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An assessment of the critical strains which can be sustained by a mar-ageing steel under bi-axial tension

- by -

R. Pearce

Mar-ageing steels are being specified more and more in advanced engineering applications, and, frequently, the components are manufactured from sheet material. Consequently, the evaluation of the sheet forming properties of this material is of paramount importance; this investigation forms part of this general program.

The aim here is two-fold, firstly, to determine the maximum strain which can be sustained under bi-axial stress, and secondly, to suggest any way in which this value can be increased.

The material has been stressed bi-axially in a variety of ways, and the critical strain measured on a grid of 0.1″ diameter circles imprinted on the sheet prior to forming by the Electromark process. This has been developed by several firms in the USA and described by Keeler(1). Deformation was carried out using the 35 ton Hille Engineering Press equipped with an Advance HR100 X-Y Recorder to give accurate load-extension curves. Serrated blankholders were installed to prevent the blank from drawing-in (figure 1). Bulging - to 50 mm. diameter - was effected using firstly the pvc-technique described by Pearce(2) and secondly using conventional oil pressure - to 100 mm. diameter. Punch stretching was carried out with a 50 mm. hemispherical punch, with and without oiled (TSD996) polyethylene film interposed between the punch and the workpiece. Typical cups are shown in figure 2.

The first work was done to see what accuracy could be expected from grid measurements. The results were somewhat disappointing, for, the thickness of the grid line was such that increasing magnification only increased the uncertainty of the positions to which measurements should be made. Thus the accuracy by this method is only about ± 4%. It was then decided to use the grid circles merely as position-determiners to measure the thickness at the estimated centre of each circle with a clock gauge reading to .0001 in. and the cup placed on a spherical seat (Fig. 3). From this measurement the thickness strain could be plotted against initial radial position, if it was desired to show the material distribution over the cup profile, and, assuming constant volume, the surface strain can be computed (see Appendix 1) at or near the pole, where a balanced bi-axial stress state obtains, to an accuracy of ±1.5%. The material used for this investigation was provided free-of-charge by Bristol Aerojet Ltd. The surface finish was poor, being heavily ridged (Figure 4). A talysurf trace of the surface profile is shown in Fig. 5. The variation in gauge is given in the tables showing the results of the various tests carried out in this investigation. Fortunately, the short-range variation was slight and six flange readings, three 'on' and three 'off' (see Figure 6) were taken on each cup and the average of these taken to be the 'gauge' of the blank. The pattern of the results obtained indicate that the errors in this assumption are small. The results of the experimental work, carried out in the manner described above, are given in the following sections.

Stretch-forming (50 mm. dia., hemispherical punch) without lubrication.

Table 1

Specimen	Average gauge (ins.)	Surface Strain %	Cup height (ins.)	Av. of 3 readings Ht. 30 Kilos
1	0.0333	18.3	0.550	353
3	0.0336	18.6	0.525	362
4	0.0330	17.9	0.540	364
5	0.0326	19.8	0.590	366
6	0.0336	19.8	0.560	360
7	0.0345	18.2	0.578	349
8	0.0334	17.8	0.542	362
9	0.0338	21.2	0.610	333
10	0.0343	21.8	0.600	364

The average maximum strain developed is 19.6%. The spread of results and properties can be seen from Table 1 and Figure 7. There is a general trend indicating greater surface strains and cup heights with lower hardness, but the correlation is not significant.

Table 2

Stretch-forming (50 mm. dia. hemispherical panels).
Lubricated with oil-coated (TSD996) polyethylene film.

Specimen	Average gauge (ins.)	Surface Strain (%)	Cup height (ins.)
1L	0.0334	20.2	0.530
2L	0.0349	25.8	0.535
3L	0.0340	17.0	0.495
4L	0.0330	21.2	0.540
5L	0.0326	22.9	0.525
6L	0.0328	28.1	0.570
7L	0.0336	29.2	0.570
8L	0.0333	25.0	0.555
9L	0.0333	28.1	0.585

The average maximum strain developed is 24.1%. Which is significantly higher than in the unlubricated case. The effect of lubrication on the load-penetration curves can be seen in Figure 8. The trend of surface strain vs. cup height seems better than in the unlubricated case.

Table 3

Bulging using pvc (IRHD 75) 'punch' (50 mm. dia.)

Specimen	Average gauge (ins.)	Surface strain %	Cup height (ins.)
HR1	0.0338	- 22.3	.573
HR2	0.6330	- 17.9	.487
HR3	0.0338	- 24.5	.608
HR4	0.0330	- 22.5	.550
HR5	0.0331	- 17.9	.520
HR6	0.0321	7.7	.435
HR7	0.0341	17.0	.493
HR8	0.0331	14.9	.490
HR9	0.0334	17.0	.505
HR10	0.0339	- 21.2	.548

Soft thiokol rubber (39 IRHD) was used originally (see Table 3a), but the high forming loads involved extruded this material down past the ram and so a hard pvc (75 IRHD) was substituted. This proved satisfactory. The average maximum strain developed is 18.3%. However, there is a particularly low reading (HR6) and if this is ignored the value rises to 19.5%. The much more erratic results here should be noted, coupled with a greater correlation between columns 3 and 4. The very low result (HR6) does correspond to the lowest gauge (0.0321") yet encountered.

Table 3a

Bulging using thiokol rubber (IRHD39) 'punch' (50 mm. dia.)

Specimen	Average gauge (ins.)	Surface strain (%)
R1	-	14.0
R2	0.0331	17.7

The height of these specimens and the surface strains generated are comparable with the values in Table 4 for the two hydraulically-bulged large specimens. This result is not unreasonable for these two modes of deformation should produce comparable results.

Table 4

Hydraulically bulged cups (100 mm. dia.)

Specimen	Average gauge (ins.)	Surface strain (%)
HY1		17.2
HY2		19.0

Only two specimens were deformed by this method as the maximum strains produced were similar to those found by other methods.

Discussion

It is most instructive to plot strain versus initial radial position for typical cups produced by the methods heading Tables 1 through 4. These are shown in Figures 9 to 13, and the different shapes of these curves and the different areas they enclose should be noted.

