ΓHE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE EFFECT OF LOW TEMPERATURE HEAT TREATMENT ON COMPRESSION SPRINGS MANUFACTURED FROM En 58A HARD DRAWN STAINLESS STEEL WIRE

by

G.E. Hale B. Met.

Report No. 303

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SUMMARY AND CONCLUSIONS

A programme of work has been undertaken to establish the optimum low temperature heat treatment for stainless steel compression springs. The effect of changes in LTHT time and temperature on the dimensions, fatigue and relaxation properties of compression springs coiled from En 58A (18/9) hard drawn stainless steel wire has been investigated.

This work has shown that the maximum elevation in the tensile strength and elastic properties of the wire occurs with a LTHT between 400° and 425° for 30 minutes, while the maximum relaxation resistance is obtained by stress-relieving the springs at 500°C for the same time.

The influence of LTHT on the fatigue behaviour of En58A springs appears to be limited. No real optimum either in time or temperature was observed. Thus, for a fatigue application, where static relaxation effects can be ignored, the optimum fatigue performance should be consistent with the maximum in tensile strength, i.e. a LTHT of 400°C for ½ hour.

If resistance to both fatigue and relaxation is necessary, then a stress-relieving treatment at 450°C for 30 minutes should be used. This gives a fairly low level of relaxation, while, at the same time, the elastic properties are not substantially lower than those obtained with the optimum 400°C/½ hour LTHT.

One of the more interesting and useful points to emerge from this work, has been the realisation that LTHT time has only a restricted effect on the properties investigated. There appears to be little benefit in using a 2 hour treatment for stainless springs, as has previously been recommended. A 30 minute stress-relieving treatment will be as effective, and will clearly be an advantage to spring-makers both in terms of fuel savings and shorter production times.

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THE EFFECT OF LOW TEMPERATURE HEAT TREATMENT ON COMPRESSION SPRINGS MANUFACTURED FROM En 58A HARD DRAWN STAINLESS STEEL WIRE

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G.E. Hale, B.Met.

1. INTRODUCTION

Following recent work at SRAMA on the effect of different low temperature heat treatments (referred to as LTHT) on cold drawn carbon steel springs[1], it was felt that a similar programme of work on stainless springs might be useful to the members of the Association.

SRAMA have for a long time been making a recommendation of 450°C for 2 hours as the standard LTHT for cold drawn stainless compression springs (the temperature is somewhat lower for stainless extension springs if there is initial tension within the spring), and this has tended to be based on a combination of experience and earlier work done by Graves on stainless wires[2]. However, there has never been any systematic attempt to determine the optimum LTHT in terms of fatigue and relaxation resistance using springs coiled from stainless steel wires. Generally, a low temperature heat treatment is given to most springs after forming to remove residual stresses resulting from the forming operations[3], e.g. wire drawing and coiling. At the same time, this treatment leads to an improvement in both the tensile strength and elastic properties of the material[1,3]. Other workers[4,5,6] have found that stress-relieving treatments between 200° and 480°C tend to alleviate peak stresses resulting from the cold working operations as well as giving a small degree of general stress-relief, thus tending to improve the dimensional stability of the component. It must be realised, however, that to obtain full stress-relief in austenitic stainless steels, much higher temperatures are needed than those generally used throughout the spring industry[4,6].

The primary objective behind this work has been to examine the effect of various low temperature heat treatments on the dimensions, fatigue and relaxation properties of springs coiled from cold drawn stainless steel wire. In addition, the effect of LTHT on the mechanical properties of the wire has been investigated.

Certain Continental wire manufacturers[7,8] quote LTHT conditions for springs coiled from their 18/8 stainless wire which are different from those currently recommended by SRAMA. It is hoped that this investigation will help to clarify the situation a little more.

2. MATERIALS

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

3. TENSILE AND TORSIONAL PROPERTY DETERMINATION

Tensile tests were carried out using the Association's vertical Amsler multi-range tensile testing machine equipped with an automatic load-extension recorder and an extensometer with a 250 mm gauge length. Duplicate tests were undertaken on samples of wire in the as-received condition, and subsequently on wires which had been LTHT'd at temperatures within the range 350° to 500°C for both ½ hour and 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 could then be calculated from the relationship:

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

where τ = shear stress (N/mm^2)

T = torque (N.mm)

and d = wire diameter (mm)

Similarly, the torsional strain was calculated from:

$$\Phi = \frac{d\theta}{2L} \qquad \text{...........(2)}$$

where Φ = torsional strain (mm/mm)
d = wire diameter (mm)
θ = angular deflection (radians)
and L = gauge length = 100 x d (mm)

The torsional properties of the En 58A material were determined in the as-received condition and after a 500°C/30 minutes LTHT.

4. SPRING DESIGN AND MANUFACTURE

Helical compression springs were coiled from the En 58A wire to the design indicated in Table II, using a Torrington 115A single point coiling machine.

After coiling, the springs were end-ground. The general practice is to end-grind after LTHT, but, in this case, end-grinding prior to heat treatment meant that the free length and other dimensions could be measured more easily after LTHT and any subsequent pre-stressing. Matched pairs of springs, arranged in accordance with the experimental design described in 5.1 below were heat treated in a Wild Barfield air circulating furnace at temperatures of 300°, 350°, 400°, 450° and 500°C for periods of both ½ hour and 2 hours. These springs were then subjected to a variety of tests, as described in the following section.

5. EXPERIMENTAL PROCEDURE

5.1 Experimental Design

It was considered that small variations in the properties being investigated resulting from the LTHT's given to the springs might not be detected by the normal 't' tests, as the experimental scatter might well mask them. However, by using a paired 't' test technique and keeping all but one of the experimental variables constant, e.g. varying LTHT time only, systematic errors can be greatly eliminated, as the paired 't' test considers the differences between the two batches under investigation.

The simplified expression used is:

$$'t' = \frac{\bar{x}}{S/\sqrt{N}} \qquad \text{...........(3)}$$

where $\bar{x}$ = mean of the difference between the pairs

S = standard deviation of the differences between the pairs

and N = total number of pairs

This statistical technique is discussed more fully in SRAMA Report No. 300[9] and also in the literature[10].

Paired 't' tests were mainly used for making comparisons between the various properties investigated after ½ hour and 2 hour treatments. However, this form of statistical test was also used in determining the significance of the changes in spring dimensions which occurred with LTHT and subsequent prestressing. To make the test as valid as possible, each matched pair of springs was clearly identified before any experimental work took place.

Standard 't' tests were used to assess the significance of any differences in the fatigue data obtained for each of the various LTHT temperatures studied.

5.2 Dimensional Changes

The changes in spring dimensions of the En 58A springs, resulting from LTHT and also from a subsequent prestress, were determined by monitoring changes occuring in coil diameter, free length and 'wind-down' (measured in degrees/coil).

The effect of LTHT's over the range 350° to 500°C in 50°C intervals, for both ½ hour and 2 hour treatments, was investigated. The experiments were based on a paired 't' test design so that they might yield as much information as possible.

5.3 Fatigue Testing

Fatigue testing was carried out on the Association's forced motion multiple station fatigue testing machine operating at 25 Hz. The maximum and minimum lengths necessary to give the required stress range were determined by load testing the springs. The requisite loads were previously calculated using the relationship:

$$P = \frac{\pi d^3 \tau}{8DK} \qquad \text{...........(4)}$$

where P = axial load (N) applied to the spring

τ = torsional stress (N/mm^2) due to 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 = $\frac{D}{d}$

Fatigue tests were carried out on as-coiled springs as well as on those which had been given a LTHT of 300°, 400° or 500°C for either ½ hour or 2 hours, after which the springs were prestressed to solid ten times.

In all the tests, the initial torsional stress was maintained at 100 N/mm^2, with the springs being tested at two maximum torsional stress levels, namely, 600 and 800 N/mm^2, preliminary work on the En 58A material having indicated that the vast majority of the springs tested at a maximum torsional stress of 400 N/mm^2 remained unbroken. Fatigue tests were carried out using eight pairs of samples at each stress level for all the LTHT conditions investigated. This means that, wherever possible, the two springs of each pair were tested simultaneously on the same machine.

Dynamic relaxation values were determined for those springs which remained unbroken at 10^7 cycles, by measuring the load necessary to give the same minimum length as that initially set on the fatigue machine to give the required original maximum stress.

5.4 Relaxation Testing

5.4.1 Stress-relaxation tests

Stress relaxation tests were carried out on springs at 300°C for 168 hours in an air-circulating oven, using the standard 'nut and bolt' assembly[11,12]. 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 stresses were calculated using the standard formula (4) given in 5.3.

Before relaxation testing, the minimum length resulting from the initial calculated load (L_O) was measured. After testing at 300°C for 168 hours, the springs were again load tested to the same minimum length and the load (L_F) remeasured.

The % relaxation, or loss in load, which occurred was then calculated from:

$$R(\%) = \frac{(L_O - L_F)}{L_O} \times 100\% \qquad \text{...........(5)}$$

A paired 't' test procedure was followed, using springs given a LTHT in the range 350° - 500°C for ½ hour or 2 hours and also a series which were in the as-coiled state. All the springs were prestressed to solid 10 times before relaxation testing. Six matched pairs of springs were tested at initial torsional stresses of 300, 600 and 900 N/mm². Two matched pairs were similarly tested at the intermediate torsional stresses of 400, 500, 700 and 800 N/mm² so that a more complete picture of the stress-relaxation behaviour could be obtained for each specific LTHT condition.

Once the results of these series of tests were available, it became clear that further relaxation tests on springs subjected to higher LTHT temperatures were needed. Relaxation tests were carried out on springs which had been given LTHT's of 550^{o} and 600^{o}C for 2 hours. Three matched pairs of springs were tested at initial torsional stresses of 300 and 900 N/mm^{2}, while a single pair were tested at stresses of 500, 600 and 700 N/mm^{2}.

5.4.2 Time-relaxation tests

Once the more likely optimum LTHT's of 450^{o} and 500^{o} for 2 hours for the En 58A springs had been determined from the stress-relaxation work described above, it was considered appropriate to check the validity of 168 hours as a suitable test time for determining the relaxation behaviour of stainless materials.

Three matched pairs of En 58A springs were tested at initial torsional stresses of 400 and 800 N/mm^{2} after a LTHT of either 450^{o} or 500^{o}C for 2 hours. The initial load on the spring was determined in the manner described above, and after load testing, the springs were put into an air-circulating oven at 300^{o}C. Sequential tests were carried out on the same set of springs, with the relaxation being determined after total times of 4, 10, 16, 32, 48, 72, 96 and 168 hours at temperature.

5.5 Intergranular Corrosion Tests

An intergranular corrosion test was carried out on six samples of En 58A wire which had been given a LTHT of 500^{o}C for 2 hours. The procedure followed was that given in Clause 8(e) of BS 2056: 1953, except that the heat treatment above was substituted for the 650^{o}C for 30 minutes given in the standard. Basically, the test involves immersing the wires in a constant composition boiling copper sulphate solution for 72 hours, after which a 90^{o} bend test around a radius 3x the wire diameter is performed on the piece of wire.

6. RESULTS

6.1 Tensile and Torsional Data

The tensile properties of the as-drawn wire and after various LTHTs are given in Table III, while a graphical representation of this data is shown in Figure 1.

The torsional data for the wire in the as-received condition and after a 500°C/½ hour LTHT can be found in Table IV.

6.2 Dimensional Changes

6.2.1 Free length determination

Measurements of the free length of the springs after grinding, after LTHT and also after a subsequent cold prestress, for each LTHT condition can be found as Tables V to VIII. (It must be noted that the values shown in the tables are the mean of two measurements on each spring). The decrease in mean free length with LTHT temperature, for LTHT only and after LTHT and prestressing, is presented as Figure 2.

6.2.2 Coil diameter measurements

As with the free length measurements, the outside coil diameter of the springs was measured after grinding, after LTHT and then after cold prestressing for each of the LTHT conditions being studied. These data are given in Tables IX to XII. (It must be realised that the values shown are the mean of four measurements on each spring). In a graphical form, the increase in mean outside coil diameter with LTHT temperature is presented as Figure 3 and 4 for LTHT only and LTHT plus prestressing respectively.

6.2.3 'Wind-down' determination

The change in number of coils of the En 58A springs with LTHT and prestressing is presented as Tables XIII to XVI. (Each value shown is the mean of two measurements, one being taken at each end of the spring). These data are presented graphically as

Figure 5.

6.3 Fatigue Testing

The variation of fatigue life with LTHT time and temperature for the En 58A springs can be seen in Figures 6 to 9, while the experimental data are given in Table XVII.

6.4 Relaxation Testing

6.4.1 Stress-relaxation tests

The effect of LTHT time and temperature on the stress-relaxation properties, at 300°C for 168 hours, of the En 58A springs can be seen as Figures 10 and 11. The corresponding experimental data are given in Tables XVIII to XX.

6.4.2 Time-relaxation tests

Plots of the variation of relaxation with increasing time at initial torsional stresses of 400 and 800 N/mm^2 carried out consecutively on the same set of En 58A springs are presented as Figures 12 and 13 respectively. The associated experimental data can be found in Table XXI.

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 I).

7.2 Discussion of Observed Tensile Behaviour

The as-drawn 2.64 mm dia. En 58A wire had a tensile strength of 1690 N/mm^2, which is close to the top of the specified strength range, 1390 - 1700 N/mm^2, for this wire size.

The maximum elevation in the tensile strength of the wire occurred with a LTHT of 400°C, although the elastic properties appeared to peak at a slightly higher temperature (see Figure 1). The tensile strength increased by a maximum of 10% after LTHT,

TABLE XIII THE EFFECT OF A 350°C LTHT ON THE WIND-DOWN OF En 58A SPRINGS

LTHT Condition	Relative Position of End-Tips (Degrees/coil)		
	After Grinding	After LTHT	After LTHT AND Prestressing
350°C, ½ Hour	1.8	1.2	0.7
	2.0	1.5	0.7
	2.0	0.9	0.2
	2.4	1.3	0.7
	1.9	1.3	0.6
	3.0	2.5	1.8
	2.5	1.5	0.5
	2.7	1.5	0.7
	2.2	0.5	0.1
	1.7	0.5	-0.1
350°C, 2 Hours	2.3	1.3	0.3
	2.3	1.1	0.4
	2.0	0.7	0
	1.9	0.9	0.2
	2.5	1.0	0.4
	2.3	1.3	0.8
	1.5	0	-0.7
	2.0	0.4	-0.2
	1.7	0.3	-0.1
	1.7	0.5	-0.2

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

7.4 Dimensional Changes

7.4.1 Free length

Figure 2 shows the effect of LTHT time and temperature on the mean free length of En 58A springs. A slight decrease in free length was caused by LTHT alone, but different temperatures seemed to have very little effect on the magnitude of this decrease. However, the decrease was much more pronounced if the free length of the springs was measured after LTHT and a subsequent cold prestress. Figure 2 suggests that at temperatures above 425°C the decrease in mean free length would become fairly constant.

