THE SPRING RESEARCH & MANUFACTURERS' ASSOCIATION

MINIMUM BEND RATIOS OF STAINLESS AND CARBON SPRING STEEL STRIP

by

D. Saynor, B.Sc.

Report No. 305

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SUMMARY

The minimum bend ratio (M.B.R.) of a strip material is the ratio of the minimum inside radius which the material may be bent around without failure to the thickness of the strip (i.e. M.B.R. = Ins. Rad. Min. ÷ t).

Experimental work has been undertaken to determine the M.B.R. for stainless spring steel strip grade 302S25 in the hardness range 400-500HV, and for hardened and tempered carbon steel strip of grades CS50, 80 and 100 in the hardness range 400-640 HV.

For both materials, M.B.R. were determined at various hardness levels for 90° and 180° bends both parallel and perpendicular to the direction of rolling. The effects on the M.B.R. of strip thickness, speed of forming and method of forming were considered. In the case of carbon steel strip the effect of the carbon content of the steel was also investigated.

For the stainless strip in the hardness range tested it was found that the M.B.R. was greatly dependent upon the direction of the bend axis relative to the direction of rolling. Parallel bends required a much larger M.B.R. than transverse bends. For the range of strip thicknesses tested the thickness was not found to significantly affect the M.B.R.

For hardened and tempered carbon steel strip it was found that neither carbon content nor strip thickness had any significant effect on the M.B.R. The only factors affecting the ratio were hardness of the sample and whether bending was parallel or perpendicular to the direction of rolling; again, parallel bends required a larger M.B.R. than perpendicular bends, although the effect was not as pronounced as that shown by the stainless strip.

For both stainless and carbon steel strip, the results showed that varying the speed of forming from 60 to 160 punches per minute had no significant effect on the M.B.R. Comparative tests, using closed die methods of bend forming in place of the Avothane blocks used throughout, produced only slightly higher M.B.R.'s. An increase of 10% on the data presented in this report should be sufficient to give safe M.B.R.'s for closed forming methods.

A theoretical method of predicting the M.B.R. of stainless strip bent through 90° perpendicular to the direction of rolling gave reasonable correlation with the test results.

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INTRODUCTION

Manufacturers of flat strip springs need to know the limits to which they can form spring strip materials for two important reasons: firstly, the ease with which a spring can be formed may be incorrectly assessed and hence an uneconomic rate quoted, and secondly, cracks invisible to the naked eye may be formed on the surface of the material inducing premature failure of the spring.

The parameter generally used by manufacturers to indicate the ease of forming of strip is the minimum bend ratio (M.B.R.). This is the ratio of the minimum inside radius which the material may be bent around without failure to the thickness of the strip.

A recent literature survey carried out by the Association (1) into existing data on M.B.R.'s for various spring strip materials indicated that information in certain areas was either non-existent or contradictory. In addition, the effect of various parameters on the M.B.R. was not clear. As a result of the survey, the present investigation was undertaken to determine the M.B.R. for both stainless spring steel strip grade 302S25 in the hardness range 400-500 HV (where data is at present limited), and for hardened and tempered carbon steel strip of grades CS50, 80 and 100 in the hardness range 400-640 HV, (where conflicting information exists as to the importance or otherwise of carbon content on the M.B.R.). The effects of speed and method of forming were also to be investigated.

A theoretical method of predicting the M.B.R. of a material, drawn from a paper by Mohrnheim (2) is outlined in this report, and it was thought that if the theory could be shown to give a reasonable approximation to the M.B.R. achieved in practice, then this would be of some use to manufacturers. It was decided therefore to calculate the M.B.R. predicted by the theory for the stainless steel strip 90° perpendicular bends and compare these with results obtained form the tests.

It should be noted that this work is intended only as a guide to flat strip spring manufacturers and the results obtained are thus only general. The sample sizes and range of punches available were not large enough to allow a rigorous statistical analysis to be conducted.

2. DEFINITION OF FAILURE

The literature survey (1) suggested that different definitions of failure could be a cause of conflicting data between sources and therefore any future work should clearly state the method used to assess the acceptability of a bend. Hence for the purpose of this investigation, failure of an individual bend was defined as that state at which surface cracks were visible when viewed under a microscope at 40x magnification. Before this stage is reached, however, there can be severe surface deformation and tarnishing, and in applications in which finish and appearance are important this should be borne in mind and a value of the M.B.R. slightly higher than those presented in this report should be used.

3. MATERIALS

The stainless steel strip was supplied as Type 302 in two nominal hardness ranges (400-450 HV and 450-500 HV) and six nominal thicknesses (0.0108", 0.012", 0.018", 0.024", 0.028", and 0.036"). However, not all thicknesses were supplied for each hardness range. Independent chemical composition tests showed that the analyses of the strip were within the British Standard (3) specified ranges for both 302S17 and 302S25 grades. The results of the chemical composition tests along with the measured hardness values are shown in Table I. The hardness values were measured on a standard Vickers hardness tester.

The carbon steel strip was supplied in grades CS50, 80 and 100 in three nominal thicknesses (0.020", 0.030", and 0.040") in the unheat treated condition. The strip was hardened and tempered on the premises to give nominal hardness values of 400, 500, 600 and 640 HV. Again, not every grade was obtained in each thickness and nominal hardness value. Independent chemical composition tests showed the analyses to be within the British Standard (4) specified ranges. The results of the composition tests along with the measured hardness values for the carbon steel strip are shown in Table II.

4. TESTS PERFORMED

The objective of the tests was to determine the M.B.R. for the stainless steel and the three grades of carbon steel at each hardness value and strip thickness for 180° and 90° bends with the bend axis both parallel and perpendicular to the rolling direction. Comparative tests were also performed, repeating the tests for the stainless at a lower punch rate of 60 punches per minute to determine to what extent the speed of forming affected the M.B.R. In place of the avothane blocks used throughout, some tests were also conducted using more conventional closed die forming methods with four types of bend for various stainless strips and for the CS50 grade 0.020" carbon steel strip. These tests were performed to assess the effect on the M.B.R. of the method of bend forming.

Tensile tests were performed on the stainless strip to determine the reduction of area of the material at fracture, as this data was needed for the comparison of the theoretical and actual M.B.R.'s.

5. PROCEDURE

5.1 Normal Forming Using Avothane

Fig. I shows diagrammatically the normal method of bend forming used in this project. Tests were performed on a Worcester 6 ton bench power press fitted with a variable speed drive having a maximum punch rate of 170 punches per minute. The strip under test was laid on an avothane block contained in a steel restraining bolster which was rigidly clamped to the bed of the press. with the strip in position the punch, which was profiled to the angle and radius of the bend required, was forced onto the strip, thus pressing the strip into the avothane block underneath. Avothane is a polyurethane synthetic rubber which is flexible but virtually incompressible and therefore the block was made to deform to accommodate the punch forcing into it. The deformation of the avothane block was restrained on the base and four vertical sides by the bolster, thus the avothane was made to deform upwards around the punch. This action pressed the strip against the punch and formed the bend according to the profile of the punch.

The depth of stroke was set by first manually lowering the punch to its lowest position in the stroke, and was then increased until a test strip which had previously been placed on the avothane block was seen to come into contact with the full profile of the punch (when the strip contacted at both points A and B on the punch in Fig. 1). Occasionally when very large punches were being used a V was cut into the top surface of the avothane in the line of action of the punch, and the strip then laid over the V. This was done to lower the resistance of the avothane during punching, which otherwise would have been too great for the press motor to overcome.

