THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE COILABILITY OF PATENTED HARD DRAWN CARBON STEEL SPRING WIRE

First Progress Report

The Elastic Properties of Spring Wires and their Correlation with Coilability

by

L.F. Reynolds, M.Sc. Tech., C.Eng., M.I.M.

Report No. 323

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SUMMARY

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The elastic properties of several patented hard drawn steel wires of known coilability have been investigated in detail. The work has shown that, within any one tensile range of wire, "good" coilability was consistently associated with a relatively low proportional limit, a relatively high rate of work hardening and a relatively high hardness. The tensile stress/strain curves obtained for wires of "good" and "poor" coilability thus intersected at true strains lying within the range 0.005-0.01 in the present instance. Calculations have shown that similar intersections may have led to the inconclusive results obtained in the past where attempts have been made to compare wires of "good" and "poor" coilability in terms of their proof stress properties in tension, such as $R_p\ 0.01$, $R_p 0.05$ etc.

A simple springback test has successfully differentiated between wires of "good" and "poor" coilability, the former wire being consistently associated with relatively high values of springback. It is suggested that the springback test may merit further investigation, as a possible means of differentiating between wires of "good" and "poor" coilability in the future.

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1. INTRODUCTION

Variation in dimensions during coiling of helical compression springs has long been acknowledged as a significant problem, with which spring manufacturers have to contend. Ideally, once a coiling machine has been carefully set up, the springs which are produced should fall without exception into the dimensional range allowed for in the appropriate specification, such as BS 1726 part 1 1964. The coiling process can then be left to continue automatically. For example, with springs having a free length of 50 mm and an index of 7.5 the BS 1726 specification would permit a free length tolerance of approximately ±1 mm on the original free length of 50 mm. When the free length is not adjusted on the coiling machine during the manufacture of springs from wire of "poor" coilability, the majority of the springs may fall outside the specified limits unless continual resetting of the machine is carried out. Such resetting can be a time consuming operation and is therefore a very costly method of alleviating the difficulty, especially where "shortterm" variation rather than "long term" drift forms the bulk of the problem. As a consequence the natural tendency of the springmaker is to reject the wire as "bad" or "uncoilable". In most cases such material will conform in general to the appropriate spring wire specification in terms of tensile strength, bend and torsion tests, and hence the springmaker will be faced with material ~~which is~~ within specification and yet which cannot be coiled.

Whilst there have been several attempts to identify important variables of the coiling process itself$^{(1-4)}$ there have been only limited investigations into the effect of material properties upon the coilability of wire. In the most comprehensive of these investigations Shipley examined statistically the relationship between the physical properties and the coilability of En 49B range 1 quality patented hard drawn carbon steel spring wire$^{(5)}$. He deduced that whilst the mean free length of the springs, which can be controlled by the springmaker, could be correlated quite closely with the $R_{p0.01}$, $R_{p0.1}$ and R_m, the short term variability in the free length (i.e. the coilability), could be similarly correlated with only one physical property, namely $R_{p0.01}$. He concluded that good coilability, when understood to mean acceptable short term variability, was associated with low values of $R_{p0.01}$. As he stated however, this property is not easily determined, and the actual values are dependent to some extent upon the sensitivity of the equipment used for their determination, and also upon the judgement of the investigator in the interpretation of the tensile load/extension graph.

The coilability or patented, hard drawn carbon steel wires has more recently been the subject of an investigation at SRAMA$^{(6)}$. This work has culminated in the development of a coiling test, involving wrapping of the wire around a mandrel which is rotated at a constant speed by means of a lathe. The test results in the formation of a close coiled helical "spring", the pitches of the "good" and the "poor" coilability wire being of even and uneven spacing respectively.

Preliminary investigations during the present work involved a determination of the residual stresses present in "circlips" which were cut from the coils thus generated for wires of equivalent grade and diameter, which were known to exhibit the appropriate characteristics of "good" and "poor" coilability. At constant strain, the magnitude of the residual stresses would depend upon the elastic properties of the material, of course, wires of high elastic limit giving correspondingly higher values of residual stress.

Consequent upon the results of the residual stress determinations, it was intended that a thorough investigation of the tensile elastic properties of wires of "good" and "poor" coilability should be undertaken.

The work of Shipley had suggested that the more usual arbiters of elastic properties, such as $R_{p0.05}$, for example, might be unable to discriminate adequately between wires of "good" and "poor" coilability. Furthermore, past experience at SRAMA had indicated that the results of the more usual methods of assessing the proportional limits directly from the load/extension graph were imprecise, depending to a large extent, upon the subsequent judgement of the individual investigator.

A substantial part of the present work therefore involved the application of analytical techniques affording more precise determination of the proportional limit from the tensile stress/strain curve.

Following upon the results of the curve analyses, a relatively simple springback test was developed, which proved to be capable of discrminating between the wires of "good" and "poor" coilability, within any particular wire grade and diameter, for the materials investigated in the present work.

2. MATERIALS

With the substantial co-operation of several member firms, seven coils of patented hard drawn steel spring wire were obtained in three grades corresponding to BS 1408, each grade of wire containing at least one representative example of "good" coilability wire and "poor" coilability wire of equivalent diameter. The materials were typical examples of wires obtained to BS 1408 range 1, BS 1408 range 3 and BS 1408 M2 and hence could be said to be broadly representative of this particular specification. The identification of the wire is shown in Table I, together with the springmaker's assessment of their coilability.

3. COILABILITY TRIALS

3.1 Materials and Spring Design

The coilability trials undertaken in a member firm were carried out using wire samples 1-3 (Table I). These wires conformed to BS 1408, R3 in all respects but had been appropriately reported by the spring manufacturer as exhibiting "good" or "poor" coilability properties respectively, in their experience.

The test springs were coiled by the member firm from which the wire was obtained, in the presence of a member of the SRAMA Engineering staff. The spring design, which is given below, was that associated with the coiling difficulties reported by the firm concerned.

Spring design for coilability trials carried out on wire samples 1, 2 and 3

Wire diameter	=	0.7 mm
Mean diameter	=	16.3 mm
Free length	=	50.16 mm
Total coils	=	13 1/4

Coilability trials were not carried out on the remaining four samples due to the limited amount of wire and time available for the metallurgical investigation.

3.2 Experimental technique

Details of the experimental procedure employed and the results obtained during the coiling trials are the subject of a separate SRAMA report(6). In the interests of completeness, however, a brief description of the procedure adopted is given below.

After the coiling machine had settled down, in the experience of the spring maker, the last 5 consecutive springs from each successive 25 were collected and identified in sequential order until 250 springs had been produced. The mean free lengths of the collected springs were measured at SRAMA using a Nikon Profile Projector, as described in an earlier report(4). From the free length data derived from each coiling trial, the variance and the standard deviation were calculated for the short term variability, the short term variance being obtained by taking the mean of the variances of the sub-samples.

3.3 Results

The results of the coilability trials are shown in Table II, together with the free length design tolerance adopted by the springmaker from whom the wire was obtained. It should be noted that the tolerance band of ±3 standard deviations (3s) encompassed 99.8% of the free length variation.

3.4 Conclusions

From the limited results, it was apparent that the coilability assessments made by SRAMA showed a high measure of agreement with the springmakers' assessment of coiling properties. It was decided therefore that the remainder of the work would attempt to correlate the various physical properties of the wire, expressed as a continuous function, with the springmaker's dichotomous assessment of coilability.

4. STATISTICAL TECHNIQUE FOR CORRELATION OF MEASURED PHYSICAL PROPERTY OF WIRE WITH COILABILITY

The point biserial correlation coefficient r_{pB} was selected for assessment of the correlation between the coilability dichotomy (good/poor) and the continuous measurement of the particular physical property considered. The calculation and interpretation of r_{pB} is shown in Appendix A, together with explanations of the variance ratio test and students 't' tests used in this report. Further information on these tests can be obtained from the relevant literature(7,8).

5. PRELIMINARY INVESTIGATIONS

The preliminary tests were carried out largely on wires 1, 2 and 3, since this material had previously been tested for coilability under the auspices of SRAMA(6).

5.1 Coiling Test and Determination of Residual Bending Stress in "Circlips" derived from Coils

These investigations followed upon previous work carried out at SRAMA into the development of a coiling test which could visually differentiate qualitatively between wires of "good" and "poor" coilability(6).

5.1.1 Experimental technique

The coiling test resulted in the formation of coils of wire, material of "good" and "poor" coilability giving pitches which were of even and uneven spacing respectively. Coils thus formed from wire 1 and 2 were supplied for the preliminary investigation. Wire 1 showed a regular pitch, whereas wire 2 exhibited pronounced variations in pitch spacing. Single circlips were cut from the coils of wire produced from samples 1 and 2 by the coiling test. In the case of wire 2, samples were identified separately, in terms of their position with respect to the zones of large pitch spacing and small pitch spacing. Measurements were made of the mean diameter of circlips using a Nikon projector. The circlips were then stress relieved at 300°C for ½ hour, which caused the diameter to decrease as the residual stress due to coiling was relieved. The diameter was then remeasured, and the residual stress in the coils was calculated from the following relationship, on the valid assumption that the circlips were circular both before and after stress relieving.

$$\sigma_B = d\,E\left(\frac{1}{D_1} - \frac{1}{D_2}\right) \qquad \ldots\ldots\ldots(1)$$

where

σ_B = Magnitude of residual stress in bending N/mm^2
E = Young's Modulus, N/mm^2
= 2.16×10^5 N/mm^2 in present instance
d = Wire diameter, mm
D_1 = Initial circlip diameter, mm
D_2 = Final circlip diameter after stress relieving at 300°C, mm

5.1.2 Results

Values of the residual bending stresses determined are shown in Table III. It is apparent that no significant difference existed in the residual bending stresses exhibited by the zones of varying pitch from wire 2. This information was therefore pooled for the remaining analyses.

A marked difference existed in the residual stresses contained by wire 1 and those in wire 2, however, the residual stresses in the "good" wire being consistently lower than those in the "poor". Analysis of the information, using the students 't' test for grouped data, showed that the difference in residual bending stresses exhibited by "good" and "poor" wires was significant at the 99.9% level of the 't' distribution. This result was confirmed when the point biserial correlation coefficient for all the data was calculated. The results of this analysis are given in Table IV.

5.1.3 Conclusion

The results suggested that "good" coilability could be associated with wires of relatively low elastic properties since, for a constant bending strain on coiling, wire exhibiting low elastic properties would give lower levels of residual stress.

5.2 Residual Torsional Stress Variations in Wire Bundles

Following upon work previously carried out by a member firm determinations were made of the residual torsional stress variation within the bundles of wire available for the preliminary investigations(9).

5.2.1 Experimental technique

The bundle of wire was suspended on a horizontal rod into which notches had been cut at regular intervals. The end of the bundle was then opened out so as to form a large helical spring whose coils rested in the notches. The coils were allowed to assume their natural diameters which were not necessarily equal to the bundle diameter. The spring thus formed possessed a pitch spacing equal to the notch spacing along its top edge. The pitches of up to 20 coils were then measured along the bottom edge of the spring, together with their corresponding coil diameters. The variation in pitch, expressed in terms of the standard deviation, S_p, and the mean coil diameter were then calculated. The variation in residual torsional stress, Δ_τ, could then be calculated from the relationship

$$\Delta\tau = \pm \frac{G}{\pi c D} \times S_p \qquad \text{..........(2)}$$

where

$\Delta\tau$ = Variation in torsional residual stress

G = Rigidity Modulus N/mm^2

D = Mean diameter of coil, mm

c = "Spring" index

= $\frac{D_o - d}{d}$ where d = wire diameter, mm

D_o = Average outside diameter of coil, m

S_p = Standard deviation of pitch spacing values, mm

5.2.2 Results

The values obtained for $\Delta\tau$ for the wires 1-5 inclusive are shown in Table V, together with rpB the point biserial correlation with coilability. There did not appear to be any significant correlation between $\Delta\tau$ and coilability.

