THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

UPON THE FACTORS AFFECTING DELAYED FAILURE IN ELECTROPLATED CARBON SPRING STEELS

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by

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Without which this work could not have been completed.

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1. INTRODUCTION

1.1 Resume of Previous Work

Hydrogen embrittlement of zinc electroplated carbon spring steels, with a hardness of 500Hv, has been the subject of intensive investigation at SRAMA.[1,2]

In this previous work, hydrogen embrittlement was introduced during zinc electroplating, and was characterized using a dynamic slow bend test which has been previously described.[2] This work resulted in three main conclusions, namely

1. Both before and after electroplating with zinc, austempered spring steels were significantly more ductile than the same hardened and tempered material of equivalent hardness.

2. For both the hardened and tempered and the austempered strips, two categories of steel were identified with respect to embrittlement and de-embrittlement behaviour, namely

    a) Category 1 steels: severely embrittled during electroplating, but relatively easy to de-embrittle by baking at 190°C for 2 hours.

b) Category 2 steels: less severely embrittled than category 1 during electroplating, but more difficult to de-embrittle, requiring a baking treatment of 190°C for 24 hours for effective de-embrittlement.

3. After electroplating with zinc, a baking treatment of 190°C for 24 hours was judged to form the best recommendation for effective de-embrittlement of carbon spring steels used in industry.

1.2 Objectives and Plan of Current Work

1.2.1 Objectives

The previous work at SRAMA used a dynamic slow bend test as a means of characterising the behaviour of spring steels with respect to hydrogen embrittlement.

Dynamic tests cannot simulate the conditions obtaining during spring service, however, where electroplated components often fracture after extended periods of time under an essentially static load. This type of fracture is often termed a Static Fatigue failure. The work at SRAMA was therefore extended to investigate the effects of hydrogen embrittlement upon the failure rate of zinc electroplated carbon steels when stressed in static bending.

The static fatigue work was carried out with the objective of generating design data for electroplated carbon steel springs, the main thrust of the work being directed towards defining the effects of microstructure, operating stress and de-embrittlement baking treatments upon the failure rate of zinc electroplated steel.

Under this contract, our work on the spring steels used in this investigation forms part of the SRAMA contribution towards a detailed collaborative study of hydrogen embrittlement between SRAMA and our colleagues at Sheffield University. The full results of this work will be published jointly in the future.

1.2.2 Experimental Plan

Our experience at SRAMA has shown us that hydrogen embrittlement failures of electroplated springs generally fall into two main categories, namely those fractures which are initiated from stress raisers such as punched holes, and those where fracture initiation is not associated with obvious stress raisers.

To simulate these two conditions, a variety of stressing techniques was adopted at SRAMA so as to generate quantitative failure rate data for electroplated strips. To this end, test strips were employed both with and without a stress raiser similar to that introduced by the punched holes encountered in real spring components.

Tests were carried out concurrently on typical spring clip zinc electroplated components, manufactured both with and without punched holes. The results of these tests on spring clips were used as a qualitative cross check on the quantitative failure rate data produced for stressed strips.

A limited amount of work was carried out on zinc electroplated compression springs stressed in torsion, since failures of these components can also occur in service.

A major part of the work involved static failure tests on electroplated spring steel strip, however.

The four test techniques thus used can be summarized as follows:-

1. Strips drilled with a 4 mm diameter hole, to simulate the stress concentration effect of a punched hole. These were stressed by bending around mandrels of known diameter (Fig 1).

2. Undrilled strips which did not therefore contain externally introduced stress raisers. These were stressed by pin ended Euler bending to give a parabolic stress distribution which was essentially zero at the ends and a maximum at the centre of the sample (Figs 2 and 4).

   In the absence of stress raisers, this mode of stressing was necessary in order to avoid the non-representative failures which can occur in embrittled samples at the gripped ends of uniformly stressed strips.

3. Spring clips, which were manufactured both with and without the normal punched fastening hole. These components were stressed in bending by clipping onto round bars of known diameter, thus simulating the loading conditions encountered in service (Figs 3 and 4).

4. Compression springs which were jig loaded to simulate the torsional stresses they would experience in service (Fig 4).

2. MATERIALS AND EXPERIMENTAL TECHNIQUES

2.1 Materials and Electroplating

For ease of cross-reference, the notation previously used for identification of the steels has been retained and extended where necessary, namely steels D, E, F and G, the first two of which were employed during the earlier investigation.[2]

Commercially available spring steel strip nominally 12.7mm wide x 0.7-0.8mm thick and with a hardness of 500-550Hv, with tensile strengths over 1600 N/mm^2 was obtained in the pre- hardened and tempered condition conforming to BS 5770: Part 3: 1981. These materials, with nominal carbon contents of 0.6-0.8%, are specified by strip manufacturers for spring applications and, as a consequence, the results obtained at SRAMA should be directly applicable to spring components made from material to this specification.

Considerable numbers of springs made from these steels are used after austempering to give a structure consisting predominantly of lower bainite, typically with a hardness in the range 500-600Hv. Most of the recently reported SRAMA work, including the present work, has therefore included austempered spring steels in the investigations. In all cases, austempering was carried out on a continuous plant operated commercially by a spring manufacturing SRAMA member.

Metallographic examination of the hardened and tempered and austempered samples revealed normal tempered martensite and lower bainitic structures respectively, with no evidence of surface defects or decarburization.

A limited amount of work was carried out on spring clip components (tool clips) made from steel strip very similar to that used for the bulk of the work. Similarly, a very limited investigation was carried out using compression valve springs made from 2.8mm diameter 0.7% carbon spring steel wire conforming to BS 2803: 1980. 093A65.HD.

The materials under investigation were barrel plated with zinc to give an average thickness of 0.008mm, conforming to Zn3 of BS 1706: 1960. All zinc plating was carried out using an automatically controlled cyanide plant which was operated commercially by a spring manufacturing SRAMA member firm.

The composition, dimensions and hardness of the strip materials used for the bulk of the present work are shown in Table I.

2.2. Test Methods

2.2.1 Drilled Strips

These samples, prepared for hardened and tempered, and austempered, steels D, E and F, were each 90mm in length.

In preparation for testing, approximately 0.5mm was removed from each "as sheared" edge by surface grinding with copious coolant to give a final width of 11.4mm, after which the ground corners were carefully hand finished using an emery stone.

A carbide tipped drill was used to jig drill a centrally located 4mm hole in each strip. The edges of the hole were not deburred, thus retaining surface defects in an attempt to simulate the defects introduced during manufacture of spring components containing punched holes of similar size. The stress concentration factor (k_t) resulting from such defects will generally be more significant than that associated with the 4mm hole itself ($k_t \sim 2.3$).

The strips were stressed by bending 20 hardened and tempered and 20 austempered samples around mandrels of known diameter to give nominal stresses in the range 1500-2670N/mm^2. The minimum stress corresponded to approximately 90% of the tensile strength of these materials. Such stresses can be encountered in these flat spring components intended for static loading conditions.

The nominal stresses were calculated using the relationship

$$s = \frac{Et}{D} \qquad \dots\dots\dots\dots 1.$$

where s = Nominal bending stress, N/mm^2

E = Youngs Modulus = 2.068×10^5 N/mm^2

t = Strip thickness, mm

D = Mandrel diameter, mm

The actual bending stresses, neglecting the stress concentration effect of the hole, were lower than the nominally applied stress, of course, as the material plastically deformed and work hardened to support the loads imposed during bending.

Corrections were applied to the nominal stresses using tensile stress/strain information supplied to SRAMA by the University of Sheffield. From this plastic stress/strain data, it was possible to estimate the real stresses imposed with due consideration for the work hardening rates of the appropriate materials, as shown in Table II.

The time to fracture of individually identified strips was measured to a precision of one minute by making each strip part of a series electrical circuit with individual electric timer units, as shown in Fig 1. Testing was generally discontinued after one week (~10,000 mins), any strips remaining unbroken at that time being noted as run-outs.

For each test, the times to fracture were obtained and ranked in ascending order.

The median rank cumulative percent failure, F(t) was defined by the relationship[3].

$$F(t) = \frac{(J - 0.3)}{(N + 0.4)} \times 100 \qquad \text{.........} \ 2.$$

where J = Number of items in ordered sequence

N = Total number of items used in test = 20.

A standard Weibull analysis technique was then used to obtain the best fit mean curve relating F(t) and the time to failure, t, from which discrete values of F(t) and t could be extracted.[4,5].

2.2.2. Parabolic Bending of Undrilled Strips

This work was carried out using both hardened and tempered and austempered samples of as sheared steel G strip, with a width of 12.5 mm and a sample length of 105mm. Stressing was carried out in pin ended Euler loading, giving essentially non-uniform stresses which reached a maximum value at the central portion of the strip, using the jigs shown in Fig 2, each of which tested 30 samples at the appropriate stress level.

Three strain gauges were bonded to the central region of typical strip samples at Sheffield University, after which a calibration curve of axial loading versus surface strain was obtained at SRAMA using pin loading platens attached to the SRAMA 2kN load testing machine. During the test, measurements were obtained of the axial deflection, axial load, central lateral deflection, and associated surface microstrains, up to a maximum surface strain of 9600 microinch/inch, at which point the tests were discontinued as a result of de-bonding of the strain gauges from the steel surface.