Avothane blocks were used as the normal method of forming in this project for three main reasons:-

1. A single avothane block replaces a range of expensive dies.

2. It is one of the least severe methods of forming because the pressure on the strip is evenly distributed.

3. Results are not affected by misalignment of punch and die.

The avothane used was a 95° grade and the block design was generally in accordance with the manufacturers' literature (5). For the parallel bend tests the sheared edges of the specimens were surface ground to eliminate any roughness and its possible effect on the test results.

5.2 Closed Die Forming

For the closed die comparative tests the punch and die were set up as an open pair on the press with the die being rigidly clamped to the bed of the press. The clearance between the punch and die was adjusted until it was equal to the thickness of the strip being used. This was done by placing lengths of solder wire across the die and punching the wire. The punched wire thickness was then measured using a point micrometer and the stroke adjusted accordingly.

5.3 Sample Size

For each bend radius ten bends were performed. If two or more individual bends failed (failure being defined by the criterion in Section 2 above) then the bend radius was considered to be too severe (i.e. too small); if one bend failed then ten further bends were performed, and if one or more of this second group failed the radius was considered to be too severe and a larger punch radius was chosen for the next test.

6. RESULTS

The results of the bend tests are presented for the stainless steel strip in Table III and for the hardened and tempered carbon steel strip in Table IV. Both tables are for tests using avothane blocks as the method of forming, at a speed of 160 punches per minute.

The results of the comparative closed die tests on the stainless and carbon steel strip are given in Table V. These test were also performed at a punch rate of 160 punches per minute. All the stainless tests were repeated at the lower speed of 60 punches per minute, and the results of these tests are detailed below Table III.

In all the above Tables the M.B.R. given is the minimum 'safe' ratio which could be determined using the range of punch sizes available. In fact, the actual M.B.R. will probably be lower and lie between the value given and the value for the next smallest size punch. However, it was decided to present 'safe' values rather than a dubious 'unsafe' range. For the thicker carbon steel strip in the hardest conditions the M.B.R. was quite high, and hence the punches used were very large (above 1" diameter). With these large punches, the strip width was not great enough for the strip to follow the full profile of the punch when making bends parallel to the rolling direction (i.e. along the strip length), and therefore such tests were invalid. Hence, for the strip of nominally 1" width there was a limiting bend ratio for the parallel bends. In Table IV the symbol (>) indicates this condition. The figure given is the maximum value of the bend ratio which could be achieved, and the actual M.B.R. lies above this figure.

7. DISCUSSION OF RESULTS

The overall scatter of the results is generally broad, indicating the difficulty of adequately controlling the many variables in the tests. It is worth repeating therefore that the results are only intended as a guide and a good first approximation to the M.B.R. which can be expected in manufacture.

7.1 Speed of Forming

Changing the speed of forming from 160 to 60 punches per minute is seen to have had only a negligible effect on the M.B.R. The three results which do indicate a difference (detailed below Table III) show a lower value for the M.B.R. at the slower speed, which was expected, since this gives a less severe forming condition. However, the effect is so small that the results obtained running at 160 punches per minute can be taken as being general, except for extremely high forming speed applications, where perhaps a slightly larger M.B.R. should be used.

7.2 Closed Die Forming

The effect of using closed die methods in place of the avothane blocks is seen from Table V to have been more pronounced than the speed effect. The trend was for a slightly larger M.B.R. to be obtained for closed die forming than for the avothane method. This indicates that closed die forming is more severe than avothane forming. Relatively, however, the effect of changing the forming methods was still small, and hence the results obtained using avothane can be used for closed die forming if the M.B.R. is increased by say 10%.

7.3 Angle of Bend

Consideration of the strain undergone by an element of metal on a bend indicated that no difference should exist between specimens bent through 180° and 90°. This is generally upheld by the results of the carbon steel tests, whereas the stainless steel strip results would seem to indicate a small but significant increase in the M.B.R. for 180° bends. This departure from theory was almost certainly due to the action of the punch drawing the material into the avothane to a greater extent on 180° bends than on 90° bends. This would have caused a greater degree of thinning of the material at the bend, and therefore resulted in a higher M.B.R. This phenomenon would have a relatively greater effect on the initially thinner strip, and this is substantiated by the stainless results. The carbon steel however, had a higher yield stress and could not undergo such large plastic deformations as the stainless, and hence this drawing effect was not so pronounced.

7.4 Thickness of Strip

Over the range of thickness used, in the tests on carbon steel strip, there was no noticeable thickness effect. For the stainless, whilst the results for the perpendicular bends may be said to exhibit a slight trend of increasing M.B.R. with increasing thickness, no such trend can be attached to the results of the parallel bend tests. Since the results were not obtained for a single hardness value level (which is one of the most important variables), no significance can be attached to a thickness effect.

7.5 Direction of Bend

Consideration of Table III for stainless steel strip indicates that the direction of the bend axis relative to the direction of rolling is a vitally important factor. The M.B.R. obtained for parallel bends is greater by a factor of four over perpendicular bends. For carbon steel strip, in Table IV, the direction of bend is also seen to be a significant factor, but the effect is not so pronounced as for the stainless strip. This is because the heat treatment carried out on the carbon strip re-orientated the grains in the steel, reducing the mechanical fibring present; whilst the stainless, which was in the cold-worked condition, still had the grains elongated along the direction of rolling, giving the material more marked anisotropy than the carbon steel strip.

7.6 Carbon Content of Carbon steel Strip

The test results in Table IV indicate that the carbon content of the steel has no significant effect on the M.B.R. Logically, one can argue that this should not have been the case, since the higher carbon content should have produced a corresponding decrease in ductility for steels of the same hardness level. However, if this effect was present it was probably so small that the number of tests was insufficient to show its significancs, and it is therefore ignored.

The results of the tests can therefore be represented by plots of M.B.R. against hardness for various bend conditions, For the stainless this is done in Figs. 2 and 3, Fig. 2 showing the results for 180° parallel and perpendicular bends and Fig. 3 showing the results for 90° parallel and perpendicular bends. For the carbon steel the results are given in Figs. 4 and 5 for perpendicular and parallel bends respectively.

For the stainless strip Figs. 2 and 3 also show the relevant data for the lower hardness values drawn from our previous literature survey (1). For the 90° bends this is according to Skelskey (6) and for the 180° bends according to the Draft British Standard (7). For the perpendicular bends the results of the tests are seen to follow on well from the existing data, although it appears that the British Standard may be over-conservative. For the parallel bends the results show a very steep increase in M.B.R. for the higher hardness range and would appear to cast some doubt on the data for the lower hardness values, although further tests in these hardness ranges would have to be carried out to substantiate this.

For the carbon steel, Fig. 4 also shows the M.B.R. according to a Draft British Standard (8) and it can be seen that the results follow the quoted reference, although a large increase in M.B.R. would appear to be required for the hardness range above 600 HV. (This value being the upper limit in the reference).