Figure 9, showing typical curves for specimens 1, 2 and 7 exemplifies (vide Ericksen cup-testing) the way in which, in unlubricated cup-stretching, fracture occurs away from the pole and it also shows the relative lack of strain in the unsupported cup walls, i.e. position 16 has strained about 4% in specimen 1 while a similar position has strained 8.5% in specimen HR1 (Figure 12). As far as maximum strains developed is concerned, the two series 1 and 1L et seq., behave over the pole as would be expected in, say, the Ericksen test, decreasing friction moving the fracture pole-wards and increasing the maximum strain developed at the pole. The average cup heights are very similar in both cases, though, which differs from the usual Ericksen result. The reason for this can be seen from a comparison of Figures 9 and 10. In Figure 9 there are two regions of high strain (~ 22%), whereas in Figure 10 there is one region of very high strain (~ 30%) and these two tend to balance. The shape of the curves near the flange is characteristic of unsupported punch-stretching. Figure 11, showing the soft-rubber bulging also shows this effect due to back-extrusion of the rubber, as previously mentioned. This produces the same 'unsupported' effect.

Figure 12 shows ± curves for pvc-bulging, where work is done over the whole area of the blank, due to hydrostatic pressure, and the validity of this experimental method is confirmed by comparing this with Figure 13 showing the oil-bulged sheets.

More work is done on the blank under the conditions shown in these last two figures, exemplified by the greater areas under the curves, and confirmed by comparing the cup shapes by eye. On the other hand, the <u>maximum</u> strains developed are shown in the lubricated metal-punch experiments.

It is thought that this is due to the wide variation of material properties, as shown by the scatter of the results. The surface finish also leaves much to be desired, the sharper of the 'grooves' could well provide sites for fracture initiation andpremature failure. Consequently, punch-stretching provides a support - the friction between the punch and the sheet - not present in the hydrostatic tests and so, here, the number of early failures is minimized. This accounts for the higher strains listed in Table 2 and also for the more consistent results. However, it blurs the real variations in material properties and so correlation between maximum surface strain and cup-height is better for the bulged than for the punch-stretched material.

Conclusions

This investigation aimed primarily to determine the maximum strain which could be sustained by this material when subjected to bi-axial tension.

This can be derived theoretically for an ideal material - homogeneous and isotropic.

Assuming the relationship:

$$\sigma = K\epsilon^{n}$$

for the true stress (σ) true strain (ϵ) curve, where n is termed the work-hardening exponent and K is a constant. It can further be shown that, at instability in uniaxial tension the true strain, ϵ, equals the work-hardening exponent;

$$\epsilon = n$$

and for balanced biaxial tension:

$$\epsilon = 2n$$

So, the available strain in the latter case is much greater than in the former. This relationship is only quantitative in the case of an ideal material, but it is likely that the general statement will apply for real materials.

In the case of the mar-ageing steels tested in this investigation, the total tensile elongation measured approximately 10%. The maximum strain at instability in the bi-axial tests varied between 7.7% and 29.2%, while 90% of the specimens gave strains in the range 16%-25%. Thus, 20% would be a reasonable practical maximum to impose for sheet metal forming operations. However, the actual range quoted shows the variations which occur and every effort should be made to improve this situation by closer metallurgical control. In addition, the surface finish leaves much to be desired.

Appendix I

Calculation of surface strain from thickness measurements

If d_o = original diameter

d = final diameter

t_o = original thickness

t = final thickness

Then

$$\frac{\pi d_o^2 t_o}{4} = \frac{\pi d^2 t}{4}$$

$$\therefore \; d_o^2 t_o = d^2 t$$

$$d = \sqrt{\frac{d_o^2 t_o}{t}}$$

$$= \frac{0.01 \; t_o}{t}$$

Percentage strain is of course, $\frac{d - d_o}{d_o} \times 100$.

Appendix II

After the above work had been completed, it was thought politic to check that the material was in the fully-annealed condition. Consequently, samples were annealed for $\frac{1}{2}$ hour at 820°C, and the Vickers hardness number checked. The results are shown in Tables 5, 6 and 7. It will be noted that in all cases the hardness has increased, the unlubricated stretch-formed cups show a marked decrease in maximum surface strain developed (see Table 1) while the others are not very different from the unannealed material.

The reason for this could well be that the annealing process affects the frictional characteristics of the metal and thus the unlubricated results would demonstrate an effect which could not operate in the lubricated or pvc-case.

Appendix III

Suggestion for the continuation of this project

1) The increase in hardness with annealing should be investigated using no special atmosphere and an argon atmosphere.

2) The effect of surface finish on stretch formability should also be studied. Material with a 'good' surface should be produced and the results, and their scatter, analyzed.

3) The general question of heat-treatment for increased ductility should be considered.

Table 5

Stretch-forming (50 mm. dia., hemispherical punch) without lubrication

Specimen	Average Gauge ins.	Surface Strain %	Hardness
1A	.0332	16.0	368
2A	.0334	17.5	373
3A	.0338	12.2	381
4A	.0340	11.2	381
5A	.0343	7.9	377
6A	.0332	8.6	377

Table 6

Stretch-forming (50 mm. dia. hemispherical panels).
Lubricated with oil-coated (TSD996) polyethylene film.

Specimen	Average Gauge ins.	Surface Strain %	Hardness
L1A	.0340	27.3	377
L2A	.0343	25.4	377
L3A	.0338	18.3	377
L4A	.0342	27.0	377

Table 7

Bulging using pvc (IRHD 75) 'punch' (50 mm. dia.)

Specimen	Average Gauge ins.	Surface Strain %	Hardness
HR1A	.0339	19.3	375
HR2A	.0350	20.2	375
HR3A	.0345	21.2	373
HR4A	.0343	21.2	373