5.2.3 Conclusion

The absence of statistical correlation between the measured values of $\Delta\tau$ and coilability may have resulted from the small number of tests possible, since large amounts of wire were required for a comprehensive evaluation of this technique. Although no significance could therefore be attached to the correlation, the negative value obtained from r_{pB} may have been an indication that "good" coilability tended to be associated with low values of $\Delta\tau$. Further work would be necessary to adequately test this tentative conclusion however.

5.3 Hardness Testing

Hardness tests were carried out on selected samples since the technique was relatively simple and used equipment which was readily available in industry.

5.3.1 Experimental technique

Transverse samples of wires 1-5 inclusive, were mounted in cold setting araldite resin which was cured at 35°C for 16 hours. The sections were polished to a metallographic finish, great care being taken to avoid excessive heating or work hardening effects during polishing. The sections thus prepared were hardness tested using a Vickers hardness machine with a load of 20 kgf, hardness values being then calculated from the relationship

$$HV = \frac{1.854\,P}{L^2} \qquad \ldots\ldots\ldots\ldots(3)$$

where

HV = Vickers Hardness, $\mathrm{Kgf/mm^2}$

P = Applied load, Kgf

L = Mean diagonal length of impression, mm

5.3.2 Results

The results of the hardness tests are shown in Table VI.

Students 't' tests, carried out on the grouped data for wire pairs 1/2, 1/3 and 4/5 showed that the differences in hardness were all significant at over the 99.9% level of the 't' distribution. Analysis of the data in terms of their correlation with coilability gave the results shown in Table VII.

5.3.3 Conclusion

In all the three cases examined, there appeared to be a significant correlation between Vickers hardness and coilability, the higher hardness values being associated with "good" coilability within any one particular wire grade.

5.4 Tensile Testing

Tensile tests were carried out with particular reference to the earlier conclusions of Shipley as mentioned in Section 1 of this report(5).

5.4.1 Experimental technique

The tests were carried out on unstraightened wires, using a vertical Amsler multi-range tensile testing machine, which had been substantially modified for direct load/extension readout and which was equipped with an automatic x/y plotter. The latter was used with an extensometer having a gauge length of 50 mm.

5.4.2 Results

Wires 1, 2 and 3 were investigated in the first instance with the results given in Table VIII. The subsequent statistical analyses are given in Tables IX and X.

5.4.3 Conclusions

The more usual tensile elastic properties, such as proof stress and tensile strength, did not appear to show any consistent correlation with coilability.

There was a tendency for "good" coilability to be consistently associated with low values for the proportional limit, however, although the relationship was probably partly obscured by the inherent uncertainties involved with the determination of this elastic property directly from the load/extension graph.

5.5 Implications of Preliminary Investigations

When considered together, the results obtained from the residual stress, hardness and tensile property determinations suggested that some disparity existed between the elastic behaviour observed for wires of "good" and "poor" coilability respectively. Thus, for example, there was evidence that, within a particular grade, wire of "good" coilability possessed elastic properties which were lower than those of the equivalent wire of "poor" coilability at the relatively small strains associated with the proportional limit measurements obtained from the tensile tests. In contrast to this behaviour, the "good" coilability wire apparently exhibited higher elastic properties than the "poor" coilability wire, at the higher strains imposed during hardness testing.

These findings suggested that a more detailed examination of the tensile properties in general, and of the proportional limit in particular, could throw further light upon the differences in elastic behaviour which might exist between wires of "good" and "poor" coilability respectively.

6. DETERMINATION OF LIMIT OF PROPORTIONALITY BY ANALYSIS OF TRUE STRESS/TRUE STRAIN RELATIONSHIPS FOR WIRES OF "GOOD" AND "POOR" COILABILITY

Experimental Technique

The tests were carried out on unstraightened wires using the technique explained in Section 5.4.1. In this case however the early part of the non-linear curve, representing plastic deformation, was to be examined in much greater detail and hence the electronic amplification available with the load/strain detecting and recording equipment was employed to provide what was essentially a magnified representation of the elastic and initial plastic behaviour up to a maximum strain of 0.01 i.e. 1% strain.

6.2 Analytical Technique

The tensiletest yielded information in the form of a load/ extension graph which could be readily converted into the stress/strain plot more usually associated with the test.

In this case, the parameters were nominal values only, the calculations for stress and strain assuming that the cross sectional area of the wire and the initial gauge length respectively, remained constant with increasing load, i.e.

$$\sigma_n = \frac{P}{A} \qquad \text{..........(4)}$$

where

σ_n = Nominal Tensile Stress, N/mm^2

P = Applied Tensile Load, N

A = Original cross sectional area, mm^2

and

$$e = \frac{\Delta \ell}{\ell_o} \qquad \text{..........(5)}$$

where

e = Nominal strain

ℓ_o = Original gauge length, mm

$\Delta \ell$ = (measured length under load - ℓ_o) mm

These assumptions were not true, of course, in that with increasing load the cross sectional area continuously decreased whilst the gauge length effective at any instant increased, hence at any load, the true value for stress was greater than the nominal value suggested, whilst the true strain was correspondingly smaller than its nominal equivalent.

The nominal stress/strain values derived from the original plot, were therefore converted into the true stress/true strain equivalents, which represented the elastic/plastic behaviour of the wire at any instant of the test.

The true stress and the true strain values were calculated from the following relationships(10).

$$\sigma_T = \sigma_n (e + 1) \qquad \text{..........(6)}$$

where

σ_T = True Stress, N/mm^2

σ_n = Nominal Stress, N/mm^2

e = Nominal Strain

and

$$\varepsilon_T = \text{Ln } (e + 1) \qquad \text{..........(7)}$$

where

ε_T = True Strain

e = Nominal Strain

The values of true stress, σ_T, and true strain, ε_T, thus obtained were used to characterise the tensile flow stress curve in terms of the elastic behaviour, represented by a straight line, and the plastic behaviour, represented by an exponential relationship. The coefficients of the equations could be obtained by appropriate linear regression techniques. The relationships could be expressed as follows

a) <u>Elastic behaviour</u>

$$\sigma_T = E\, \varepsilon_T + C \qquad \text{..........(8)}$$

b) <u>Plastic behaviour</u>

$$\sigma_T = A\, \varepsilon_T^{\,n_a} \qquad \text{..........(9)}$$

where

σ_T = True Stress, N/mm^2

ε_T = True Strain

E = Young's Modulus

C = Constant, (ideally zero)
A = Constant
n_a = Apparent work hardening exponent

Equation (9) could be converted into a form suitable for regression analysis since

$$\mathrm{Ln}\,\sigma_T = n_a \,\mathrm{Ln}\,\varepsilon_T + \mathrm{Ln}\,A \qquad \ldots\ldots\ldots(10)$$

Hence, a regression of Ln σ_T/Ln ε_T yielded the respective values of the coefficients n_a and A in equation (9).

A full description of the analytical technique for the determination of the proportional limit and the true work hardening exponent n_T is given in Appendix B.

6.3 Results of Analysis for Elastic/Plastic Properties

The results of the analyses for the respective values of proportional limit σ_p and the true work hardening coefficient n_T are given in Table XI.

The data given in this table, for appropriate wires within the same specification grade, were tested for statistically significant differences between samples from "good" and "poor" coilability batches respectively. The students 't' test for grouped data was selected as the appropriate statistical test, Snedecor's 'F' test having shown that the variances for the appropriate quantities could be assumed to be independent estimates of the same population variance. (When Snedecor's 'F' test indicated that such was not the case, a modified 't' test was used as described in Appendix A).

The results of the 't' test are shown in Table XII, whilst the point biserial correlations of the appropriate parameter with coilability assessment are shown in Table XIII.

From the results of the data analyses shown in Table XII and XIII, it can be seen that, in the present instance at least, good coilability was closely associated with relatively low values of proportional limit, σp, but with relatively high rates of work hardening, as represented by n_T. This conclusion suggested that within any one grade of wire, the respective tensile true stress/true strain curves for the "good" and "poor" coilability wires tended to intersect after a certain degree of plastic strain had occurred. The differences between the two categories of wire therefore tended to decrease up to and then increase after, this degree of plastic strain.

Typical true stress/true strain graphs for the appropriate wires of "good"/"poor" coilability are shown in Figs 1-4, which illustrate quite clearly that intersection of the curves occurred at true strains varying from .0067-.0103 in the examples shown.

6.4 Proof Stress Analysis

Appropriate true proof stress values were calculated, using the technique given in Appendix B. The proof stress values thus obtained are shown plotted against offset strain for the appropriate wire pairs in Figs 5-8. The curves were fitted by linear regression techniques and in each case demonstrate that intersection occurred at proof strains lying within the range 0.2%-0.1%.

Further support for this conclusion can be drawn from Tables XIV-XVII, which show the results of calculations for the proof stress values at offset proof strains of 0.1% amd 0.05% together with their respective statistical analyses.

When the 99% level of significance is accepted as establishing a statistically significant difference between the appropriate wire pairs, it is immediately apparent that no difference could be detected at the $R_{p0.05}$ proof stress level, but that one pair out of the four showed a significant difference in elastic behaviour at the $R_{p0.01}$ proof stress level.

These findings therefore essentially supported Shipley's conclusions that the difference in the elastic properties of the wire of "good" and "poor" coilability, could not generally be detected at proof stress values corresponding to offset proof strains in excess of 0.01%.

6.5 Conclusions

The work has suggested that "good" coilability in patented hard drawn carbon steel wires can be consistently associated with

1. relatively low values of the proportional limit and

2. relatively high rates of work hardening as represented by the true work hardening coefficient n_T.

The correlations with coilability were generally significant at the 99.9% level of the 't' distribution although the reasons for the association between coilability and the elastic/plastic properties are not yet clear.

The work has shown that the combination of elastic/plastic properties leads to intersection of the tensile true stress/true strain curves at strains lying within the range 0.0067-0.0103 in the examples considered.

Statistical analysis of the results further suggested that the differences in the proportional limits of "good" and "poor" coilability wires, were generally less than 200 N/mm^2 and that they could be as little as 75 N/mm^2 for wires in the lower end of the tensile range i.e. range 1. These relatively small differences therefore required sensitive analytical techniques for their consistent detection.

Examination of the proof stress values obtained by analytical techniques from the true stress/true strain relationships has confirmed Shipley's findings that the usual elastic properties measured in the tensile test, such as $R_{p0.05}$ would probably be incapable of consistently differentiating between wires of "good" and "poor" coilability.

7. MEYER ANALYSIS OF WIRES 1 AND 2

In view of the small but significant differences in work hardening rate between wires of "good" and "poor" coilability respectively, wires 1 and 2 were investigated by means of the Meyer analysis technique, the use of which is well documented in the general literature(10).

7.1 Experimental Technique

Meyer proposed an empirical relationship between the size of the indentation d produced by a spherical indentor under an applied load P.

The relationship is usually termed 'Meyer's law' and can be expressed as follows

$$P = k\, d^{n'} \qquad \ldots\ldots\ldots\ldots(11)$$

where

P = Applied load, Kgm
d = Diameter of indentation, mm
n' = Meyer strain hardening exponent
k = a material constant

The Meyer exponent n' can thus be easily obtained, being the slope of the straight line produced by plotting log P/log d.