The relationship between surface microstrain and axial deflection was characterized by a polynomial expression as follows:

$$Y = A + Bx + Cx^2 + Dx^3 \qquad \text{..........} \; 3.$$

where Y = Microstrain, microinches/inch

x = Axial deflection, mm

$A = 946.747588$

$B = 1205.69658$

$C = -82.2951827$

$D = 2.56121822$

From this calibration graph, a range of deflections was selected to give nominal stresses between 1200 and 2800 N/mm^2. The nominal stresses are shown in Table III, together with the corrected stresses estimated from tensile stress/strain data supplied by the University.

Also shown in Table 3 are the nominal stresses estimated from the load/deflection data, obtained during the strain gauge tests, by means of the relationship

$$\text{Fibre stress } (\text{N/mm}^2) = 6LP/Bt^2 \qquad \text{..........} \; 4.$$

Where L = Lateral deflection at centre of strip, mm

P = Axial load, N

B = Width of strip (12.5 mm)

t = Thickness of strip (0.7 mm)

The electroplated test strips were maintained under stress for one week (10,000 mins), after which the number of broken strips was counted for each stress level and plated condition.

2.2.3. Spring Clip Tests

These tests were carried out using standard spring steel tool clips, which were supplied by a SRAMA member firm from part of their normal production run. The clips were made from annealed 0.7% carbon spring steel strip with "as sheared" edges, to the standard design shown in Fig 5.

During the production run, half of the clips were manufactured with the normal 4mm diameter punched hole. An equal number of clips were then produced in the identical process, but omitting the punched hole.

After manufacture, half of each batch of clips were hardened and tempered, whilst the remaining clips were austempered using a commercial austempering plant employed for all the austempered steels used in this work.

Vickers hardness tests were carried out on clips selected at random from the two heat treated batches, giving the following results.

Hardened and Tempered clips: 566-593 Hv5.
Austempered clips: 540-549Hv5.

The clips were stressed by clipping onto mandrels with a range of diameters between 27.5 and 32 mm.

Attempts were made to calculate, and efforts were made to estimate from strain gauge data, the stress imposed on loading these spring clips. The geometry of the clip proved too complex for analysis at SRAMA or Sheffield University, and so no meaningful conclusions, regarding the stress in the clips, with or without holes, was derived. As a consequence, the results of this test were essentially qualitative in nature, in that they seemed to highlight the differences in behaviour of hardened and tempered/austempered clips both with and without the stress raising effects of the punched hole.

2.2.4. Compression Springs

These components were made from a standard BS 2803 pre-hardened and tempered spring wire with a hardness of 463-470Hv.

The spring design was as follows:

Wire diameter = 2.8mm

Outside coil diameter = 25.3mm

Free length* = 43.4mm

Total coils = 5.5

Ends: Closed and ground

(*After stress relieving at 400°C for 30 mins, end grinding and cold prestressing).

Two torsional stresses were used for these tests, namely 980N/mm^2 and 1110N/mm^2, representing 75% and 85% respectively of the solid stress for this spring design. The higher value (1110N/mm^2) was selected as being the maximum stress recommended for compression springs if coil to coil contact is to be avoided under load.

The load corresponding to each stress was determined from the relationship

$$P = \frac{q \pi d^3}{8DK} \qquad \text{.......... } 5.$$

where P = Load (N)

q = Torsional stress (N/mm^2)

d = Wire diameter (mm)

D = Mean coil diameter (mm)

= Outside coil diameter - wire diameter

K = stress correction Factor

$$= \frac{(D/d) + 0.2}{(D/d) - 1}$$

For each of the two stresses, 8 test springs were load tested to determine the mean length at the appropriate calculated loads.

After zinc plating, the test springs were installed in 2 jigs, and were compressed to the lengths appropriate to each stress level.

Each spring was individually identified, and the integrity of the springs was monitored by periodic load testing to detect any abrupt change in loading behaviour, which would have signified the development of significant cracks across the cross section of the wire.

2.3 Scanning Electron Fractography

From the samples broken during the time to failure tests on drilled strips, a number of fractures, of known static fatigue life, were selected for detailed examination and characterisation on the SRAMA S4 Scanning Electron Microscope.

Samples were chosen from both the hardened and tempered and austempered batches, both in the "as plated" condition and after plating with a subsequent bake at 190°C for 24 hours.

The fractures were characterized with respect to the fracture mode, ie Intergranular (IG), Quasi-cleavage (QC) and Microvoid Coalescence (MVC), and the proportion of each mode was established visually for each fracture examined.

3. EXPERIMENTAL RESULTS

3.1 Drilled Strips

In total, 28 static "time to failure" tests were carried out on Steels D, E and F using this technique, at nominal stresses between 1500-2670 N/mm^2.

Tests carried out on unplated strips at a high nominal stress of 2580 N/mm^2 verified that there were no failures after 20,000 minutes.

The zinc plated strips usually failed due to cracks initiated at the drilled hole, although a small number of samples also showed secondary failures not associated with the hole. The reason for these secondary failures is as yet unknown, however.

3.1.1 Tests on "As Plated" Strips

A typical Weibull plot for Steel E is shown as Fig 6, illustrating the differing behaviour of hardened and tempered and austempered samples. A series of Weibull curves was constructed for both hardened and tempered and austempered materials tested over the full range of nominal stresses examined. From the curves, the time to failure for 5%, 10% and 50% cumulative percent failures was determined and the values of failure times thus obtained are shown in Tables IV and V for the hardened and tempered and the austempered steels respectively.

It is evident that, even at the lowest nominal stress of 1500 N/mm^2, all the "as plated" strips exhibited a very high proportion of failures within one week, irrespective of the heat treated structure.

This finding confirms that, for spring components which will usually contain holes or sharp radii, whilst being highly stressed, it is imperative to apply appropriate de-embrittlement treatments in order to reduce the risks of delayed failure due to hydrogen embrittlement.

Examination of the data in Tables IV and V revealed little consistent difference between the behaviour of the Category 1 Steel D and the Category 2 Steels E and F in either heat treated condition.

This finding suggests that, under a static strain, the differences in fracture behaviour were not as apparent as those previously observed during dynamic bend testing, where the strain continuously increases to the moment of failure.[1, 2]

The information obtained in static testing was therefore pooled for each heat treated condition.

The static fatigue data thus obtained for 5%, 10% and 50% failures are shown plotted graphically in Figs 7, 8 and 9 respectively. Although the scatter of data was generally too high to plot a meaningful regression curve, it is immediately apparent from this data that the austempered steels consistently exhibited times to failure which were generally an order of magnitude greater than those obtained for hardened and tempered steels at equivalent stresses. This confirms the findings of previous dynamic bend test work at SRAMA, which suggested that austempered steel was consistently more ductile than the equivalent hardened and tempered steel.[2]

3.1.2 Tests on De-Embrittled Strips

Weibull curves typical of those obtained for strips which were baked after plating are shown as Figs 10 and 11.

Times for 5%, 10% and 50% failure are shown for the hardened and tempered and the austempered steel in Tables IV and V respectively, and are presented graphically in Fig 12.

Although baking at 190°C/24 hours and 220°C/24 hours significantly increased the time to 5% failure for the hardened and tempered strips, Fig 12 nevertheless shows that hardened and tempered steel was not de-embrittled effectively at any of the nominal stresses investigated.

In contrast to this behaviour, the austempered was effectively de-embrittled by baking at 190°C/24 hours for samples stressed to 1530 N/mm^2, and 220°C/24 hours for samples stressed to 2580 N/mm^2. Strips baked at 190°C/24 hours and stressed at 2580 N/mm^2 still showed significant failures, however, although the failure times were generally increased over the equivalent hardened and tempered strips by a factor of 3 to 4.

3.2 Parabolic Bending of Undrilled Strips

The results of the tests on both hardened and tempered and austempered strips of Steel G are presented in Table VI, whilst the hardened and tempered results only are shown graphically in Fig 13.

In the "as plated" condition, there were no failures of the hardened and tempered strips up to and including a nominal stress of 1600 N/mm^2. Above this stress, however, there was a progressive increase, with stress, in the number of strips failing after an elapsed time of 10,000 minutes.

Baking at 190°C for 24 hours increased the nominal stress for no failures from 1600 N/mm^2 to 2400 N/mm^2.

There were no failures of the austempered strips tested in the "as plated" condition, and hence the tests on these samples are ongoing. Any failures in the future will be noted and reported separately for these austempered samples.

3.3 Spring Clip Tests

These tests were continued for times up to 5 weeks (∿50,000 minutes), and the results are summarized in Table VII.

The punched clips invariably failed at the punched hole, whilst the unpunched clips fractured at the sharp bend radii, as shown in Fig 5.

It is clear that, in the "as plated" condition, the austempered clips were consistently better than the hardened and tempered clips in terms of resistance to hydrogen embrittlement failure, with none of the austempered components failing at a mandrel size below 32 mm.

Furthermore, the stress raising effect of the 4 mm diameter punched hole is clearly evident, in that, irrespective of the structure, the punched clips showed a failure rate which was generally a factor of 2 to 8 times greater than that of the unpunched clips.

