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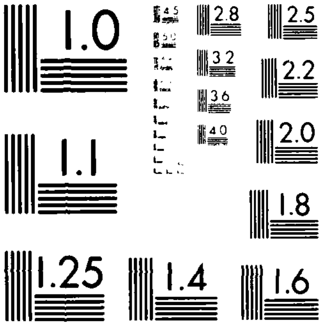
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MELBOURNE, VICTORIA

Structures Technical Memorandum 383

EVALUATION OF THE BLIND HOLE DRILLING METHOD FOR THE MEASUREMENT OF RESIDUAL STRESS.

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C. S. DENTRY and J. G. SPARROW

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SUMMARY

The blind hole drilling method has been employed to measure uniform residual stress fields; and an evaluation made of one approach to using this method when the stress field varies with depth. In particular stress fields generated by the application of uniaxial loads, by shot-peening and by heat treatment have been evaluated. The technique has been applied to the measurement of the residual stress field in the tyre bead seat region of a Boeing 727 main undercarriage wheel. This region has been found to have a significant level of residual stress perhaps indicative of the action of surface rolling.

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CONTENTS

NOTATION

σ_1, σ_2	principal residual stresses
$\varepsilon_{1,2,3}$	measured relaxed strains in the directions 0°, 45° and 90° respectively
k_1, k_2	constants dependent on hole diameter and depth
Z	depth of hole at any point
E	Young's modulus
ν	Poisson's ratio
a	hole radius
ε_A	longitudinal strain in a calibrated beam strained uniaxially in the longitudinal direction
ε_A'	measured longitudinal relaxed strain due to hole drilling in the longitudinally loaded calibration beam
ε_T'	measured transverse relaxed strain due to hole formation in the longitudinally loaded calibration beam
σ_{AI}	applied uniaxial stress
σ_1', σ_2'	principal stresses measured by blind hole drilling method
$\Delta\varepsilon_{1,2,3}$	measured relaxed strains
α	angle of most positive principal stress to gauge No. 1

1. INTRODUCTION

In 1980 the now Department of Aviation requested the Aeronautical Research Laboratories to conduct an investigation into the possibility of measuring the residual stress in the rim of the Boeing 727 aircraft main undercarriage wheel[1]. In particular, the hole drilling strain gauge method was specified as the technique to be used[2]. This request coincided with the Laboratories desire to improve the methods of experimental stress analysis then being used in Structures Division.

The aim of the present investigation was therefore twofold, viz:

(a) to determine the limitations and practicality of the hole-drilling method for measuring residual stress; and

(b) to use this technique, if possible, for the measurement of the residual stress in the Boeing 727 aircraft wheel.

2. RESIDUAL STRESS

Residual stress can occur in a component as a result of fabrication, assembly, load history, heat treatment or welding. It can be introduced deliberately or accidently. The effect can be advantageous or detrimental; in general, residual compressive stresses are beneficial in fatigue situations. Whatever the origin of the residual stress, its determination is becoming recognised as an essential component in the accurate assessment of a component's fatigue life and residual strength.

The three basic mechanisms giving rise to residual stress are[3]:

(a) heat treatment/quenching

Residual stress generated during quenching of heated material arises during the final stages of cooling. At this time the still warm core of the material contracts thereby pulling in the cooler surface layer. The resulting stress field is compressive in the outer layers and tensile in the inner section. A similar mechanism is responsible for the residual stress arising from welding.

(b) machining

Machining may produce residual stress by one or both of two mechanisms. It is believed that the generation of heat during machining can give rise to a tensile residual stress, while plastic deformation due to chip formation produces compressive residual stresses at the cut surface. Corresponding balancing residual stresses are generated some distance from the machined surface.

(c) shot peening

Shot peening is a process aimed at producing beneficial compressive residual stresses on a metallic surface. This is achieved by directing a stream of high velocity shot at the metal surface under controlled conditions. When individual shot hits the metal it produces a small indentation which causes plastic flow of the metal. This plastic flow extends to a depth of between 0.12 - 0.25 mm, resulting in an equilibrium state of compressive residual stress in the surface layer and tensile stress below. A similar mechanism acts during the process of surface rolling although in this case the depth of the compressive residual stress field may be 2 - 3 times larger.