8. COMPARISON OF THEORY AND PRACTICAL RESULTS

8.1 Nomenclature

A_f = reduction in area of material at fracture

A_t = reduction in area of material at fracture measured from tensile test specimen

A_b = apparent reduction in area of material in bend test

b_o = original specimen width in tensile test

b_1 = reduced specimen width after fracture in tensile test

ε_f = strain in material at fracture

ε_b = strain at fracture in bend test

ε_t = strain at fracture in tensile test

K_s = speed factor

M = minimum bend ratio

R_{in} = inside radius of bend (i.e. radius of punch)

S = rate of strain

S_b = rate of strain of specimen in bend test

S_t = rate of strain of specimen in tensile test

t_o = original strip thickness

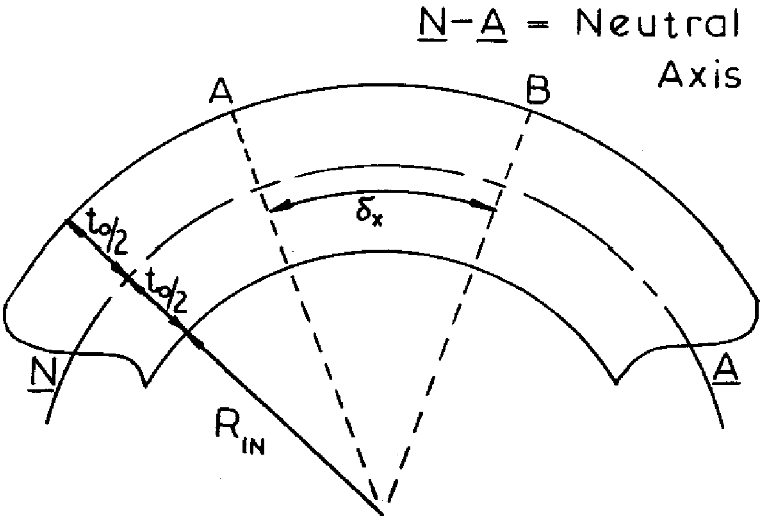
t_1 = reduced strip thickness after fracture in tensile test

t_b = reduced strip thickness at bend in bend test

δ_x = elemental strip length

8.2 Theory

Consider an elemental length of strip, δ_x long along the neutral axis of the strip. When the strip is bent around a punch of radius R_{in}, if the neutral axis is assumed to remain along the centre of the strip, then the situation is as shown below:-



Before bending, length AB = δ_x

$$\text{After bending, arc AB} = \left\{\frac{R_{in} + t_o}{R_{in} + t_{o/2}}\right\} . \ \delta_x$$

$$\therefore \text{ strain at outer fibre } (\varepsilon) = \frac{\left\{\frac{R_{in} + t_o}{R_{in} + t_{o/2}}\right\} . \ \delta_x - \delta_x}{\delta_x}$$

$$\therefore \varepsilon = \frac{1}{\frac{2R_{in}}{t_o} + 1}$$

but, R_{in}/t_o = bend ratio

When the strain at the outer fibre equals the strain at fracture of the material, then the bend ratio is the minimum bend ratio

$$\therefore \varepsilon = \varepsilon_f = \frac{1}{2M + 1} \qquad \text{..............} \quad (1)$$

Equation (1) is the simplest theoretical expression relating the M.B.R. to a material property ε_f, but in practice ε_f is impossible to measure. However, ε_f is related to the reduction of area at fracture (A_f) by the following relationship, and A_f is a measurable property of the material

$$\varepsilon_f = \frac{A_f}{1 - A_f}$$

Hence, equation (1) becomes

$$M = \frac{0.5 - A_f}{A_f} \qquad \text{..............} \quad (2)$$

Equation (2) is still purely theoretical and subject to the assumption made in the derivation, the three most notable being:-

a) The neutral axis remains central in bending
b) Speed of forming has no effect on the value of A_f
c) The material remains the same thickness at the bend

In practice, due to the difference in material properties in tension and compression, the neutral axis of the strip moves towards the inside of the bend as the bend is formed. This results in higher stresses at the outside of the bend with a corresponding increase in M.B.R. over that given by equation (2). Several attempts have been made to modify equation (2) to give a better approximation to the value of M.B.R. obtained in practice. Most notable amongst these are the following:-

$$M = \frac{0.6 - A_f}{A_f}$$

and $$M = \frac{0.585 - 1.085\ A_f}{A_f}$$

However, Mohnheim (2) attempts to reconcile empirical expressions such as those above and to replace them by a rational formula. He suggests, therefore, the following, which he states is in reasonable agreement with the above:-

$$M = \frac{(1 - A_f)^2}{1 - (1 - A_f)^2} \quad \text{..............} \quad (3)$$

Now, the value of A_f will be determined from measurements made on a specimen after fracture in a tensile test. However, the value of A_f is not a constant for a given material but is dependent upon various test conditions. When considering M.B.R. for use in high speed presswork the most important of these is the rate of strain (S). The value of the reduction (red.) of area at fracture measured from the tensile test (A_t) must be modified to obtain the value of A_f relevant to the speed of forming used in the press (A_b).

The relationship between the red. of area at speed in the bend test (A_b) and the red. of area of the tensile test (A_t) is

$$A_b = \frac{K_s - (1 - A_t)}{K_s} \quad \text{..............} \quad (4)$$

Where $$K_s = \frac{2.25 - 0.04 \log_{10} S_b}{2.25 - 0.04 \log_{10} S_t} \quad \text{..............} \quad (5)$$

Hence, by calculating or estimating the rate of strain of the bend test specimen in the press, (S_b), and the rate of strain of the tensile test specimen, (S_t), the factor K_s can be determined and used along with the measured red. of area at fracture from the tensile test specimen (A_t) to calculate the apparent red. of area at the press speed (A_b). The calculated value A_b can then be used as the relevant value of A_f in equation (3) above, to give the M.B.R. of the material at the press speed.

It is worth noting that equations (4) and (5) show the effect of speed of forming on the M.B.R. However, since the relationship is logarithmic a speed difference of a factor of 10 between two methods will only produce a slight change in A_b and hence in the M.B.R. Also, quite large errors in the estimate of S_b and S_t can be tolerated with only a relatively small effect on K_s.

The third major assumption of the theory which is not true in practice is that the thickness of the material at the bend remains the original thickness. In fact the material thins at the bend and the material must withstand both the deformation due to the bending and the thinning. To determine the thinning which will occur at a bend, Keifer (9) recommends the following relationship:-

$$t_b = \frac{2t_o}{2 + \varepsilon_f} \qquad \text{..............} \quad (6)$$

Now, $\varepsilon_f = \varepsilon_b = \dfrac{A_b}{1 - A_b}$,

Therefore using equation (4),

$$\varepsilon_b = \frac{K_s - (1 - A_t)}{(1 - A_t)}$$

Hence, substituting this into (6) above:-

$$t_b = \frac{2(1 - A_t)}{K_s + (1 - A_t)} \cdot t_o \qquad \text{..............} \quad (7)$$

Using the above equation (7), the material thickness at the bend can be calculated from the tensile test reduction of area, the speed factor, and the original thickness.

Using the above equation for the bend thickness in equation (3), for the M.B.R., the following can be derived:-

$$M = \frac{1}{\dfrac{4K_s^{\,2}}{K_s + (1-A_t)^2} - 1} \qquad \text{.............. (8)}$$

For the derivation of the above, see the Appendix. The M.B.R. predicted by equation (8) above takes into account the variation in reduction of area brought about by the different strain rates present in the tensile test and the press bend tests, the movement of the neutral axis during bending, and the thinning of the material at the bend during forming.