Baking at 190°C for 24 hours effectively de-embrittled all the clips, irrespective of structure or whether or not punched holes were present in the samples.

3.4 Compression Springs

None of the "as plated" springs had failed after an elapsed time of 24 weeks (240,000 minutes) and, consequently, the springs remain on test with any failures to be reported in the future.

3.5 Scanning Electron Fractography

Examination of fractures on the Scanning Electron Microscope revealed several interesting features, as depicted in the typical fractographs shown in Fig 14 for Steel E electroplated strips broken at a nominal stress of 2580 N/mm^2. Visual estimates of the fracture modes in these samples gave the following results for the hardened and tempered (H) and austempered (A) strips.

Heat Treated Condition	Plated Condition	Time to Failure (Minutes)	Estimated % Fracture* Mode		
			IG	QC	MVC
H	As plated	201	100	0	0
H	Plated and baked 190°C/24 hr	4768	50	0	50
A	As plated	776	40	30	30
A	Plated and baked 190°C/24 hr	14430	10	40	50

* IG = Intergranular Fracture

QC = Quasi-Cleavage Fracture

MVC = Micro-Void Coalescence Fracture

From these estimates of the fracture mode and from the appearance of the fractures shown in Fig 14 for plated Steel E, it is clear that the "as plated" hardened and tempered steel was significantly more embrittled than the austempered steel, with IG fracture contents of 100% and 40% respectively. Furthermore, baking at 190°C for 24 hours, increased the proportion of essentially ductile fracture (QC + MVC) in the austempered steel from 60% in the "as plated" condition to approximately 90% after baking.

By contrast, the same baking treatment applied to the hardened and tempered steel increased the proportion of ductile fracture from 0% in the "as plated" condition to approximately 50% (MVC only) after baking.

Our colleagues at Sheffield University are now investigating in more detail these fundamental differences in fracture morphology which are revealed by the Scanning Electron Microscope.[6]

4. DISCUSSION

During the course of this work on zinc electroplated carbon spring steel strip, one of the most consistent findings was that austempered steel was substantially more resistant to hydrogen embrittlement failure than the equivalent hardened and tempered material.

Thus, for drilled samples in the "as plated" condition, the evidence of Weibull analyses clearly indicated that austempered steels survived for times which were an order of magnitude higher than those observed for the equivalent hardened and tempered material. Similarly, the results obtained from the parabolic bend tests on undrilled strips clearly showed that the nominal stress threshold, for zero failures in 10,000 minutes, was approximately 1600 N/mm^2 for the hardened and tempered strips, but was 2800 N/mm^2 for the austempered samples.

The spring clip tests qualitatively verified these findings, in that the stress threshold for failure in austempered clips was significantly higher than that producing failure of the hardened and tempered components.

The work has shown the significant part played by stress raisers, such as punched holes, in hydrogen embrittlement failures of these spring steels. Thus, for "as plated" samples, all the hardened and tempered drilled strips failed at a nominal stress of 1500 N/mm^2, whereas none of the undrilled strips failed when stressed to approximately 1600 N/mm^2 in parabolic bending. Similarly, the majority of the austempered, drilled strips failed at 1500 N/mm^2, but there were no failures of the undrilled samples nominally stressed to 2800 N/mm^2.

The spring clip tests again verified this finding, the incidence of failure in punched clips generally being 2 to 8 times greater than that for unpunched clips.

De-embrittlement baking at 190°C for 24 hours proved ineffective for the drilled strips made from hardened and tempered steel, which failed at a nominal stress of 1500 N/mm^2.

The stress threshold for failure in the undrilled samples was raised from 1600 N/mm^2 to 2400 N/mm^2, by baking at 190°C for 24 hours, however.

For the austempered, drilled samples, a de-embrittlement bake at 190°C for 24 hours was effective for the lower stress of 1500 N/mm^2, but 220°C for 24 hours was required for effective de-embrittlement of drilled samples stressed at 2600 N/mm^2.

Expressed in conservative terms, it follows that de-embrittlement treatments are unlikely to remove the possibility of delayed failure in hardened and tempered springs which have been zinc plated when the springs contain stress raisers such as punched holes.

By contrast, moderately stressed austempered components containing stress raisers were successfully de-embrittled by baking at 190°C for 24 hours, whilst highly stressed austempered springs were de-embrittled by baking at 220°C for 24 hours.

These findings are confirmed by the results of Scanning Electron Fractography, which indicated that the austempered steel was consistently more ductile than the equivalent hardened and tempered material.

When examined in their entirety, the findings of this work suggest that hydrogen embrittlement failures of zinc electroplated springs made from carbon steel strip can best be avoided by austempering the components prior to electroplating when the springs contain stress raisers. Baking at temperatures between 190°C and 220°C for 24 hours will effectively de-embrittle such austempered springs, the higher temperature being used for highly stressed springs.

When sacrificial protection is required for hardened and tempered springs, consideration can be given to non-electrolytic processes such as Dacromet or Mechanical Plating, neither of which introduce hydrogen embrittlement during coating. In principle, however, the porosity of such coatings could result in the development of hydrogen embrittlement during service due to galvanic coupling, as the sacrificial coating carries out its normal protective function.[7] This aspect of such coatings may warrant further investigation.

Standard quality control tests using strip samples stressed in parabolic bending should be an effective technique for either detecting hydrogen embrittlement in "as plated" springs or checking the effectiveness of de-embrittlement treatments. The test strips should contain stress raisers similar to those present in the spring components. Ultimately, however, static tests on plated components may be the best alternative for items of complex geometry, which may contain stress raisers introduced during manufacture.

Finally, in the light of these findings, it is likely that BS 1706 will require revision, to include provision for austempered components. This will be particularly relevant for highly stressed plated components made from steel with tensile strengths over 1450 N/mm^2.

5. CONCLUSIONS

Within the limitation of one plater and four steels the following conclusions can be drawn, but need confirmation with other platers and steels before they can be used with confidence.

1. With respect to the effects of hydrogen embrittlement, austempered steels with a bainitic microstructure are less susceptible to embrittlement than hardened and tempered steels with a martensitic microstructure.

2. For hardened and tempered steels, de-embrittlement at 220°C for 24 hours will be more effective than the 190°C treatment.

3. When stress concentrations are present, however, a significant risk of hydrogen embrittlement failure will always exist in hardened and tempered steel even after the recommended de-embrittlement treatments.

4. Austempered springs containing stress concentrations can be adequately de-embrittled by a 24 hour bake at 190°C for moderately stressed springs and at 220°C for more highly stressed springs.

5. Where stress concentrations are absent, the nominal stress threshold for survival of plated springs is 1600 N/mm^2 in hardened and tempered springs and 2800 N/mm^2 in austempered springs.

   Baking at 190°C for 24 hours raises the nominal stress threshold to 2400 N/mm^2 for hardened and tempered springs.

6. Austempered springs which are low stressed can be used without de-embrittlement in circumstances where the consequences of failure are not severe.

7. Highly stressed zinc electroplated components made from high strength steel should be designed with a bainitic microstructure produced by austempering. Some failures are highly probable in similar components made from hardened and tempered steels with a martensitic microstructure.

8. The composition of carbon spring steel has no significant influence on the incidence of static failure due to hydrogen embrittlement.

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TABLE I SPRING STEEL STRIP INVESTIGATED IN BENDING TESTS

Steel* Ident	Test Sample Dimensions, mm	Composition, Wt %						Hardness, HV+	
		C	Mn	Si	S	P	Al	H	A
D	11.4 x 0.84	0.635	0.66	0.25	0.012	0.012	0.009	501	523
E	11.4 x 0.81	0.625	0.71	0.27	0.030	0.020	0.028	502	523
F	11.4 x 0.83	0.80	0.70	0.19	0.003	0.011	0.018	525	526
G	12.5 x 0.7	0.765	0.71	0.29	0.003	0.014	0.055	491	494

* Steels D, E and F: Ground and chamfered edges.
Steel G: As sheared edges.