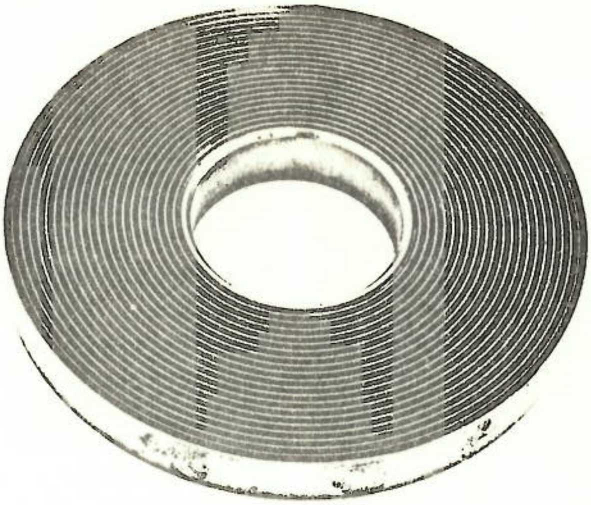


Figure 1

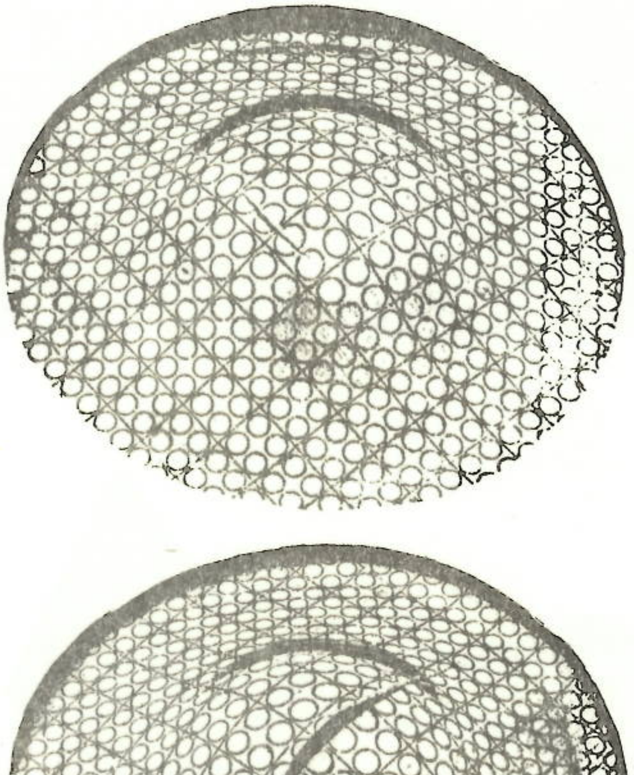


Figure 2

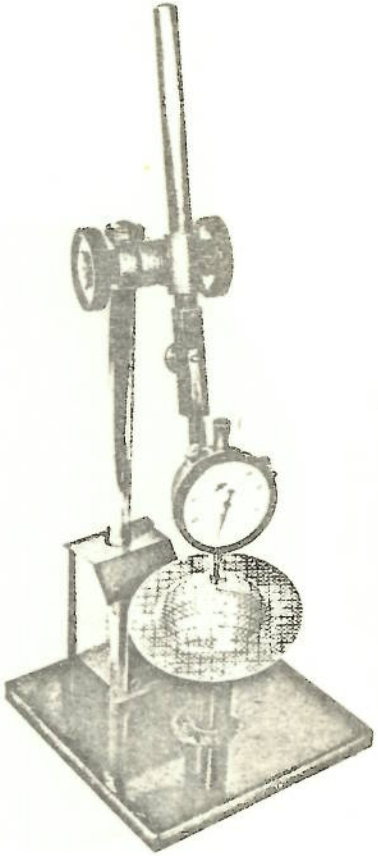