8.3 Calculation of Speed Factor (K_s)

To calculate the value of the speed factor, K_s, from equation (5), it is necessary to determine best possible estimates of the rate of strain in the press, (S_b), and the rate of strain in the tensile test, (S_t).

For the stainless steel specimens used, the average (ave.) reduction of area in the tensile tests was 0.42 (42%). Hence, the ave. value for the strain at fracture in the tensile test was:-

$$(\varepsilon_t)_{ave} = \frac{0.42}{1 - 0.42} = 0.72 \ (72\%)$$

The ave. duration of each tensile test was approximately 1½ minutes. Therefore, the ave. rate of strain in the tensile test was:-

$$S_t \approx \frac{0.72}{1.5} = 0.48 \text{ mm/mm/min}$$

As a first approximation to K_s in order to approximate the strain at fracture in the press, use $K_s \approx 0.95$. If the calculations reveal this to be grossly in error then they can be repeated with a better approximation to K_s.

If $K_s \approx 0.95$

$$(A_b)_{ave} = \frac{0.95 - (1 - 0.42)}{0.95} = 0.39 \ (39\%)$$

$$\therefore \ (\varepsilon_b)_{ave} = \frac{0.39}{1 - 0.39} = 0.64 \ (64\%)$$

The press rate = 160 punches/min.
press stoke = 32 mm

$\therefore$ ave. press velocity = 160 x 2 x 32 = 10240 mm/min

The ave. depth of stroke to bend the specimen through 90° was approximately 5 mm.

Hence, the ave. time to bend the specimen = $\frac{5}{10240} \approx 5.10^{-4}$ min.

Therefore, the ave. rate of strain in the press was:

$$S_b \simeq \frac{0.64}{5.10^{-4}} = 1280 \text{ mm/mm/min.}$$

$$\therefore K_s = \frac{2.25 - 0.04(\log_{10} 1280)}{2.25 - 0.04(\log_{10} 0.48)}$$

$$\therefore K_s = 0.94$$

This is very close to the first approximation of 0.95 used to determine the above value, and thus no significant improvement in the accuracy of the value of K_s will be achieved by repeating the calculation using $K_s = 0.94$ as a second approximation.

8.4 Discussion of Results

The values of M.B.R. predicted by equation (8) using the value of 0.94 for the speed factor are compared with the actual values determined from the bend tests in Table VI. The M.B.R. determined from the tests are quoted as ranges within which the actual M.B.R. would lie.

For the material tested it can be seen that the theoretical prediction gives a very good first approximation to the actual M.B.R. obtained in practice. It must be remembered that the results of the tests themselves were subject to appreciable error since the results were intended only as a guide. The theoretical results are generally seen to predict M.B.R.'s which are slightly higher than those obtained in practice, which is not altogether undesirable since manufacturers prefer M.B.R. data to be slightly conservative, for good reasons.

The theory would seem to cast doubt on the validity of presenting data on M.B.R.'s in the form of M.B.R. against hardness (hardness being used as a measure of ultimate strength). Hardness is not directly related to the material ductility, whereas the reduction of area is. It would seem more logical and accurate to present data in the form of M.B.R. against reduction of area, as it is the latter which is the controlling variable.

9. CONCLUSIONS

1. Data has been produced for the M.B.R. for stainless steel strip in the hardness value range 400-500 HV, and for hardened and tempered carbon steel in the hardness range 400-640 HV.

2. The effect of the method of forming on the M.B.R. has been investigated for avothane and closed die techniques. It has been determined that the effect is relatively small, the results reflecting the fact that closed die bend forming is a more severe method. It is suggested that to make use of the data presented in this report for situations where closed die bend forming methods are being used, an increase of approximately 10% on the M.B.R. should be used.

3. The effect of the speed of forming has been shown to be negligible over the punch speed range 160 to 60 punches per minute.

4. The effect of strip thickness on M.B.R. has not been shown to be significant for the range of thickness used.

5. The effect of the carbon content of the hardened and tempered carbon steel strip on the M.B.R. has been shown to be too insignificant to be determined by the tests employed in this project.

6. A theoretical method of predicting the M.B.R. based upon measurements of the reduction of area of the material in tensile testing has been presented, and the M.B.R. predicted by the method has been found to be in good agreement with the results from the tests on stainless steel strip for 90°

perpendicular bends.

10. SUGGESTIONS FOR FURTHER WORK

The work carried out in this project has opened up several possible avenues of further work, all of which would be of use to the spring industry. Possibly the most immediately important area is that of verifying the M.B.R. for parallel bends with stainless steel across a much wider hardness range. This is considered important because the results from this project in the high hardness range cast some doubt on the accuracy of the M.B.R. obtained from the literature for the lower hardness values.

Another important line of work would be to investigate the effect of strip width and edge conditions on the M.B.R. Several sources in our literature survey (1) state that strip width only becomes important in situations where the width/thickness ratio is less than 8, but no evidence is given to substantiate this and no information is given on the relationship between M.B.R. and width below this figure.

Strip edge conditions are widely thought to be another important factor affecting the M.B.R. obtained in practice and requires investigating. Work done in this project suggests that this factor will not be significant for stainless specimens, since almost all fractures obtained in the stainless initiated at the centre of the strip. However, it is more than likely that the edge condition will be significant for the carbon steel strip, since all cracks progressed from the edge, and the presence of stress raisers at the edge due to shearing marks, etc. can be expected to result in a higher M.B.R.

Further work could be directed at extending to other metals the validity of the theoretical approach presented in the report for approximating the M.B.R. To do this, the sensitivity of different materials to the speed of forming must be determined, in order that the speed factor may be calculated. The relationship expressed in equation (5) is taken ultimately from information presented by Kiefer (9). His report states that experimental evidence exists to substantiate the relationship but this evidence is not given, neither does it state for what materials the expression is valid. It may be general for all materials but this is unlikely, although it does give reasonable results for stainless steel as shown by this report. The expression can be expected to be valid for carbon steels, since it is used by Keifer in his article for calculations on the crimping of carbon steel wire. If this work is undertaken a much larger range of punches will be required in order to narrow the range within which an experimentally determined M.B.R. can lie. This will enable any discrepancies between theory and practice to be more accurately evaluated.

11. REFERENCES

1. Webb C. J. "Minimum Bend Ratios for Spring Strip Material - a Literature Survey". SRAMA Report No. 278. July, 1977.
2. Mohrnheim A. F. "Elongation, Strain and Minimum Bend Radius of Rod and Wire". Wire and Wire Products, 1964, Aug., pp. 1182-1186.
3. BS 1449. Part 2: 1975. "Stainless and Heat Resisting Steel Plate, Sheet and Strip".
4. BS 1449. Part 1: 1972. "Carbon Steel Plate Sheet and Strip".
5. Edgar Allen Balfour Steels. "Avothane".
6. Skelskey Jr. J. J. "Designing Strip Parts for Four Slides". Springs, 1965, Oct., pp. 16-23.
7. Draft BS 1449. Part 4. "Steel Strip for Spring Manufacturers - Martensitic and Austenitic Stainless Steel".
8. Draft BS 1449. Part 3. "Steel Strip for Spring Manufacturers - Prehardened and Tempered Steel".
9. Keifer J. M. "Guide for the Crimping or Bending of Wire". Metal Progress, 1962, May, pp.95-97.