\+ H = Hardened and tempered
A = Austempered

TABLE II FIBRE STRESSES APPLIED TO DRILLED STRIPS BENT AROUND MANDRELS

Steel Ident	Mandrel Diam mm	Nominal Stress, N/mm^2	Corrected Stress, N/mm^{2*}	
			H	A
D	65	2670	1605	1560
"	85	2040	1450	1415
"	95	1830	1395	1360
E	65	2580	1615	1640
"	85	1970	1515	1515
"	95	1760	1480	1460
"	112	1500	1425	1395
F	112	1530	1430	1400

* H = Hardened and Tempered
A = Austempered
Stress corrected for plastic strain using tensile stress/ strain data supplied by Sheffield University

TABLE III FIBRE STRESSES APPLIED TO UNDRILLED STEEL G STRIPS IN PARABOLIC BENDING

Axial Deflection mm	Lateral Displacement at Centre mm	Load on Strip Ends, N	Fibre Stress, N/mm^{2*}		
			Nominal (1) Value	Nominal (2) Value	Corrected (3) Value
6.05	19	74	1200	1380	1350
11.25	23	76	1600	1710	1445
16.05	27	77	2000	2040	1520
18.9	29	78	2400	2220	1585
20.85	30	79	2800	2320	1645

* Nominal (1) = Stress estimated from strain gauge data

Nominal (2) = Stress estimated from load/lateral displacement data

Corrected (3) = Nominal (1) values corrected using plastic stress/strain data obtained by tensile testing

TABLE IV RESULTS OF WEIBULL ANALYSIS FOR DELAYED FAILURE OF DRIL AND ZINC PLATED STRIPS MADE FROM HARDENED AND TEMPERED STEEL

Steel Ident	Sample Condition	Nominal Stress, N/mm^2	Time to Failure (Minutes) at Cumulative % Failure		
			5%	10%	50%
D	As Plated	2670	0.02	0.1	5.6
"	"	2040	0.5	1.4	21.3
"	"	1830	1.4	2.7	109
E	"	2580	1	2.9	42.7
"	"	1970 (1)	3.6	5.2	20
"	"	1970 (2)	0.4	0.8	5.2
"	"	1760	14.6	19.1	187
"	"	1500 (1)	2	3.8	49
"	"	1500 (2)	11.2	13.2	50
F	"	1530	5.6	7.6	16.6
E	Baked 190°C/24 hours	2580	3250	3990	6750
"	Baked 220°C/24 hours	2580	4970	7040	∿17000
F	Baked 190°C/24 hours	1530	4680	6360	14200

TABLE V RESULTS OF WEIBULL ANALYSIS FOR DELAYED FAILURE OF DRILLED AND ZINC PLATED STRIPS MADE FROM AUSTEMPERED STEEL

Steel Ident	Sample Condition	Nominal Stress, N/mm^2	Time to Failure (Minutes) at Cumulative % Failure		
			5%	10%	50%
D	As Plated	2670	59	64	97
"	"	2040	126	131	209
"	"	1830	62	69	413
E	"	2580	370	460	970
"	"	1970 (1)	62	72	215
"	"	1970 (2)	43	55	160
"	"	1760	312	335	393
"	"	1500 (1)	281	424	3365
"	"	1500 (2)	104	115	446
F	"	1530	19	21	106
E	Baked 190°C/24 Hours	2580	14300	16440	∿24000
"	Baked 220°C/24 Hours	2580	Unbroken at 29900		
F	Baked 190°C/24 Hours	1530	Unbroken at 11400		

TABLE VI RESULTS OF DELAYED FAILURE TESTS FOR UNDRILLED AND ZINC PLATED STRIPS OF STEEL G STRESSED IN PARABOLIC BENDING

Axial Deflection, mm	Nominal Stress, N/mm^2	Test Samples Failed after 1 Week ($\sim$10000 minutes)*		
		Hardened and Tempered		Austempered, As Plated Only
		As Plated	Baked 190°C/24 hours	
6.05	1200	0	0	0
11.25	1600	0	0	0
16.05	2000	3	0	0
18.9	2400	6	0	0
20.85	2800	7	1	0

* 30 samples on test for each test stress

TABLE VII RESULTS OF DELAYED FAILURE TESTS ON ZINC ELECTROPLATED CARBON SPRING STEEL CLIPS

Plated Condition of Test Clips	Bar Diameter mm	Heat Treated Structure*	Number of Samples Broken after Time Under Stress (Minutes)$^{+}$					
			Clips Without Punched Hole			Clips with Punched Hole		
			1500	4500	50000	1500	4500	50000
As Plated "	27.5 27.5	H A	1 0	2 0	5 0	12 0	12 0	12 0
As Plated "	29 29	H A	3 0	4 0	4 0	27 0	28 0	29 0
As Plated	30.5	A	0	0	0	0	0	0
As Plated	32	A	1	2	2	7	14	16
Baked 190°C/24 hr	32	H	0	0	0	0	0	0
Baked 190°C/24 hr	32	A	0	0	0	0	0	0

* H = Hardened and tempered (566-593 HV5)
A = Austempered (540-549 HV5)

\+ 64 clips tested for each test result

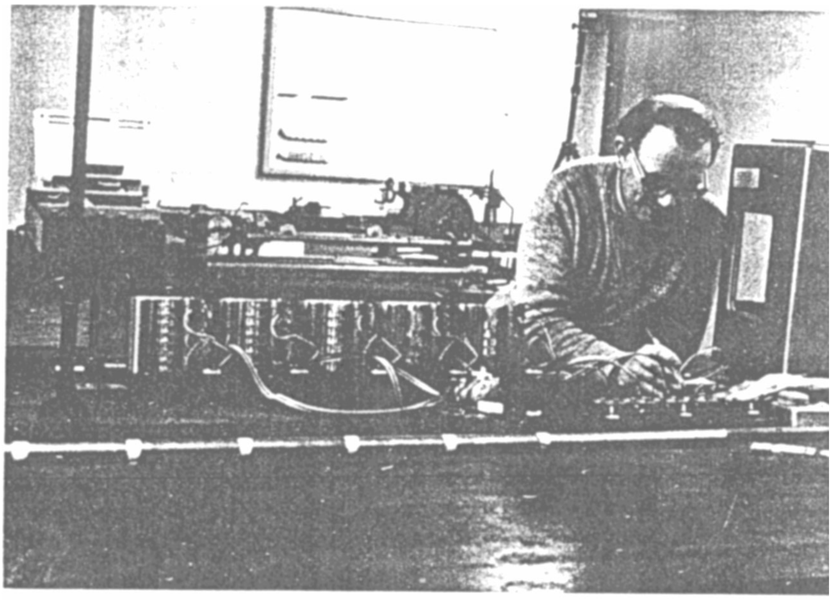


Fig. 1.
Jig and timer units used for time to failure tests of drilled strips.

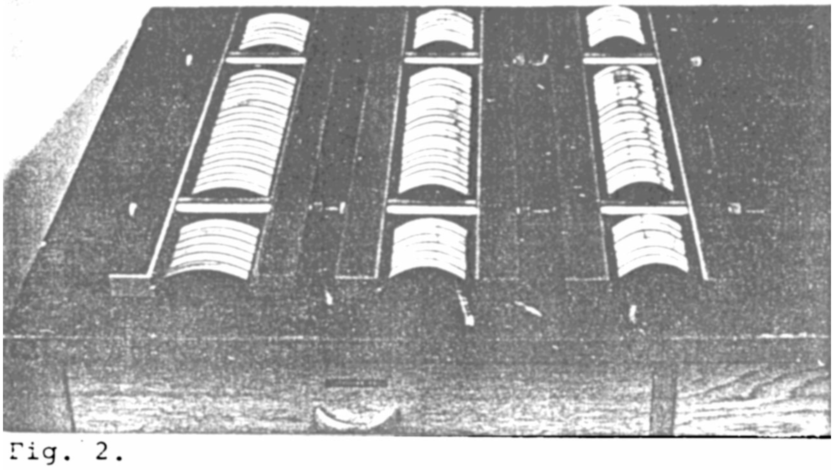


Fig. 2.
Parabolic bending jigs used for delayed failure tests of undrilled strip.

Fig. 3.
Mandrel jigs used for delayed failure of spring clips.

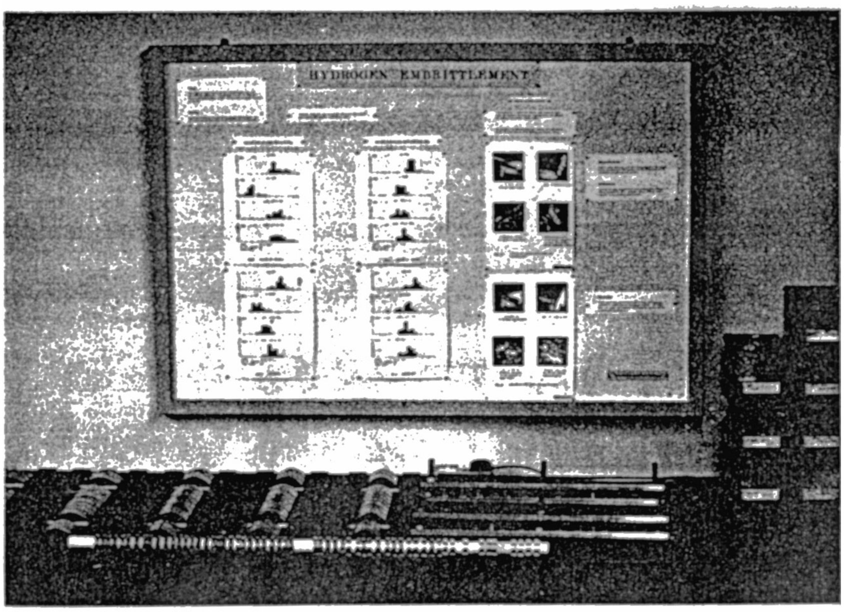
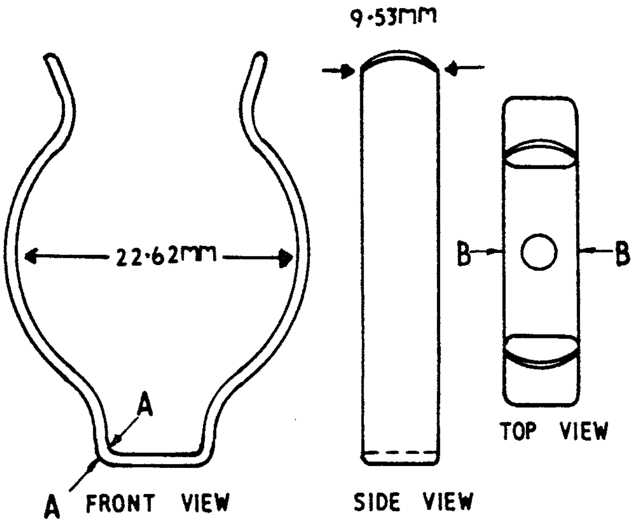


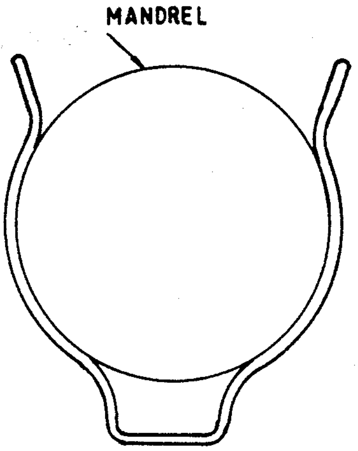
Fig. 4.
Jigs used for delayed failure tests of spring strip, clips and compression springs.