The results of the statistical paired 't' tests, used to establish if the decreases in free length were meaningful, are given in Table XXII. In every case, the differences are significant at the 99.9% level, indicating that there was a distinct decrease in the mean free length of En 58A springs both with LTHT and also after a cold prestressing operation.

Paired 't' tests between the ½ hour and 2 hour treatments indicate that there is no difference (at the 95% level of significance) between these two times for any of the LTHT temperatures studied (see Table XXIII).

7.4.2 Coil diameter

The change in the mean outside coil diameter of En 58A springs with LTHT temperature is plotted in Figures 3 and 4 for LTHT only and LTHT plus prestressing respectively.

Statistical comparisons using a paired 't' test (see Table XXIV) indicated that, although the mean outside coil diameter tended to increase with LTHT, the effect of increasing temperature was small. Furthermore, reference to Figures 3 and 4 and Table XXIV showed that a subsequent cold prestressing operation had very little extra effect on the mean outside coil diameter, in comparison to the changes arising from a low temperature heat treatment only.

Further paired 't' tests comparing the ½ hour and 2 hour treatments (see Table XXV) indicated that any differences in coil diameter, arising from variations in treatment time, were unlikely to be of practical significance.

It is possible to determine the tolerance allowable when coiling springs from wire of this diameter. The appropriate expressions can be found in BS 1726: Part 1: 1964: Appendix A.

The tolerance on coil diameter (T) is given by:

$$T = \pm 2ct \qquad \text{...........(6)}$$

where c = spring index (refer to equation (4))
t = wire diameter tolerance (mm)

For the 2.64 mm dia. En 58A wire under investigation:

$t = \pm 0.025$ mm (see BS 2056: 1953: Clause 5)

Using equation (6)

$T = \pm 0.44$ mm

This tolerance band has been plotted on Figure 3 and 4, indicating that the variations resulting from the LTHT and prestressing operations are small in comparison to the variations in coil diameter which can arise from the coiling operation.

Obviously, therefore, the effect of low temperature heat treatments on coil diameter can be considered negligible.

7.4.3 'Wind-down' of En 58A springs

The 'wind-down' of stainless springs, i.e. the relative position of the end-tips, is known to be affected by low temperature heat treatment variables. Following a similar pattern to that used for the free length and coil diameter measurements, the 'wind-down' was determined before and after various LTHT's and also after cold prestressing. Figure 5 is a graphical representation of the changes occuring with LTHT, while Table XXVI is a statistical interpretation of the data.

It becomes clear that as the LTHT temperature increases, the springs unwind slightly, i.e. the relative position of the end-tip decreases. It can also be seen that a prestress after LTHT further enhances this 'wind-down'. Although some statistically significant differences were detected from the paired 't' tests, comparing the ½ hour and 2 hour treatments (see Table XXVII), the actual change in number of coils with LTHT is very small. It is considered unlikely therefore, that these differences are of any practical significance.

Figure 5 also suggests that as the 'wind-down' is continuing to rise, then there must still be some residual stress in the springs, and much higher temperatures would be needed to remove them completely.

It must be realised that the magnitude of the 'wind-down' in the springs is fairly small; the maximum angular rotation observed was 18.5°, i.e. 3.4 degrees/coil for the spring design used. This occurred for a $500^{\circ}C$/2 hour LTHT plus prestress. As the angle measured can only be accurately determined to the nearest 0.5°, then obviously the actual experimental values given are subject to a certain amount of error. In real terms, this means that although the general trend in 'wind-down' behaviour can be determined, the absolute magnitude of the values obtained must be treated with care. It may well be that the changes in 'wind-down' which occur with LTHT are so small that they may be virtually disregarded for any practical application.

7.4.4 <u>Overall effect of LTHT on spring dimensions</u>

For En 58A stainless steel compression springs, a low temperature heat treatment after coiling causes the springs to 'wind-down', leading to a reduction in free length, an increase in coil diameter, and a decrease in the number of coils in the spring. This contrasts with the situation occurring for carbon steel springs(1), where the springs tend to 'wind-up', reducing both the free length and coil diameter while increasing the number of coils. The real reason for this behaviour is not at present clearly understood, but it is likely to be related to the way in which the stress distribution within the springs after drawing and coiling is changed by stress relief.

A prestressing operation after LTHT leads to a further reduction in free length and a greater amount of 'wind-down' in the springs. However, the coil diameter appears to remain fairly constant after prestressing. In any case, the tolerance allowed on coil diameter as a result of coiling is much greater than any other change which may take place.

In terms of dimensional stability, there seems to be little point in using a 2 hour treatment, since within 30 minutes at temperature, any effective changes in dimensions appear to be complete. However, the results do bring out the point that, provided only dimensional stability and the removal of peak stresses are needed, then the stress-relieving temperatures currently used are high enough[3,4,5,6].

7.5 Fatigue Data

7.5.1 Fatigue of En 58A springs

The fatigue performance of the En 58A springs after treatment times of ½ hour and 2 hours at a number of LTHT temperatures are shown as Figures 6 to 9. From these graphs, it is clear that the fatigue behaviour after the two treatment times is very similar. In fact, using a paired 't' test, no difference at the 95% level of significance was detected between the two treatment times after LTHT's at 300°, 400° and 500°C (see Table XXVIII).

At a maximum stress of 800 N/mm^2 (Figures 6 and 7), the mean value of the data for each individual LTHT temperature is close to 10^5 cycles. A normal 't' test, using means and standard deviations, which is much less discriminating than the paired 't' test (and hence any difference found is more likely to be a real one) was applied to the data, so that a comparison between the various LTHT temperatures at one treatment time could be made. For a ½ hour LTHT any differences between the various temperatures were not significant at the 95% level (see Table XXIX). Similarly for a 2 hour LTHT, although a significant difference at the 95% level was found between the as-coiled condition and the 300°C LTHT, the remainder of the comparisons showed that there were no differences at the 95% level of significance (see Table XXX). Furthermore, the difference between the as-coiled and 300°C/2 hour LTHT was only just statistically significant at the 95% level, and it is doubtful whether this difference is of any practical significance.

Overall, at a maximum stress of 800 N/mm^2, LTHT appears to have little effect on the fatigue performance of En 58A springs. It may well be that at such short lives, other factors have a predominant effect, e.g. surface condition, surface defects and structural changes. However, much more work would be needed to confirm if the above is correct.

At a maximum stress of 600 N/mm^2 (see Figure 8 and 9), it can be seen that the scatter on the experimental results is much larger than at 800 N/mm^2. This increase in scatter can be attributed to the reduced stress, which is obviously much closer to the fatigue limit of the springs.

If the fatigue behaviour after a ½ hour treatment is considered, then, referring to Figure 8, it is possible that there may be a peak LTHT temperature in the region 400° - 450°C. By using a normal 't' test, as described above, comparisons of the fatigue data after treatment at a number of LTHT temperatures were carried out. These statistical comparisons showed that any differences between the various sets of fatigue data (see Table XXIX) are unlikely to be of any practical significance in an industrial application.

Furthermore, all the statistical comparisons between the various LTHT temperatures after a 2 hour treatment indicated that there were no differences at the 95% level significance between these sets of fatigue data (see Table XXX).

It can be suggested, therefore, from the work undertaken, that the overall effect of LTHT on the fatigue properties of En 58A springs is fairly limited. In terms of treatment time, there is little to be gained by using a 2 hour treatment in preference to a 30 minute treatment.

In a fatigue application, therefore, the LTHT chosen should be fairly similar to that used to give the optimum mechanical properties and dimensional stability, provided that static relaxation effects can be ignored.

7.5.2 Dynamic relaxation of En 58A springs

The dynamic relaxation of those springs which remained unbroken at 10^7 cycles were measured. The dynamic relaxation (R_D) is determined by using an expression identical to equation (5). The dynamic relaxation is a measure of the load loss and consequently reduction in maximum applied stress, which occurs during fatigue testing.

Table A below details the dynamic relaxation values of those En 58A springs whichsurvivedto 10^7 cycles.

TABLE A THE DYNAMIC RELAXATION OF En 58A SPRINGS AFTER 10^7 CYCLES

L.T.H.T. Condition	Dynamic Relaxation (R_D) % after 10^7 cycles, at a Max. Stress of 400 N/mm^2, at 20^{o}C		Mean Value R_D	S_{R_D}
As-coiled	1.2 -0.4 0.8 -0.4	-0.8 0.8 0 -0.8	0	0.8
500^{o}C/ 2 Hours	-2.0 -0.4 -2.5 -1.2	-2.0 -1.6 -2.5	-1.7	0.8

From the limited number of results available, it can be seen that the as-coiled springs appeared to have suffered no loss of load during fatigue testing up to 10^7 cycles, while by contrast, those springs given a stress-relieving treatment at 500°C for 2 hours showed a small amount of dynamic recovery i.e. the springs had 'grown' slightly. It should be noted, however, that the largest change in load measured was only 3N and it is likely therefore, that the amount of dynamic relaxation/recovery occurring during fatigue testing is negligible.

Since the springs given intermediate LTHT temperatures were not fatigue tested at this stress level, it is not possible to say whether a more distinct trend exists between LTHT temperature and level of dynamic relaxation after 10^7 cycles.

Further work in this area, including fatigue testing at a stress of 400 N/mm^2 after LTHTs of 300° and 400°C, would help to indicate if there is any definite trend between dynamic relaxation and LTHT temperature and could lead to a better understanding of the mechanisms behind these effects.

7.6 Relaxation Behaviour of En 58A Springs

7.6.1 Stress-relaxation properties

Figures 10 and 11 show the variation of relaxation with stress-relieving temperature, after ½ hour and 2 hour treatments respectively, at three stress levels. The graphs indicate that the relaxation after 168 hours at 300°C decreased as the LTHT temperature rose until a minimum in relaxation was reached at some temperature, beyond which the relaxation increased as the LTHT temperature was further increased. This effect is seen most clearly in Figure 11, where additional relaxation tests after stress-relieving treatments of 550° and 600°C for 2 hours were carried out.

Both graphs indicate that the relaxation fell up to 500°C, but on Figure 11, the additional tests at temperatures greater than 500°C clearly show that the maximum relaxation resistance occurred at 500°C for the stresses investigated. The curves presented as Figure 11 have been fitted by eye and, although it would be possible to use an elaborate curve-fitting exercise on the data, it is felt that this would have very little effect on the shape of the curves although there might be some slight adjustments to their minima.

The relaxation data relevant to the ½ hour and 2 hour treatments were compared, using paired 't' tests, for each of the stresses investigated (see Tables XXXI to XXXIII). These analytical tests indicate that there are some statistically significant differences between the relaxation after a ½ hour LTHT and that after a 2 hour treatment. For a 350°C LTHT, a 2 hour stress-relieving treatment will most probably give better relaxation properties than a 30 minute LTHT. It should be noted however, that a 350°C stress-relief does not give optimum tensile or relaxation properties for this material and there would therefore appear to be little point in using this temperature in commercial practice, for En 58A (18/9) compression springs. Furthermore, at the higher LTHT temperatures, i.e. 400°, 450° and 500°C, it is considered unlikely that the observed statistical differences will be of any practical significance in commercial terms. Clearly, therefore, a minimum in relaxation occurs at or around 500°C, and in practical terms, a 30 minute stress-relief will give comparable levels of relaxation to a 2 hour treatment.

Since it is fairly common knowledge that a similar effect can often be achieved during heat treatment either by increasing the temperature or time, there may be grounds for suggesting that a 450°C/2 hour LTHT will give similar levels of relaxation to a 500°C/½ hour LTHT (Note: the rate of a chemical reaction, i.e. atomic movements, is approximately doubled for each 10°C increase in temperature). Referring to Tables XIX and XX, it can be seen that the level of relaxation after 450°C/2 hour and 500°C/½ hour LTHT's were similar at stresses up to 700 N/mm^2, although above this stress, the 500°C/½ hour treatment appeared to give lower levels of relaxation for the same stress. Comparisons between these two treatments were made using a standard 't' test and the analytical results of these tests are given in Table B below.

TABLE B STANDARD 't' TESTS ON RELAXATION DATA AFTER 450°C/2 HOUR AND 500°C/½ HOUR LTHTs

Initial Stress (N/mm^2)	Total No. of Samples	't'	Comments
300	12	0.06	No significant difference at the 95% level
600	12	0.08	No difference at the 95% level of significance
900	12	4.26	Significant difference at the 99% level

On the basis of the work undertaken, these tests indicate that a 500°C/½ hour LTHT gives a better relaxation resistance than a 450°C/2 hour stress-relief, especially at the higher stresses investigated. It would be interesting, therefore, to undertake further relaxation testing on springs given a LTHT of a fixed temperature but for a number of different times. This could lead to a better understanding of the exact relationship between LTHT temperature and time and their effect on maximising the relaxation resistance of En 58A springs.

7.6.2 Overall stress-relaxation behaviour of En 58A compression springs after a LTHT at 500°C for 30 minutes

Figure 14 is a plot of the variation of relaxation with initial torsional stress for En 58A springs given a stress-relief of 500°C for 30 minutes and subsequently relaxation tested at 300°C for 168 hours.

By using a least mean squares procedure, the data was fitted to a straight line relationship of the form:

$$R = a\tau + b \qquad \text{...........(7)}$$

where R = relaxation (%)

preferential corrosive attack occurs in the chromium-impoverished zone around the grain boundaries. This phenomenon is often known as weld decay or intergranular corrosion.

It was considered that stress-relieving treatments at 500°C might show some susceptibility to intergranular attack. Six wire samples given a 500°C/2 hour LTHT were subjected to an intergranular corrosion test as specified in BS 2056: 1953: Clause 8(e). All the wires tested in this manner survived at least seven bends before failure (the specification asks for one bend). This can be compared with the as-drawn wire which underwent 10 bends before fracture.

A transverse metallographic specimen was prepared from one of the wires. There was no evidence of any precipitation within the austenite grain boundries when the specimen was examined under an optical microscope.