TABLE I STAINLESS STRIP HARDNESS AND COMPOSITION

Thickness (in)	Ave. Measured Hardness (HV)	Composition		
		Carbon (%)	Nickel (%)	Chrome (%)
0.036	476	0.05	10.1	18.4
0.036	449	0.05	10.2	18.8
0.028	464	0.05	10.9	18.9
0.028	434	0.05	9.05	18.3
0.024	438	0.05	10.7	18.3
0.018	473	0.04	9.85	19.1
0.018	450	0.05	11.04	18.7
0.012	473	0.04	10.7	18.5
0.0108	452	0.05	8.75	18.5

TABLE II CARBON STEEL STRIP HARDNESS AND COMPOSITION

Steel Grade	Composition		Nominal Thickness (in)	Nominal Hardness (HV)	Ave. Measured Hardness (HV)
	Carbon (%)	Manganese (%)			
CS50	0.53	0.75	0.020	400	409
				600	608
				640	658
	0.52	0.80	0.030	400	396
				600	601
	0.50	0.80	0.040	400	385
				600	587
				640	630
CS80	0.74	0.79	0.020	400	402
				500	507
				640	637
	0.81	0.75	0.030	400	391
				500	515
				640	634
	0.78	0.72	0.040	400	373
				500	511
				640	629
CS100	0.97	0.41	0.020	400	395
				500	480
				600	607
	0.92	0.42	0.040	400	393
				500	489
				600	594

TABLE III STAINLESS TEST RESULTS

Thickness (HV)	Hardness (HV)	M.B.R.			
		Perpendicular		Parallel	
		90°	180°	90°	180°
0.036	476	2.7	2.8		
0.036	449	2.7	2.8		
0.028	464	2.1	2.5		
0.028	434	1.4	1.9		
0.024	438	1.2	1.8		8.8
0.018	473	1.6		8.7	8.4
0.018	450	1.6		8.7	9.5
0.012	473			6.6	7.7
0.0108	452			10.9	13.0

At the slower speed of 60 punches/min. all values for the M.B.R. remained the same except the following:-

0.036"/449 HV 180°⊥ 2.4
0.028"/434 HV 90°⊥ 1.1
0.028"/434 HV 180°⊥ 1.8

TABLE IV CARBON STEEL TEST RESULTS

Nominal Thickness (in)	Nominal Hardness (HV)	CS50			CS80			CS100		
		Bend Angle	M.B.R.		Bend Angle	M.B.R.		Bend Angle	M.B.R.	
			⊥	//		⊥	//		⊥	//
0.020"	400	90° 180°	3.0 2.7	4.0 3.4	90° 180°	2.8 3.2	5.6 6.7	90° 180°	3.0 3.3	4.9 4.5
	500				90° 180°	5.6 6.7	7.5 6.7	90° 180°	4.9 5.0	7.9 7.0
	600	90° 180°	8.0 7.1	8.0 7.6				90° 180°	9.8 8.6	9.8 12.5
	640	90° 180°	7.9 10.7	7.9 9.8	90° 180°	11.9 11.9	11.9 14.9			
0.030"	400	90° 180°	3.5 2.8	3.5 3.5	90° 180°	2.8 3.2	5.6 5.0			
	500				90° 180°	5.6 5.4	11.2 11.2			
	600	90° 180°	8.3 5.7	8.3 10.4						
	640				90° 180°	8.9 8.9	13.4 >11.2			
0.040"	400	90° 180°	2.8 3.3	3.7 3.5	90° 180°	2.7 2.7	5.8 5.8	90° 180°	3.3 4.2	6.9 5.9
	500				90° 180°	5.7 5.7	12.8 >7.1	90° 180°	5.5 7.0	8.7 8.7
	600	90° 180°	7.3 7.3	13.1 >7.3				90° 180°	10.3 10.3	10.3 >8.6
	640	90° 180°	10.3 10.3	>14.7 >7.4	90° 180°	12.8 12.8	>14.2 >7.1			

NOTE: The symbols ⊥ and // indicate perpendicular and parallel bends respectively.
The symbol > indicates that the M.B.R. is greater than the figure given.
Due to limitations in strip width the punch radius is limited to the size at which the strip just follows the punch profile fully. At M.B.R. greater than the figure given the strip is not bent through the full 90° or 180°.

TABLE V CLOSED DIE COMPARATIVE TEST RESULTS

A. Stainless Strip

Bend Details	Strip (Thk/HV)	M.B.R.	
		Closed Die	Avothane
90° ⊥	0.036/449	2.8	2.7
90° //	0.018/450	8.8	8.7
180° ⊥	0.036/449	2.8	2.8
180° //	0.024/438	9.1	8.8

B. Carbon Steel Strip (CS50 0.020" thick)

Bend Details	Hardness (HV)	M.B.R.	
		Closed Die	Avothane
90° ⊥	400 600 640	3.0 8.0 8.3	3.0 8.0 7.9
90° //	400 600 640	4.0 8.3 8.3	4.0 8.0 7.9
180° ⊥	400 600 640	3.0 8.0 10.7	3.0 8.7 10.7
180° //	400 600 640	4.0 8.3 9.8	4.0 8.3 9.8

TABLE VI COMPARISON OF THEORETICAL AND PRACTICAL RESULTS

Strip Details (Thk/HV)	Tensile Test Measurements					Calc. M.B.R.	Experimental M.B.R.
	Original Thickness (mm)	Original Width (mm)	Reduced Thickness (mm)	Reduced Width (mm)	Reduction of Area		
0.036/476	0.91	11.34	0.595	11.18	0.36	2.4	2.2-2.7
0.036/449	0.91	11.51	0.605	11.35	0.34	2.6	2.2-2.7
0.028/464	0.71	11.26	0.400	11.13	0.44	1.8	1.4-2.1
0.028/434	0.71	11.51	0.400	11.31	0.45	1.7	1.0-1.4
0.024/438	0.60	11.42	0.325	11.21	0.47	1.6	0.6-1.2
0.018/473	0.46	11.51	0.275	11.40	0.41	2.0	0.8-1.6
0.018/440	0.46	11.68	0.260	11.47	0.44	1.7	0.8-1.6