A-A = LOCATION OF FRACTURE IN UNPUNCHED CLIPS.

B-B = LOCATION OF FRACTURE IN PUNCHED CLIPS.

a COMPONENT



b TEST JIG.

FIG. 5. COMPONENT AND JIG USED FOR DELAYED FAILURE TESTS OF SPRING CLIPS.

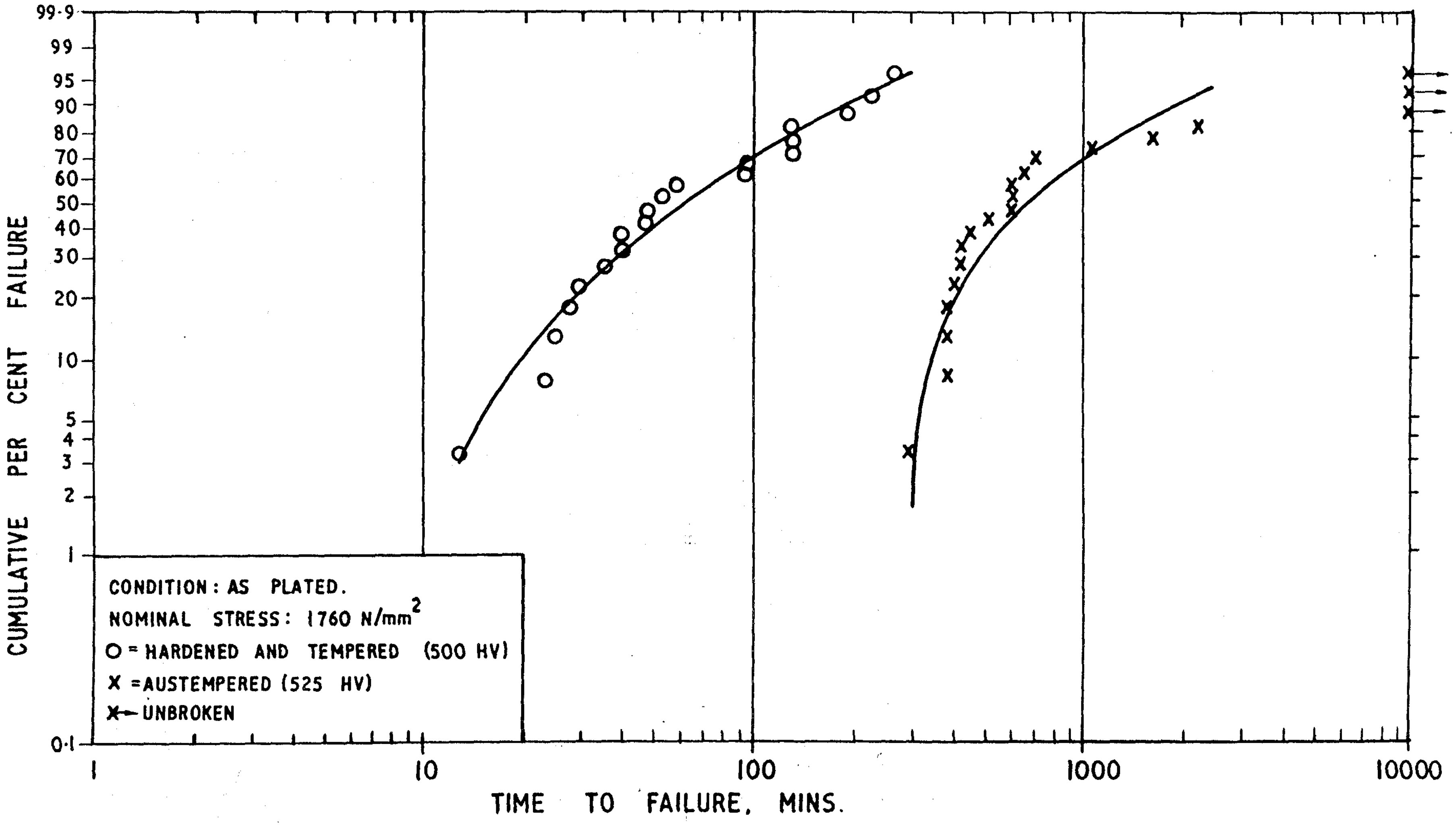


FIG. 6 WEIBULL PLOTS FOR ZINC PLATED DRILLED STRIP STRESSED IN BENDING.