This is in agreement with previously published work[4,19] which suggested that sensitisation in an 18/8 stainless steel only occurs with heat treatments of more than 3 hours at 500°C.

7.8 Electrical Resistivity Determinations

Measurements of the electrical resistivity of the En 58A wire used in this investigation were made for a variety of stress-relieving conditions (see Table XXXVI), ranging from the hard drawn as-received wire to samples which had been recrystallised. The maximum difference detected over the range of conditions investigated was 0.08 microhm-m. It seems unlikely therefore that this method can be used for determining the relief of residual stresses in hard drawn wires.

The value of electrical resistivity measured for the recrystallised wire compares favourably with values published by International Nickel Company Ltd[20] for En 58A steel.

Sequential tests were carried out on the same springs, the relaxation being measured at appropriate time intervals. This allowed the two LTHT conditions to be compared by a paired 't' test technique.

Figures 12 and 13 show the variation of relaxation with time at initial torsional stresses of 400 and 800 N/mm^2 respectively. It is clear that for both stresses, the 500^oC/2 hour LTHT consistently gave lower relaxations than the 450^oC/2 hour treatment.

The results of the paired 't' tests are given in Table C below, showing that a 500^oC/2 hour treatment gives lower relaxations over the whole time range than the 450^oC/2 hour LTHT at the same initial stress.

TABLE C PAIRED 't' TESTS BETWEEN SETS OF TIME-RELAXATION DATA AFTER LTHTs OF 450^oC/2 HOURS AND 500^oC/2 HOURS

Initial Torsional Stress (N/mm^2)	Total No. of Pairs N	Mean Value $\bar{T}$	S_T	't' Value	Comments
400	23	0.9	1.1	3.92	Difference significant at the 99.9% level
800	24	2.3	0.6	18.38	Difference significant at the 99.9% level

where T = (relaxation at time, t, for springs given a 450^oC/2 hour LTHT)
minus (relaxation at time, t, for springs given a 500^oC/2 hour LTHT)

The curves plotted in Figures 12 and 13 have been fitted to a logarithmic expression of the form:

$$R = c \ln t + d \qquad \text{...........(10)}$$

where R = % relaxation
t = time (hours)

c and d are analytically derived constants

The values of the constants c and d are given in Table XXXV. Both sets of curves gave correlations which were significant at the 99.9% level.

If these curves are extrapolated to 500 hours, it is then possible to express the 168 hour - relaxation as a percentage of the total relaxation which might possibly occur in 500 hours (see Table D below).

TABLE D RELAXATION AFTER 168 HOURS AS A PROPORTION OF THE POSSIBLE 500 HOUR-RELAXATION

LTHT Condition	168 Hour-Relaxation as a % of the Projected 500 Hour-Relaxation, at Stresses of	
	400 N/mm^2	800 N/mm^2
450^oC 2 Hours	83%	88%
500^oC 2 Hours	87%	89%

This suggests that during tests of 168 hours duration a high proportion of the total relaxation that might occur in 500 hours will have taken place. Furthermore, it can also be shown that 95% of the total relaxation which could occur in 240 hours has taken place within 168 hours. This is in fairly close agreement with the work of Zimmerli(16) on stainless springs, who suggested that 10 days (240 hours) was necessary to obtain full equilibrium when testing stainless springs. He also found that around 95% of the relaxation in 240 hours had occurred within 168 hours.

7.7 Intergranular Corrosion Tests

Unstabilised stainless steels (e.g. En 58A) are known to be susceptible to 'sensitisation' in the temperature range 500^o - 850^oC(4,17,18). Heat treatment within this range can lead to precipitation of large $Cr_{23}C_6$ particles at the austenite grain boundaries. This locally lowers the chromium content, so that preferential corrosive attack occurs in the chromium-impoverished zone around the grain boundaries. This phenomenon is often known as weld decay or intergranular corrosion.

It was considered that stress-relieving treatments at 500°C might show some susceptibility to intergranular attack. Six wire samples given a 500°C/2 hour LTHT were subjected to an intergranular corrosion test as specified in BS 2056: 1953: Clause 8(e). All the wires tested in this manner survived at least seven bends before failure (the specification asks for one bend). This can be compared with the as-drawn wire which underwent 10 bends before fracture.

A transverse metallographic specimen was prepared from one of the wires. There was no evidence of any precipitation within the austenite grain boundries when the specimen was examined under an optical microscope.

This is in agreement with previously published work[4,19] which suggested that sensitisation in an 18/8 stainless steel only occurs with heat treatments of more than 3 hours at 500°C.

7.8 Electrical Resistivity Determinations

Measurements of the electrical resistivity of the En 58A wire used in this investigation were made for a variety of stress-relieving conditions (see Table XXXVI), ranging from the hard drawn as-received wire to samples which had been recrystallised. The maximum difference detected over the range of conditions investigated was 0.08 microhm-m. It seems unlikely therefore that this method can be used for determining the relief of residual stresses in hard drawn wires.

The value of electrical resistivity measured for the recrystallised wire compares favourably with values published by International Nickel Company Ltd[20] for En 58A steel.

7.9 Possible Explanations for the Observed Improvements in Elastic and Relaxation Properties with LTHT

It can be seen that the general shape of the curves relating changes in elastic properties and relaxation behaviour with stress-relieving temperature are similar for both patented hard drawn carbon steel wires[1] and hard drawn stainless wires. This indicates that the basic metallurgical processes taking place during LTHT are likely to be similar.

During the initial stages of LTHT (i.e. region A, Figure 15), the predominating process is the relief of macrostresses within the wire, set up during the drawing operation. (As the elastic properties and tensile strength of such wires are normally increased by LTHT, then it is probable that these residual surface stresses are tensile in nature, i.e. a Bauschinger effect). The strain energy associated with such stresses will be fairly high, and thus only a small amount of thermal activation will be required to initiate dislocation movement[21,22,23] i.e. high stresses require lower temperatures for a given amount of stress relief and, conversely, low stresses require higher temperatures.

As the peak of the 'elastic properties' curve is reached (see Figure 15), then the relief of microstresses within the material begins. Generally, such stresses are low in magnitude and are randomly oriented so that the overall stress is effectively zero. Since the stresses are low, the strain energy associated with them is also low and therefore higher temperatures are required to cause dislocation movements than those necessary to relieve the macrostresses. The relief of these microstresses leads to a reduction in the elastic properties of the material as the LTHT temperature rises. Furthermore at this stage, those dislocation sources which can aid relaxation and creep processes are being removed and relaxation therefore decreases (i.e. region B, Figure 15). In other words, the relaxation resistance of the material is improved. In essence, these effects are the primary stages of the recovery process.

Eventually, as the stress-relieving temperature is further increased, the dislocation density of the material is lowered still further as recovery continues, and relaxation therefore increases as the number of obstacles to dislocation movement are reduced (i.e. Region C, Fig. 15). Clearly, this is only a broad outline of the situation and much more work is required to understand fully the mechanisms involved in these processes.

In carbon steels, the stacking fault energy of the ferrite grains is high, i.e. the stacking fault bands are narrow, and thus glide of dislocations is relatively easy. On the other hand, austenitic nickel-chromium stainless steels are known to have a much lower stacking fault energy, i.e. wide stacking fault bands[24,25], which makes cross-slip and glide much more difficult. It is also postulated that the presence of a low carbon martensitic structure in hard drawn stainless wires[26,27] also tends to restrict dislocation mobility. This means that higher stress-relieving temperatures are needed in hard drawn stainless wires than in hard drawn carbon steel wires.

Therefore, the optimum LTHT temperatures in terms of improvement in elastic properties and relaxation behaviour are 400° - 425°C and 500°C respectively for hard drawn stainless wires, whereas in patented hard drawn carbon steel wires the respective temperatures are 200° - 225°C and 350°C.

It can also be seen that the increase in elastic properties of carbon steel wire with LTHT is much greater than in stainless steel wire (see 7.2 above). It is thought that a further strengthening mechanism operates in carbon steels, in addition to the relief of the macrostresses caused by drawing. Dislocations which would generally be mobile in this temperature range, up to 225°C, are considered to be pinned in some manner, either by solute interaction, as proposed by Cottrell[28,29,30] or fine precipitates, as suggested by Gray[31], although the true situation may be somewhere between these two extremes[32].

In reality, this can be looked at as an 'age-hardening' effect, which provides a considerable lift in strength to the material.

8. CONCLUSIONS

1. The maximum elevation in the tensile strength and elastic properties of 2.64 mm dia. En 58A (18/9) stainless steel wire occurs with a stress-relieving treatment between 400°C and 425°C for 30 minutes.

2. For En 58A stainless steel compression springs, a low temperature heat treatment after coiling causes the springs to 'wind-down', leading to a reduction in the free length, an increase in coil diameter and a decrease in the number of coils in the spring.

3. Stress-relieving at temperatures up to 500°C for 30 minutes leads to improved dimensional stability in En 58A stainless steel compression springs.

4. From the work undertaken, the effect of LTHT on the fatigue properties of En 58A compression springs is limited. Therefore, it is likely that the optimum stress-relieving treatment for fatigue will be very similar to that giving the maximum lift in tensile strength, i.e. 400°C for 30 minutes, provided that static relaxation effects can be ignored.

5. For applications where relaxation resistance is of prime importance, En 58A stainless steel compression springs should be given a low temperature heat treatment after coiling of 500°C for 30 minutes.

6. A 450°C/½ hour LTHT will give a compromise where resistance to both fatigue and relaxation is required.

7. Time-relaxation tests have indicated that 95% of the total relaxation which might occur in 240 hours, has taken place within 168 hours. Therefore it was considered appropriate to use 168 hours as the basic test period for the stress-relaxation work.

8. Intergranular corrosion tests on wire samples given a LTHT of 500°C for 2 hours showed no evidence of any gross carbide precipitation in the austenite grain boundaries.

9. As previously suggested, the observed improvements in both the elastic properties and relaxation resistance can be tentatively explained on the basis of the interaction of mobile dislocations with a variety of obstacles in the structure.

9. RECOMMENDATIONS FOR FUTURE WORK

1. At the present time, the standard LTHT recommended for stainless steel springs after shot-peening is the same as that given to carbon steel springs, i.e. 220° to 230° for 30 minutes. However, it is possible that a higher temperature than this might be appropriate for stainless springs and it is suggested that a programme of work be set up to optimise the LTHT after shot peening for stainless springs with reference to both the fatigue and relaxation behaviour of the springs.

2. The effect of LTHT on the dynamic relaxation behaviour of En 58A compression springs after fatigue testing has not really been quantified and it is thought that further work in this area might also lead to greater understanding of the mechanisms involved in dynamic relaxation.

3. Further investigation of the interaction between LTHT time and temperature is required, so that their effect on the relaxation behaviour of En 58A compression springs can be more easily predicted.

4. A programme of work including a thorough search of the literature together with appropriate experimental testing should be undertaken to investigate and hopefully explain the difference in 'wind-up' behaviour between carbon steel springs and stainless steel springs.

5. It is suggested that work should be carried out so that the basic physical metallurgy leading to the observed improvements in both elastic properties and relaxation resistance with stress-relief is more clearly understood.

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11. ACKNOWLEDGEMENTS

The assistance of Mr. Thomason of Arthur Lee and Sons Ltd. in carrying out the intergranular corrosion tests is greatly appreciated.

TABLE I 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 $\geqslant$ 25.0

TABLE II 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 grinding (mm)	50.0
Free length after optimum LTHT and prestressing (mm)	47.0
Solid stress (N/mm^2)	1210
R_m (as-received) N/mm^2	1690

TABLE III VARIATION OF TENSILE PROPERTIES WITH LTHT FOR 2.64 mm En 58A STAINLESS SPRING WIRE

LTHT Condition	R_m (N/mm^2)	Proof Stresses (N/mm^2)			Limit of Proportionality (N/mm^2)	A (Elongation%) (on a 2" gauge length)	Z (Reduction in Area %)
		R_p 0.2	R_p 0.1	R_p 0.05			
20°C (as-received)	1690 1690	1525 1525	1335 1390	1115 1205	705 715	3.1 3.1	38 38
350°C ½ hour	1805 1810	1665 1710	1475 1485	1270 1290	800 795	3.1 3.1	43 43
350°C 2 hrs	1790 1810	1655 1700	1415 1485	1205 1295	735 755	3.1 3.1	36 36
400°C ½ hour	1850 1855	1745 1680	1495 1465	1270 1250	845 775	3.1 3.1	36 36
400°C 2 hrs	1825 1855	1670 1720	1445 1515	1230 1310	785 855	3.1 3.1	36 36
450°C ½ hour	1785 1815	1700 1645	1495 1435	1325 1240	860 755	3.1 3.1	43 43
450°C 2 hrs	1835 1820	1700 1680	1475 1485	1280 1280	860 860	3.1 3.1	39 39
475°C ½ hour	1760 1760	1605 1640	1425 1450	1235 1280	725 710	- -	42 41
480°C 2 hrs	1760 1785	1585 1580	1405 1370	1175 1160	635 690	- -	42 41
500°C ½ hour	1740 1750	1530 1590	1290 1375	1040 1165	645 645	3.1 3.1	41 41
500°C 2 hrs	1750 1740	1560 1560	1390 1405	1220 1240	770 710	- -	42 42

TABLE IV TORSIONAL PROPERTIES OF 2.64 mm DIA. En 58A STAINLESS SPRING 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
After LTHT of 500°C, ½ hr	-	910	790	540	-	7.2
	-	915	815	545	-	7.3

TABLE V EFFECT OF A 350°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Spring (mm)		
	After Grinding	After LTHT	After Prestressing
	50.800	50.225	46.725
	50.800	49.950	46.700
	49.500	48.850	45.825
	50.300	49.650	46.075
350°C, ½ Hour	50.800	50.225	47.050
	50.775	50.250	47.100
	50.225	49.650	46.725
	50.225	49.575	46.550
	50.100	49.525	46.550
	49.275	48.675	45.900
	50.825	50.225	47.100
	50.150	49.500	45.950
	49.650	49.000	45.825
	50.550	49.975	46.600
350°C, 2 Hours	49.725	49.100	45.950
	49.925	49.275	46.350
	49.975	49.425	46.225
	50.550	49.950	46.750
	49.700	49.125	46.325
	50.575	49.875	47.075