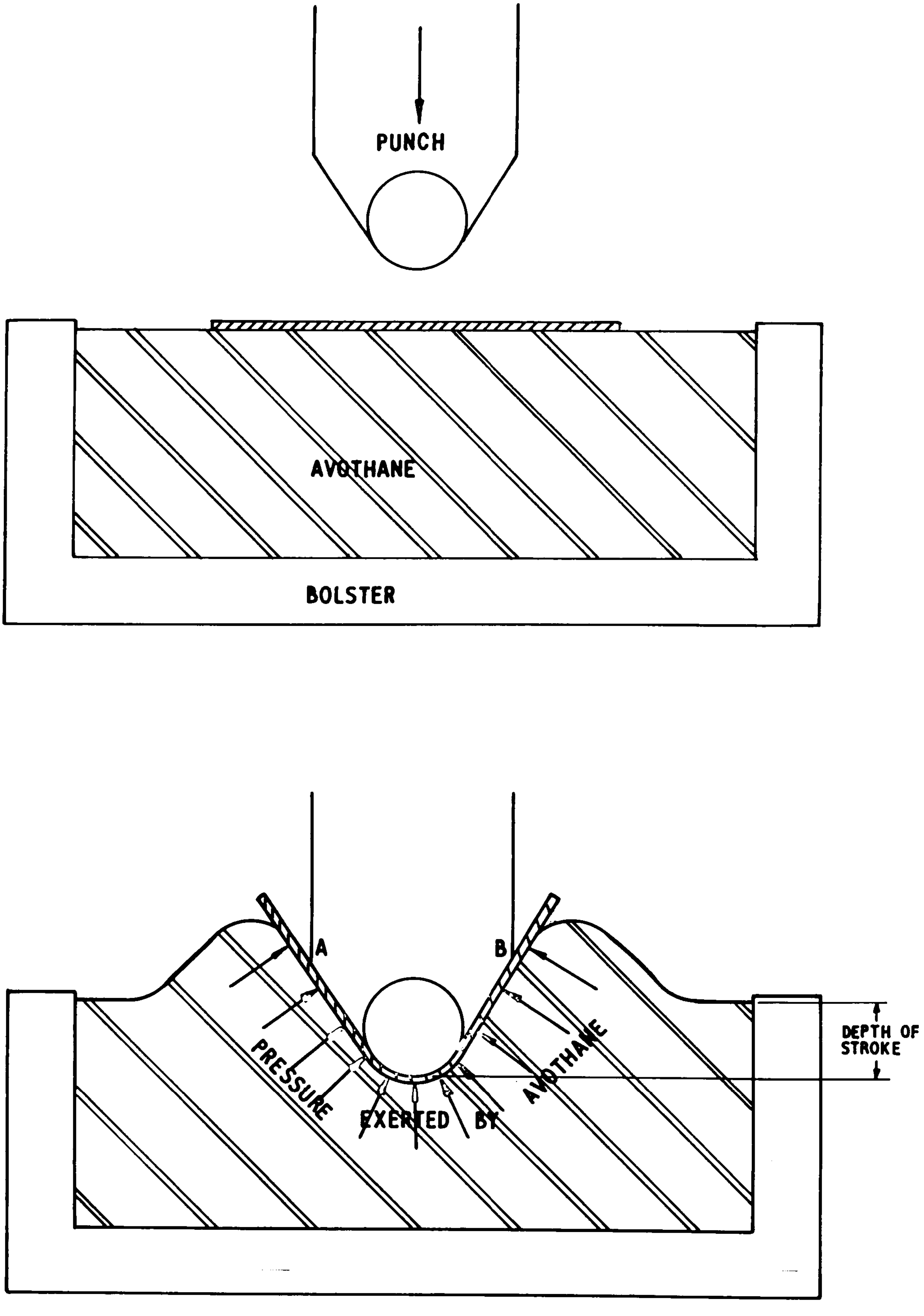


FIG. I. DIAGRAM ILLUSTRATING AVOTHANE FORMING.

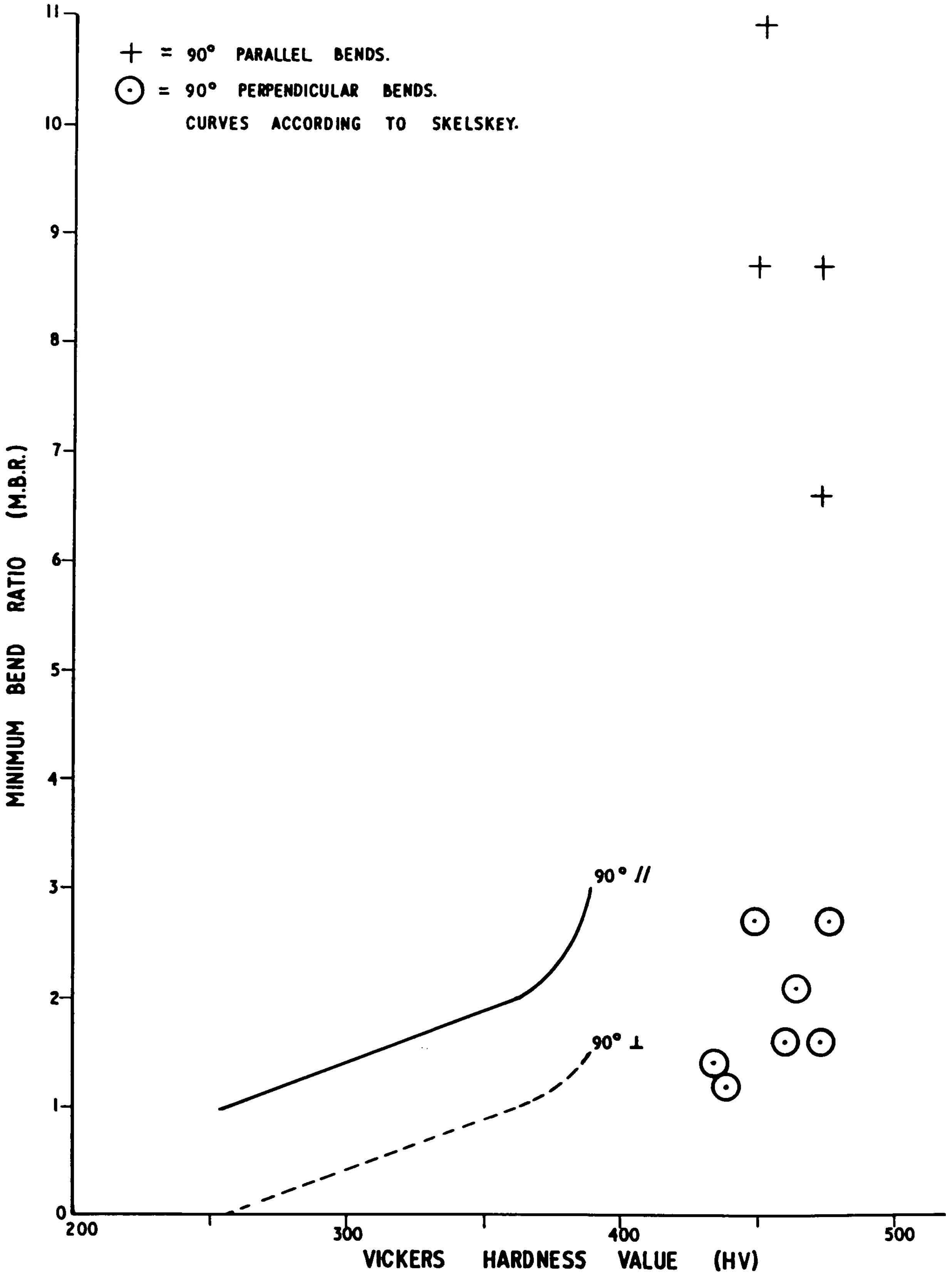


FIG. 2 M.B.R. Vs. HARDNESS FOR 302 TYPE STAINLESS STEEL STRIP 90° BENDS.