Figure 3

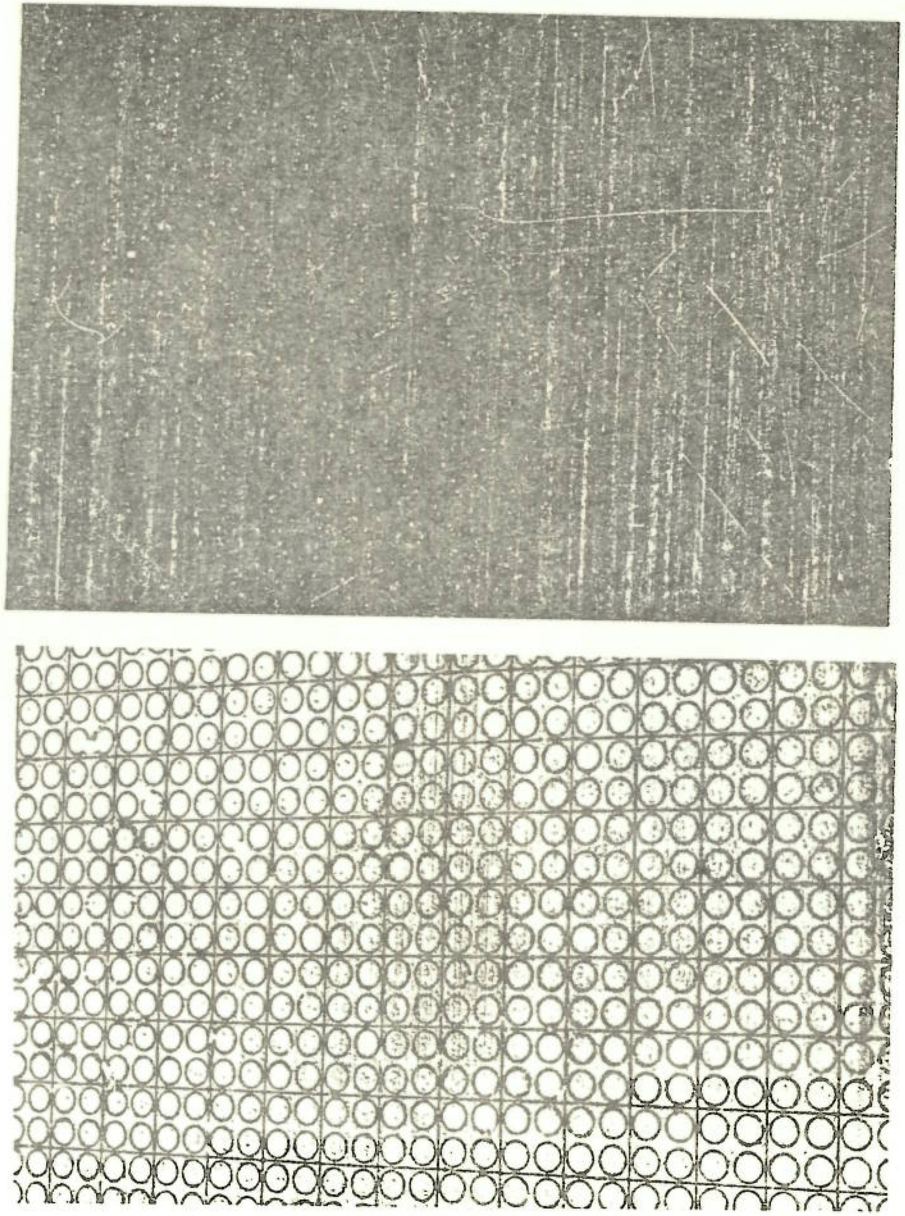


Figure 4

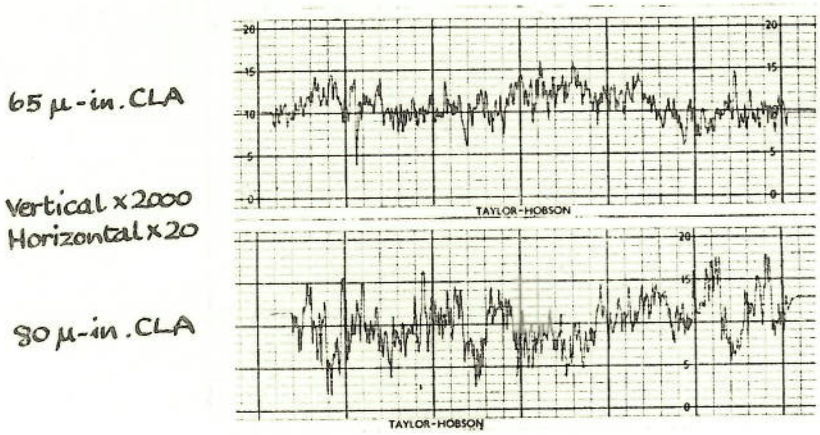


Figure 5

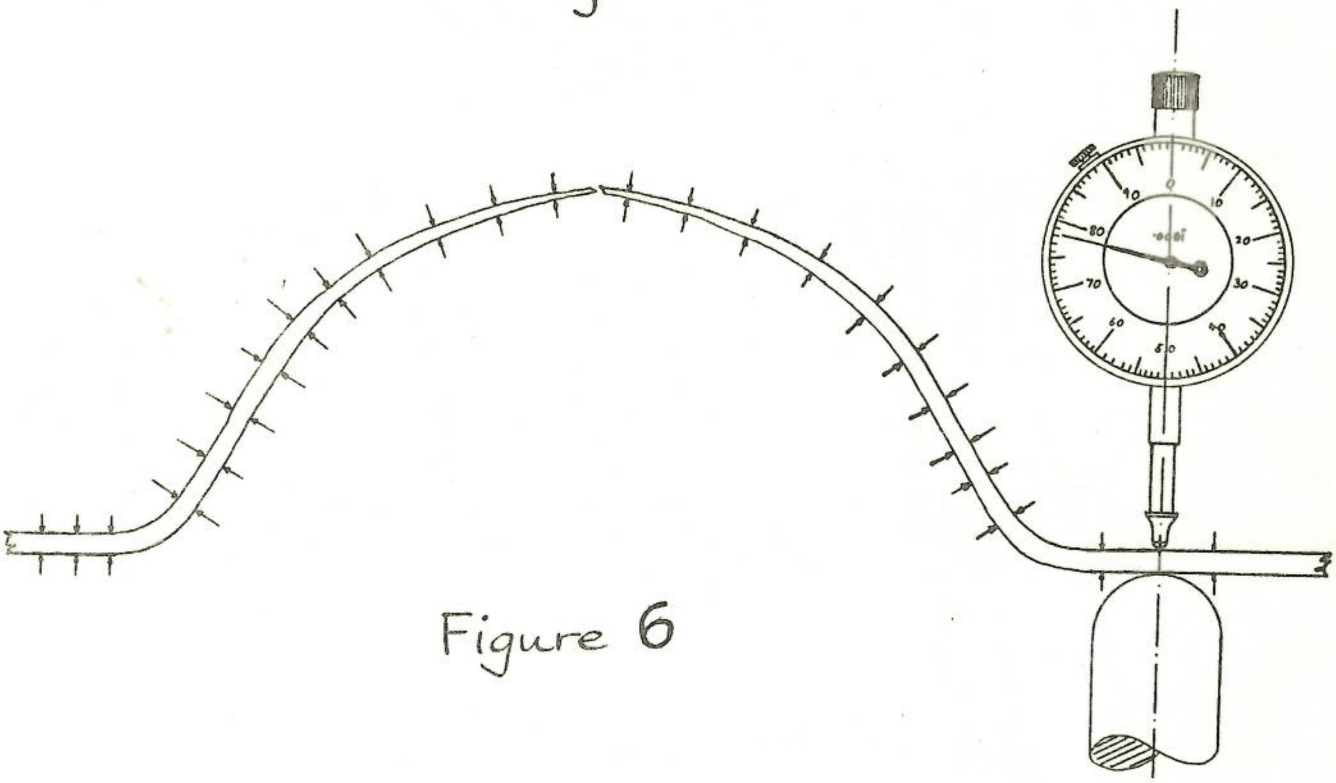