3. HOLE DRILLING STRAIN GAUGE METHOD

This semi-destructive method is capable of measuring residual stress near the surface of a material. The method involves attaching a strain gauge rosette to the surface, drilling a hole in the centre of the gauge array (Figure 1) and measuring the relaxation strains. The measured strains can then be related to relieved principal stresses through the following equations which were developed by Procter and Beaney[4], and others[5,6].

$$\sigma_{1,2} = -\frac{1}{K_1}\,\frac{E}{2}\left[\frac{\varepsilon_1+\varepsilon_3}{1-\nu\frac{K_2}{K_1}} \pm \frac{1}{1+\nu\frac{K_2}{K_1}}\sqrt{(\varepsilon_3-\varepsilon_1)^2+(\varepsilon_3+\varepsilon_1-2\varepsilon_2)^2}\right] \qquad [1]$$

$$\alpha = \frac{1}{2}\tan^{-1}\left[\frac{\varepsilon_1+\varepsilon_3-2\varepsilon_2}{\varepsilon_3-\varepsilon_1}\right]$$

where the symbols are defined in Appendix 1 and the Notation listing. The above equations have been shown to be equivalent to those given in the ASTM Standard[2]. Equations [1] were derived on the assumption of a stress field uniform with depth. Full strain relaxation is achieved when the hole depth exceeds the hole diameter.

The standard blind hole drilling method (BHDM) is inapplicable if there is a non-negligible variation of stress with depth. To overcome this limitation Chant et al[7] have extended the above equations to those given below:

$$\sigma_{1,2} = -\frac{1}{dK_1/dz}\,\frac{E}{2}\left[\frac{\frac{d\varepsilon_1}{dz}+\frac{d\varepsilon_3}{dz}}{1-\nu\frac{dK_2}{dz}\Big/\frac{dK_1}{dz}} \pm \frac{1}{1+\nu\frac{dK_2}{dz}\Big/\frac{dK_1}{dz}}\right. \quad \mathrm{X} \qquad [2]$$

$$\sqrt{\left(\frac{d\varepsilon_3}{dz} - \frac{d\varepsilon_1}{dz}\right)^2 + \left(\frac{d\varepsilon_3}{dz} + \frac{d\varepsilon_1}{dz} - 2\,\frac{d\varepsilon_2}{dz}\right)^2}\;\Bigg]$$

$$\alpha = \frac{1}{2}\tan^{-1}\left[\frac{\dfrac{d\varepsilon_1}{dz} + \dfrac{d\varepsilon_3}{dz} - 2\,\dfrac{d\varepsilon_2}{dz}}{\dfrac{d\varepsilon_3}{dz} - \dfrac{d\varepsilon_1}{dz}}\right]$$

It should be noted that equations [2] are in differential form and thus the constants K_1 and K_2 and the strain relaxation must be measured as a function of depth.

In this investigation two different types of gauge rosette have been used. Micromeasurements gauges Type 062RE required the application of optical positioning prior to hole drilling. Initially this was achieved by means of a "Houser" jig boring machine; later measurements employed the Micromeasurement Drilling Guide RS-200 for drill positioning. Hottinger gauges Type RY61 have been designed with a bush centered between the gauge array which allows drill centering without optical guidance. Two different types of drill have been employed, viz:

hand held mechanical drill	~	200 rpm
Houser jig borer	~	3000 rpm

4. EXPERIMENTAL PROGRAM

4.1 Comparison of BHDM measurements and applied stress

Both Hottinger and Micromeasurement strain gauge rosettes were applied to a uniaxial tensile loading specimen made of 2011 T6 aluminium alloy (Figure 2) prior to its insertion in a Universal Testing Machine. Measurements of the outputs of the three gauges in each of the two rosettes were made for a range of loads up to 100 kN. Holes were then drilled in both rosettes to a depth equivalent to the hole diameter (1.51 mm). The specimen was reloaded and a second series of strain measurements taken.

The results of these measurements are summarised in Table 1, along with the derived principal stresses obtained from equations [1] using values of the coefficients K_1 and K_2 quoted in Appendix 1. It should be noted that a linear regression fit between applied load and measured strain has been used to eliminate the small zero offset apparent in the individual strain gauge results. Table 1 indicates that the hole drilling method has been successful in determining the applied stress within the assumed accuracy of the technique (±10%)[4,6]. However the above regression analysis would have resulted in the removal of any residual stress generated by the drilling process.

4.2 Measurement of residual stress in heat treated/quenched material

Three small specimens (approx. 30 x 25 x 10 mm) made from aluminium alloy DTD383 (an earlier version of 7075) were heated to 413°C and held for a short time to ensure temperature uniformity. Two of the specimens were quenched in an oil bath while the other was water quenched. Micromeasurement gauges were attached to each of the specimens and the residual stresses determined by the hole drilling method using the 3000 rpm drill. The analysis assumed the existence of a uniform stress field with depth. Each of the specimens was also subjected to x-ray diffraction (XRD) analysis to obtain an independent assessment of the residual stress field. The comparison between the BHDM and the XRD measurements for the three specimens is given in Table 2.

