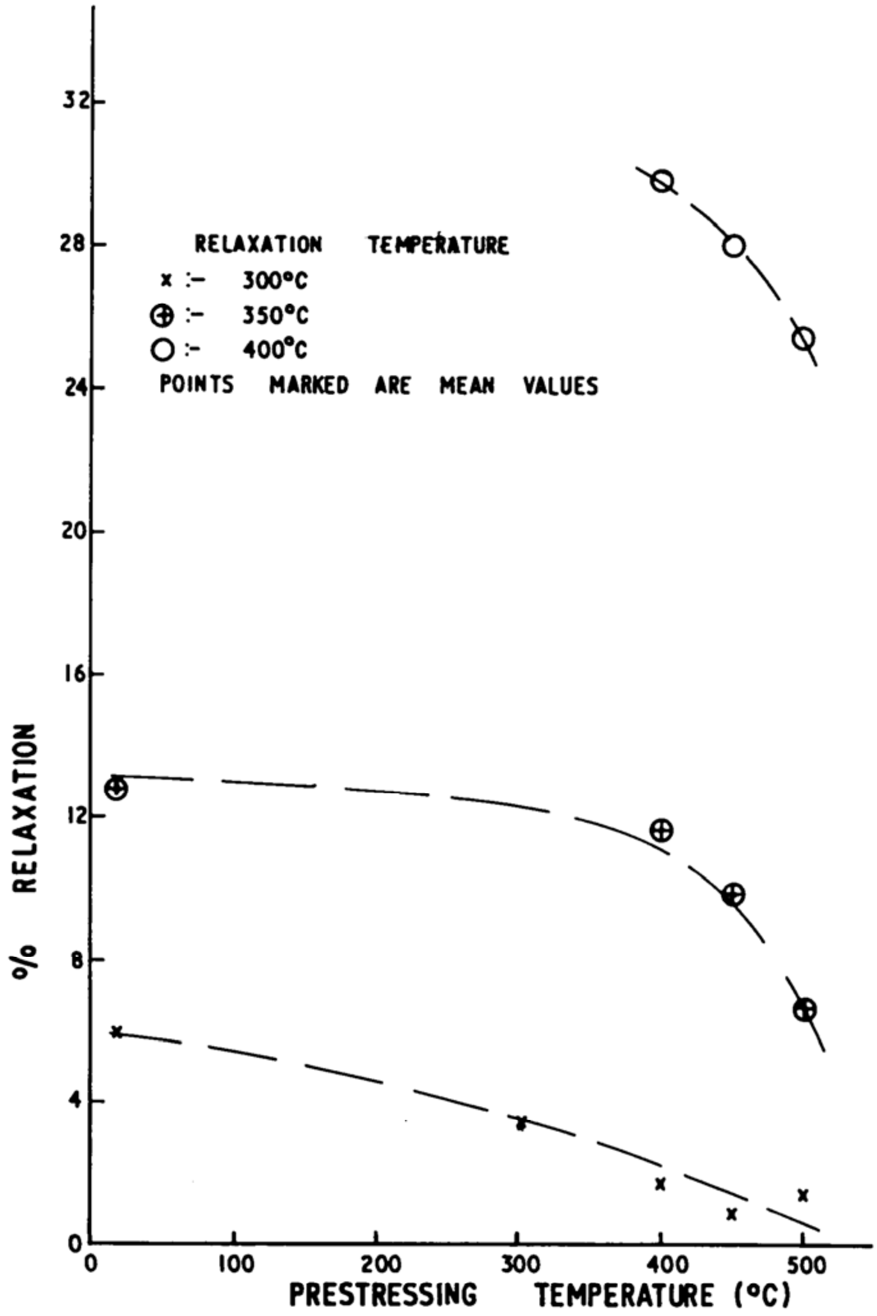

FIG. 4. VARIATION OF RELAXATION (AFTER 168 HOURS) WITH PRESTRESSING TEMPERATURE AT AN INITIAL STRESS OF 600 N/mm^2

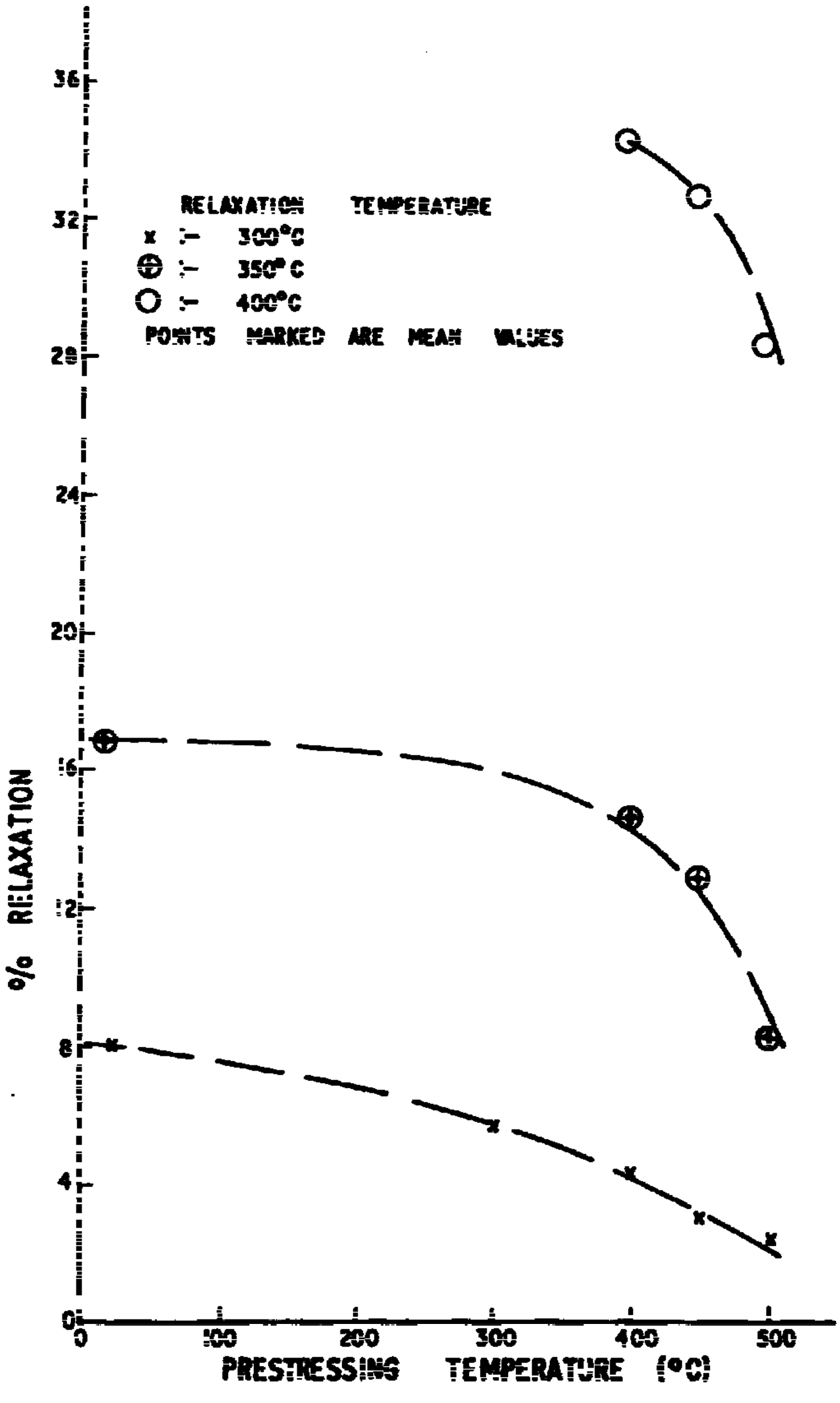