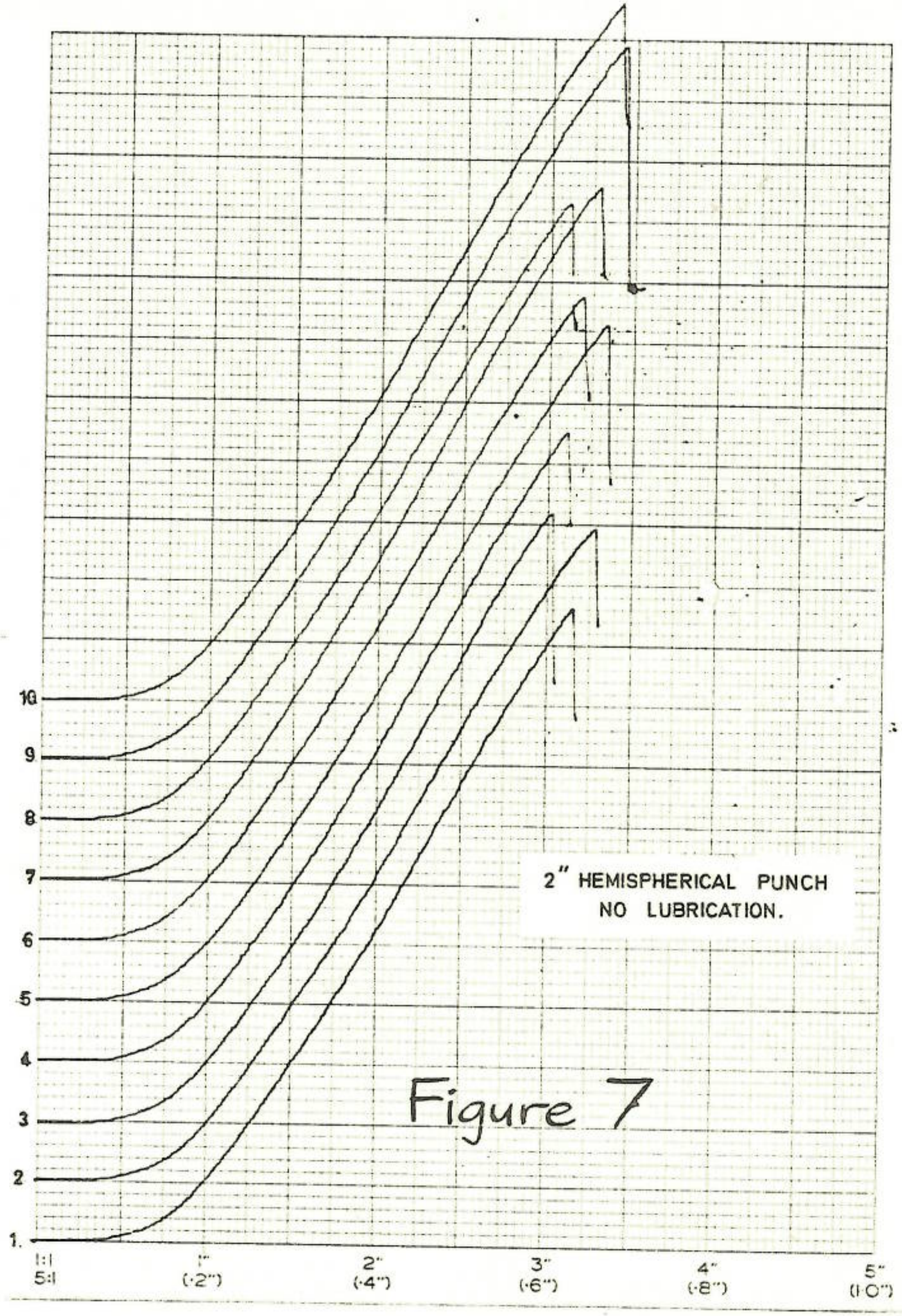
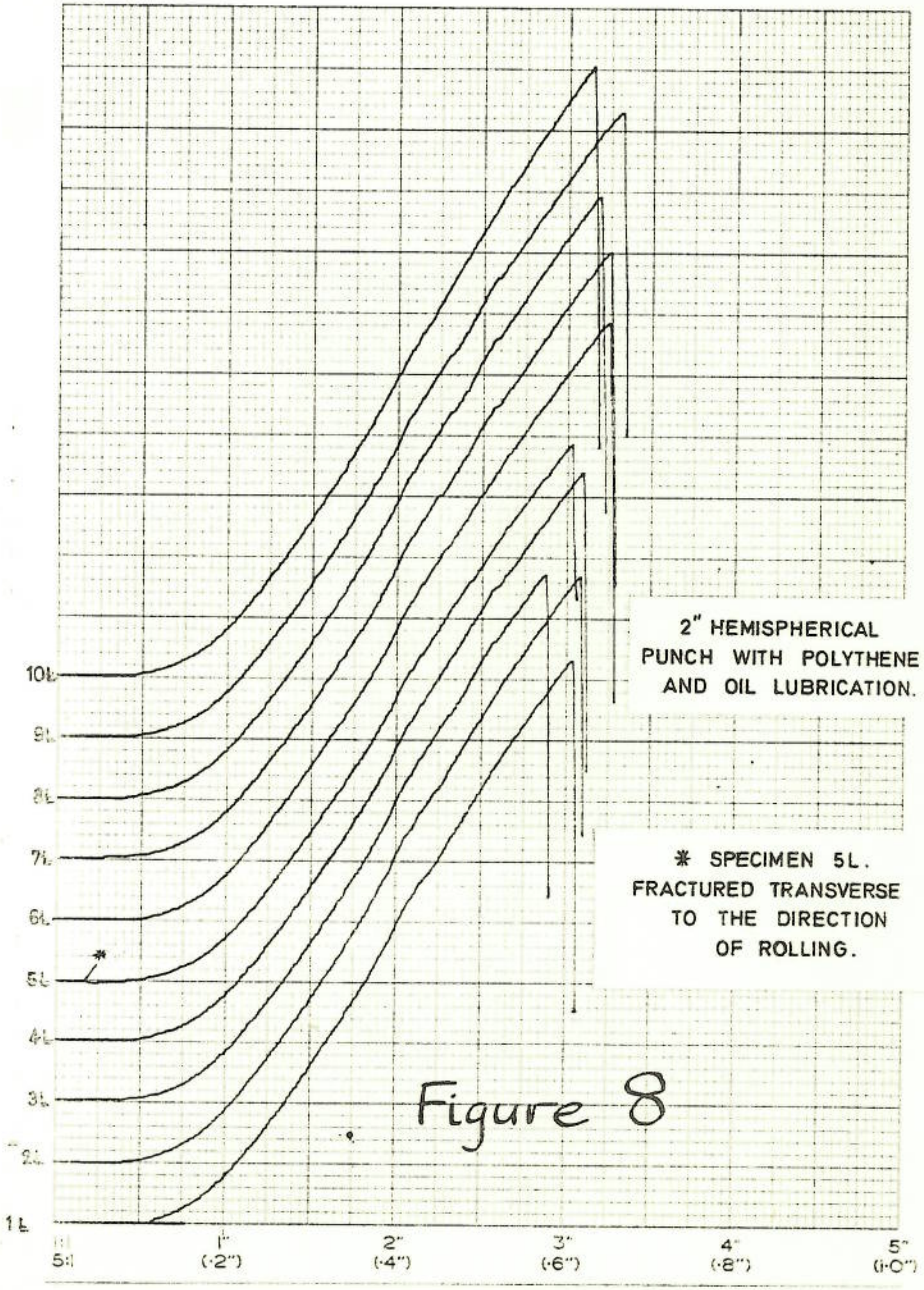


Figure 6



2" HEMISPHERICAL PUNCH
NO LUBRICATION.