It is known that

$$n_T \simeq n' - 2 \qquad \ldots\ldots\ldots\ldots(12)$$

where

n_T = True work hardening exponent

Hence, a knowledge of n' should permit an estimate to be made of the magnitude of n_T.

The appropriate wires were prepared as previously shown in Section 5.3.1. The analysis was carried out by means of a Vickers hardness testing machine, using a 1 mm dia hardened steel ball indentor with loads of 15, 20 and 25 kg. The diameter of the impressions was measured using the ocular eyepiece attached to the machine.

Since the wires were only 0.7 mm in diameter, it was only possible to indent each microsection once. Several wires could be cold-mounted simultaneously in one araldite mount, however, thus permitting the full range of loads to be applied to the wires.

7.2 Results and Conclusions

The following values were obtained for n'.

Wire 1: n' = 2.298

Wire 2: n' = 2.306

The difference between n' for these two wires was an order of magnitude smaller than that detected by n_T (see Table XI) implying that the Meyer analysis was not sufficiently sensitive to consistently detect the relatively small differences in n_T.

The work using this technique was therefore discontinued.

8. BEND TEST FOR MEASUREMENT OF SPRINGBACK IN WIRES OF "GOOD" AND "POOR" COILABILITY

8.1 Introduction

The results of the tensile analyses suggested that the appropriate true stress/true strain curves for the wires of "good" and "poor" coilability respectively, intersected at true strains lying within the approximate range 0.005-0.01. This clearly implied that the flow curves diverged again at strains in excess of 0.01 thus suggesting that deformation of the wires to strains sufficiently above or below this value could lead to measurable differences in subsequent elastic behaviour.

Initial experiments were carried out using a bend test for the measurement of springback after the wires were bent through a known angle over a mandrel of known diameter. This technique was particularly convenient in that the maximum strain in the surface of the wire could be easily estimated since

$$\varepsilon_s = \frac{d}{D + d} \qquad \text{.........(13)}$$

where

ε_s = Maximum strain in surface fibres of wire

d = Wire diameter, mm

D = Mandrel diameter, mm

8.2 Experimental Technique

The springback of the wires, in degrees, was measured after bending in the direction of the cast over a 25.4 dia mandrel through an included angle of 90°. A mandrel of this diameter gave a maximum surface strain which varied from 0.026 for the 0.7 mm wire, to 0.059 for the 2.5 x 1.6 mm flattened wire section. These values proved quite adequate for discrimination between wires and "good" and "poor" coilability in the present instance. It is possible however, that the discrimination could be further improved by optimisation of the relationship between wire diameter and mandrel diameter.

The initial tests quickly revealed that significant differences existed in the springback behaviour of the wires. The differences were small in magnitude, however, being typically of the order of 7° for the 0.7 mm wire and only 2° for the 2.5 x 1.6 mm section wire.

To detect such small differences consistently it was necessary to arrange for the wire and the zero reference point of the bend tester to form part of a battery/indicator electrical circuit. This increased the precision when setting the zero reference point before bending and when measuring the springback angle from the same reference point after bending. Originally this technique resulted in further difficulties in that arcing regularly occurred at the steel wire/brass reference contact interface leading to oxidation of the steel and loss of electrical conductivity of the steel wire surface. This difficulty was circumvented by cleaning the wires with very fine abrasive paper, after which they were flash copper coated by immersion in a dilute copper sulphate solution which was slightly acidified with dilute sulphuric acid. The electrical circuit was thus essentially completed by a brass/copper contact, resulting in a lower contact resistance than the original brass/steel contact.

The consistency of indication was found to be yet further improved when the wires were coated with Electrolube contact fluid which tended to reduce arcing and subsequent oxidation of the two contacting surfaces as the circuit was repeatedly made and broken. The general arrangement of the bend tester and associated equipment is shown in Fig. 9.

8.3 Results

The results of the bend test are shown in Table XVIII and Fig. 10, whilst the statistical analyses are shown in Tables XIX and XX.

It is immediately apparent that a high correlation existed between the results of the springback test and the springmakers assessment of coilability, the wires of "good" coilability being consistently associated with relatively high angles of springback within any particular wire grade. This finding tends to support the conclusions of the tensile data, namely that the flow curves of the "good" and "poor" coilability wires intersected and then diverged again at strains in excess of approximately 0.01.

8.4 Conclusions

The wires of "good" coilability consistently exhibited a higher angle of springback than wires of a similar grade which possessed "poor" coiling properties, after bending through 90° to surface strains greater than 0.025 in the present instance. Furthermore, the correlation between springback angle and the springmakers assessment of coilability was consistently significant at the 99.9% level of the 't' distribution.

9. DISCUSSION

Of the six techniques considered in this report for the assessment of elastic properties, four showed a consistent correlation with wire coilability. These four tests could be summarised as

1. The analytical tensile test.
2. The assessment of residual stress in bending after forming into circlips.
3. The measurement of the angle of springback after bending through 90° over a mandrel of known diameter.
4. The Vickers Diamond hardness test.

Detailed analysis of the true stress/true strain results obtained from the tensile test showed that "good" coilability was associated with a low proportional limit and a high rate of work hardening. (The terms "low" and "high" are purely relative to those for the wire of "poor" coilability in the present context). The evidence of the present work further suggested that the differences between the tensile elastic properties of "good" and "poor" coilability wires were too small for consistent detection using the more generally employed nominal stress/strain information derived directly from the load/extension curve. This appeared to be at least partly due to the fact that the proportional limit could not be established directly from the curve to the required level of precision, whilst differences in the elastic properties, represented by the appropriate proof stress values, tended to be reduced as a result of the intersection of the tensile curves, for wires of "good" and "poor" coilability, within the plastic region of the curve.

The information derived from the remaining three tests given above (items 2, 3 and 4) appeared to support the findings of the tensile analyses. Thus measurements of the residual stresses induced in the formation of "circlips" confirmed the lower elastic properties of the "good" wire, where the elastic properties are here represented by the true proportional limit, whilst measurements of springback indicated that the "good" wire had higher elastic properties at high strains. Furthermore, the hardness test, which can be considered to involve plastic deformation under conditions of high localised compressive strain, also implied that wire of "good" coilability exhibited the higher elastic properties at relatively high strains, as suggested by the intersection of the tensile curves for wires of "good" and "poor" coilability.

These findings do not explain why hard drawn carbon steel wires of relatively high proportional limit should prove more difficult to coil, although they may suggest that a simple, rapid test, such as the springback test, could in theory differentiate between those wires which will coil readily and those which may only coil with greater difficulty.

Furthermore, the reasons for the higher proportional limit, associated with "poor" coilability, are not yet clear, although the combination of higher proportional limit and lower rate of work hardening suggests that a form of strain ageing mechanism may be at least partly responsible for the phenomenon.

Such a mechanism of dynamic strain ageing was held to be responsible for similar effects which were observed by Evan et al, who investigated the influence of warm straining on the physical properties of a lead patented entectoid carbon steel wire which had been hard drawn by 77% R. of A., to give a final diameter of 5 mm(11). They found that warm straining the hard drawn material by 1-2% in tension at a temperature of 300°C, followed by immediate cooling to room temperature, resulted in a significant increase in the elastic properties, as represented by the proportional limit, but that the tensile strength was relatively unaffected by the process.

Subsequent analysis of their data at SRAMA, using the technique outlined in Appendix B of this report, has revealed that warm straining increased the true proportional limit, σ_p, from its initial value of 990 N/mm^2 to a final value of 1370 N/mm^2, whilst simultaneously reducing the true work hardening exponent, n_T, from 0.091 to a final value of 0.032.

The fact that such alterations in the tensile elastic/plastic properties were readily induced by a simple warm straining process implies that similar, perhaps equally extreme, variations in elastic properties could be induced by inadvertent temperature increases during the wire drawing process. Recognition of this implication in the wire drawing industry has, in fact, led some sections of the industry to develop techniques of water cooling which can be applied directly to the wire during drawing. Apart from helping to avoid the risk of reduced torsional ductility often associated with the marked increases in elastic properties incurred by increases in wire temperature during drawing, such cooling techniques also permit the use of higher drawing speeds, resulting in an increased production capacity(12,13).

It is therefore possible that, in the case of the present work, the higher proportional limits and reduced work hardening exponents associated with poor coilability could have resulted from phenomena similar to those resulting from the warm straining investigations given above.

Furthermore, it is possible that poor coilability may be associated with variations in elastic/plastic properties along the length of the appropriate wires, although it has been suggested than an important part may also be played by the total elastic/plastic strain energy absorbed during the deformation accompanying the coiling process(14). Further work will be necessary, however, if these aspects of poor coilability are to be understood more fully in the future.

10. GENERAL CONCLUSIONS OF WORK

1. The more usual arbiters of tensile elastic properties were not sufficiently sensitive to consistently differentiate between wires of "good" and "poor" coilability.

2. "Good" coilability was consistently associated with higher values of Vickers pyramidal hardness, the correlation between the two factors being significant at over the 99.9% level of the 't' distribution.

3. Detailed analysis of the true stress/true strain tensile flow curve revealed that "good" coilability was consistently associated with relatively low values of the true proportional limit and with relatively high rates of work hardening. The correlation between "good" coilability and the true proportional limit was consistently significant at the 99.9% level of the 't' distribution, although the reason for the correlation is not yet clear.

4. The tensile true stress/true strain flow curves of the wires of "good" and "poor" coilability investigated in the present work intersected at strains lying within the approximate range 0.005-0.01.

5. Analysis of the true stress/true strain data indicated that intersection of the flow curves, for wires of "good" and "poor" coilability, occurred at proof strains within the range 0.02%-0.1% in the present instance.

This behaviour suggests that the more usual measurements of elastic properties, such as $R_{p0.05}$, $R_{p0.1}$, etc., would be unable to consistently differentiate between wires of "good" and "poor" coilability.

6. Meyer analysis was not sufficiently sensitive to consistently detect the difference in the work hardening rates of wires of "good" and "poor" coilability.

7. A simple springback test has differentiated between the wires of "good" and "poor" coilability, the former wires consistently having given a higher angle of springback than the latter wires within a given tensile range of the specification. The positive correlation between "good" coilability and angle of springback was consistently significant at the 99.9% level of the 't' distribution.

11. RECOMMENDATIONS

1. Further work should be carried out to investigate the reasons for the association between "poor" coilability and high proportional limit.

   In particular further work should be carried out to detect any variations in elastic properties along the length of wire of "poor" coilability.

2. It is suggested that the springback test and the analytical proportional limit will be the most suitable techniques for detecting such differences. Since any variations may be small, the springback test may require further refinement to increase its sensitivity and to reduce systematic experimental errors.

3. At the time of writing, information concerning the springback and tensile properties of spring wires is not generally available in a form suitable for the prediction of coilability properties. The acquisition of this information is likely to be a long term process and should therfefore be expedited in order to make such predictions possible in the future.

4. The basic reasons for the differences in elastic properties between wires of "good" and "poor" coilability require investigation if positive action to improve the coilability properties of patented hard drawn steel spring wire is to be considered in the future. Such investigations may involve the determination of compositional variations, interlamellar pearlite spacing, strain ageing and/or the assessment of the residual stresses present in the drawn wires.

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13. APPENDIX A

Statistical Techniques

13.1 Statistical Inference using the Point Biserial Correlation Coefficient

The Point Biserial Correlation coefficient r_{pB}, can be used to assess the degree of correlation between two variables, one of which varies continuously whilst the other variable forms a dichotomy, i.e. a "pass" or "fail" characterisation.