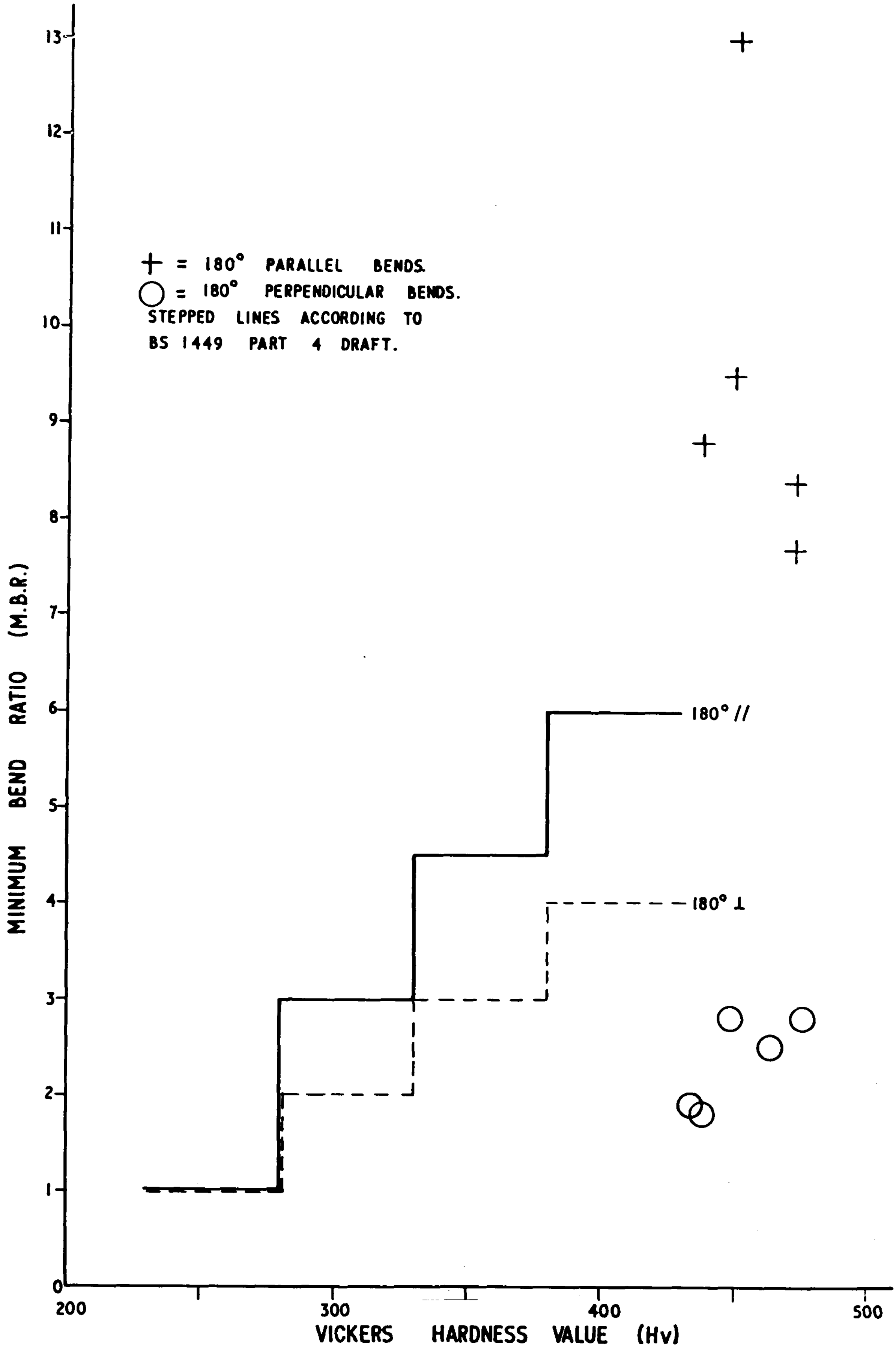


FIG. 3. M.B.R. Vs. HARDNESS FOR 302 TYPE STAINLESS STEEL STRIP. 180° BENDS.

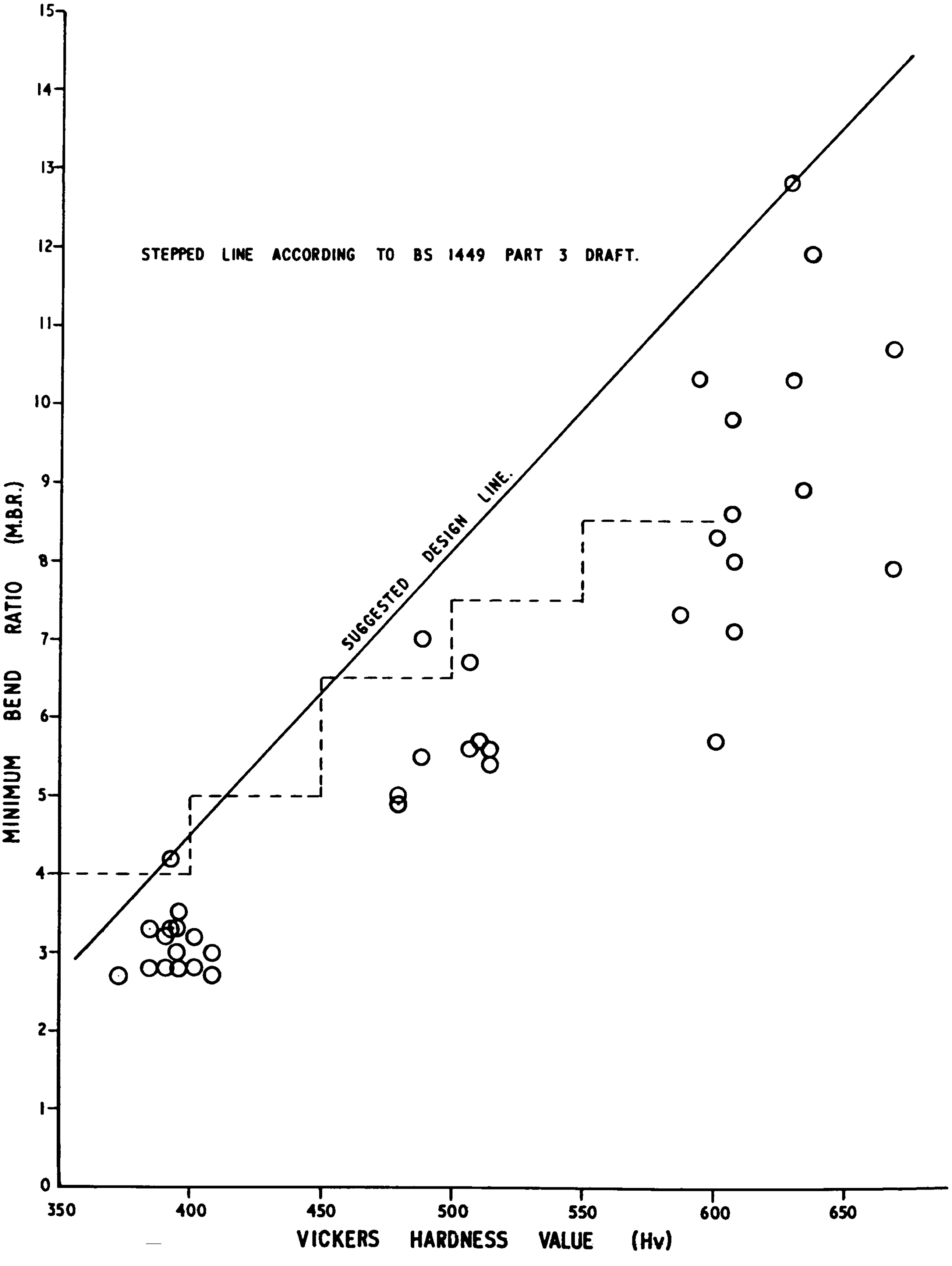


FIG. 4 M.B.R. Vs. HARDNESS FOR HARDENED AND TEMPERED CARBON STEEL STRIP PERPENDICULAR BENDS.