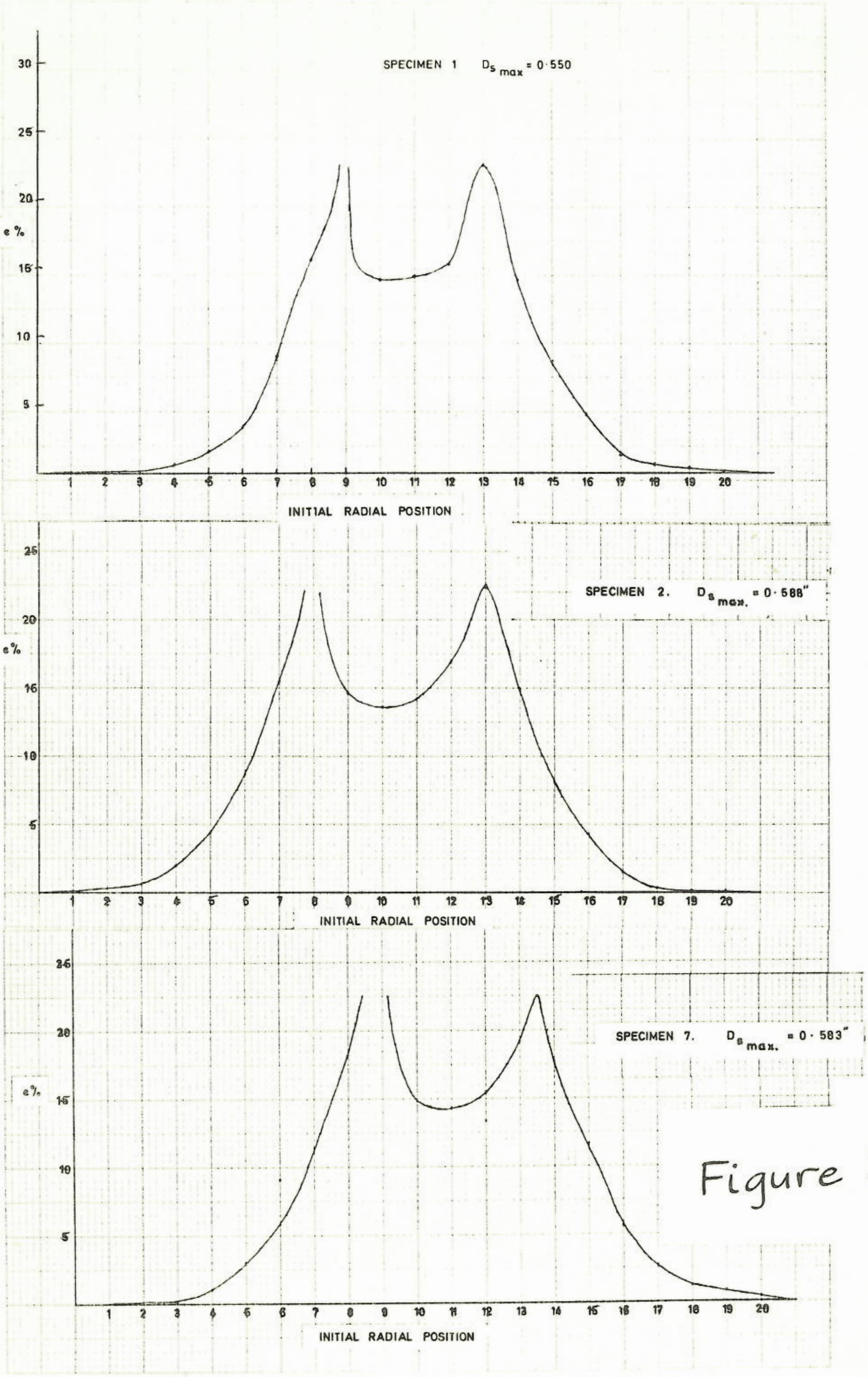
Figure 7



2" HEMISPHERICAL
PUNCH WITH POLYTHENE
AND OIL LUBRICATION.

✱ SPECIMEN 5L.
FRACTURED TRANSVERSE
TO THE DIRECTION
OF ROLLING.

Figure 8


SPECIMEN 1 $D_{s\,max}$ = 0·550
e %
30
25
20
15
10
5
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION
SPECIMEN 2. $D_{s\,max.}$ = 0·588"
e%
25
20
15
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION
SPECIMEN 7. $D_{s\,max.}$ = 0·583"
e%
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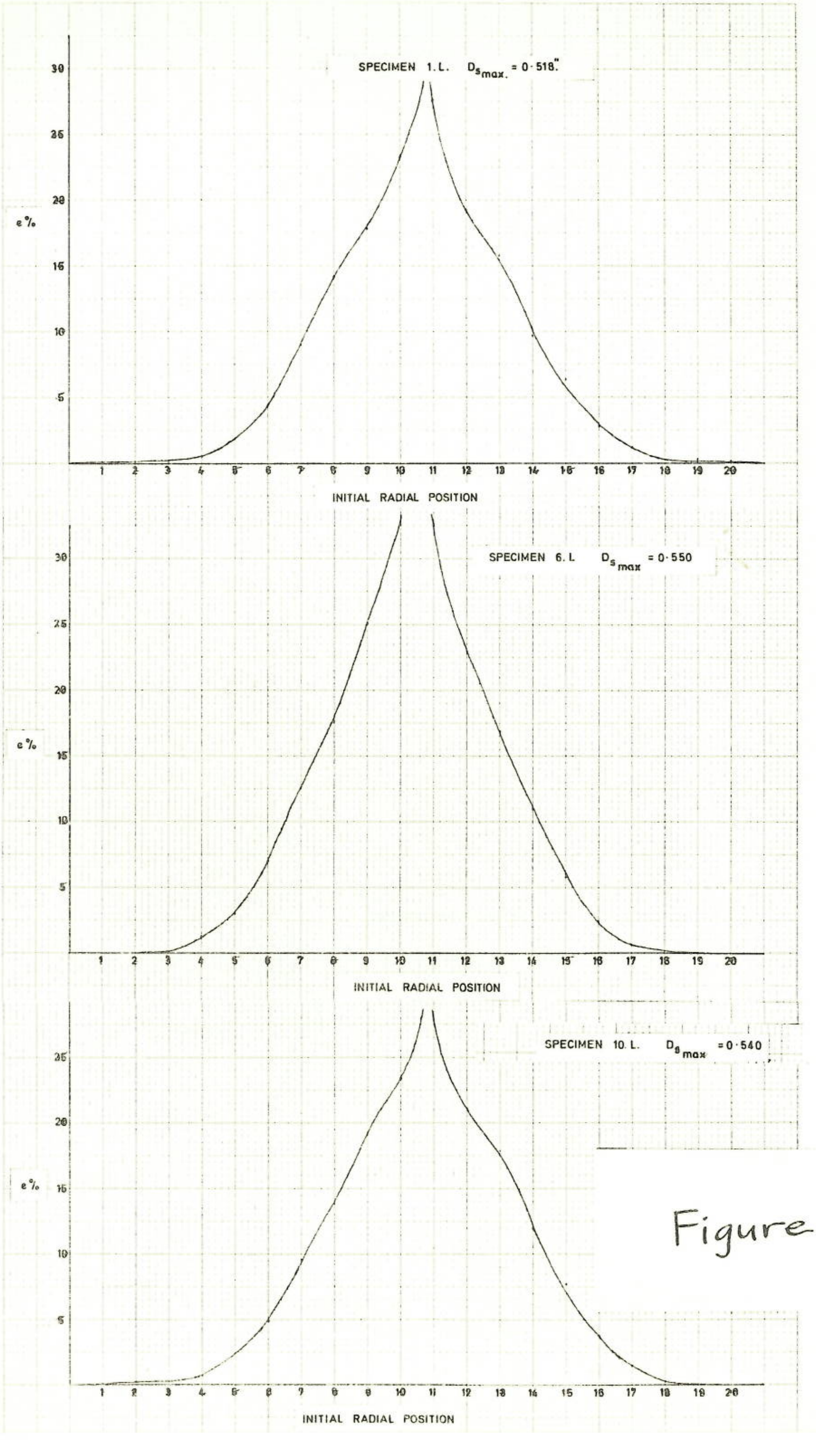
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION