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE VI EFFECT OF A 400°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Spring (mm)		
	After Grinding	After LTHT	After Prestressing
400°C, ½ Hour	50.275	49.600	46.975
	50.275	49.575	46.675
	50.950	50.300	46.850
	49.750	49.050	46.450
	50.950	50.325	47.275
	49.450	48.800	46.400
	50.050	49.350	46.575
	50.700	50.050	47.225
	50.075	49.425	46.700
	49.950	49.300	46.650
400°C, 2 Hour	50.575	49.875	47.075
	49.800	49.150	46.725
	50.525	49.875	47.250
	50.525	49.875	47.050
	50.725	50.275	47.550
	49.425	48.775	46.475
	49.025	48.200	46.075
	50.025	49.300	46.775
	49.375	48.625	46.375
	50.825	50.125	47.425

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE VII EFFECT OF A 450°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Springs (mm)		
	After Grinding	After LTHT	After Prestressing
450°C, ½ Hour	50.575	49.975	47.450
	50.700	50.075	47.450
	50.550	49.650	46.675
	50.000	49.325	46.650
	49.825	49.125	46.750
	50.800	50.125	47.350
	49.725	49.000	46.675
	50.525	49.875	47.450
	50.475	49.775	47.375
	49.900	49.375	47.025
450°C, 2 Hours	50.400	49.675	47.350
	50.450	49.825	47.475
	50.875	50.200	47.575
	50.650	50.050	47.625
	50.050	49.200	46.950
	50.250	49.425	47.200
	50.525	49.700	47.225
	50.775	50.150	47.525
	49.600	48.875	46.625
	49.300	48.550	46.450

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE VIII EFFECT OF A 500°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Springs (mm)		
	After Grinding	After LTHT	After Prestressing
500°C, ½ Hour	50.525	49.900	47.400
	49.650	49.075	46.725
	50.925	50.275	47.325
	49.850	49.400	46.900
	50.400	49.750	47.250
	50.675	50.075	47.450
	50.625	49.925	47.200
	50.875	50.375	47.825
	49.775	49.025	46.650
	50.900	50.400	47.750
500°C, 2 Hours	49.950	49.475	46.725
	50.825	50.025	47.350
	49.900	49.050	46.600
	50.375	49.650	47.150
	49.525	49.350	46.950
	49.275	48.725	46.400
	50.400	49.850	47.075
	49.875	49.275	46.875
	50.525	49.975	46.850
	50.300	49.725	46.950

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE IX EFFECT OF A 350°C LTHT ON THE MEAN OUTSIDE COIL DIAMETER OF En 58A SPRINGS

LTHT Condition	Mean Outside Coil Diameter (mm)		
	After Grinding	After LTHT	After LTHT AND Prestressing
350°C, ½ Hour	25.76	25.82	25.79
	25.78	25.80	25.75
	25.66	25.81	25.82
	25.62	25.79	25.71
	25.66	25.79	25.75
	25.51	25.58	25.59
	25.56	25.68	25.71
	25.60	25.75	25.70
	25.74	25.85	25.80
	25.55	25.76	25.75
350°C, 2 Hours	25.66	25.71	25.71
	25.66	25.74	25.72
	25.65	25.76	25.80
	25.68	25.75	25.79
	25.55	25.70	25.71
	25.54	25.69	25.70
	25.71	25.88	25.85
	25.82	25.80	25.82
	25.60	25.78	25.76
	25.75	25.85	25.84

Values shown are the mean of four measurements on each spring.

All springs prestressed to solid ten times.

TABLE X EFFECT OF A 400°C LTHT ON THE MEAN OUTSIDE COIL DIAMETER OF En 58A SPRINGS

LTHT Condition	Mean Outside Coil Diameter (mm)		
	After Grinding	After LTHT	After LTHT AND Prestressing
400°C, ½ Hour	25.62	25.78	25.75
	25.68	25.88	25.88
	25.80	25.90	25.90
	25.51	25.68	25.74
	25.62	25.68	25.69
	25.66	25.84	25.84
	25.50	25.61	25.62
	25.79	25.85	25.91
	25.60	25.71	25.75
	25.59	25.68	25.72
400°C, 2 Hours	25.64	25.71	25.72
	25.50	25.74	25.75
	25.82	25.92	25.91
	25.81	25.92	25.92
	25.66	25.75	25.78
	25.59	25.79	25.81
	25.55	25.81	25.84
	25.60	25.75	25.74
	25.65	25.88	25.88
	25.75	25.84	25.86

Values shown are mean of four measurements on each spring.

All springs prestressed to solid ten times.

TABLE XI EFFECT OF A 450°C LTHT ON THE MEAN OUTSIDE COIL DIAMETER OF En 58A SPRINGS

LTHT Condition	Mean Outside Coil Diameter (mm)		
	After Grinding	After LTHT	After LTHT AND Prestressing
450°C, ½ Hour	25.59	25.81	25.75
	25.61	25.75	25.79
	25.61	25.62	25.68
	25.72	25.94	25.96
	25.49	25.65	25.66
	25.62	25.78	25.78
	25.61	25.85	25.86
	25.61	25.78	25.79
	25.61	25.78	25.79
	25.59	25.88	25.81
450°C, 2 Hours	25.72	25.89	25.92
	25.52	25.68	25.76
	25.56	25.78	25.72
	25.71	25.89	25.92
	25.56	25.79	25.76
	25.65	25.90	25.90
	25.58	25.78	25.78
	25.71	25.86	25.86
	25.71	25.96	25.98
	25.68	25.95	25.95

Values shown are the mean of four measurements on each spring.

All springs prestressed to solid ten times.

TABLE XII EFFECT OF A 500°C LTHT ON THE MEAN OUTSIDE COIL DIAMETER OF En 58A SPRINGS

LTHT Condition	Mean Outside Coil Diameter (mm)		
	After Grinding	After LTHT	After LTHT AND Prestressing
500°C, ½ Hour	25.52	25.72	25.75
	25.71	26.01	26.00
	25.76	25.89	25.88
	25.54	25.82	25.80
	25.64	25.84	25.84
	25.80	25.80	25.82
	25.70	25.88	25.88
	25.80	25.92	25.92
	25.46	25.70	25.70
	25.55	25.69	25.66
500°C, 2 Hours	25.65	25.91	25.89
	25.84	25.95	25.96
	25.59	25.89	25.86
	25.78	25.96	25.94
	25.60	25.95	25.91
	25.51	25.86	25.86
	25.66	25.89	25.90
	25.66	25.85	25.91
	25.55	25.78	25.78
	25.59	25.80	25.79

Values shown are the mean of four measurements on each spring.

All springs prestressed to solid ten times.

TABLE XIII THE EFFECT OF A 350°C LTHT ON THE WIND-DOWN OF En 58A SPRINGS

LTHT Condition	Relative Position of End-Tips (Degrees/coil)		
	After Grinding	After LTHT	After LTHT AND Prestressing
350°C, ½ Hour	1.8	1.2	0.7
	2.0	1.5	0.7
	2.0	0.9	0.2
	2.4	1.3	0.7
	1.9	1.3	0.6
	3.0	2.5	1.8
	2.5	1.5	0.5
	2.7	1.5	0.7
	2.2	0.5	0.1
	1.7	0.5	-0.1
350°C, 2 Hours	2.3	1.3	0.3
	2.3	1.1	0.4
	2.0	0.7	0
	1.9	0.9	0.2
	2.5	1.0	0.4
	2.3	1.3	0.8
	1.5	0	-0.7
	2.0	0.4	-0.2
	1.7	0.3	-0.1
	1.7	0.5	-0.2

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE XIV THE EFFECT OF A 400°C LTHT ON THE WIND-DOWN OF En 58A SPRINGS

LTHT Condition	Relative Position of End-Tips (Degrees/coil)		
	After Grinding	After LTHT	After LTHT AND Prestressing
400°C, ½ Hour	2.1	0.3	0
	1.6	0.4	-0.4
	1.5	0.4	-0.5
	2.6	0.7	0.1
	3.1	1.2	0.9
	1.6	0	-0.8
	3.5	1.2	1.1
	1.5	0.1	-0.4
	2.4	0.6	0
	2.3	0.9	0.1
400°C, 2 Hours	2.2	0.3	-0.2
	2.4	0	-0.1
	1.7	-0.3	-0.5
	1.7	0	0.9
	2.8	1.3	0.5
	1.5	0.3	-0.4
	2.4	0.5	0.1
	2.5	0.5	0
	1.6	-0.4	-1.3
	1.6	-0.2	-0.5

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE XV THE EFFECT OF A 450^{o}C LTHT ON THE WIND-DOWN OF En 58A SPRINGS

LTHT Condition	Relative Position of End-Tips (Degrees/coil)		
	After Grinding	After LTHT	After LTHT AND Prestressing
450^{o}C, ½ Hour	2.1	0.2	-0.2
	2.9	0.6	0.1
	2.2	0.5	-0.2
	1.7	-0.6	-1.4
	3.0	0.7	0.4
	2.5	0.5	0.4
	2.2	-0.5	-0.5
	2.6	0.2	-0.1
	2.5	0.1	-0.1
	2.1	-0.2	-0.4
450^{o}C, 2 Hours	1.9	-0.5	-0.9
	2.8	0.1	0
	2.8	0.4	0.2
	2.0	0.1	-0.5
	2.4	0	-0.3
	2.0	-0.2	-0.7
	2.5	0.2	-0.2
	2.0	0	-0.5
	1.5	-1.3	-1.6
	1.5	-0.8	-1.6

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE XVI THE EFFECT OF A 500°C LTHT ON THE WIND-DOWN OF En 58A SPRINGS

LTHT Condition	Relative Position of End-Tips (Degress/coil)		
	After Grinding	After LTHT	After LTHT AND Prestressing
500°C, ½ Hour	2.5	0	-0.1
	1.0	-1.8	-1.8
	2.1	-0.5	-0.9
	3.1	0	0
	2.2	-0.5	-0.6
	2.2	-0.4	-0.8
	1.8	-0.5	-0.9
	1.8	-0.4	-1.0
	3.5	0.2	0
	3.4	1.2	0.5
500°C, 2 Hours	2.3	-0.5	-1.0
	1.6	-0.9	-1.2
	2.2	-0.6	-0.6
	1.5	-1.5	-1.6
	2.0	-1.1	-1.4
	2.2	-0.9	-0.8
	1.8	-0.5	-0.8
	2.0	-0.6	-1.1
	2.8	0.3	0
	2.8	0	-0.5

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE XVII FATIGUE DATA FOR En 58A SPRINGS AFTER VARIOUS LOW TEMPERATURE HEAT TREATMENTS

Stress Range (N/mm^2)	Cycles to Failure for Appropriate Heat Treatment ($X\ 10^3$)						
	As-Coiled	300°C, ½ Hour	300°C, 2 Hours	400°C, ½ Hour	400°C, 2 Hours	500°C, ½ Hour	500°C, 2 Hours
100-800	225	72	81	117	99	117	90
	126	144	108	99	108	-	81
	171	126	81	117	81	-	108
	117	99	90	126	108	108	81
	117	99	90	144	135	81	-
	108	99	36	144	108	126	90
	81	81	108	126	126	153	117
	117	-	108	90	117	108	144
Mean Value $\bar{X}_{100-800}$	127	100	84	119	109	113	100
100-600	294	2079	2250	1935	558	2538	8460 U/B
	194	1116	666	1332	1485	2043	414
	1953	1125	2070	2700	351	1395	10620 U/B
	402	567	315	1854	1656	2187	999
	394	1197	729	2403	3060	-	-
	316	666	1593	774	1494	684	1683
	1397	-	567	540	468	-	1935
	397	315	396	1323	360	603	540
Mean Value $\bar{X}_{100-600}$	486	868	843	1426	883	1367	938
100-400	U/B	NOT TESTED					U/B
	U/B						U/B
	U/B						U/B
	U/B						U/B
	U/B						U/B
	U/B						U/B
	U/B						2711
	U/B						U/B

(U/B:- 10^7 cycles unbroken
The data is tabulated with each member of a matched pair opposite its counterpart).

TABLE XVIII RELAXATION DATA AT A NUMBER OF STRESS LEVELS FOR En 58A SPRINGS AT 300°C FOR 168 HOURS, IN THE AS-COILED CONDITION AND AFTER A 350°C LTHT

Initial Torsional Stress (N/mm^2)	Relaxation (%) After Appropriate Heat Treatment		
	As-coiled	350°C, ½ Hour	350°C, 2 Hours
300	37.9	16.1	11.8
	38.3	18.0	12.7
	37.2	17.0	11.7
	36.5	18.9	12.2
	37.5	16.6	13.6
	37.8	15.4	12.4
400	36.9	17.8	15.3
	38.0	19.6	15.3
500	38.2	20.9	16.9
	37.8	20.2	19.0
600	40.0	22.3	18.6
	40.3	24.2	17.5
	40.6	22.4	17.5
	40.7	23.5	20.0
	45.1	24.2	17.9
	40.2	22.2	18.5
700	40.0	23.9	20.1
	41.4	23.4	21.3
800	43.3	26.5	23.4
	42.8	26.5	23.6
900	43.9	29.3	26.0
	45.1	33.0	24.4
	44.5	29.6	27.7
	44.6	29.0	26.9
	46.3	27.7	26.1
	43.8	27.6	26.3

The data is tabulated with each member of a matched pair opposite its counterpart.

TABLE XIX RELAXATION DATA AT A NUMBER OF STRESS LEVELS FOR En 58A SPRINGS AT 300°C FOR 168 HOURS, AFTER LTHT's OF 400° and 450°C

Initial Torsional Stress (N/mm^2)	Relaxation (%) After Appropriate Heat Treatment			
	400°C, ½ Hour	400°C, 2 Hours	450°C, ½ Hour	450°C, 2 Hours
300	6.6	9.3	4.1	4.9
	7.2	6.2	4.2	5.7
	8.0	6.0	4.9	6.0
	7.1	6.4	3.8	4.6
	7.2	6.0	4.2	4.1
	7.7	5.2	3.6	4.5
400	10.3	7.8	6.8	6.0
	10.5	8.5	5.6	6.4
500	11.4	9.9	9.2	8.2
	10.5	9.1	9.0	6.5
600	12.4	11.5	9.0	7.5
	13.5	11.2	9.3	7.6
	12.3	12.3	7.3	8.7
	12.4	10.7	8.5	7.2
	13.0	10.8	9.2	8.2
	13.8	11.0	10.1	7.9
700	14.7	13.4	9.9	8.5
	14.1	12.4	10.3	9.7
800	16.9	13.4	11.1	10.0
	16.7	16.3	11.3	10.5
900	20.5	18.4	13.2	12.6
	20.3	16.6	14.4	12.6
	22.0	16.3	13.6	11.5
	20.2	16.8	13.1	12.0
	20.3	20.0	15.0	12.4
	20.2	16.2	15.9	11.9

This data is tabulated with each member of a matched pair opposite its counterpart.