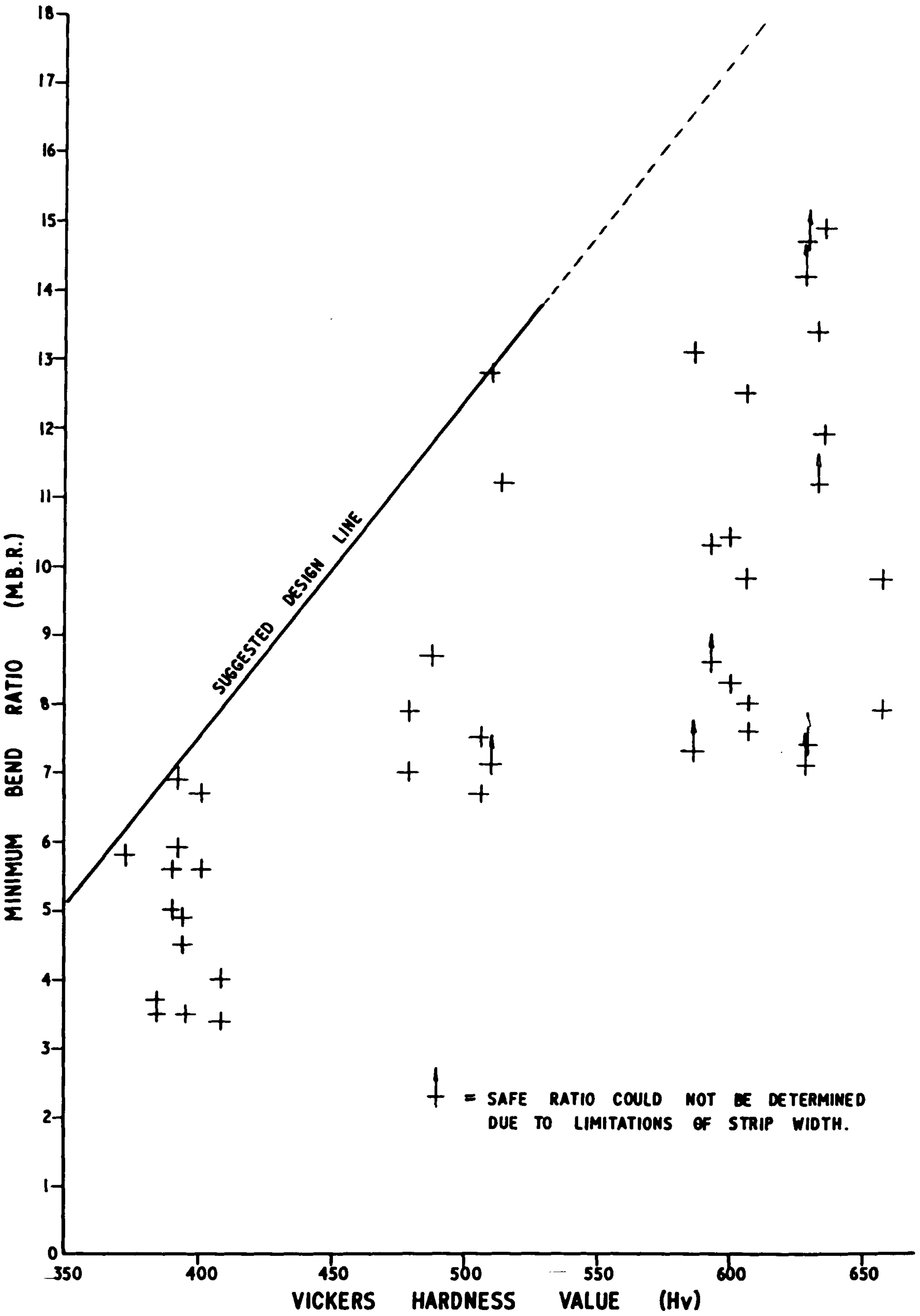


FIG. 5. M.B.R. Vs HARDNESS FOR HARDENED AND TEMPERED CARBON STEEL STRIP PARALLEL BENDS.

APPENDIX   DERIVATION OF EQUATION (8) PAGE 14

Mohrnheim introduces an elongation factor due to thinning (E_t) defined as

$$E_t = \frac{t_o}{t_b}$$

and, to account for thinning in the bending operation he suggests the relationship of equation (3) page 12 for approximating the M.B.R. becomes

$$M = \frac{E_t^{\,2}(1 - A_b)^2}{1 - E_t^{\,2}(1 - A_b)^2} \qquad \text{..............} \quad \text{(A)}$$

However, to account for speed (equation (4) page 12)

$$A_b = \frac{K_s - (1 - A_t)}{K_s} \qquad \text{..............} \quad \text{(B)}$$

Now, $A_t = \dfrac{a_o - a_1}{a_o}$ where a_o = original cross sectional area of tensile specimen a_1 = reduced cross sectional area after fracture.

$$\therefore\ 1 - A_t = \frac{a_1}{a_o} = \frac{b_1 t_1}{b_o t_o} \qquad \text{..............} \quad \text{(C)}$$

Substituting this relationship into equation (B) gives

$$A_b = \frac{K_s - \left\{ b_1 t_1 / b_o t_o \right\}}{K_s} = 1 - \left\{ \frac{b_1 t_1}{K_s b_o t_o} \right\}$$

Substituting this into equation (A) gives

$$M = \frac{K_t^2 \cdot \left\{\dfrac{b_1 t_1}{K_s b_o t_o}\right\}^2}{1 - E_t^2 \cdot \left\{\dfrac{b_1 t_1}{K_s b_o t_o}\right\}^2}$$

But $E_t = \dfrac{t_o}{t_b}$

$$\therefore\ M = \frac{\left\{\dfrac{b_1 t_1}{K_s b_o t_b}\right\}^2}{1 - \left\{\dfrac{b_1 t_1}{K_s b_o t_b}\right\}^2}$$

$$\therefore\ M = \frac{\left\{b_1 t_1\right\}}{(K_s b_o t_b)^2 - (b_1 t_1)^2} \qquad \ldots\ldots\ldots\ldots\ldots \text{(D)}$$

However, from equation (7) page 12

$$t_b = \left\{\frac{2\ (1 - A_t)}{K_s + (1 - A_t)}\right\} \cdot t_o$$

Substituting for $(1 - A_t)$ from equation (C) into above gives

$$t_b = \frac{2 b_1 t_1}{b_o t_o} \cdot t_o \cdot \left\{\frac{1}{K_s + \left\{\dfrac{b_1 t_1}{b_o t_o}\right\}}\right\}$$

$$\therefore \; t_b = \frac{2b_1t_1}{b_o} \cdot \left\{ \frac{b_o t_o}{K_s b_o t_o + b_1 t_1} \right\}$$

$$\therefore \; t_b = \left\{ \frac{2b_1t_1}{K_s b_o t_o + b_1 t_1} \right\} \cdot t_o$$

$$\therefore \; K_s b_o t_b = \frac{2K_s b_o t_o b_1 t_1}{K_s b_o t_o + b_1 t_1} = b_1 t_1 \left\{ \frac{2K_s}{K_s + \left\{ b_1 t_1 / b_o t_o \right\}} \right\}$$

Substituting the above into equation (D) gives

$$M = \frac{1}{\left\{ \dfrac{4K_s^{\,2}}{\left\{ K_s + (1 - A_t) \right\}^2} \right\}} - 1$$

The above relationship is equation (8) page 14 proved.