The estimated uncertainty of the XRD analysis is ±10 MPa[9]. For the hole drilling technique in aluminium alloy, Procter and Beaney[4] quote an error of ±10% and a possible drilling-induced stress of up to 15 MPa depending on the method of drilling used. With these uncertainties, it is apparent that good agreement between the two determinations has been achieved for both the water-quenched specimens. Any residual stress that had been induced in the oil-quenched specimen is below the threshold of both measurement techniques.

4.3 Measurement of residual stress in a crack growth specimen

A request was received to undertake residual stress measurements on a small compact tension specimen made of 7075 T73511 (AMS 4341). Three Micromeasurement strain gauge rosettes were mounted in the locations shown in Figure 3. In position 1 it was thought that residual stress may have been present in the specimen as a result of plastic deformation due to its proximity to final fracture; positions 2 and 3, on opposite faces of the specimen, were chosen in order to investigate if residual stress had been present in the original specimen prior to loading.

Results of the three measurements are given in Table 3. The calculated values of the principal stresses at positions 2 and 3 are small and of opposite sign at the two locations. Although it could be argued that the stresses induced by drilling were counter-balanced by prevailing initial residual stresses, this explanation is considered to be extremely unlikely, particularly in view of the random strain variation with depth.

It is therefore concluded that this technique, using a drilling speed of 300 rpm should be capable of measuring residual stresses greater than about 10 MPa, i.e. that errors, including those contributed by induced drilling stresses, must be less than this value. Furthermore, in this particular specimen, positions 2 and 3 could not have had a residual stress greater than 10 MPa. In position 1, a marginally significant compressive residual stress was recorded.

4.4 Investigation of induced drilling stresses

A section of dimensions 80 x 65 x 12.5 mm was taken from the rim of a Boeing 727 main undercarriage wheel and fully annealed to relieve any residual stresses. These wheels are made of 2014 T6 aluminium alloy. A Micromeasurement strain gauge rosette was applied, placed under the RS-200 drilling guide and the BHDM measurements taken using a drilling speed of approximately 200 rpm. The results are plotted in Figure 4 which indicates that drilling induced strains were of the order of 40$\mu\varepsilon$. This is considerably lower than the value quoted by Flaman[10] for an aluminium alloy (169 $\mu\varepsilon$), indicating that the technique used in this study is satisfactory for the measurement of large uniform stresses in aluminium.

4.5 Measurement of the residual stress resulting from shot peening

ARL had been informed that the section of the wheel under investigation had been shot peened and surface rolled. It was therefore decided that it was necessary to investigate whether the BHDM was capable of being extended to measure such stress fields.

A small block of DTD383 aluminium alloy (50 x 30 x 7 mm) was fully stress relieved by heating it to 435°C and maintaining it at this temperature for a short time prior to air cooling. The specimen was then shot peened at Commonwealth Aircraft Corporation using standard aircraft techniques appropriate to this material. A Micromeasurement strain gauge rosette was applied and the specimen placed under the RS-200 drilling guide. Incremental drilling, at a speed of 200 rpm, and measurement of the relaxation strain was made to a hole depth of 1.65 mm. The results are given in Table 4 and plotted in Figure 5, together with the strain variation with depth expected from a uniform stress field. It is noted that due allowance must be made for the thickness of the gauge substrate (0.04 mm) when determining hole depth; and that the strain derivatives required in equation [2] can only be calculated for depths below that of the first drilling increment. The values of K_1 and K_2 as a function of depth were obtained from tests conducted in a uniaxial loading rig (similar to Section 4.1); these values are plotted in Figures 6 and 7.

It is apparent from Figure 5 that the shape of the surface strain plots for a shot-peened specimen differs significantly from that obtained from a stress field constant with depth; and thus the two underlying stress fields must be dissimilar. The variation of measured surface strain with hole depth for the shot peened specimen is consistent with the results of Bathgate et al[11]. However Figure 5 is inconsistent with the strain variation expected on the basis of equations [2]. Such equations demand zero values of the differential strains at the crossover depth between the near surface compressive stress field and the lower tensile field as depicted in Figure 8. The results of this investigation do not support such a contention. This disagreement may result from one or more of the following sources:

(a) the specimen examined may not have had a stress field typical of that generated by shot peening. The softened state of the fully annealed specimen may have been expected to increase the depth of the stress crossover point resulting from shot peening. However it is considered extremely unlikely that this depth would have exceeded 1.5 mm.