In its most general form, r_{pB} can be calculated from the relationship,

$$r_{pB} = \frac{N_t\ (\Sigma f_p Y) - N_p\ (\Sigma f Y)}{\sqrt{N_p . N_w . \left[N_t\ (\Sigma f Y^2) - (\Sigma f Y)^2\right]}} \qquad \ldots\ldots\ldots\ldots(1)$$

where

Y = Value of continuous variable assessed

N_t = Total number of Y values assessed

N_p = Total number of Y values corresponding to a "pass" in the particular test for X (e.g. good coilability, X = 1)

N_w = Total number of Y values corresponding to a "fail" in the test for X (e.g. poor coilability, X = 0)

f_p = Frequency of the Y values passing the test X for the particular value of Y.

f = Total frequency of the Y values assessed for the test X, for the particular value of Y.

If we put the values of the continuous variable equal to Y, and the response to the test (coilability) equal to X, then we can say that Y will have some value corresponding to a value of X = 1 (good coilability) or X = 0 (poor coilability).

In the present case, each discrete value of Y can be associated with only one discrete value of X for a particular coil of wire, since the wire either will coil or it will not, i.e. as stated above.

$X = 1$ (good coilability)
or
$X = 0$ (poor coilability)

Hence, for any particular Y value,

$f_p = f = 1.$

The above general relationship can therefore be simplified to

$$r_{pB} = \frac{N_t \Sigma Y - N_p \Sigma Y}{\sqrt{N_p . N_w \left[N_t (\Sigma Y^2) - (\Sigma Y)^2 \right]}} \quad \ldots\ldots\ldots\ldots (2)$$

A particular advantage of the point biserial correlation coefficient lies in the fact that r_{pB} is a special case of the Pearson product-moment coefficient, r, which is more usually associated with the assessment of linear regression relationships.

As a Pearson's correlation coefficient, therefore, r_{pB} can be tested for significance via the student's 't' distribution to assess the probability that the observed value of r_{pB} might have arisen by chance. Hence,

$$t = \frac{r_{pB} \sqrt{N_t - 2}}{\sqrt{1 - r^2_{pB}}} \quad \ldots\ldots\ldots\ldots (3)$$

The resulting value for 't' can then be tested in the usual way for (N_t-2) degrees of freedom, using the standard tables for the percentage points of the 't' distribution, which are widely published in the literature.

This technique of correlating a continuous variable with a dichotomous variable is described more fully in the literature, which should be consulted for further information(7).

13.2 Snedecors F Variance Ratio Test and Students 't' Test

The students 't' test makes three assumptions about the available data.

1. The original observations are normally distributed. This can usually be assumed to be the case, if a large enough number of observations is taken.

2. Each observation is independent of all the other observations. A little thought given to the experimental design can usually ensure that this condition is met.

3. The two variances obtained from the two sets of data can be assumed to be independent estimates of the same population variance. This assumption is more important, in that it can be shown that large differences in variance can lead to serious errors in the inferences of significance made by the use of the 't' statistic.

13.2.1 Variance ratio test

The validity of the last assumption given above can be ascertained by use of the variance ratio, or Snedecor's 'F' test, which is calculated from the relationship

$$F = \frac{\left(\frac{n_1}{n_1-1}\right) S_1^2}{\left(\frac{n_2}{n_2-1}\right) S_2^2} \qquad \ldots\ldots\ldots\ldots(4)$$

where

$$\left(\frac{n_1}{n_1-1}\right)S_1^2 > \left(\frac{n_2}{n_2-1}\right) S_2^2$$

and S_1^2 and S_2^2 are the sample variances for n_1 and n_2 observations respectively i.e.

$$F = \frac{\text{Greater variance estimate}}{\text{Lesser variance estimate}}$$

The value obtained for 'F' can then be checked against the published tables for the appropriate significance levels of the variance ratio, using n_1-1 (horizontal scale) and n_2-1 (vertical scale) degrees of freedom.

13.2.2 Students 't' Test when $S_1^2 = S_2^2$

This test applies when the requirements of the variance ratio test are met.

Then 't' can be calculated from the relationship

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 S_1^2 + n_2 S_2^2)}{n_1 + n_2 - 2} \left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \qquad \text{..........(5)}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means. The significance of the differences in the mean values $\bar{x}_1 - \bar{x}_2$, can then be ascertained in terms of the probability that the difference could have arisen by change, by comparing the calculated value of 't' against the published tables for this function, for $\nu = (n_1 + n_2 - 2)$ degrees of freedom.

13.2.3 Modified 't' Test for $S_1^1 \neq S_2^2$

When the sample variances cannot be assumed to be independent estimates of the same population variance, the 't' test can be applied in the following modified form.

The modified 't' statistic, 't*', is calculated from the relationship

$$t^* = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \qquad \text{..........(6)}$$

and the modified degrees of freedom, f, are calculated,

$$\frac{1}{f} = \frac{S_1^{\;4}}{k^2\, n_1^{\;2}\,(n_1 - 1)} + \frac{S_2^{\;4}}{k^2\, n_2^{\;2}\,(n_2 - 1)} \qquad \text{........(7)}$$

where

$$k = \frac{S_1^{\;2}}{n_1} + \frac{S_2^{\;2}}{n_2}$$

The resulting values of 't*' and 'f' are then compared to the published values of 't' and 'ν' in the usual way.

Further information on these tests can be readily obtained from the published literature(7,8).

14. APPENDIX B

Analytical Technique for determination of Proportional Limit, True Work Hardening Exponent and Proof Stress

14.1 Technique

A brief explanation of the technique may be useful.

The elastic portion of the tensile flow curve may be represented by an expression of the form

$$\sigma_T = E\,\varepsilon_T + C \qquad \text{..........(1)}$$

where

σ_T = True Stress, N/mm^2

ε_T = True Strain, mm/mm

E = Youngs modulus, $= \dfrac{d\sigma_T}{d\varepsilon_T}$

C = Constant (ideally, $C = 0$)

Similarly, the plastic portion of the curve can be represented by an expression of the form

$$\sigma_T = A\,\varepsilon_T^{\,n_a} \qquad \text{..........(2)}$$

where

n_a = Apparent work hardening exponent
(The greater the value of n_a, the higher the rate of hardening)

A = Constant

14.2 Proportional Limit, σ_p

Since the true proportional limit is the point at which expressions 1 and 2 intersect, then, at intersection,

$$A\,\varepsilon_p^{\,n_a} - E\,\varepsilon_p - C = 0 \qquad \text{..........(3)}$$

where

ε_p = True strain at proportional limit.

Equation 3 can be solved to obtain the value of ε_p and hence σ_p can be subsequently easily found, since

σ_p = True proportional limit

$$= A\ \varepsilon_p{}^{n_a} \qquad \text{..........(4)}$$

14.3 True Work Hardening Exponent, n_T

The above value of n_a, the apparent work hardening exponent, is calculated using the sum of both the elastic and the plastic strains. The true work hardening exponent, however, only considers the plastic strain, and hence

$$\sigma_T = A\ (\varepsilon_{T(T)} - \varepsilon_p)^{n_T} \qquad \text{..........(5)}$$

where

A = Constant

$\varepsilon_{T(T)}$ = Total (elastic + plastic) true strain

ε_p = True (elastic) strain at proportional limit
 = Total elastic strain

Hence n_T can be found as the slope of the plot Log σ_T/Log $(\varepsilon_{T(T)} - \varepsilon_p)$

14.4 Proof Stress, σ_R

The true strain at a true stress corresponding to a given offset strain can be found from the relationship

$$A\ \varepsilon_R{}^{n_a} - E\ \varepsilon_R + (E\ \varepsilon_o - C) = 0 \qquad \text{..........(6)}$$

where

ε_o = Offset strain $\left(= \dfrac{\%\ \text{proof strain}}{100}\right)$

ε_R = True strain at true proof stress, σ_R

and A, E and n_a are as shown previously

Hence the true proof stress can be determined, since

$$\sigma_R = A\,\varepsilon_R^{\,n_a} \qquad \text{..........(7)}$$

TABLE I WIRES INVESTIGATED AND ASSESSMENT OF COILABILITY

Wire quality	Nominal wire size, mm	Sample No.	Springmakers assessment of coilability
BS 1408 R3	0.71 diam.	1	G = Good
		2	P = Poor (variable free length)
		3	P = Poor (" " ")
BS 1408 M2	0.76 diam.	4	G = Good
		5	P = Poor (variable free length)
BS 1408 R1	2.5 x 1.6 flattened wire	6	G = Good
		7	P = Poor (variable coil diameter)

TABLE II RESULTS OF COILABILITY TRIALS ON BS 1408 R3 WIRE

Wire No.	Mean free length, mm	Short term free length variability 3S*, mm	Springmakers design tolerance, mm
1	52.43	±2.86	±2.54
2	50.23	±9.91	"
3	51.00	±4.63	"

*S = Standard Deviation

TABLE III RESIDUAL BENDING STRESS IN "CIRCLIPS" MADE FROM WIRES 1 AND 2

Wire No.	Residual bending stress, N/mm²		Number of tests, N
	Mean Value	Standard Deviation	
1	301.5	25.2	19
2a+	362	19.7	10
2b†	356.1	23.2	7

+Samples from large pitch zone of coil

†Samples from small pitch zone of coil

TABLE IV POINT BISERIAL CORRELATION OF RESIDUAL BENDING STRESS IN CIRCLIPS WITH COILABILITY ASSESSMENT

Wires Compared	r_{pB}	t	ν*	Comments
1-2	-0.7908	-7.53	34	Correlation significant at 99.9% level Low residual stress => good coilability

*ν = Degrees of Freedom = N-2

TABLE V VARIATION IN TORSIONAL RESIDUAL STRESS, $\Delta\tau$, IN WIRE BUNDLES, AND POINT BISERIAL CORRELATION WITH COILABILITY

Wire No.	$\Delta\tau$ N/mm^2	r_{pB} and Comments
1	5.6	r_{pB} = -0.286
2	15.75	t = -0.298 for 3 D.F.
3	1.85	No significant correlation between $\Delta\tau$ and coilability
4	3.9	
5	5.1	

TABLE VI RESULTS OF VICKERS DIAMOND HARDNESS TESTS ON BS 1408 WIRES OF VARYING COILABILITY

Wire No.	Hardness, HV20, Kgf/mm^2		Number of tests, N
	Mean	Standard Deviation	
1	588.3	8.2	15
2	557.9	7.6	9
3	535.6	7.6	17
4	615.6	8.3	23
5	600.9	6.8	24

TABLE VII POINT BISERIAL CORRELATION OF VICKERS HARDNESS TEST RESULTS WITH COILABILITY ASSESSMENT

Wires Compared	r_{pB}	t	ν	Comments
1-2	0.8878	9.051	22	Correlation significant at 99.9% level High hardness => good coilability
1-3	0.9601	18.798	30	" " " "
4-5	0.7044	6.657	45	" " " "

TABLE VIII RESULTS OF INITIAL TENSILE TESTS ON BS 1408 WIRES

Wire No.	Mean ($\bar{x}$) and Standard Deviation (Sx) of Tensile tests											
	L of P N/mm^2			$R_{p0.01}$ N/mm^2			$R_{p0.05}$ N/mm^2			Rm N/mm^2		
	$\bar{x}$	Sx	N	$\bar{x}$	Sx	N	$\bar{x}$	Sx	N	$\bar{x}$	Sx	N
1	894.1	85.6	12	1188.5	134.8	12	1716	161	12	2333.6	37.2	14
2	980.8	109.1	13	1225.5	99.2	13	1677.6	72.6	13	2249.9	50	14
3	1085.7	99.4	14	1284	102.6	14	1676.3	60.2	14	2311.7	30.5	15