TABLE XX RELAXATION DATA AT A NUMBER OF STRESS LEVELS FOR En 58A SPRINGS AT 300°C FOR 168 HOURS, AFTER LTHT's OF 500°, 550° AND 600°C

Initial Torsional Stress (N/mm^2)	Relaxation (%) After Appropriate Heat Treatment			
	500°C, ½ Hour	500°C, 2 Hours	550°C, 2 Hours	600°C, 2 Hours
300	6.0 4.3 5.1 3.6 5.4 5.6	4.2 3.1 3.7 4.4 2.6 2.0	6.3 5.0 5.7	5.3 5.2 5.4
400	5.3 4.9	5.1 4.6	- -	- -
500	6.1 6.7	5.7 5.4	8.5	7.4
600	6.8 8.4 8.3 7.9 7.9 8.0	7.2 5.6 6.2 5.9 5.7 7.5	9.2	8.7
700	8.4 8.0	7.0 6.5	10.6	12.6
800	8.9 9.2	7.9 7.4	-	-
900	10.7 10.5 11.5 11.0 11.5 10.9	9.1 9.3 10.8 9.2 9.3 11.9	15.1 15.4 16.0	20.3 19.4 20.7

Only limited tests were carried out at the 550°C and 600°C LTHT, so that the overall trend in relaxation behaviour could be established.

The data is tabulated with each member of a matched pair opposite its counterpart.

TABLE XXI EFFECT OF TIME ON THE RELAXATION BEHAVIOUR OF En 58A SPRINGS AT 300°C, AFTER LTHT's of 450° AND 500°C FOR 2 HOURS

Tøtal Time At Temperature (Hours)	Relaxation (%) After Appropriate Heat Treatment, At Stresses of			
	400 N/mm²		800 N/mm²	
	450°C, 2 Hours	500°C, 2 Hours	450°C, 2 Hours	500°C, 2 Hours
4	3.3 3.2 2.9	3.8 3.0 3.4	6.9 6.8 7.1	5.4 5.5 5.7
10	4.5 4.9 4.5	4.3 4.2 3.8	7.6 8.2 7.5	5.8 6.3 6.2
16	4.9 3.2 3.3	4.3 4.2 4.2	8.6 8.8 8.8	6.7 7.3 7.2
32	7.0 6.1 5.4	4.7 5.5 5.5	9.8 10.5 10.2	7.5 8.1 8.0
48	7.0 6.5 6.6	4.3 5.0 5.0	10.9 11.1 10.9	7.7 8.3 8.6
72	7.4 7.3 6.6	5.5 5.5 5.5	11.1 11.5 11.1	8.1 8.8 8.2
96	7.8 7.3 7.0	6.3 6.7 6.7	11.9 12.3 11.5	8.5 9.6 9.5
168	9.9 9.0 -	7.6 7.5 -	12.1 12.7 12.1	8.9 10.0 9.9

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

LTHT Condition	Mean Value $\bar{A}$ (mm)	Std. Dev S_A	't'* Value	Mean Value $\bar{B}$ (mm)	Std. Dev S_B	't'* Value	Comments
350°C, ½ Hr	0.62	0.09	21.78	3.76	0.28	42.46	Differences all significant at the 99.9% level
350°C, 2 Hrs	0.62	0.05	39.21	3.75	0.23	51.56	
400°C, ½ Hr	0.66	0.03	69.57	3.46	0.29	37.73	
400°C, 2 Hrs	0.67	0.10	21.19	3.20	0.20	50.60	
450°C, ½ Hr	0.68	0.09	23.89	3.22	0.28	36.37	
450°C, 2 Hrs	0.72	0.09	25.30	3.09	0.16	61.07	
500°C, ½ Hr	0.60	0.09	21.08	3.17	0.21	47.74	
500°C, 2 Hrs	0.59	0.19	9.82	3.21	0.31	32.74	

where A = (Free length after grinding - Free length after LTHT)

and B = (Free length after grinding - Free length after LTHT and prestressing)

* Total number of pairs in each case = 10

TABLE XXIII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON FREE LENGTH MEASUREMENTS AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature	Mean Value $\bar{C}$ (mm)	Std. Dev S_C	't'* Value	Mean Value $\bar{D}$ (mm)	Std. Dev S_D	't'* Value	Comments
350°C	0.11	0.68	0.512	0.10	0.70	0.452	No significant differences at 95% level
400°C	0.17	0.67	0.802	-0.10	0.43	0.735	No difference at 95% level of significance
450°C	0.06	0.62	0.306	-0.12	0.57	0.666	Differences not significant at 95% level
500°C	0.31	0.83	1.181	0.36	0.57	1.997	No differences at 95% level of significance

where C = {(Free length after a ½ Hr LTHT) - (Free length after a 2 Hr LTHT)}

and D = {(Free length after a ½ Hr LTHT and subsequent prestress) - (Free length after a 2 Hr LTHT and subsequent prestress)}

* Total number of pairs in each case = 10

TABLE XXIV ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON COIL DIAMETER MEASUREMENTS

LTHT Condition	Mean Value $\overline{E}$ (mm)	Std. Dev S_E	't'* Value	Mean Value $\overline{F}$ (mm)	Std. Dev S_F	't'* Value	Comments
350°C, ½ Hr	-0.12	0.06	6.32	-0.09	0.07	4.07	All differences significant at the 99.8% level
350°C, 2 Hrs	-0.10	0.06	5.27	-0.11	0.06	5.80	
400°C, ½ Hr	-0.12	0.05	7.59	-0.14	0.05	8.85	
400°C, 2 Hrs	-0.15	0.07	6.78	-0.16	0.08	6.32	
450°C, ½ Hr	-0.18	0.08	7.12	-0.18	0.05	11.38	
450°C, 2 Hrs	-0.21	0.04	16.60	-0.22	0.04	17.39	
500°C, ½ Hr	-0.18	0.09	6.32	-0.18	0.08	7.12	
500°C, 2 Hrs	-0.24	0.08	9.49	-0.24	0.07	10.84	

where E = {(Outside coil diameter after grinding) - (Outside coil diameter after LTHT)}

and F = {(Outside coil diameter after grinding) - (Outside coil diameter after LTHT and prestressing)}

* Total number of pairs in each case = 10

TABLE XXV ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON COIL DIAMETER MEASUREMENTS AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature	Mean Value $\bar{\bar{G}}$	Std. Dev S_G	't'* Value	Mean Value $\bar{\bar{H}}$	Std. Dev S_H	't'* Value	Comments
350°C	0	0.10	0	-0.03	0.08	1.186	Differences not significant at the 95% level
400°C	-0.05	0.14	1.129	-0.04	0.13	0.973	
450°C	-0.06	0.09	2.108	-0.07	0.09	2.460	Differences just significant at the 95% level
500°C	-0.06	0.09	2.108	-0.06	0.07	2.711	

where G = {(Outside coil diameter after a ½ hour LTHT)
- (Outside coil diameter after a 2 Hour LTHT)}

and H = {(Outside coil diameter after a ½ Hour LTHT and subsequent prestress)
- (Outside coil diameter after a 2 Hour LTHT and subsequent prestress)}

* Total number of pairs in each case = 10

TABLE XXVI ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON THE 'WIND-DOWN' OF EN 58A SPRINGS

LTHT Condition	Mean Value $\bar{I}$	Std. Dev S_I	't'* Value	Mean Value $\bar{J}$	Std. Dev S_J	't'* Value	Comments
350°C, ½ Hr	1.0	0.4	7.91	1.6	0.4	12.65	Difference all significant at 99.9% level
350°C, 2 Hrs	1.3	0.2	20.56	1.9	0.2	30.04	
400°C, ½ Hr	1.6	0.4	12.65	2.2	0.2	34.79	
400°C, 2 Hrs	1.8	0.3	18.97	2.2	0.6	11.60	
450°C, ½ Hr	2.2	0.3	23.19	2.6	0.3	27.41	
450°C, 2 Hrs	2.3	0.3	24.24	2.8	0.2	44.27	
500°C, ½ Hr	2.6	0.4	20.56	2.9	0.3	30.57	
500°C, 2 Hrs	2.8	0.3	29.52	3.0	0.3	31.62	

* Total number of pairs in each case = 10

where I = {(Number of degrees/coil after grinding) - (Number of degrees/coil after LTHT)}

and J = {(Number of degrees/coil after grinding) - (Number of degrees/coil after LTHT and a subsequent prestress)}

TABLE XXVII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON THE 'WIND-DOWN' of En 58A SPRINGS AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperatures	Mean Value $\bar{K}$	Std. Dev S_K	't'* Value	Mean Value $\bar{L}$	Std. Dev S_L	't'* Value	Comments
350°C	0.5	0.5	3.16	0.5	0.4	3.95	Differences significant at 98% level
400°C	0.4	0.5	2.53	0.2	0.7	0.90	Difference just significant at 95% level for LTHT only Difference not significant at 95% level for LTHT and pre-stressing
450°C	0.4	0.7	1.81	0.4	0.7	1.81	Differences not significant at 95% level
500°C	0.4	0.7	1.81	0.3	0.7	1.36	Differences not significant at 95% level

where K = {(Number of degrees/coil after a ½ Hr LTHT) − (Number of degrees/coil after a 2 Hr LTHT)}

and L = {(Number of degrees/coil after a ½ Hr LTHT and subsequent prestress) − (Number of degrees/coil after a 2 Hr LTHT and subsequent prestress)}

* Total number of pairs in each case = 10

TABLE XXVIII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED FATIGUE TESTS AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature (°C)	Total No. of Pairs	Max. Stress 600 N/mm^2			Max. Stress 800 N/mm^2			Comments
		Mean Value $\bar{P}$	Std. Dev S_P	't' Value	Mean Value $\bar{Q}$	Std. Dev S_Q	't' Value	
300	7	-0.0118	0.2535	0.12	0.0947	0.1845	1.36	There is no difference at the 95% level of significance for any of the temperatures investigated
400	8	0.2081	0.4055	1.45	0.0376	0.0885	1.20	
500	4	0.1726	0.4591	0.75				
	5				0.0753	0.1127	1.49	

where $P = \log N (\frac{1}{2}\ Hr.\ LTHT)_{600} - \log N (2\ Hr.\ LTHT)_{600}$

and $Q = \log N (\frac{1}{2}\ Hr.\ LTHT)_{800} - \log N (2\ Hr.\ LTHT)_{800}$

TABLE XXIX STANDARD COMPARATIVE 't' TESTS ON FATIGUE DATA FOR EN 58A SPRINGS AFTER A ½ HR LTHT

LTHT Conditions under Comparison	Total No. of Samples N	't' Values		Comments
		Max. Stress 600 N/mm^2	Max. Stress 800 N/mm^2	
As-Coiled and 300°C	15	1.45	1.53	No difference at the 95% level of significance
As-Coiled and 400°C	16	2.93	0.50	600 N/mm^2: A significant difference at the 95% level 800 N/mm^2: No significant difference at the 95% level
As-Coiled and 500°C	14	2.44	0.72	600 N/mm^2: A significant difference at the 95% level 800 N/mm^2: No difference at the 95% level of significance
300°C and 400°C	15	1.53	1.51	No difference at the 95% level of significance
300°C and 500°C	13	1.22	0.90	No significant difference at the 95% level
400°C and 500°C	14	0.12	0.44	No significant difference at the 95% level

TABLE XXX STANDARD COMPARATIVE 't' TESTS ON FATIGUE DATA FOR En 58A SPRINGS AFTER A 2 HR LTHT

LTHT Conditions under Comparison	Total No. of Samples N	't' Value		Comments
		Max. Stress 600 N/mm^2	Max. Stress 800 N/mm^2	
As-Coiled and 300°C	16	1.33	2.32	600 N/mm^2: No significant difference at the 95% level 800 N/mm^2: A significant difference at the 95% level
As-Coiled and 400°C	16	1.38	1.17	No difference at the 95% level of significance
As-Coiled and 500°C	13	1.41		No difference at the 95% level of significance
	15		1.64	
300°C and 400°C	16	0.11	1.78	No significant difference at the 95% level
300°C and 500°C	13	0.24		No difference at the 95% level of significance
	15		1.03	
400°C and 500°C	13	0.13		No significant difference at the 95% level
	15		0.90	

TABLE XXXI ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED RELAXATION TESTS, AT AN INITIAL STRESS OF 300 N/mm^2, AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature (°C)	Initial Torsional Stress 300 N/mm^2				Comments
	No. of Pairs N	Mean Value $\bar{R}$	Std. Dev S_R	't' Value	
350	6	4.8	1.8	6.53	Difference significant at 99.8% level
400	6	0.8	1.8	1.09	No significant difference at the 95% level
450	6	-0.8	0.5	3.92	A difference at the 95% level of significance.
500	6	1.7	1.5	2.78	Difference significant at the 95% level

where R = {(Relaxation (%) after a ½ Hr LTHT) - (Relaxation (%) after a 2 Hr LTHT)}

TABLE XXXII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED RELAXATION TESTS, AT AN INITIAL STRESS OF 600 N/mm^2, AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature (°C)	Initial Torsional Stress 600 N/mm^2				Comments
	No. of Pairs N	Mean Value $\bar{T}$	Std. Dev S_T	't' Value	
350	6	5.0	1.3	9.42	Difference significant at the 99.9% level
400	6	1.8	1.3	3.39	Difference significant at the 95% level
450	6	1.0	1.3	1.88	No significant difference at 95% level
500	6	1.5	1.2	3.06	Difference significant at the 95% level

where T = {(Relaxation (%) after a ½ Hr LTHT) - (Relaxation (%) after a 2 Hr LTHT)}

TABLE XXXIII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED RELAXATION TESTS, AT AN INITIAL STRESS OF 900 N/mm^2, AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperature (^{o}C)	Initial Torsional Stress 900 N/mm^2				Comments
	No. of Pairs N	Mean Value $\bar{U}$	S_U	't' Value	
350	6	3.1	2.8	2.71	Difference significant at the 95% level
400	6	3.2	1.8	4.35	Difference significant at the 99% level
450	6	2.0	1.2	4.08	Difference significant at the 99% level
500	6	1.1	1.1	2.45	No significant difference at the 95% level

where U = {(Relaxation (%) after a ½ Hr LTHT) - (Relaxation after a 2 Hr LTHT)}

TABLE XXXIV VALUES OF THE ANALYTICAL CONSTANTS FOR THE STRESS-RELAXATION PLOT AT 300°C FOR 168 HOURS, AFTER A LTHT AT 500°C FOR 30 MINUTES