Figure 9


SPECIMEN 1. L. $D_{s_{max.}} = 0\cdot518''$
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION
SPECIMEN 6. L. $D_{s_{max}} = 0\cdot550$
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1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION
SPECIMEN 10. L. $D_{s_{max}} = 0\cdot540$
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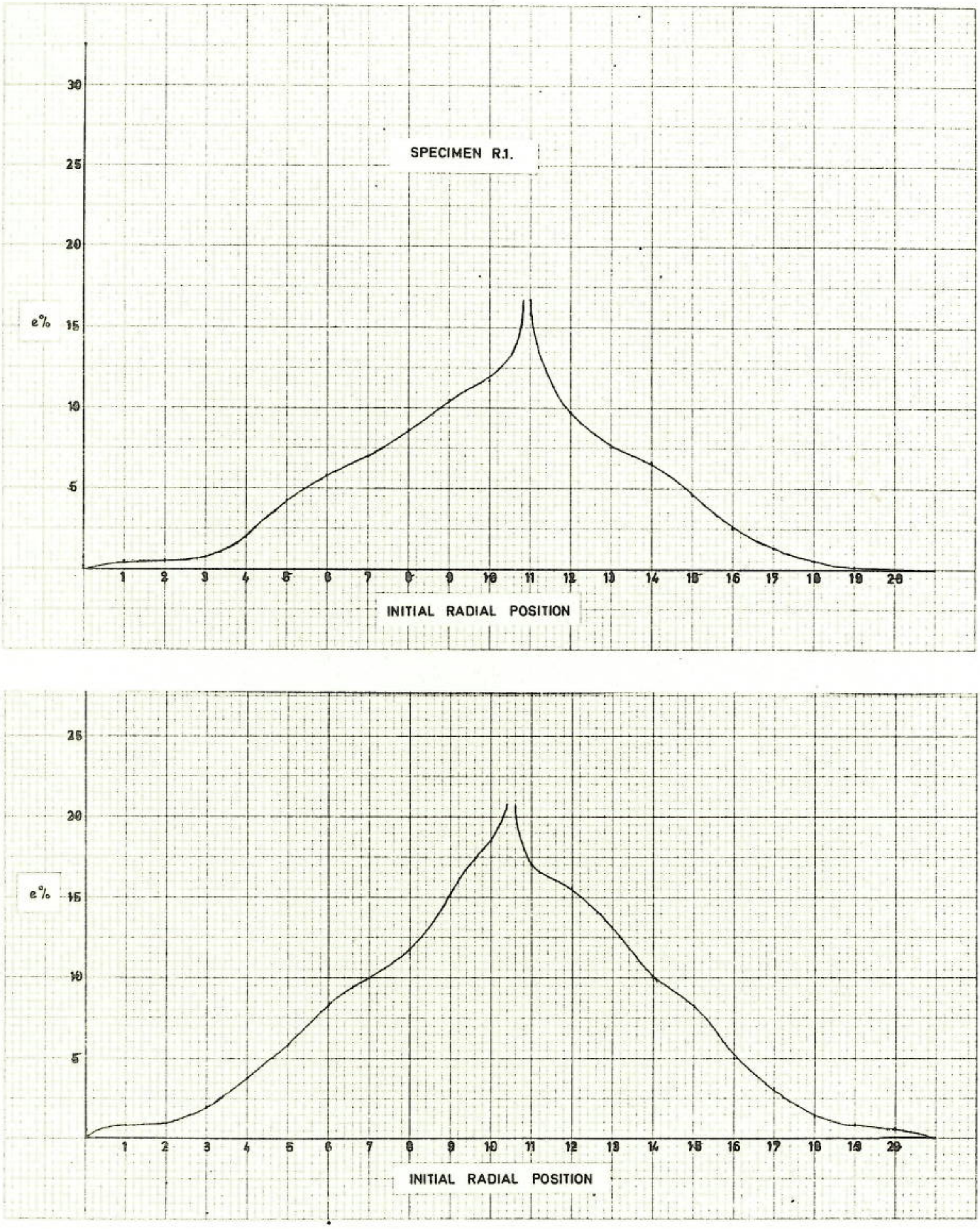
INITIAL RADIAL POSITION