TABLE IX POINT BISERIAL CORRELATION OF TENSILE TEST RESULTS FOR WIRES 1 AND 2 WITH COILABILITY ASSESSMENT

Tensile property correlated	r_{pB}	t	ν	Comments
L of P	-0.4163	-2.195	23	Correlation significant at 95% level Low L of P => good coilability
$R_{p0.01}$	-0.1616	-0.79	23	No significant correlation
$R_{p0.05}$	0.1604	0.78	23	" " "
Rm	0.7022	5.03	26	Correlation significant at 99.9% level High Rm => good coilability

TABLE X POINT BISERIAL CORRELATION OF TENSILE TEST RESULTS FOR WIRES 1 AND 3 WITH COILABILITY ASSESSMENT

Tensile property correlated	r_{pB}	t	ν	Comments
L of P	-0.729	-5.217	24	Correlation significant at 99.9% level Low L of P => good coilability
$R_{p0.01}$	-0.3859	-2.049	24	No significant correlation
$R_{p0.05}$	0.1725	0.858	24	" " "
Rm	0.142	0.7454	27	" " "

TABLE XI RESULTS OF TENSILE TRUE STRESS/TRUE STRAIN ANALYSES

Wire No.	No.of wires tested	L of P, σ_p N/mm^2		True work hardening exponent, n_T	
		Mean	Standard Deviation	Mean	Standard Deviation
1	9	916.0	56.2	0.243	0.027
2	7	1114.8	74.9	0.169	0.048
3	7	1096.9	54.8	0.186	0.033
4	9	1177.6	102.5	0.169	0.029
5	9	1328.8	74.2	0.138	0.020
6	5	817.1	24.1	0.198	0.011
7	5	892.8	26.5	0.172	0.012

TABLE XII STATISTICAL COMPARISON OF ANALYTICAL TENSILE TEST RESULTS USING STUDENTS 't' TEST FOR GROUPED DATA

Wires compared	Parameter	t value	ν	Comments
1-2	σ_p	5.673	14	Difference significant at 99.9% level
	n_T	3.648	14	" " " 99.5% "
1-3	σ_p	6.04	14	Difference significant at 99.9% level
	n_T	3.553	14	" " " 99.5% "
4-5	σ_p	3.38	16	Difference significant at 99.5% level
	n_T	2.489	16	" " " 97% "
6-7	σ_p	4.225	8	Difference significant at 99.5% level
	n_T	3.234	8	" " " 98% "

TABLE XIII POINT BISERIAL CORRELATION OF ANALYTICAL TENSILE TEST RESULTS WITH COILABILITY ASSESSMENT

Wires Correlated	Tensile property correlated	r_{pB}	t value	ν	Comments
1-2	σ_p	-0.8516	-6.08	14	Correlation significant at 99.9% level Low σ_p => good coilability
	n_T	0.722	3.904	14	Correlation significant at 99.8% level High n_T => good coilability
1-3	σ_p	-0.8651	-6.453	14	Correlation significant at 99.9% level Low σ_p => good coilability
	n_T	0.712	3.794	14	Correlation significant at 99.8% level High n_T => good coilability
4-5	σ_p	-0.6674	-3.585	16	Correlation significant at 99.5% level Low σ_p => good coilability
	n_T	0.5564	2.678	16	Correlation significant at 98% level High n_T => good coilability
6-7	σ_p	-0.858	-4.725	8	Correlation significant at 99.8% level Low σ_p => good coilability
	n_T	0.7878	3.617	8	Correlation significant at 99% level High n_T => good coilability

TABLE XIV ANALYTICAL PROOF STRESSES AT 0.01% OFFSET STRAIN

Statistical Parameter	0.01% True proof stress for wire number						
	1	2	3	4	5	6	7
Mean	1132.3	1213.5	1192.3	1360.1	1491.2	865.3	931
Standard deviation	86.4	104.5	64.5	126.7	73.9	20.3	23.9
Number of samples	9	7	7	9	9	5	5

TABLE XV STATISTICAL ANALYSIS OF ANALYTICALLY DETERMINED 0.01% TRUE PROOF STRESS FOR WIRES OF "GOOD" AND "POOR" COILABILITY

Wires compared	t value	ν	Comments
1-2	1.591	14	Difference not significant at 99% level
1-3	1.435	14	" " " " " "
4-5	2.528	16	" " " " " "
6-7	4.19	8	Difference significant at 99.5% level

TABLE XVI ANALYTICAL PROOF STRESSES AT 0.05% STRAIN

Statistical parameter	0.05% True proof stress for wire number						
	1	2	3	4	5	6	7
Mean	1777.7	1696.3	1577.9	1938	2017.4	1030.5	1065.3
Standard Deviation	209.8	102.4	71.2	235.8	89.3	12	17.8
Number of samples	9	7	7	9	9	5	5

TABLE XVII STATISTICAL ANALYSIS OF ANALYTICALLY DETERMINED 0.05% TRUE PROOF STRESS FOR WIRES OF "GOOD" AND "POOR" COILABILITY

Wires compared	t value	ν	Comments
1-2	0.882	14	Difference not significant at 99% level
1-3	2.666	10	" " " " " "
4-5	0.945	10	" " " " " "
6-7	3.242	8	" " " " " "

TABLE XVIII SPRINGBACK ANGLE θ° OF PATENTED HARD DRAWN CARBON STEEL WIRES BENT THROUGH 90° OVER 25.4 mm DIAMETER MANDREL

Parameter	Springback, θ degrees, for wire number						
	1	2	3	4	5	6	7
Mean	62.7	55.8	57.9	61.9	55.2	35.7	33.8
Standard Deviation	0.6	0.8	0.9	0.4	0.7	0.4	0.7
Number of samples	20	20	33	20	20	10	10

TABLE XIX STATISTICAL ANALYSIS OF ANGLE OF SPRINGBACK RESULTS FOR WIRES OF "GOOD" AND "POOR" COILABILITY

Wires Compared	t	ν	Comments
1-2	30.076	38	Difference significant at 99.9% level
1-3	23.271	51	" " " " "
4-5	37.165	38	" " " " "
6-7	7.07	18	" " " " "

TABLE XX POINT BISERIAL CORRELATION OF SPRINGBACK ANGLE, θ°, WITH COILABILITY ASSESSMENT

Wires Correlated	r_{pB}	t value	ν	Comments
1-2	0.9808	31.002	38	Correlation significant at 99.9% level High Springback => good coilability
1-3	0.962	25.16	51	" " " " "
4-5	0.9885	40.398	38	" " " " "
6-7	0.8679	7.414	18	" " " " "

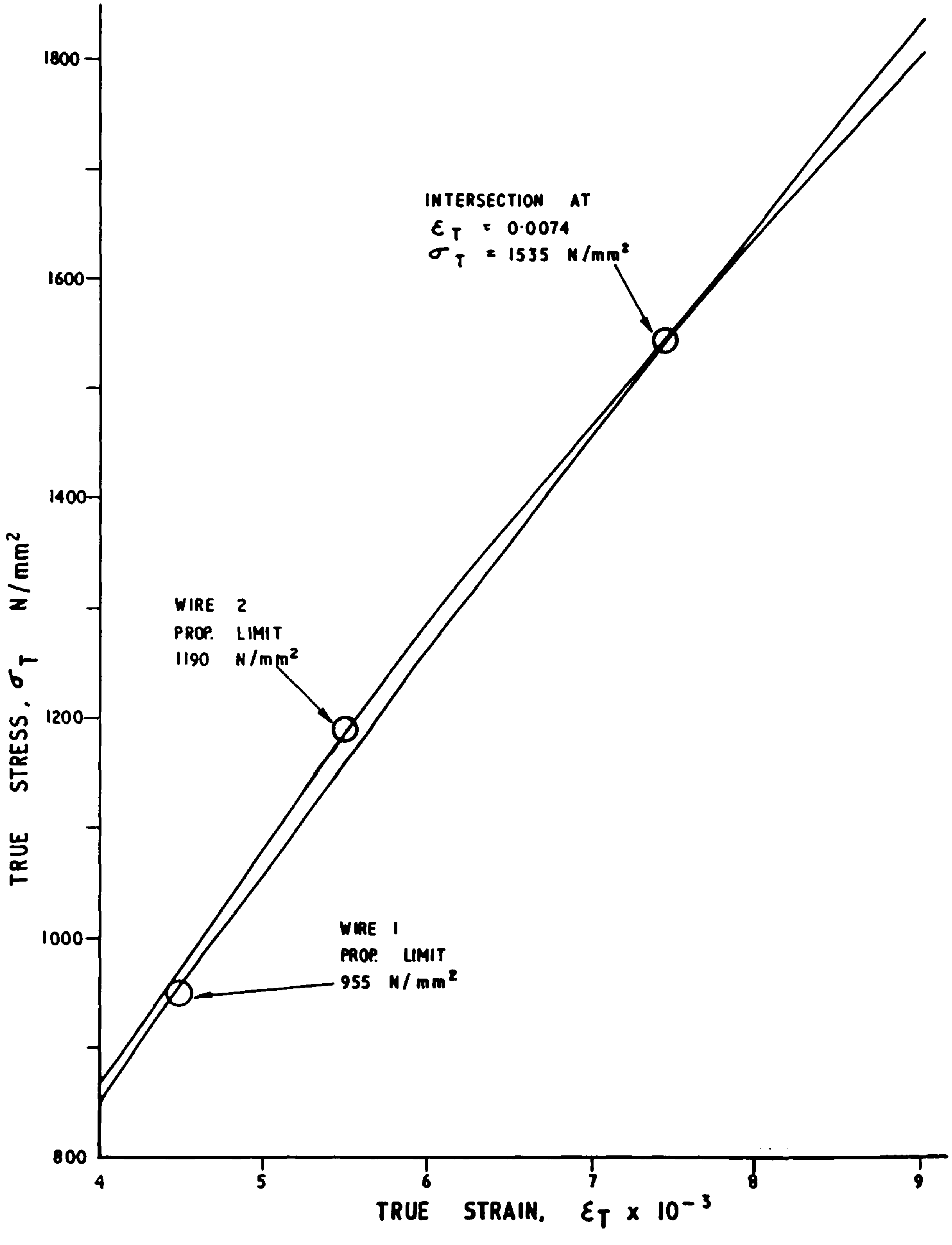

FIG. 1 DETAIL OF TYPICAL TRUE STRESS / TRUE STRAIN TENSILE CURVES FOR WIRE 1 (GOOD COIL $^{\gamma}$) AND WIRE 2 (POOR COIL$^{\gamma}$)