Constants for $R = a\tau + b$		Increment for 95% confidence $= \pm 1.96\ S_y\ (1-r^2)^{\frac{1}{2}}$
a	b	
0.01	1.7	1.3

TABLE XXXV VALUES OF THE ANALYTICAL CONSTANTS FOR THE LOGARITHMIC TIME-RELAXATION RELATIONSHIPS DETERMINED FOR En 58A SPRINGS

LTHT Condition	Initial Torsional Stress (N/mm^2)	Constants for $R = c\ln t + d$	
		c	d
450° 2 Hours	400	1.5	0.7
	800	1.6	4.6
500°C 2 Hours	400	1.0	1.7
	800	1.1	3.8

TABLE XXXVI ELECTRICAL RESISTIVITY MEASUREMENTS ON SAMPLES OF En 58A WIRE AFTER VARIOUS HEAT TREATMENTS

LTHT Condition	Electrical Resistance (ohm) At 22°C	Electrical Resistivity (microhm-m at 22°C)
As-Received	0.0706	0.77
	0.0711	0.78
300°C/2 Hours	0.0697	0.76
	0.0702	0.77
350°C/2 Hours	0.0697	0.76
	0.0696	0.76
400°C/2 Hours	0.687	0.75
	0.0686	0.75
450°C/2 Hours	0.0681	0.75
	0.0680	0.74
500°C/2 Hours	0.0670	0.73
	0.0668	0.73
835°C/2 Hours	0.0635	0.70
	0.0638	0.70

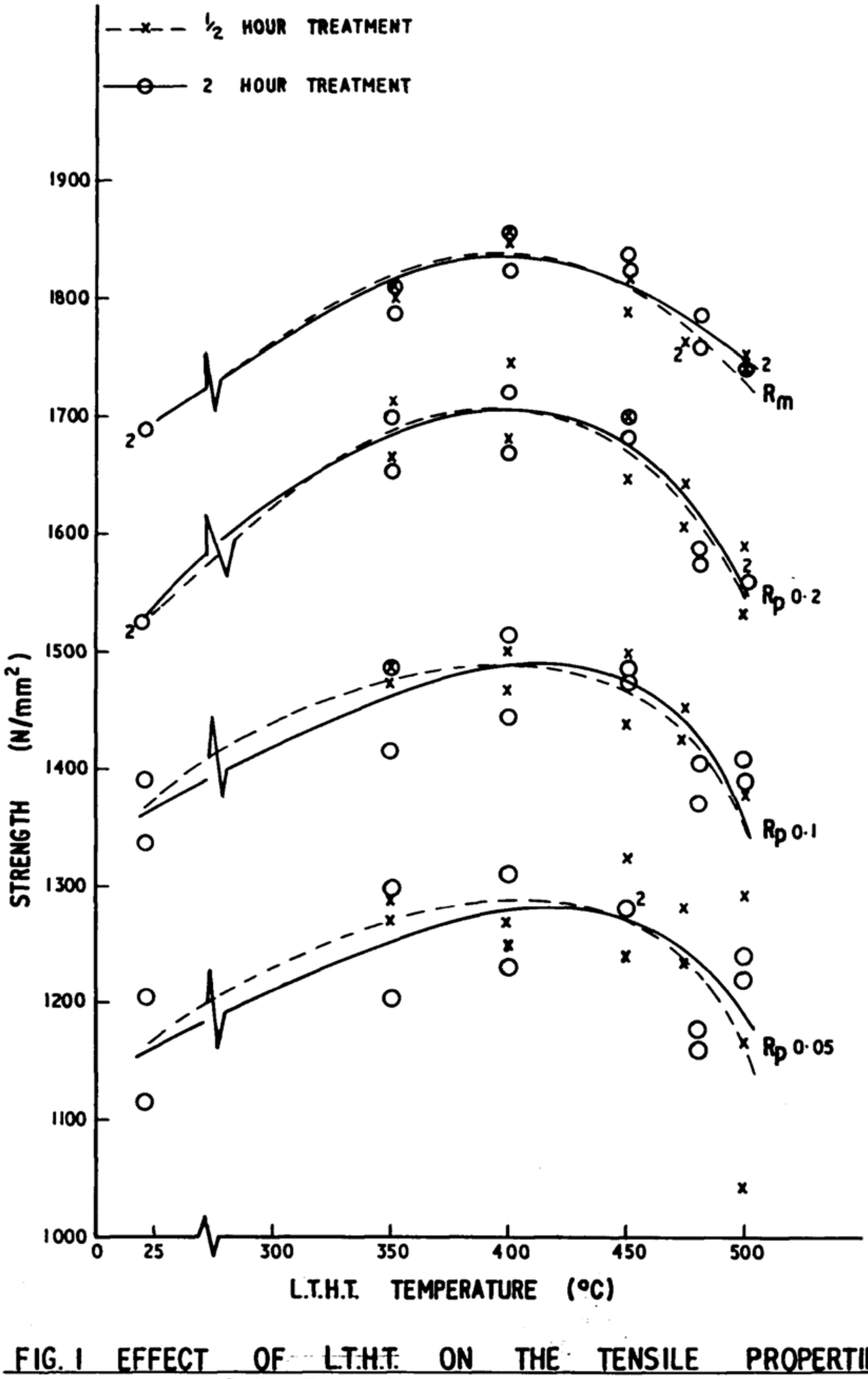


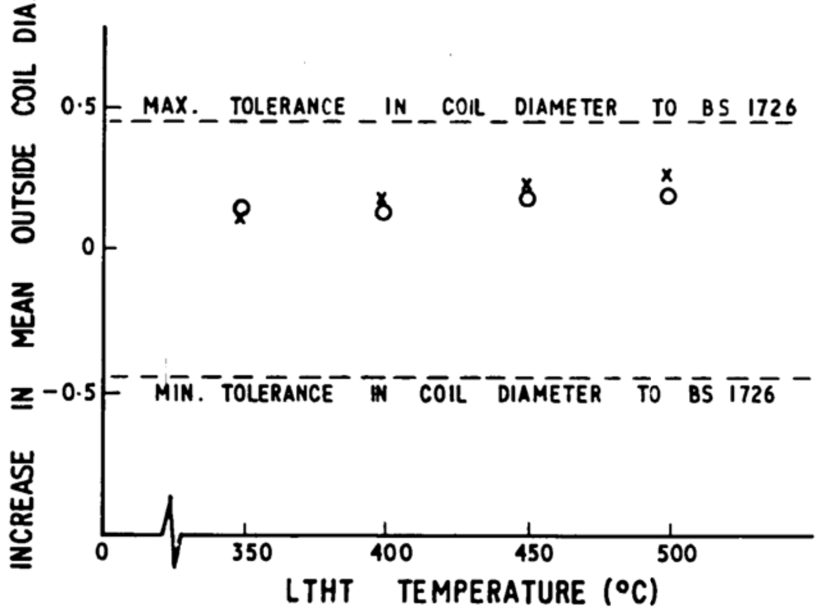
FIG. 1 EFFECT OF L.T.H.T. ON THE TENSILE PROPERTIES OF 2·64 mm DIA. En 58 A SPRING WIRE.

[illegible] SPRINGS AT 300°C FOR 168 HOURS, IN THE AS-COILED CONDITION AND AFTER A 350°C LTHT

Initial Torsional Stress (N/mm^2)	Relaxation (%) After Appropriate Heat Treatment		
	As-coiled	350°C, ½ Hour	350°C, 2 Hours
300	37.9	16.1	11.8
	38.3	18.0	12.7
	37.2	17.0	11.7
	36.5	18.9	12.2
	37.5	16.6	13.6
	37.8	15.4	12.4
400	36.9	17.8	15.3
	38.0	19.6	15.3
500	38.2	20.9	16.9
	37.8	20.2	19.0
600	40.0	22.3	18.6
	40.3	24.2	17.5
	40.6	22.4	17.5
	40.7	23.5	20.0
	45.1	24.2	17.9
	40.2	22.2	18.5
700	40.0	23.9	20.1
	41.4	23.4	21.3
800	43.3	26.5	23.4
	42.8	26.5	23.6
900	43.9	29.3	26.0
	45.1	33.0	24.4
	44.5	29.6	27.7
	44.6	29.0	26.9
	46.3	27.7	26.1
	43.8	27.6	26.3

The data is tabulated with each member of a matched pair opposite its counterpart.

O :- ½ HOUR TREATMENT
x :- 2 HOUR TREATMENT
POINTS MARKED ARE MEAN VALUES



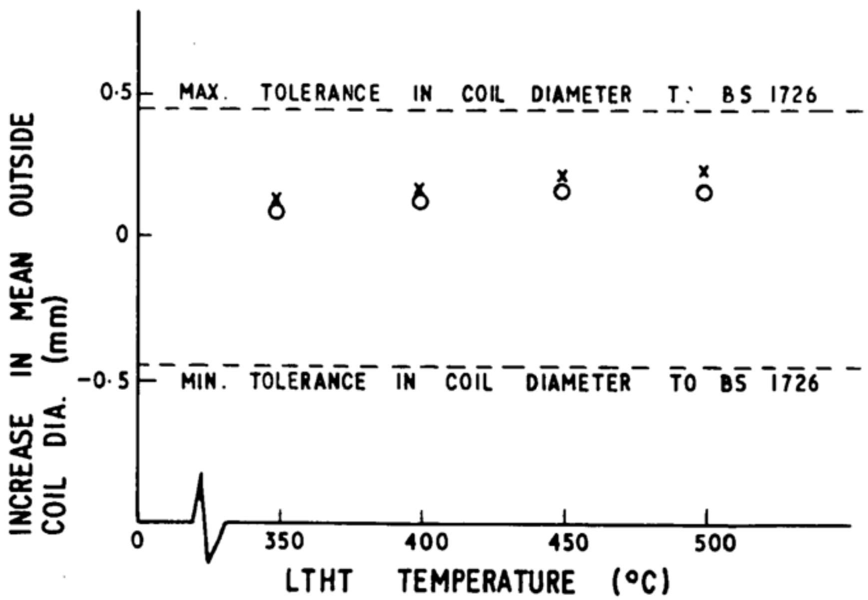


FIG. 3 THE EFFECT OF LTHT TIME AND TEMPERATURE ON THE MEAN OUTSIDE COIL DIAMETER OF EN 58 A SPRINGS AFTER LTHT ONLY.

FIG. 4 THE EFFECT OF LTHT TIME AND TEMPERATURE ON THE MEAN OUTSIDE COIL DIAMETER OF EN 58 A SPRINGS AFTER LTHT AND PRESTRESSING.

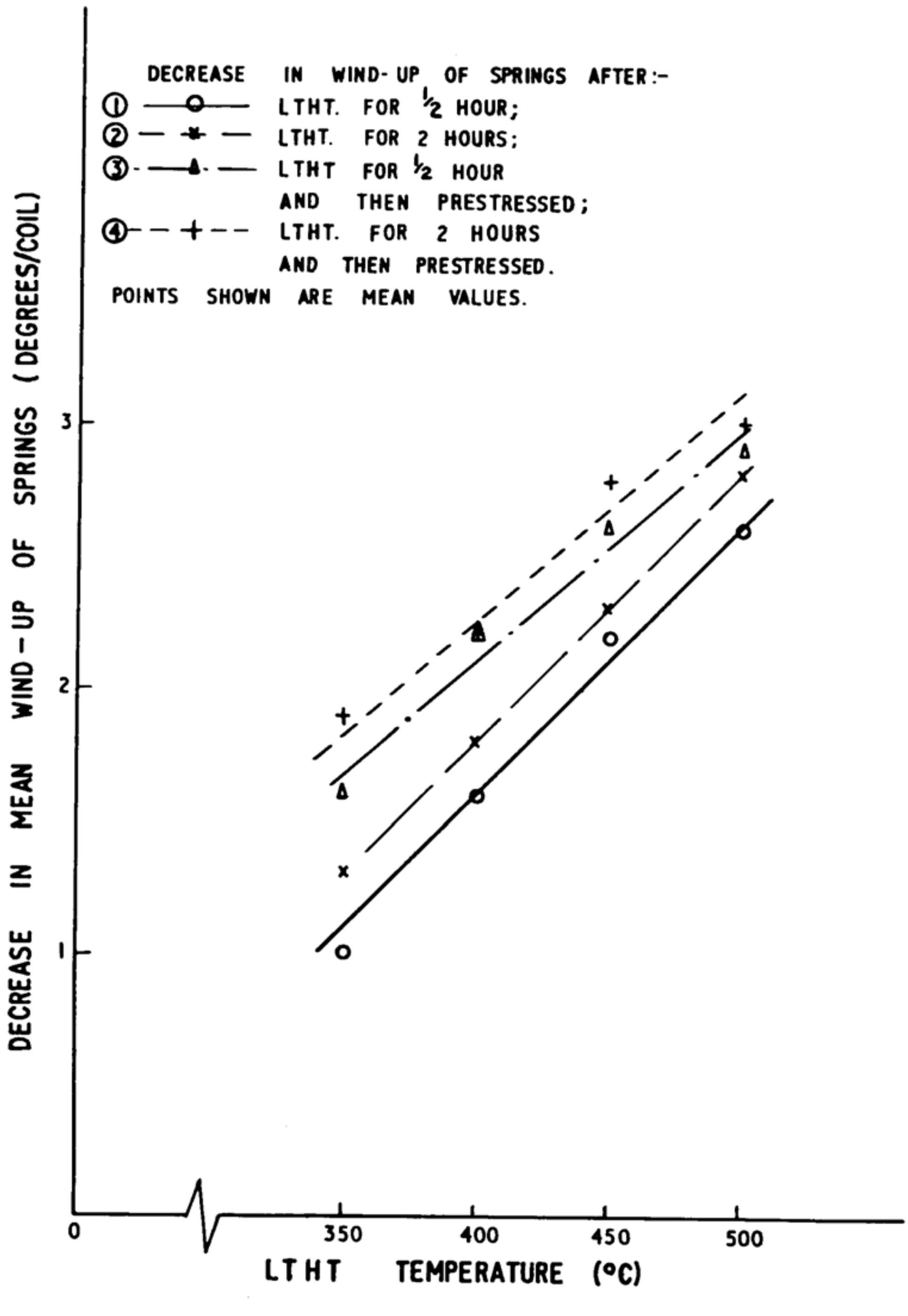


FIG. 5 THE EFFECT OF LTHT TIME AND TEMPERATURE ON THE MEAN 'WIND-UP' OF EN 58A SPRINGS AFTER LTHT AND ALSO AFTER A SUBSEQUENT PRESTRESS.