Figure 10


SPECIMEN R.1.
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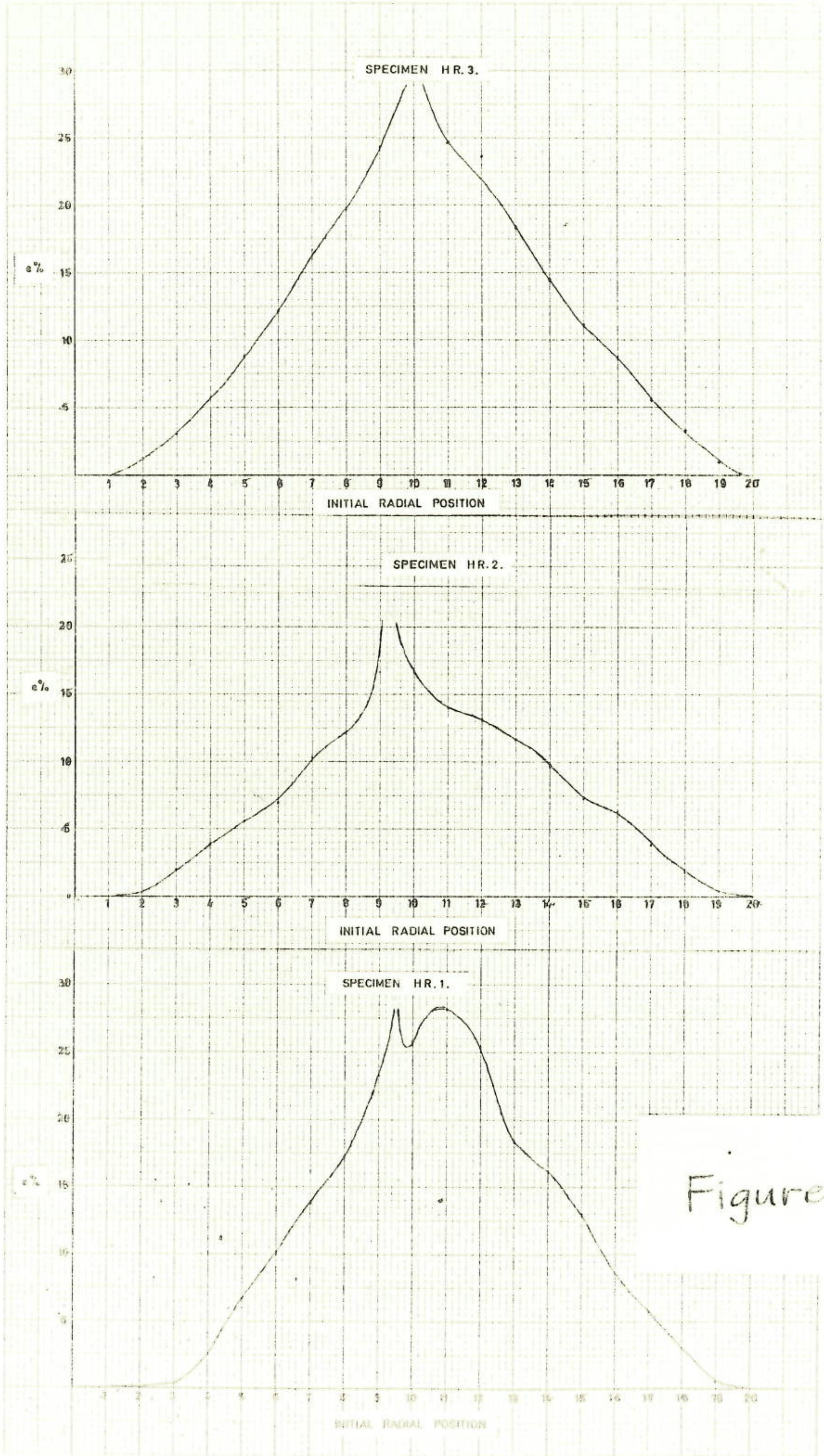
INITIAL RADIAL POSITION

Figure 11


SPECIMEN HR.3.
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INITIAL RADIAL POSITION
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INITIAL RADIAL POSITION
SPECIMEN HR.1.
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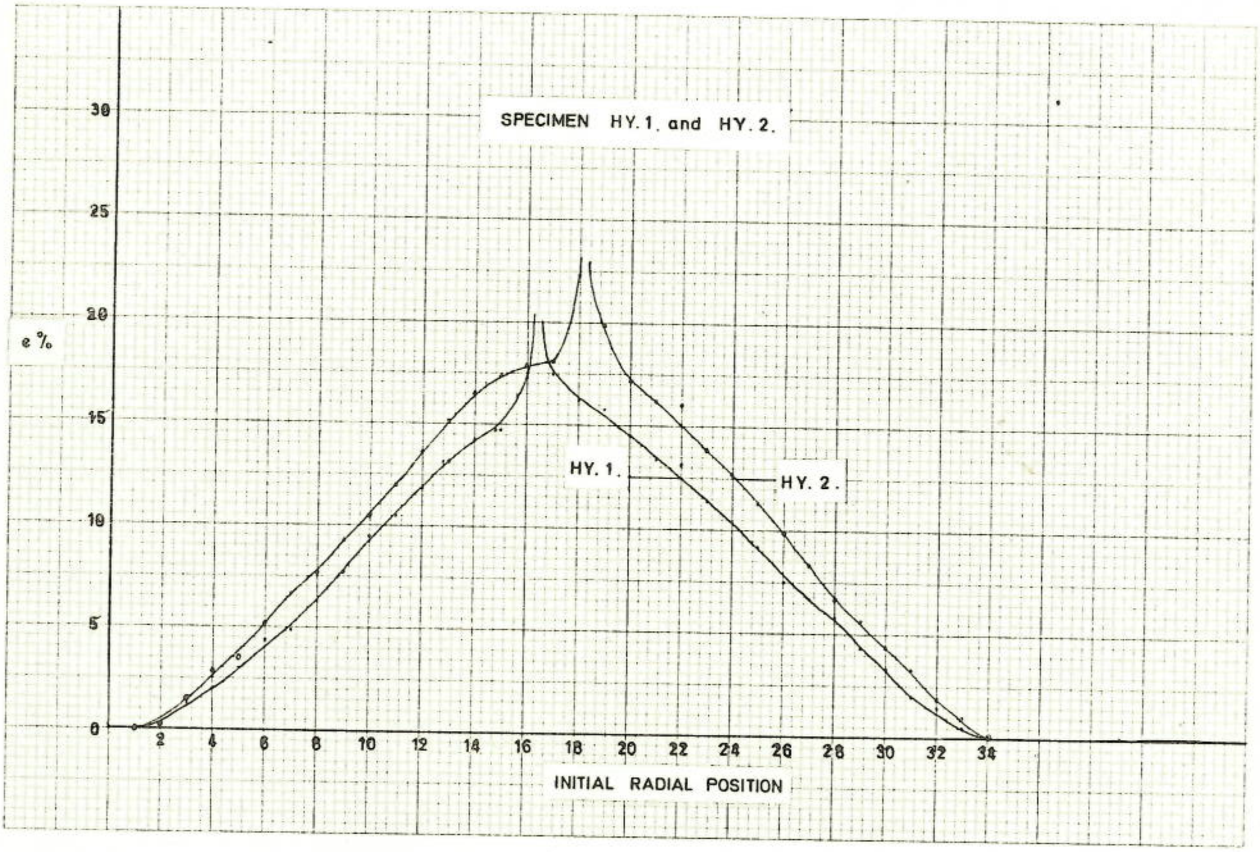
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
INITIAL RADIAL POSITION

Figure 12


SPECIMEN HY. 1. and HY. 2.
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28
30
32
34
INITIAL RADIAL POSITION
HY. 1.
HY. 2.

Figure 13