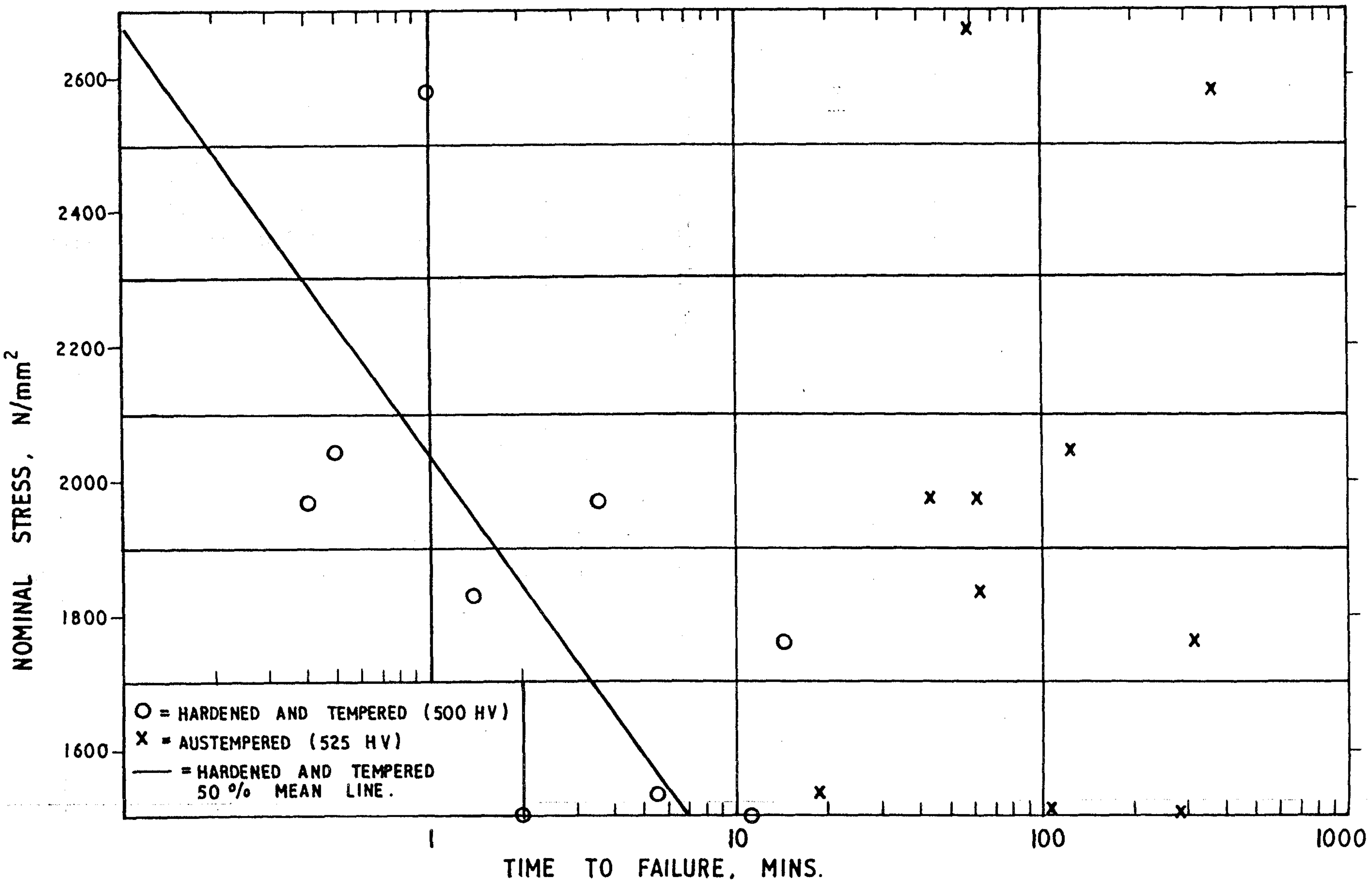


FIG. 7. STATIC FATIGUE DATA FOR 5% FAILURE IN AS PLATED DRILLED STRIP

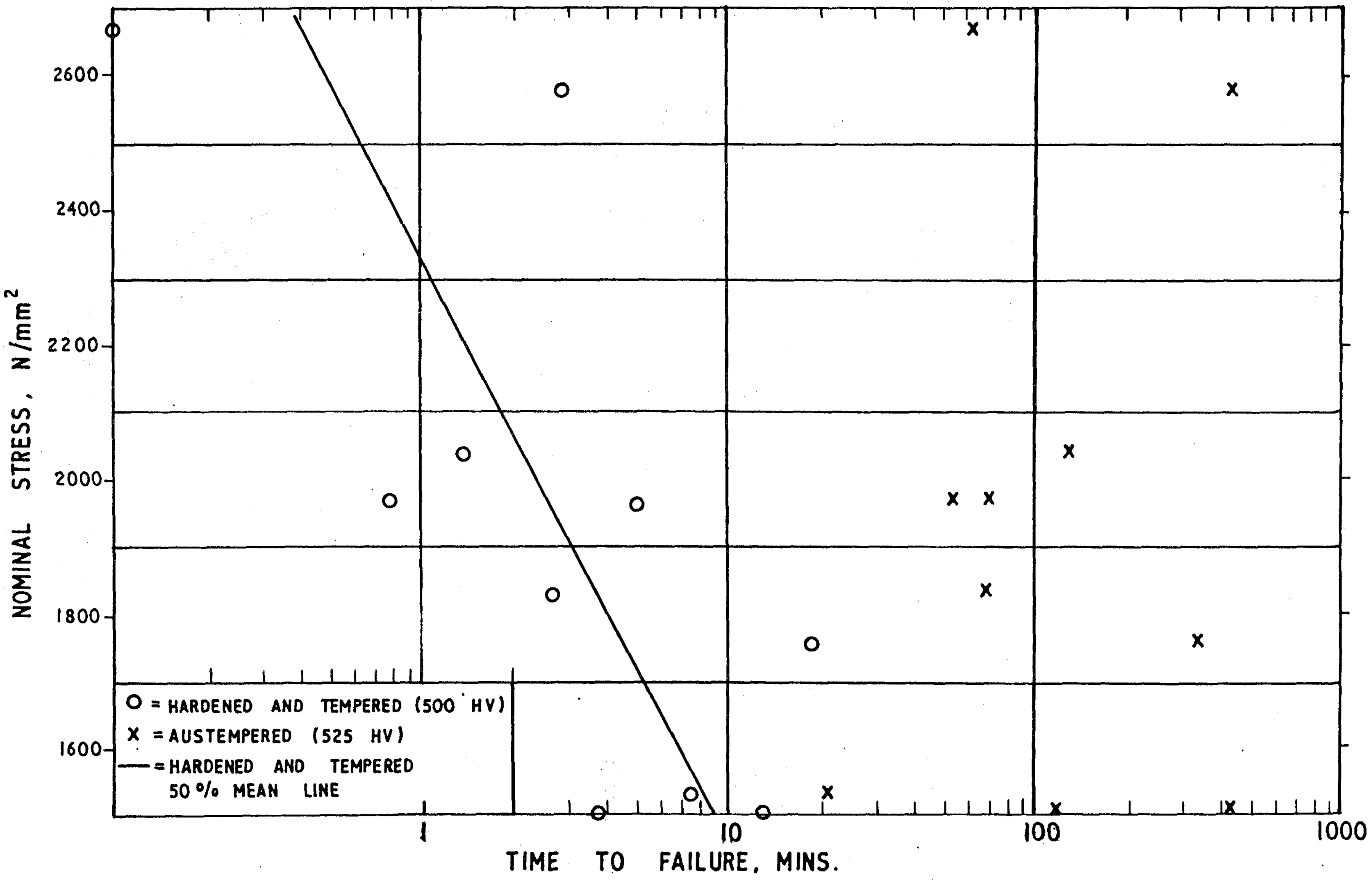


FIG. 8 STATIC FATIGUE DATA FOR 10% FAILURE IN AS PLATED DRILLED STRIP.

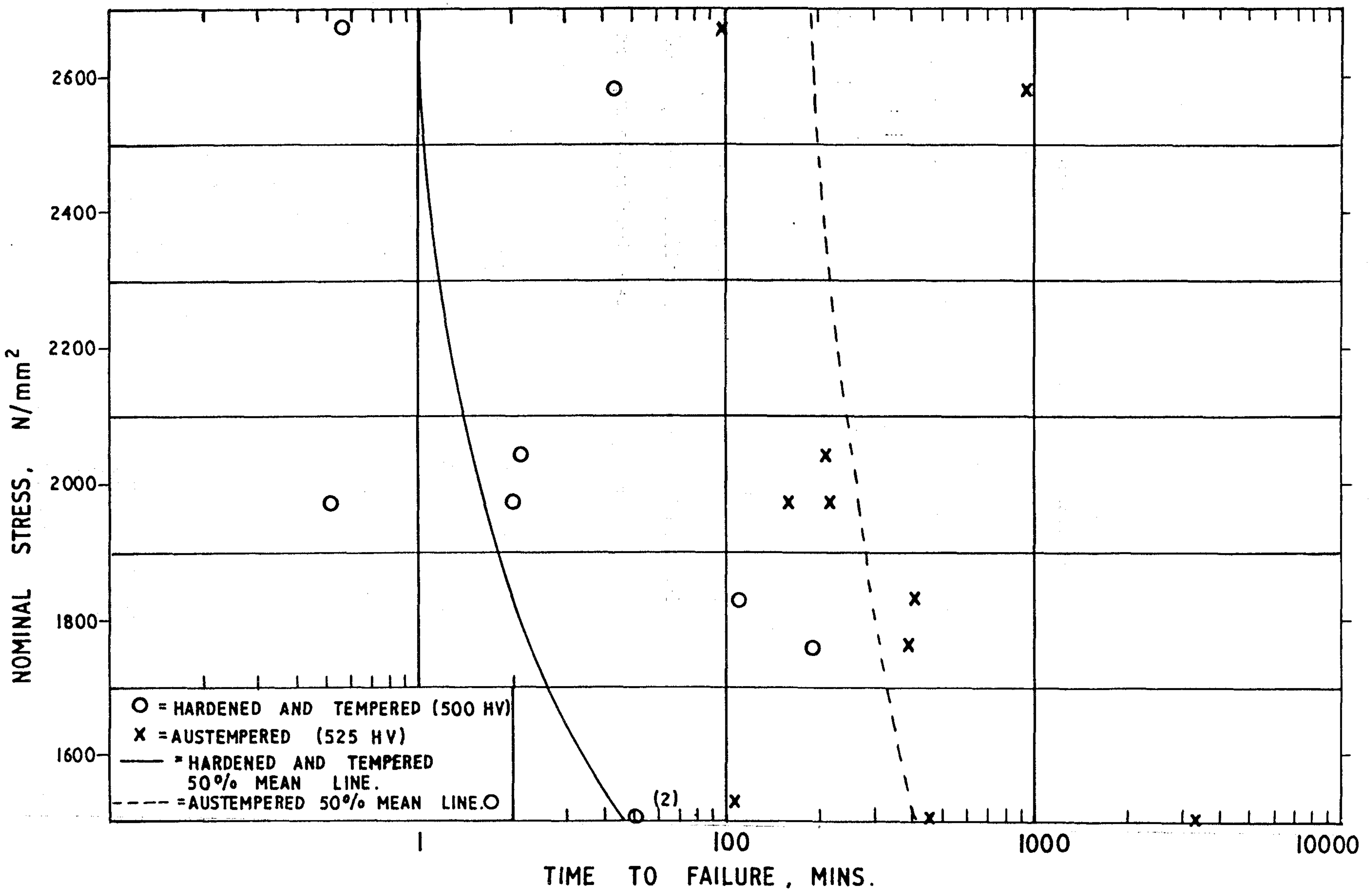


FIG. 9 STATIC FATIGUE DATA FOR 50% FAILURE IN AS PLATED DRILLED STRIP.