TABLE VIII EFFECT OF A 500°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Springs (mm)		
	After Grinding	After LTHT	After Prestressing
500°C, ½ Hour	50.525	49.900	47.400
	49.650	49.075	46.725
	50.925	50.275	47.325
	49.850	49.400	46.900
	50.400	49.750	47.250
	50.675	50.075	47.450
	50.625	49.925	47.200
	50.875	50.375	47.825
	49.775	49.025	46.650
	50.900	50.400	47.750
500°C, 2 Hours	49.950	49.475	46.725
	50.825	50.025	47.350
	49.900	49.050	46.600
	50.375	49.650	47.150
	49.525	49.350	46.950
	49.275	48.725	46.400
	50.400	49.850	47.075
	49.875	49.275	46.875
	50.525	49.975	46.850
	50.300	49.725	46.950

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

TABLE XXVII ANALYTICAL RESULTS AND INTERPRETATION OF PAIRED 't' TESTS ON THE 'WIND-DOWN' of En 58A SPRINGS AFTER ½ HOUR AND 2 HOUR TREATMENTS

LTHT Temperatures	Mean Value $\bar{K}$	Std. Dev S_K	't'* Value	Mean Value $\bar{L}$	Std. Dev S_L	't'* Value	Comments
350°C	0.5	0.5	3.16	0.5	0.4	3.95	Differences significant at 98% level
400°C	0.4	0.5	2.53	0.2	0.7	0.90	Difference just significant at 95% level for LTHT only Difference not significant at 95% level for LTHT and pre-stressing
450°C	0.4	0.7	1.81	0.4	0.7	1.81	Differences not significant at 95% level
500°C	0.4	0.7	1.81	0.3	0.7	1.36	Differences not significant at 95% level

where K = {(Number of degrees/coil after a ½ Hr LTHT) − (Number of degrees/coil after a 2 Hr LTHT)}

and L = {(Number of degrees/coil after a ½ Hr LTHT and subsequent prestress) − (Number of degrees/coil after a 2 Hr LTHT and subsequent prestress)}

* Total number of pairs in each case = 10

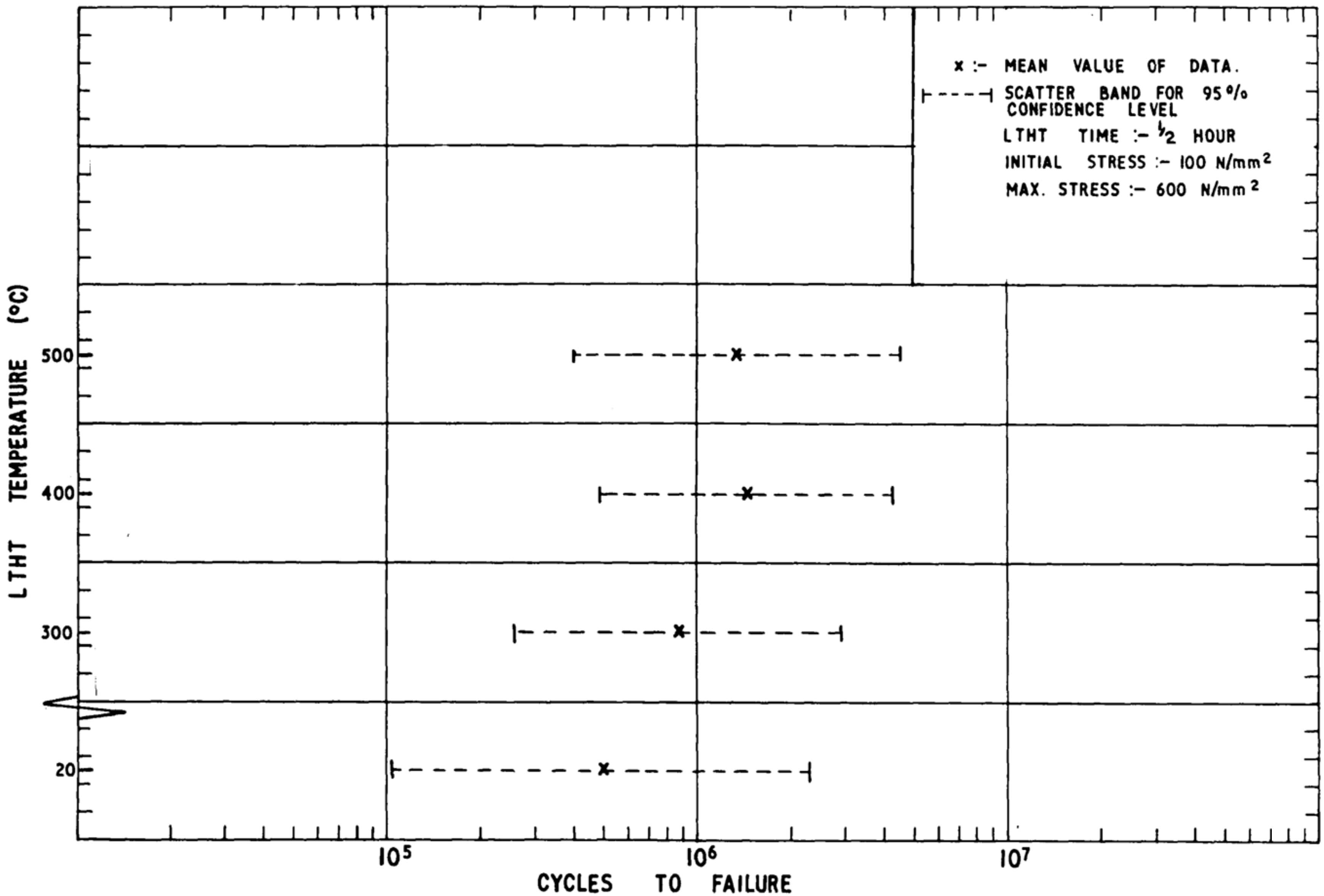


FIG. 8 EFFECT OF LTHT TEMPERATURE ON THE FATIGUE LIFE OF EN 58 A SPRINGS AT A MAXIMUM STRESS OF 600 N/mm^2, AFTER A ½ HOUR TREATMENT.

TABLE VIII EFFECT OF A 500°C LTHT ON THE FREE LENGTH OF En 58A SPRINGS

LTHT Condition	Free Length of Springs (mm)		
	After Grinding	After LTHT	After Prestressing
500°C, ½ Hour	50.525	49.900	47.400
	49.650	49.075	46.725
	50.925	50.275	47.325
	49.850	49.400	46.900
	50.400	49.750	47.250
	50.675	50.075	47.450
	50.625	49.925	47.200
	50.875	50.375	47.825
	49.775	49.025	46.650
	50.900	50.400	47.750
500°C, 2 Hours	49.950	49.475	46.725
	50.825	50.025	47.350
	49.900	49.050	46.600
	50.375	49.650	47.150
	49.525	49.350	46.950
	49.275	48.725	46.400
	50.400	49.850	47.075
	49.875	49.275	46.875
	50.525	49.975	46.850
	50.300	49.725	46.950

Values shown are the mean of two measurements on each spring.

All springs prestressed to solid ten times.

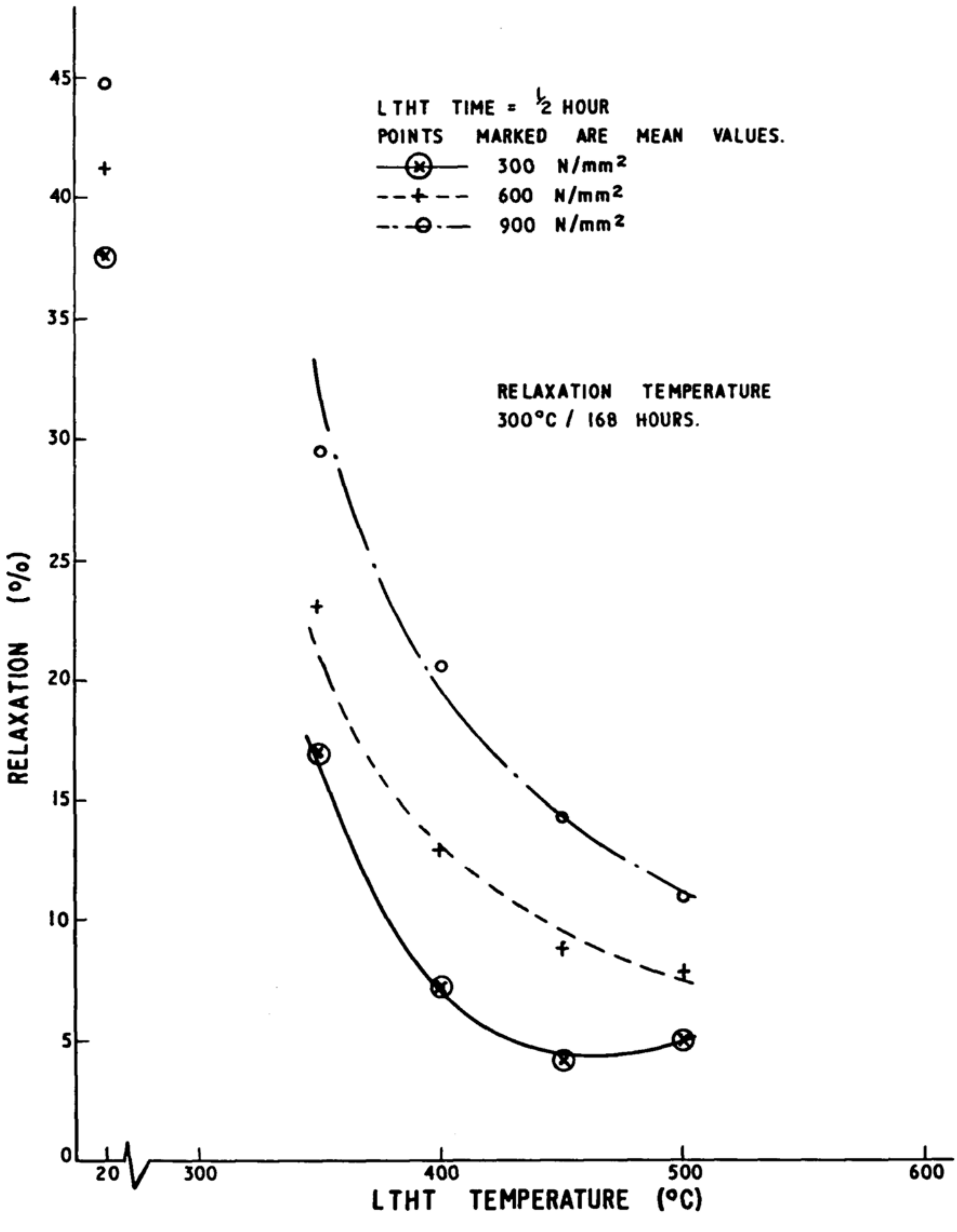


FIG. 10 EFFECT OF LTHT TEMPERATURE ON THE RELAXATION PROPERTIES OF SPRINGS COILED FROM 2·64 mm DIA. EN 58 A WIRE, AFTER A ½ HOUR TREATMENT.

Effect of LTHT on the Tensile Properties of 2.64 mm dia. En 58A Springs

The Effect of LTHT Time and Temperature on the Mean Free Length of En 58A Springs after LTHT and also after a Subsequent Prestress

The Effect of LTHT Time and Temperature on the Mean Outside Coil Diameter of En 58A Springs after LTHT only

The Effect of LTHT Time and Temperature on the Mean Outside Coil Diameter of En 58A Springs after LTHT and Prestressing

The Effect of LTHT time and Temperature on the Mean 'Wind-down' of En 58A Springs after LTHT and also after a Subsequent Prestress

Effect of LTHT Temperature on the Fatigue Life of En 58A Springs at a Maximum Stress of 800 N/mm^2, after a ½ hour Treatment

Effect of LTHT Temperature on the Fatigue Life of En 58A Springs at a Maximum Stress of 800 N/mm^2, after a 2 hour Treatment

Effect of LTHT Temperature on the Fatigue Life of En 58A Springs at a Maximum Stress of 600 N/mm^2, after a ½ hour Treatment

Effect of LTHT Temperature on the Fatigue Life of En 58A Springs at a maximum Stress of 600 N/mm^2, after a 2 hour Treatment

Effect of LTHT Temperature on the Relaxation Properties of Springs Coiled from 2.64 mm dia. En 58A Wire, after a ½ hour Treatment

Effect of LTHT Temperature on the Relaxation Properties of Springs Coiled from 2.64 mm dia. En 58A Wire, after a 2 hour Treatment

Time-Relaxation Curves for En 58A Springs at an Initial Stress of 400 N/mm^2

Time-Relaxation Curves for En 58A Springs at an Initial Stress of 800 N/mm^2

Stress-Relaxation Behaviour of En 58A Springs at 300°C for 168 hours after a LTHT of 500°C for 30 minutes