(b) the magnitude of experimental errors which might mask the presence of turning points in the differential strains. The limits to the experimental errors in these measurements have been discussed earlier. The largest error would be expected as a result of drilling-induced stresses, although in Section 4.4 these were shown to be less than $40\mu\varepsilon$. The relaxed surface strains resulting from shot peening were of the order of $350\mu\varepsilon$, indicating that any error ascribed to drilling-induced stresses would not have been sufficient to mask the presence of a zero stain differential if it existed (as required by equations [2] at the stress crossover depth).

The absence of any significant error due to hole bellmouthing is confirmed by the accuracy of the BHDM measurements discussed in Section 4.1.

(c) equations [2] may not be applicable. The possibility of this more fundamental source of error has been intimated by the authors of the equations[7]. As discussed more fully by Schajer[12], the assumption that the change in surface strain for incremental increases in hole depth is proportional to the stress at the depth is incorrect. This will be examined in more detail in Section 5.1.

4.6 Stress field in the Boeing 727 wheel rim

Micromeasurement strain rosettes were attached to three locations in the tyre bead seat region of a Boeing 727 main undercarriage wheel (Figure 9). Incremental hole drilling was carried out using a drilling speed of 200 rpm and measurements of relaxed strain taken to a depth of 1.6 mm. The data are plotted in Figures 10, 11 and 12 and listed in Tables 5, 6 and 7. A number of conclusions can be derived from these results, viz:

(a) at position 1, the surface strain variation as a function of hole depth is small and follows closely that expected from a uniform stress field;

(b) both positions 2 and 3 recorded significant surface strains and the variations with depth were noticeably different from those expected from a uniform stress field. If the stress field were assumed to be uniform, the principal surface stresses at position 3 would have been - 150 and -240 MPa. In view of the surface strain variation recorded, the true surface stresses must be higher than these values.

(c) visual observations under a low power microscope showed the presence of only scattered impressions that might be attributed to the impact of shot.

(d) the shape of the surface strain variations with hole depth for positions 2 and 3 appear to be indicative of a complex stress field, compressive near the surface, which may have resulted from surface rolling.

(e) an earlier study[13] found no evidence of shot peening in the tyre bead seat region. This investigation has shown that the surface strains vary rapidly in the vicinity of the bead seat. It is therefore difficult to compare present work with the earlier study without knowing the exact location where these latter measurements were taken.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 The blind hole drilling method

This study has made use of the blind hole drilling technique on aluminium alloys with stress fields uniform with depth. Induced surface strains resulting from use of a low speed hand-drill (200 rpm) have been found to be of the order of $40\mu\varepsilon$. A number of comparative studies have confirmed that for high uniform (with depth) stress fields, a measurement accuracy of ±10% is practical with this method.