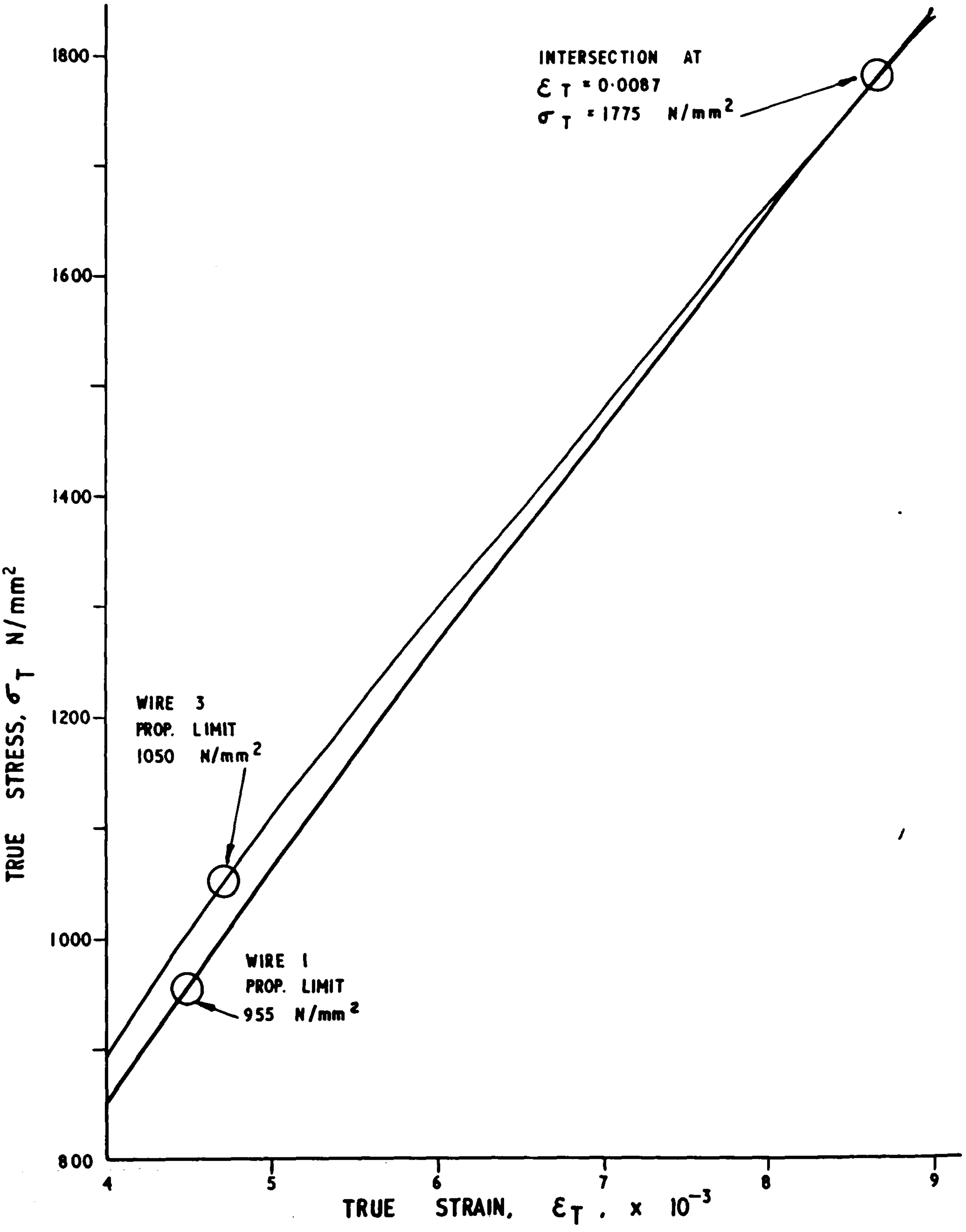

FIG. 2 DETAIL OF TYPICAL TRUE STRESS / TRUE STRAIN TENSILE CURVES FOR WIRE 1 (GOOD COIL $^{\gamma}$) AND WIRE 3 (POOR COIL $^{\gamma}$)

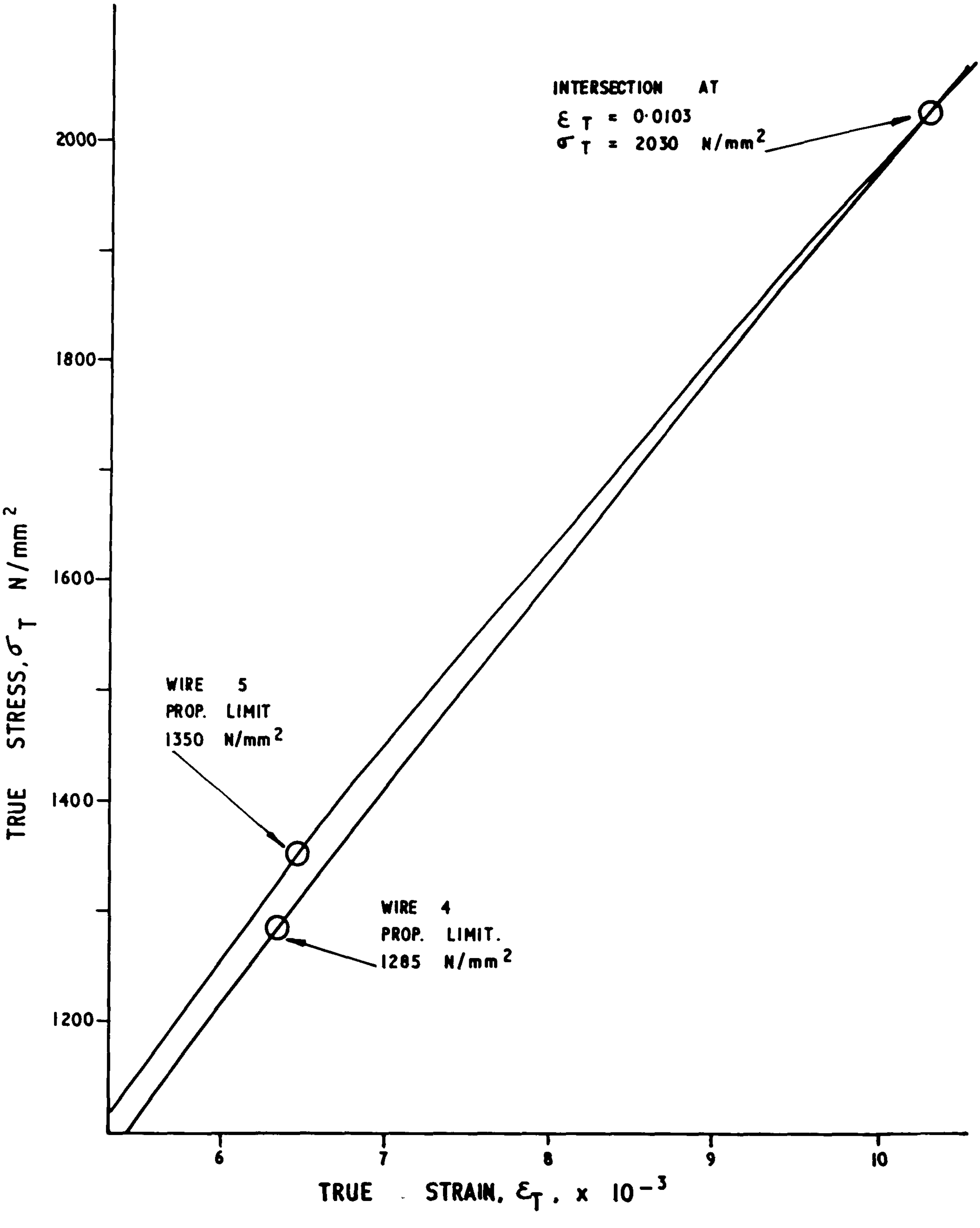

FIG. 3 DETAIL OF TYPICAL TRUE STRESS / TRUE STRAIN TENSILE CURVES FOR WIRE 4 (GOOD COIL$^\gamma$) AND WIRE 5 (POOR COIL$^\gamma$)

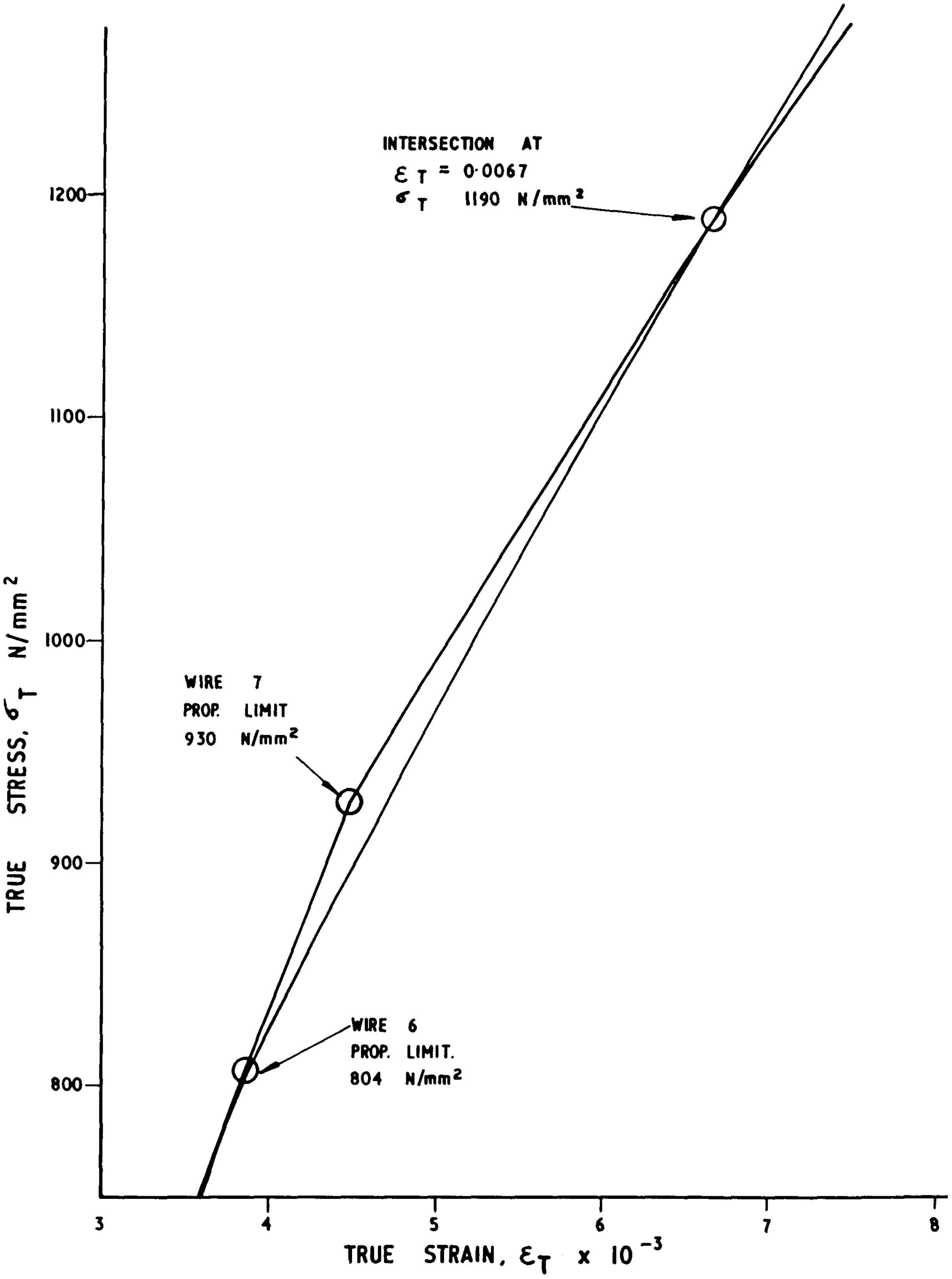

FIG. 4 DETAIL OF TYPICAL TRUE STRESS/ TRUE STRAIN TENSILE CURVES FOR WIRE 6 (GOOD COIL) AND WIRE 7 (POOR COIL)