FIG. 5 VARIATION OF RELAXATION (AFTER 168 HOURS) WITH PRESTRESSING TEMPERATURE AT AN INITIAL STRESS OF 800 N/mm²

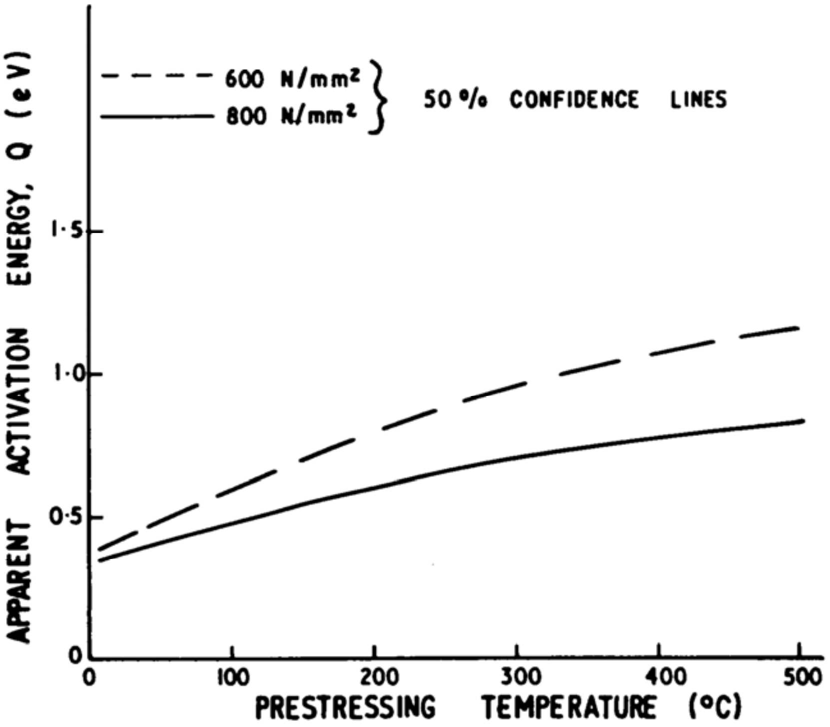

FIG. 6 VARIATION OF APPARENT ACTIVATION ENERGY (Q) WITH PRESTRESSING TEMPERATURE.