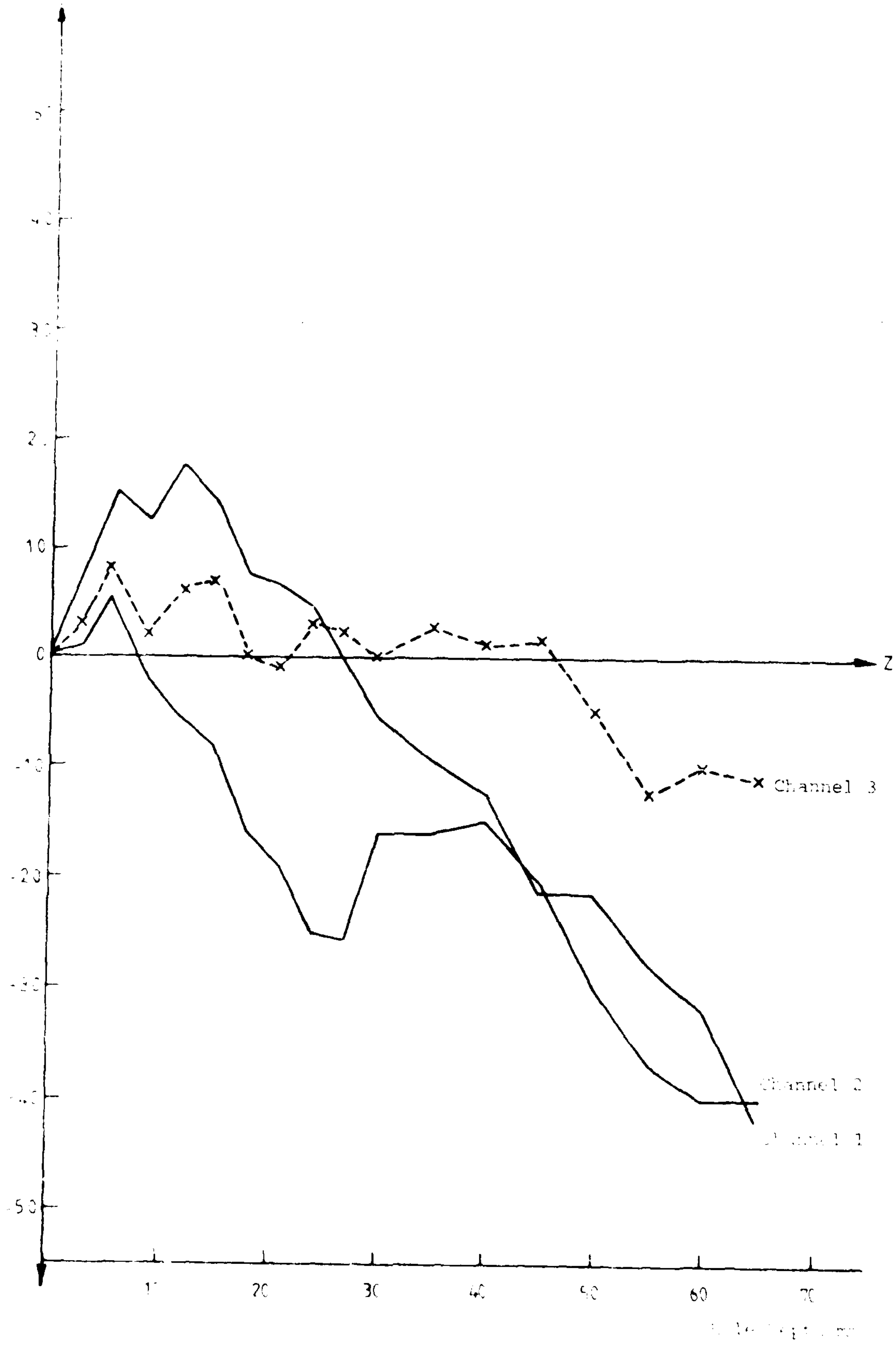
The equations employed by Chant et al[7] were not successful in converting measured surface strains to a realistic stress variation with depth in the case of a shot peened surface. Schajer[12] has suggested a possible explanation for this inconsistency; this may be illustrated by reference to Figure 13. The equations correspond to the requirement for the superposition of loadings (d) and (e) being equivalent to (a) whereas the correct situation equates (a) to (b) plus (c). In order to develop an alternative method of analysing a non-uniform (with depth) stress field it is proposed that finite element methods should be employed.

A low speed hand-drill has been shown to be adequate when the BHDM is used for measuring large uniform stress fields in aluminium alloys; for high strength alloys (e.g. D6AC), or for small uniform stress fields, or for non-uniform stress fields in aluminium alloys a drilling technique which generates a lower induced strain would be advantageous. It is recommended that an ultra-high speed (400,000 rpm) tungsten carbide reverse-cone dental burr[13] be investigated as a possible means of decreasing the induced drilling stresses.

5.2 Boeing 727 wheel rim

This investigation has found that within close proximity of the tyre bead seat region of the Boeing 727 wheel there is a significant level of non-uniform residual stress; at the surface the principal stress (compressive) exceeds 240 MPa. At the present time it is not possible to convert these surface relaxed strains to their equivalent stress field with depth. However the strong near-surface compressive stress field shows a rapid decrease with depth (similar to that indicated in Figure 5 for a shot peened surface). In view of the evidence against this arising from shot peening, the action of surface rolling may be indicated.

Further measurements in the tyre bead seat region with the BHDM and analysis as suggested in section 5.1 is fore-shadowed.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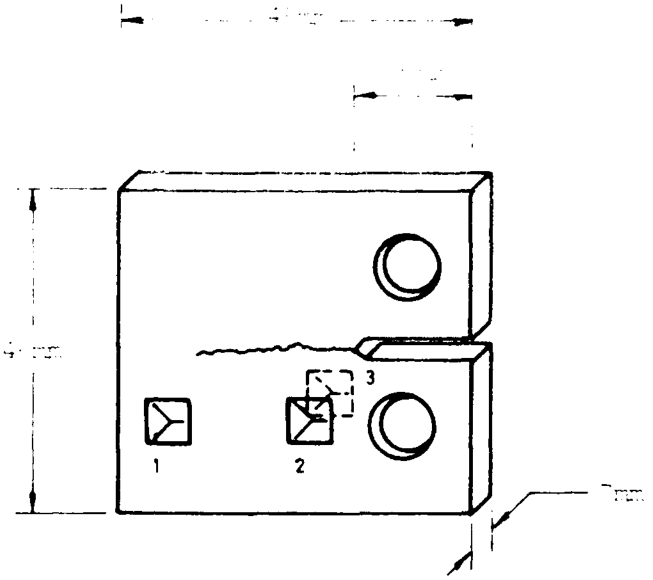