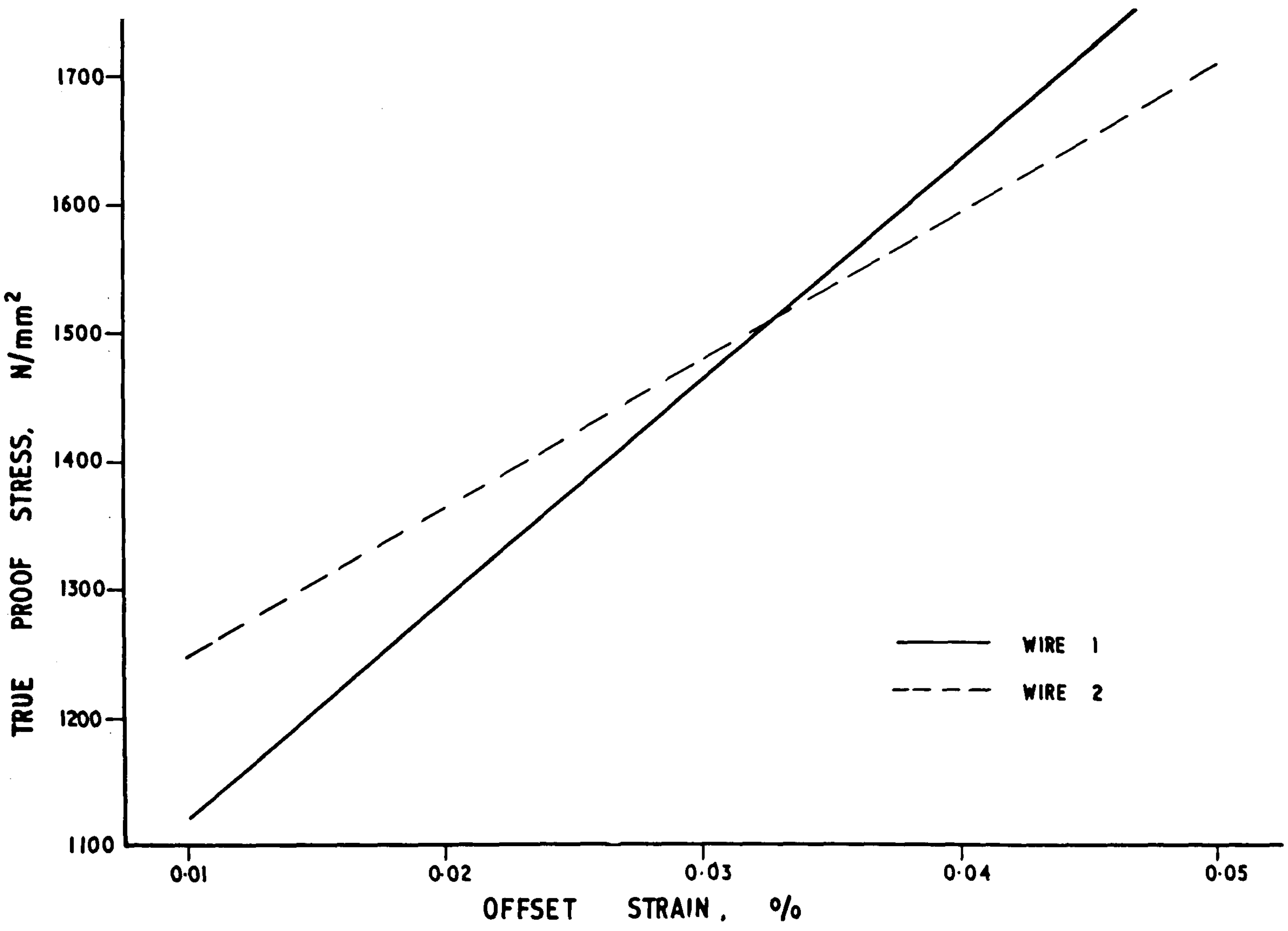

FIG. 5 TYPICAL TRUE PROOF STRESS/ OFFSET STRAIN CURVES FOR WIRE 1 (GOOD COILABILITY) AND WIRE 2 (POOR COILABILITY)

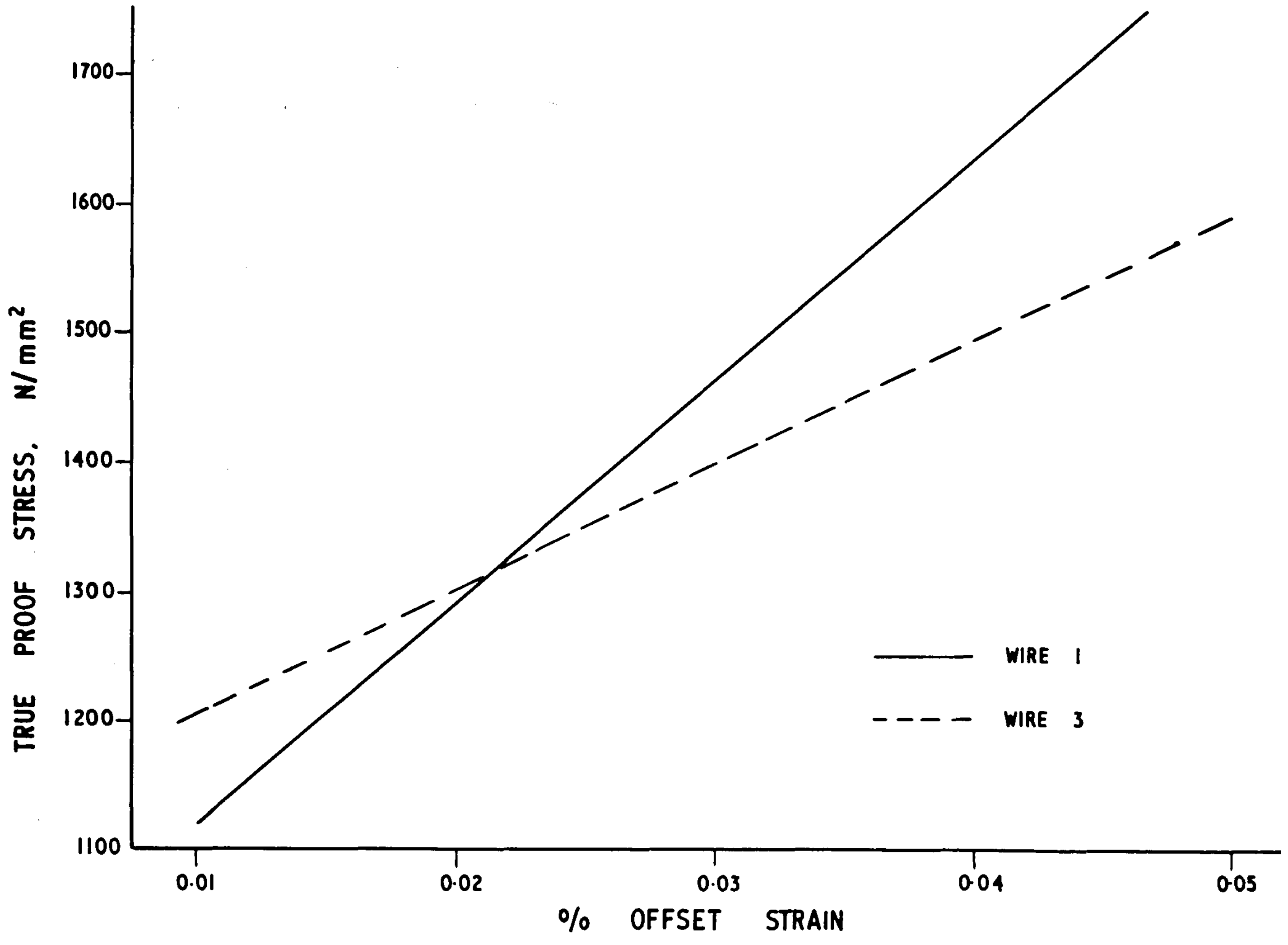

FIG. 6 TYPICAL TRUE PROOF STRESS / OFFSET STRAIN CURVES FOR WIRE 1 (GOOD COILABILITY) AND WIRE 3 (POOR COILABILITY)

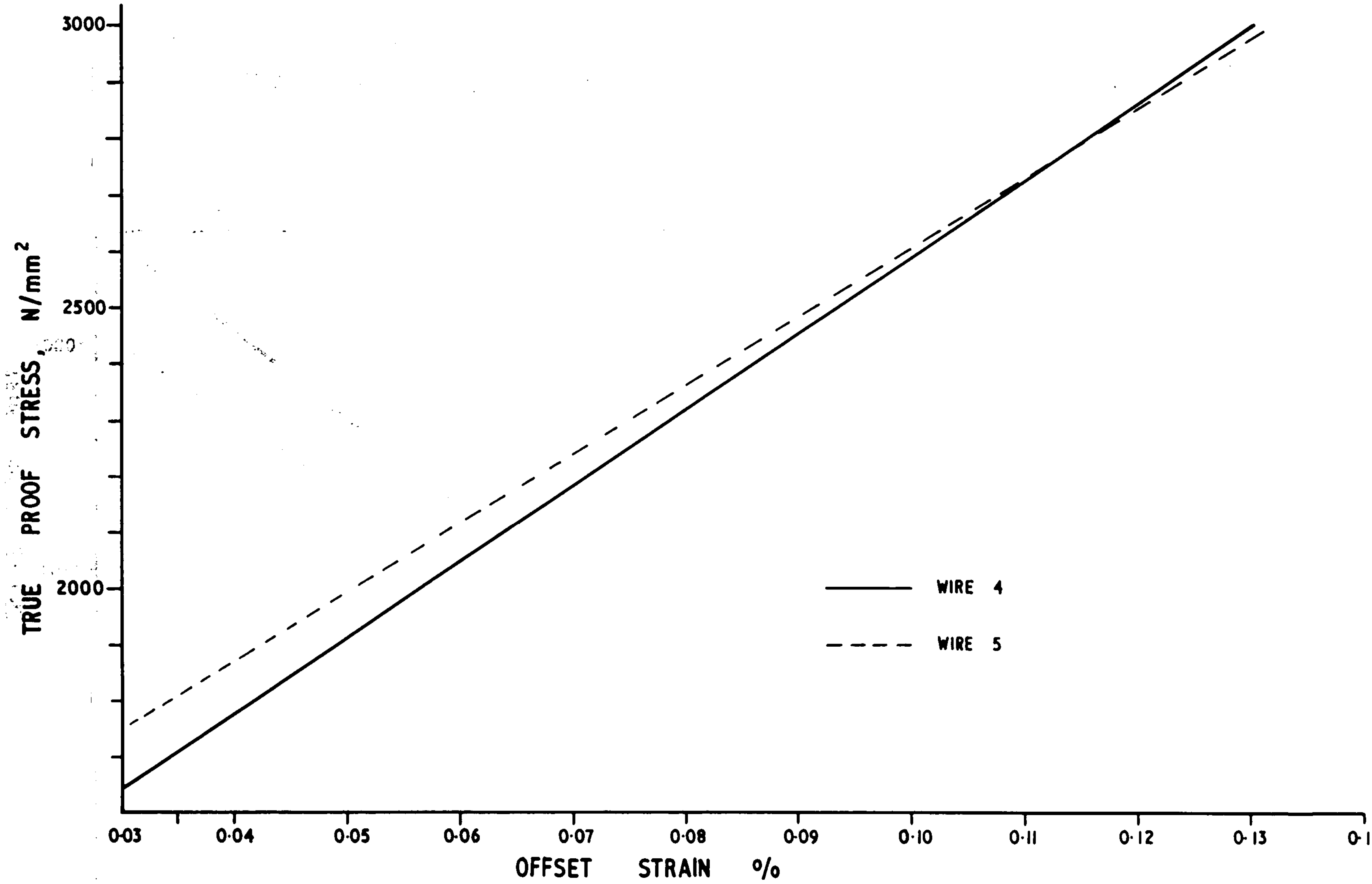

FIG. 7 TYPICAL TRUE PROOF STRESS / OFFSET STRAIN CURVES FOR WIRE 4 (GOOD COILABILITY) AND WIRE 5 (POOR COILABILITY)