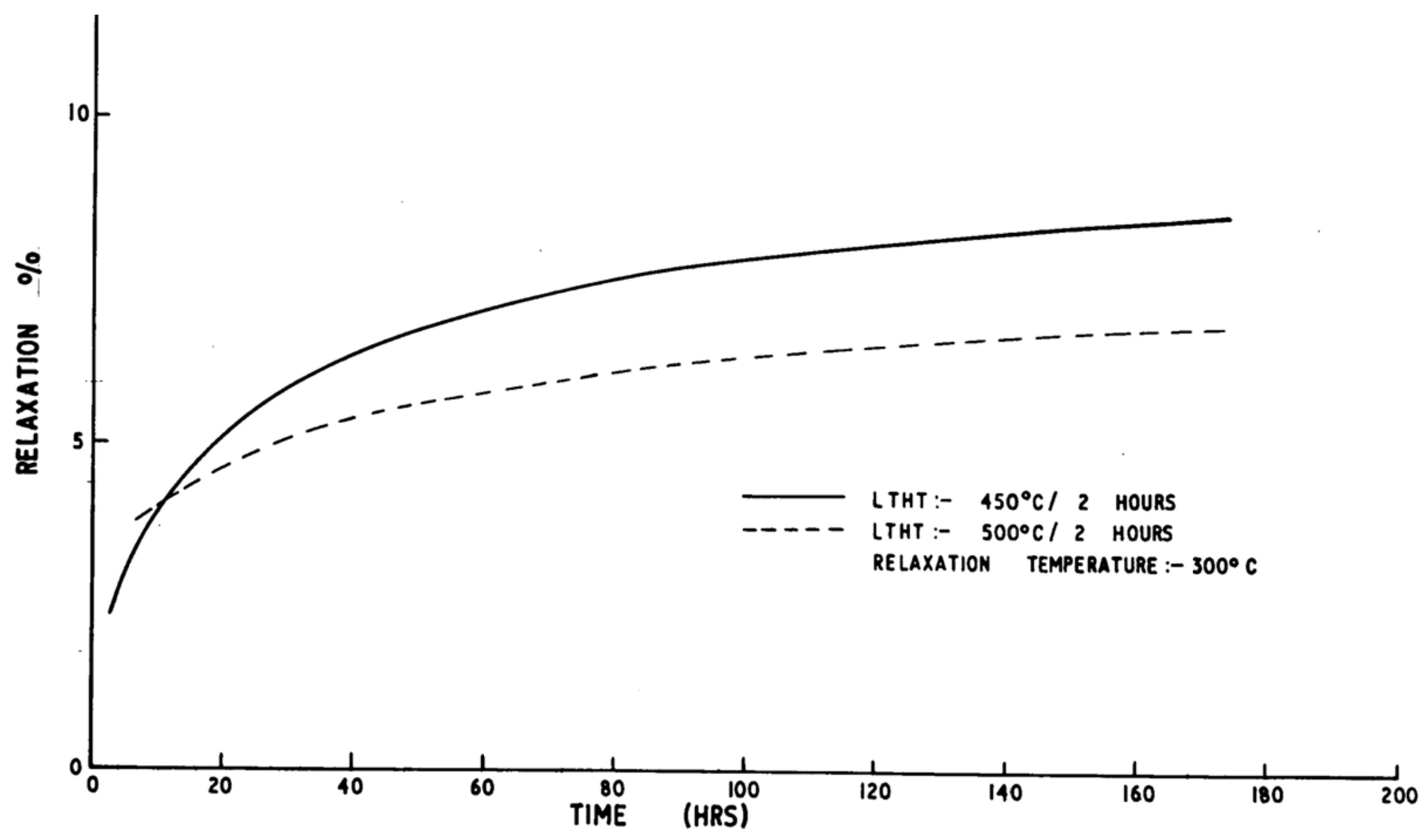


FIG. 12 TIME - RELAXATION CURVES FOR EN 58 A SPRINGS AT AN INITIAL STRESS OF 400 N/mm^2

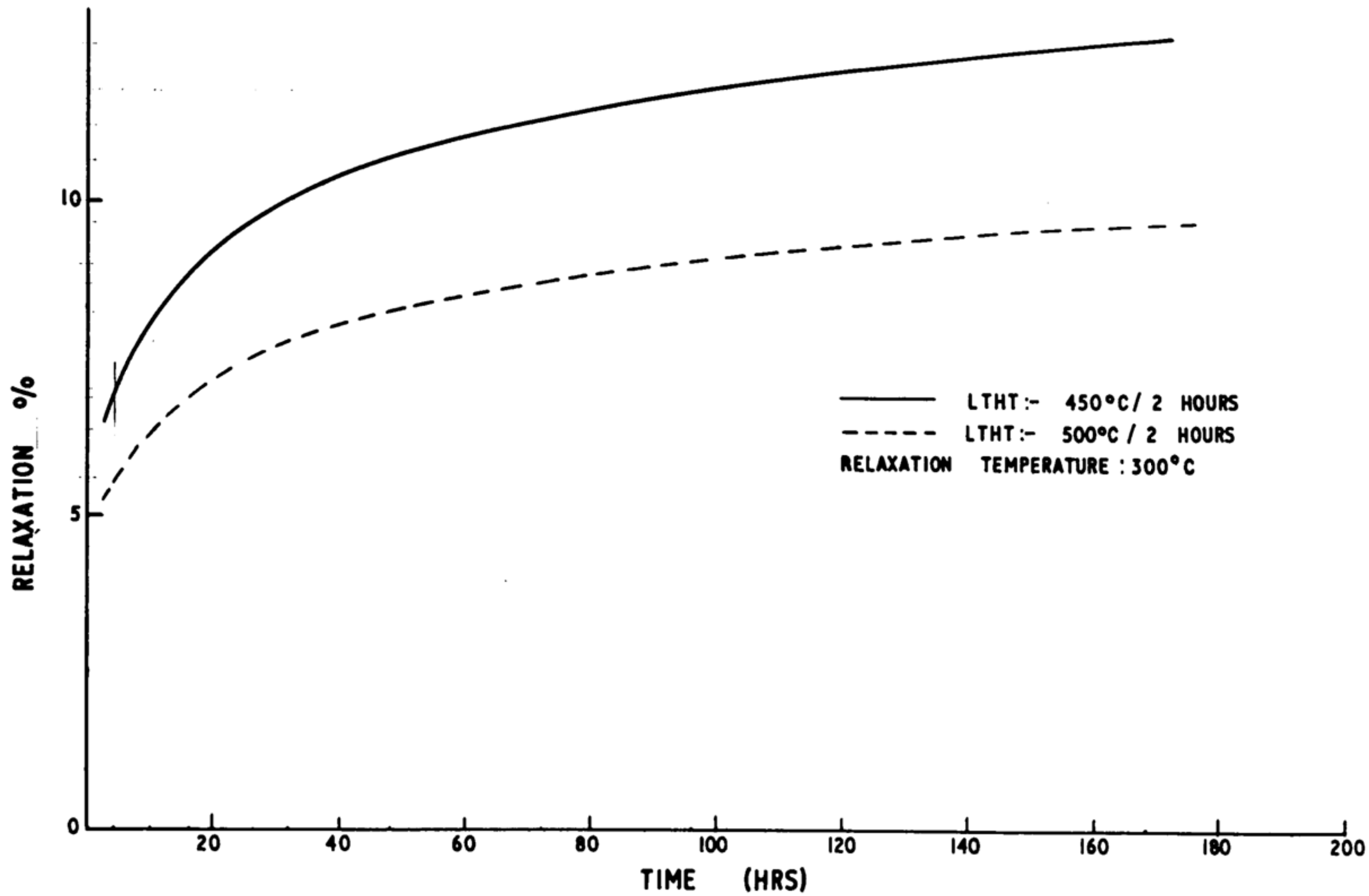


FIG. 13 TIME RELAXATION CURVES FOR EN 58A SPRINGS AT AN INITIAL STRESS OF 800 N/mm^2

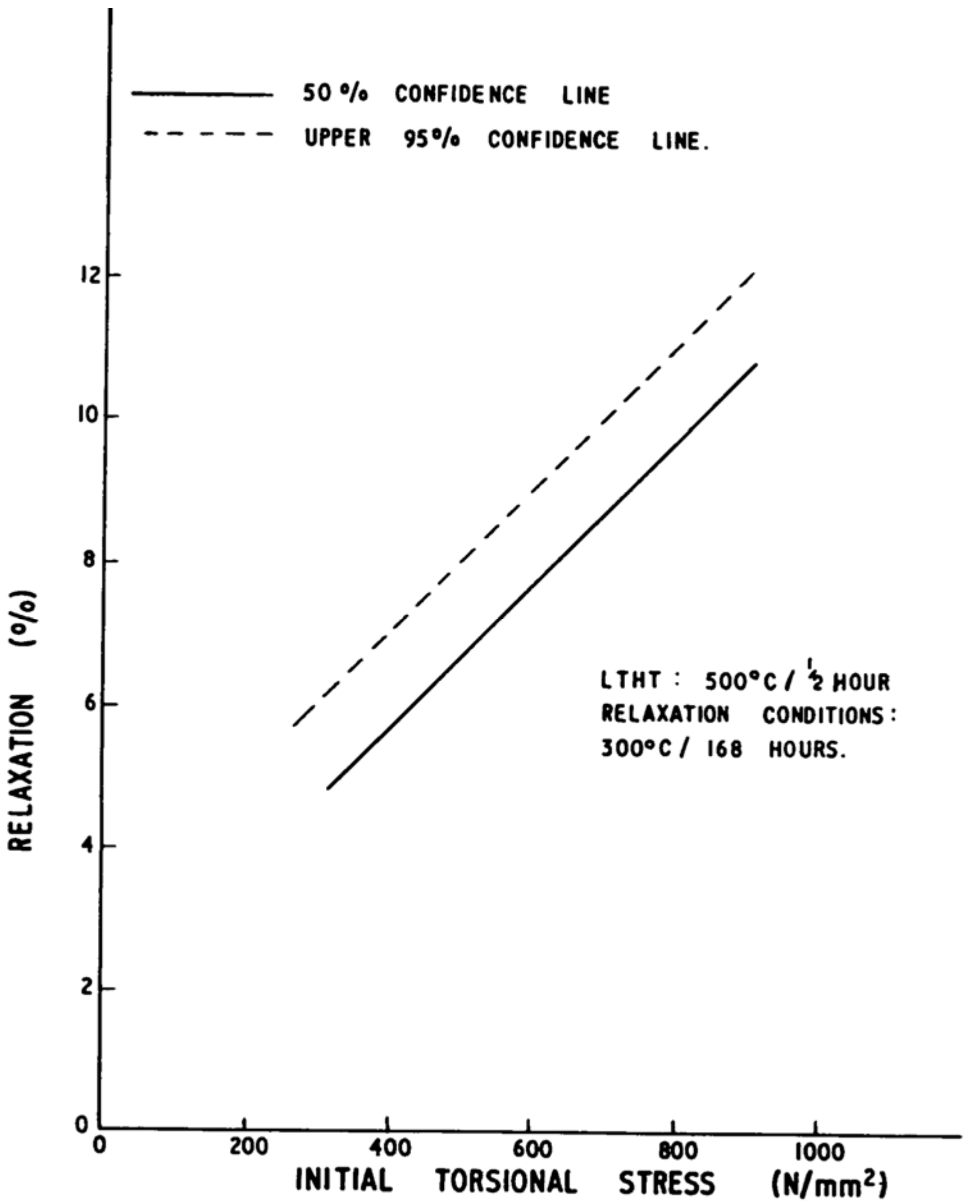


FIG. 14 STRESS-RELAXATION BEHAVIOUR OF EN 58 A COMPRESSION SPRINGS AT 300°C FOR 168 HOURS, AFTER A LTHT OF 500°C FOR 30 MINUTES.

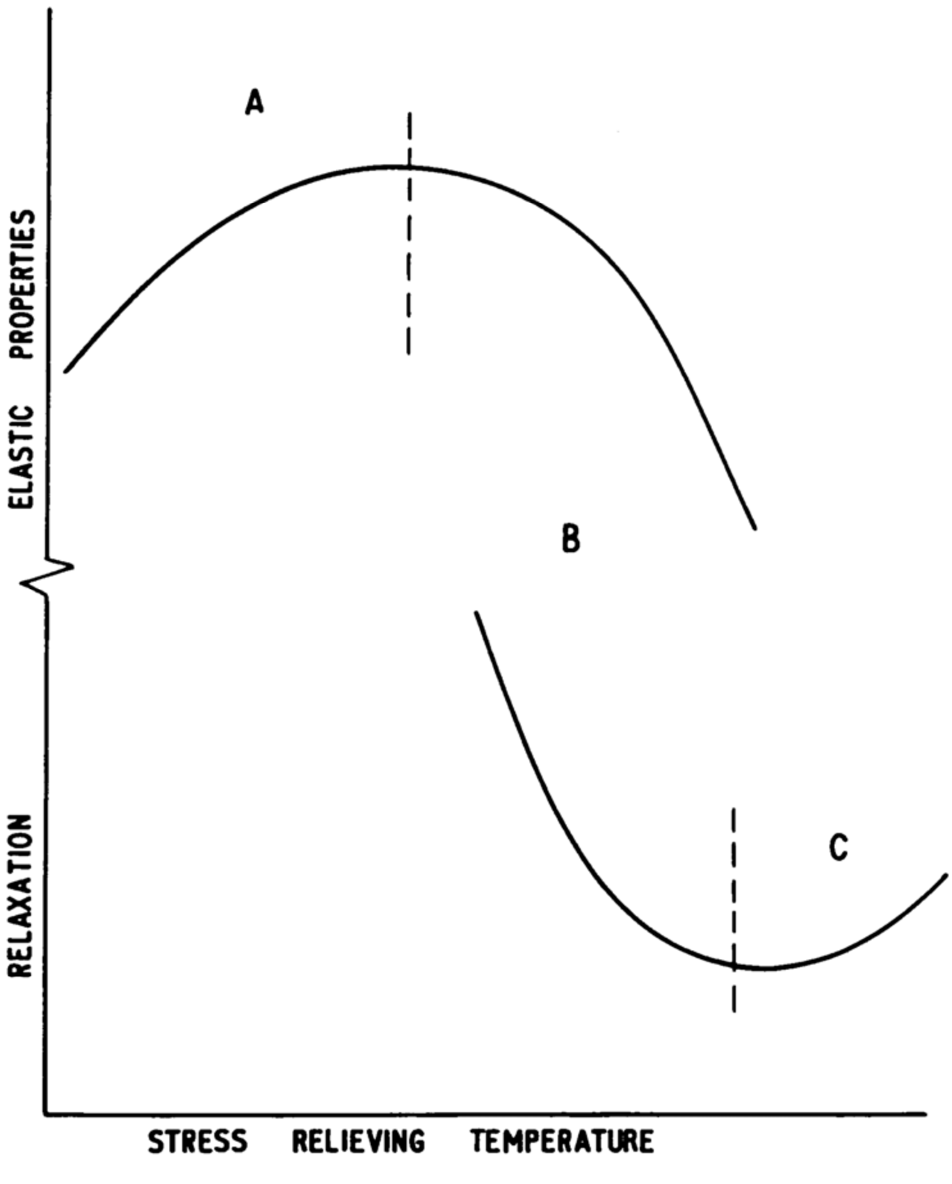


FIG. 15 GENERAL EFFECT OF STRESS-RELIEVING TEMPERATURE ON THE ELASTIC AND RELAXATION PROPERTIES OF IRON ALLOYS.