FIG. 5 COMPACT TENSION SPECIMEN

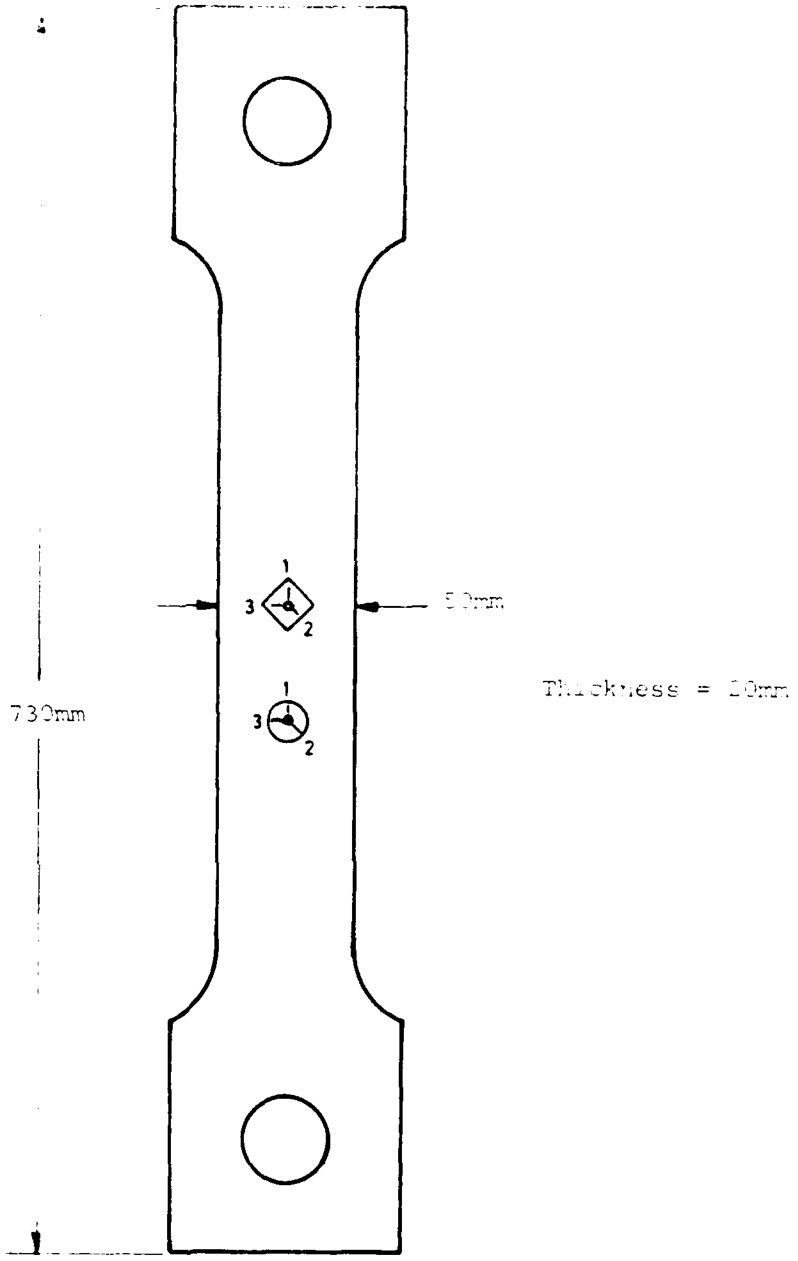

FIG. 2 UNIAXIAL TENSILE LOADING SPECIMEN

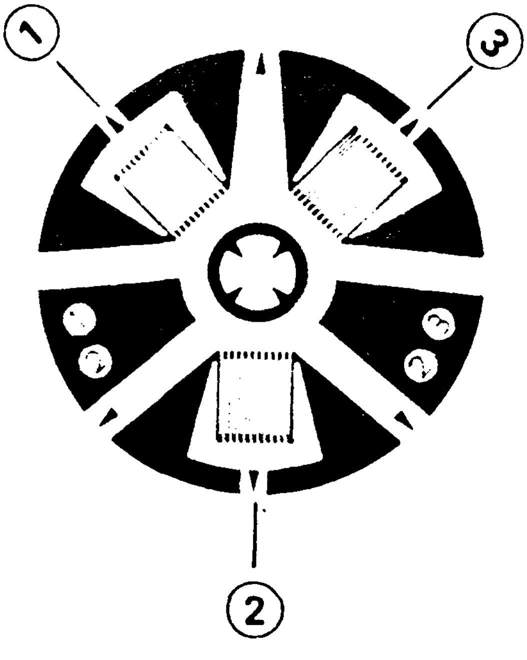

FIG. 1 MICRO-MEASUREMENTS RE-PATTERN STRAIN GAGE ROSETTE FOR RESIDUAL STRESS MEASUREMENT BY THE BLIND-HOLE-DRILLING METHOD

TABLE 7 BOEING WHEEL - MEASURED RELAXED STRAINS AT POSITION 3 (HOLE DIAMETER 1.70MM).

DEPTH MM	$\Delta\varepsilon_1$ $\times10^{-6}$	$\Delta\varepsilon_2$ $\times10^{-6}$	$\Delta\varepsilon_3$ $\times10^{-6}$
0	0	0	0
0.08	14	6	-1
0.15	55	33	22
0.23	105	63	46
0.30	153	98	69
0.38	197	131	93
0.46	258	174	113
0.53	295	193	113
0.61	340	221	119
0.69	386	249	132
0.76	422	266	132
0.89	458	286	141
1.02	492	292	123
1.14	512	302	118
1.27	528	303	104
1.40	544	306	99
1.52	557	312	96
1.65	561	313	93
1.78	563	310	88

TABLE 6 BOEING WHEEL - MEASURED RELAXED STRAINS AT POSITION 2. (HOLE DIAMETER 1.70MM).

DEPTH MM	$\Delta\varepsilon_1$ $\times 10^{-6}$	$\Delta\varepsilon_2$ $\times 10^{-6}$	$\Delta\varepsilon_3$ $\times 10^{-6}$
0	0	0	0
0.08	102	55	22
0.15	167	87	34
0.23	168	100	31
0.30	203	148	73
0.38	200	158	77
0.46	208	157	74
0.53	219	163	88
0.61	225	188	101
0.69	243	208	115
0.76	232	267	131
0.89	223	266	141
1.02	221	265	135
1.14	219	264	137