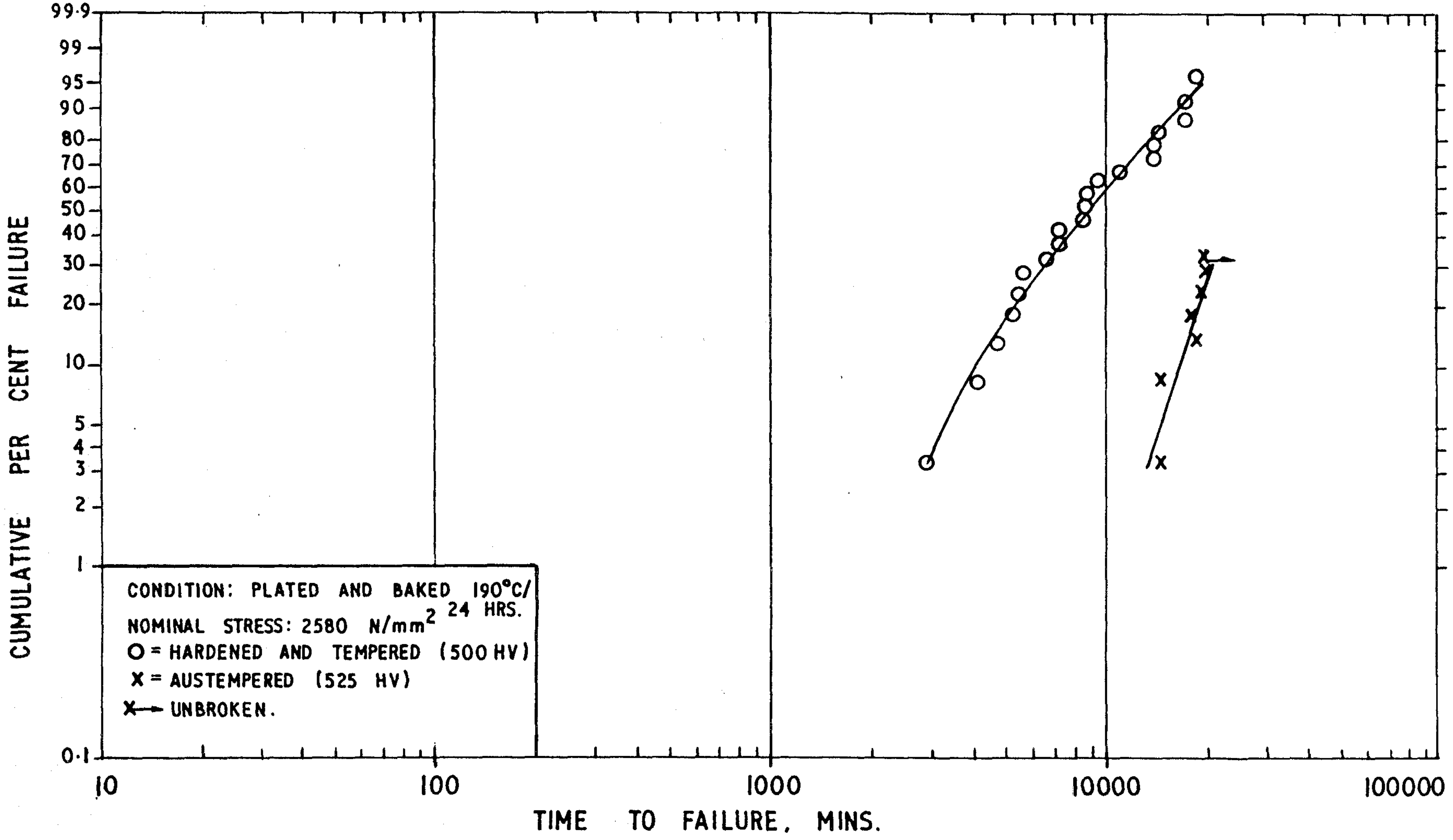


FIG. 10. WEIBULL PLOTS FOR ZINC PLATED AND BAKE DRILLED STRIP STRESSED IN BENDING.

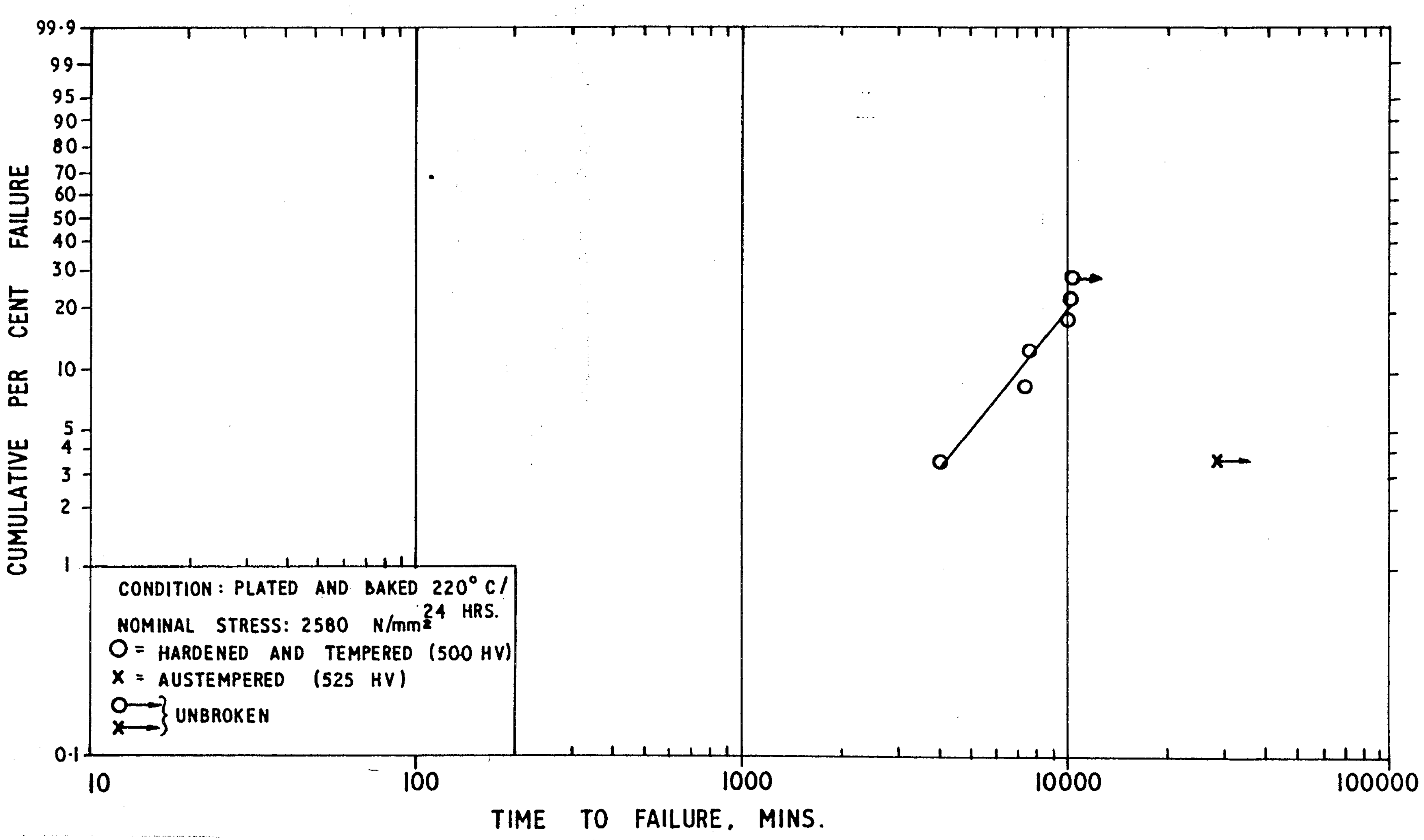


FIG. 11. WEIBULL PLOTS FOR ZINC PLATED AND BAKED DRILLED STRIP STRESSED IN BENDING.