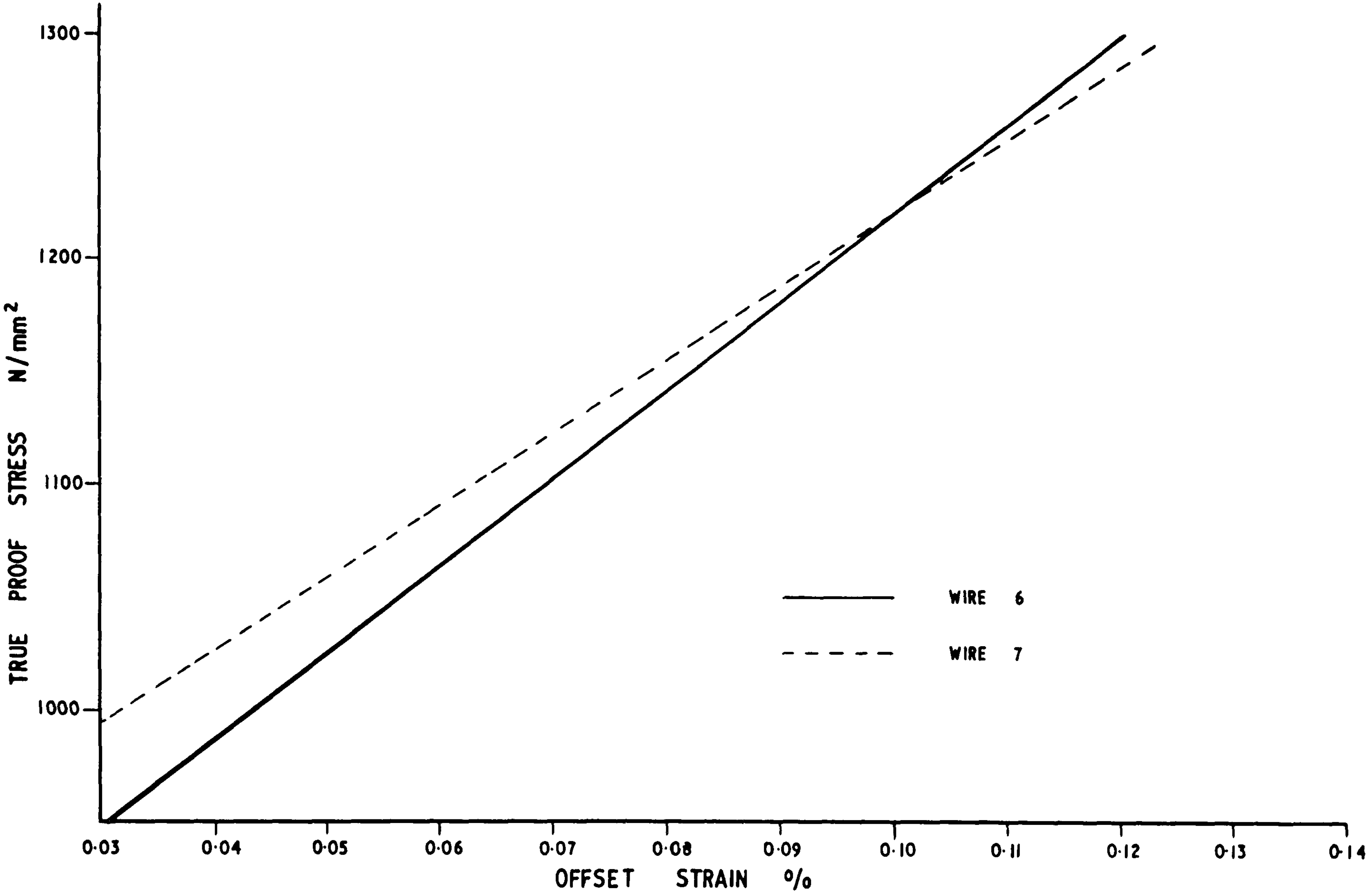

FIG. 8 TYPICAL TRUE PROOF STRESS/ OFFSET STRAIN CURVES FOR WIRE 6 (GOOD COILABILITY) AND WIRE 7 (POOR COILABILITY)

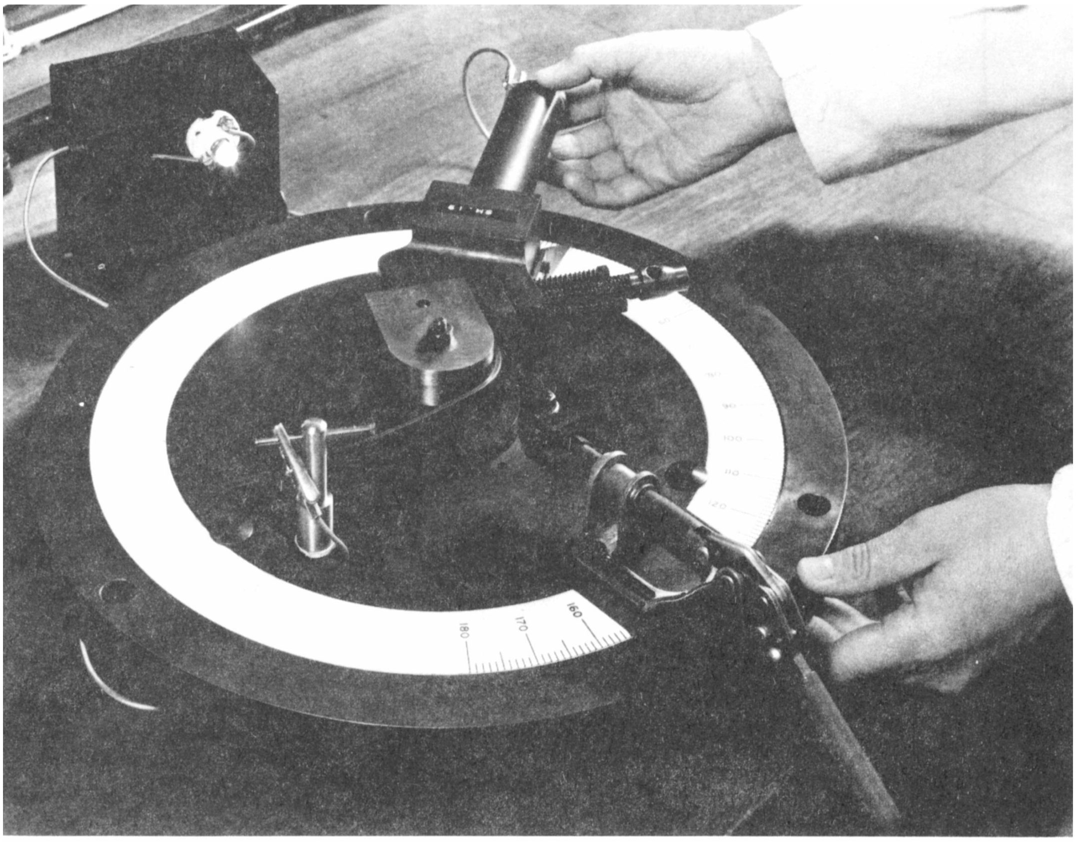

Fig. 9. SRAMA Wire Springback Tester

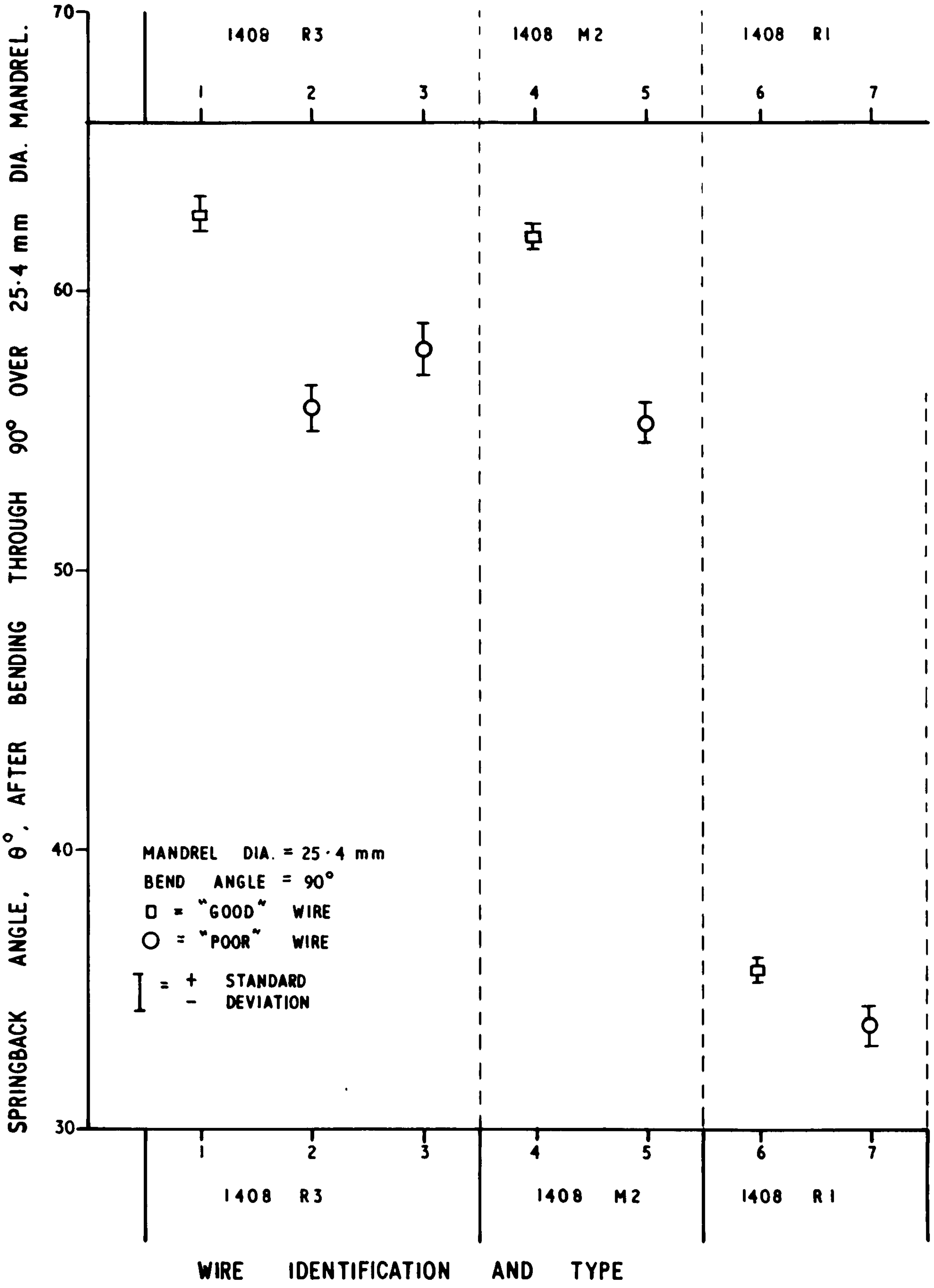

FIG. 10 COMPARISON OF SPRINGBACK ANGLES FOR "GOOD" AND "POOR" WIRES.