1.27	219	261	136
1.40	224	264	140
1.52	223	265	141
1.65	218	265	134

TABLE 5 BOEING WHEEL - MEASURED RELAXED STRAINS
AT POSITION 1 (HOLE DIAMETER = 1.70MM

DEPTH MM	$\Delta\varepsilon_1$ $\times 10^{-6}$	$\Delta\varepsilon_2$ $\times 10^{-6}$	$\Delta\varepsilon_3$ $\times 10^{-6}$
0	0	0	0
0.08	1.0	4.5	2.0
0.15	6.5	8.5	0.5
0.23	14.5	11.5	2.0
0.30	11.5	9.5	-2.0
0.38	23.5	23.5	6.0
0.46	33.0	23.5	16.0
0.53	41.5	32.5	20.0
0.61	45.5	44.5	25.0
0.69	48.5	44.5	19.0
0.76	59.5	59.5	28.0
0.89	64.5	61.5	33.0
1.02	67.5	57.5	33.5
1.14	73.5	67.5	35.0
1.27	74.0	63.5	35.0
1.40	74.5	66.5	35.0
1.52	72.5	63.5	32.0
1.65	71.5	62.5	28.5
1.72	71.0	63.5	26.0

TABLE 4 MEASURED STRAIN RELAXATION OF SHOT PEENED ALUMINIUM ALLOY 7075 SPECIMEN (HOLE DIAMETER = 1.70MM)

DEPTH MM	$\Delta\varepsilon_1$ $\times 10^{-6}$	$\Delta\varepsilon_2$ $\times 10^{-6}$	$\Delta\varepsilon_3$ $\times 10^{-6}$
0	0	0	0
0.075	8.5	11	14.4
0.15	43.5	45	47.5
0.23	68.5	67	72.5
0.30	140.5	122	130.5
0.38	168.5	146	155.5
0.46	216.5	186	192.5
0.53	241.5	212	220.5
0.61	269.5	234.5	239.5
0.69	288.5	244	255.5
0.76	292.5	259	256.5
0.89	308.5	268	268.5
1.02	317.5	275	276.5
1.14	321.5	278	279.5
1.27	323.5	286	284.5
1.40	337.5	290	290.5
1.52	346.5	295	296.5
1.65	349.5	298	301.5