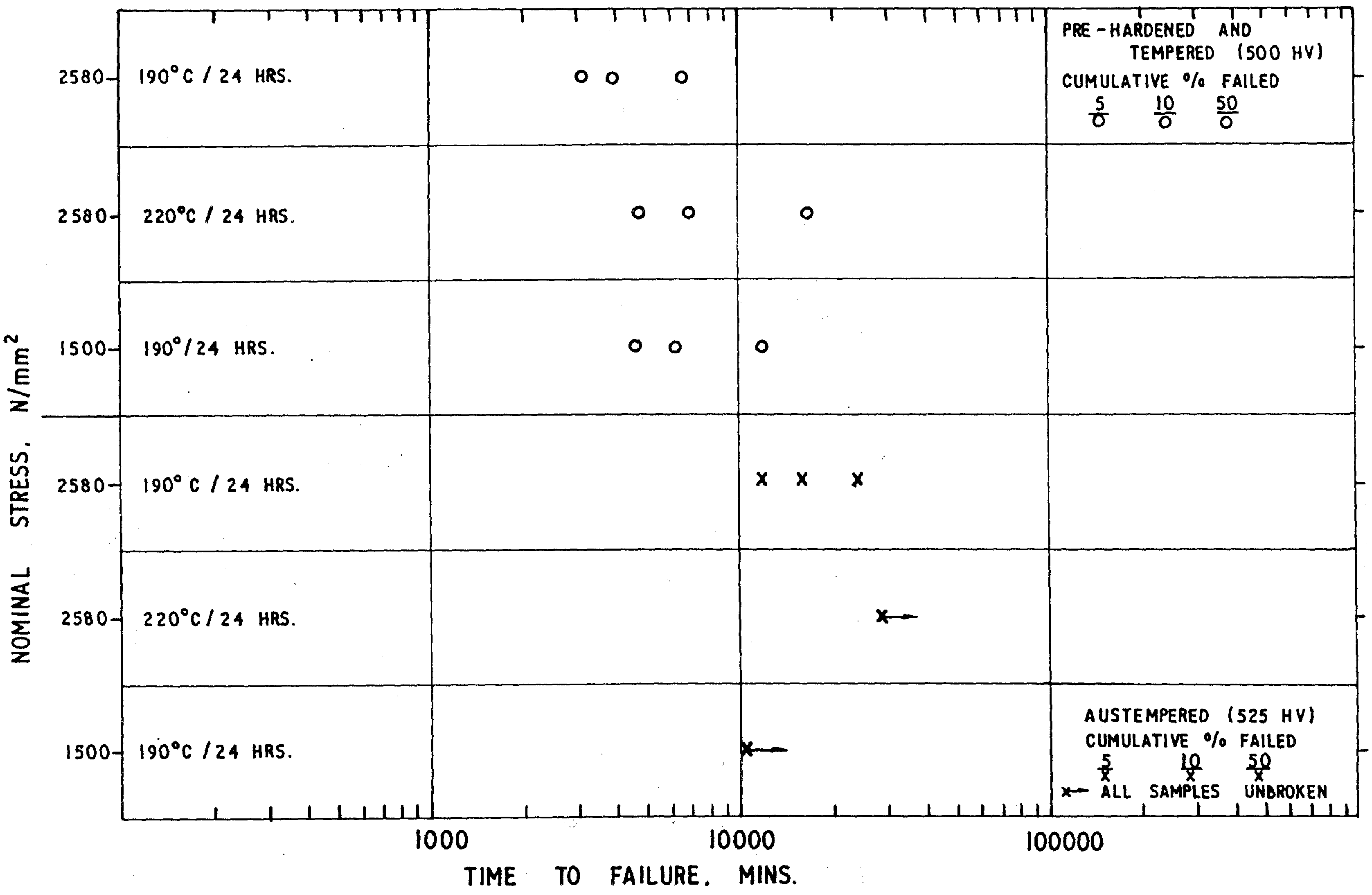


FIG. 12 EFFECT OF BAKING TREATMENTS ON EMBRITTLEMENT BEHAVIOUR OF ZINC PLATED DRILLED STRIP

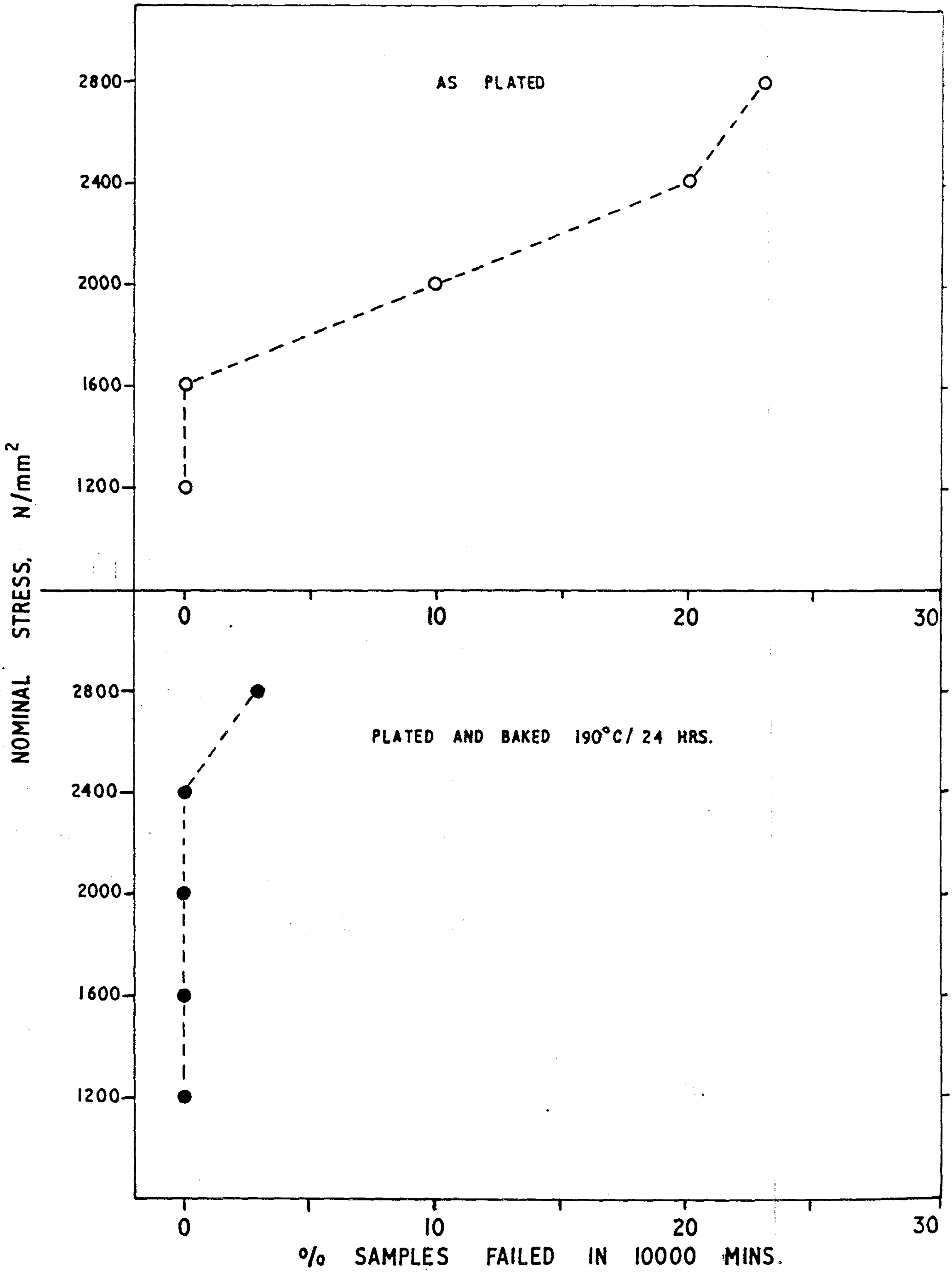


FIG. 13. EFFECT OF ZINC PLATING AND SUBSEQUENT BAKING TREATMENT ON EMBRITTLEMENT OF HARDENED AND TEMPERED UNDRILLED STRIP (500 HV)

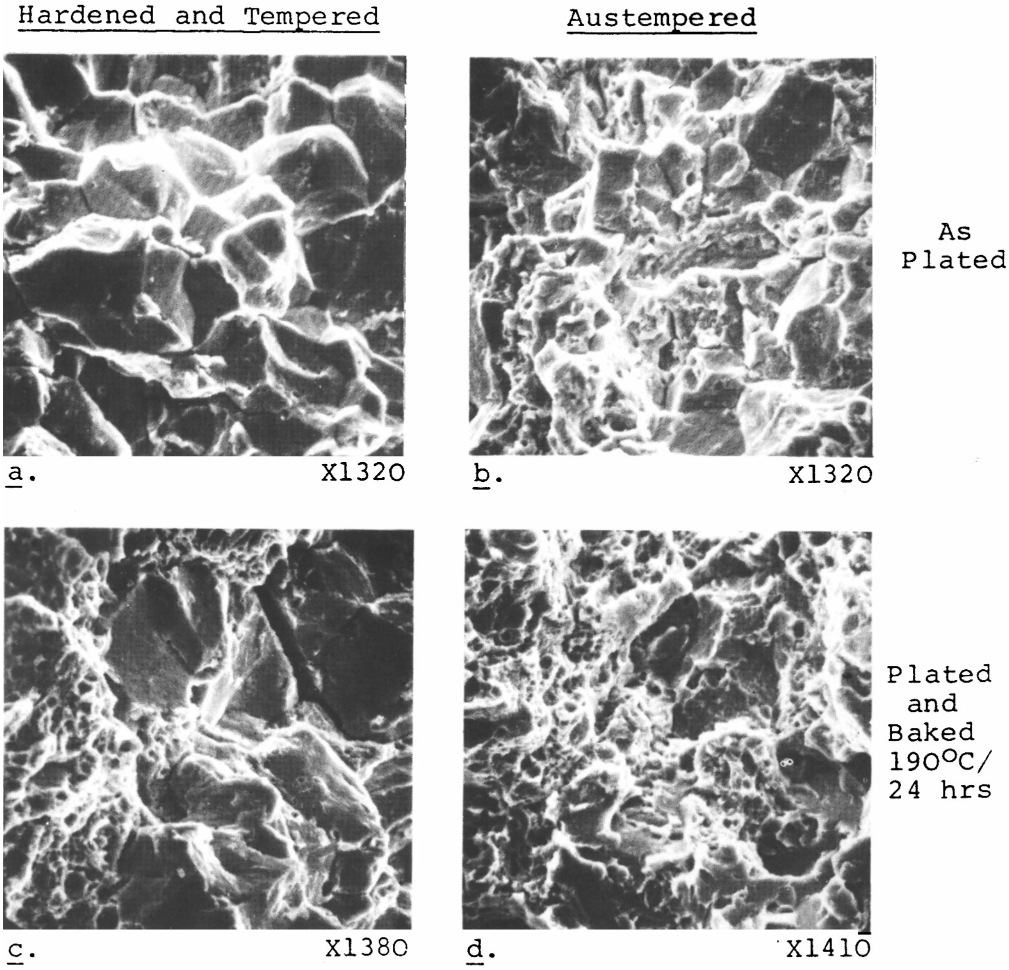


Fig 14. Fracture characteristics of zinc electroplated carbon steel strip.