TABLE 3 BHDM MEASUREMENTS OF THREE POSITIONS ON CRACK GROWTH SPECIMEN. CONSTANT STRESS WITH DEPTH ASSUMMED

DEPTH MM	ε_1 x10^{-6}	ε_2 x10^{-6}	ε_3 x10^{-6}
0	0	0	0
0.08	14	6	-1
0.15	55	33	22
0.23	105	63	46
0.30	153	98	69
0.38	197	131	93
0.46	258	174	113
0.53	295	193	113
0.61	340	221	119
0.69	386	249	132
0.76	422	266	132
0.89	458	286	141
1.02	492	292	123
1.14	512	302	118
1.27	528	303	104
1.40	544	306	99
1.52	557	312	96
1.65	561	313	93
1.78	563	310	88

TABLE 2 COMPARISON BETWEEN PRINCIPAL STRESSES IN HEATED/QUENCHED SPECIMENS MEASURED BY XRD AND BHDM TECHNIQUES.

	XRD	BHDM
BLOCK 1 WATER QUENCHED	-160 MPa -165 MPa	-180 MPa -192 MPa
BLOCK 2 WATER QUENCHED	-168 MPa -168 MPa	-132 MPa -181 MPa
BLOCK 3 OIL QUENCHED	- 22 MPa - 14 MPa	- 10 MPa - 1 MPa

TABLE 1 COMPARISON BETWEEN BHDM MEASUREMENTS AND APPLIED STRESSES

σ_{A1}	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	$\Delta\varepsilon_3$	σ_1'	σ_2'
20	-64	-18	21	21	3
40	-127	-37	43	41	6
60	-190	-55	65	61	8
80	-254	-73	86	82	11
100	-317	-92	108	102	14

HOTTINGER GAUGE (Drill Speed = 200 RPM)

σ_{A1}	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$	$\Delta\varepsilon_3$	σ_1'	σ_2'
20	-67	-21	20	20	3
40	-134	-42	39	39	7
60	-201	-63	59	59	10
80	-268	-83	79	78	14
100	-336	-104	99	98	17

MICROMEASUREMENT GAUGE (Drill Speed = 3,000 RPM)

Thus for $\nu = 0.341$

$K_1 = 0.263$ for a hole diameter of 1.6 mm

$= 0.233$ for a hole diameter of 1.5 mm

$K_2 = 0.347$ for a hole diameter of 1.6 mm

$= 0.310$ for a hole diameter of 1.5 mm

The hole diameter for the Micromeasurement rosette is 1.6 mm while for the Hottinger rosette it is 1.5 mm.

APPENDIX 1

Reference 4 gives the equations relating principal residual stresses to measured relaxed strains as:

$$\sigma_{1,2} = -\frac{1}{K_1}\frac{E}{2}\left[\frac{(\varepsilon_1 + \varepsilon_2)}{1 - \frac{\nu K_2}{K_1}} \pm \frac{1}{1 + \frac{\nu K_2}{K_1}}\sqrt{(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)^2}\right]$$

where

ε_A = longitudinal strain in a calibrated beam strained uniaxially in the longitudinal direction

ε_A' = measured longitudinal relaxed strain due to hole formation in the longitudinally loaded calibration beam

ε_T' = measured transverse relaxed strain due to hole formation in the longitudinally loaded calibration beam

$\sigma_{1,2}$ = principal residual stresses

$\varepsilon_{1,2,3}$ = measured relaxed strain in the directions 0°, 45° and 90° respectively

E = Young's modulus

ν = Poisson's ratio

In order to determine the values of K_1 and K_2 the following procedure was adopted. From reference 14 the above equation is given in the following form:

$$\sigma_{1,2} = -\frac{E}{4A}(\varepsilon_1 + \varepsilon_3) \pm \frac{E}{4B}\sqrt{(\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_1 + \varepsilon_3 - 2\varepsilon_2)^2}$$

where $A = \frac{a^2[1 + \nu]}{11.88}$ and $B = \frac{a^2}{2.97}[1 - a^2(1 + \nu) \times 0.1422]$

with a = the hole radius (mm).

From the equivalence of the two equations $K_1 = A + B$

$$\nu K_2 = B - A$$

../2..

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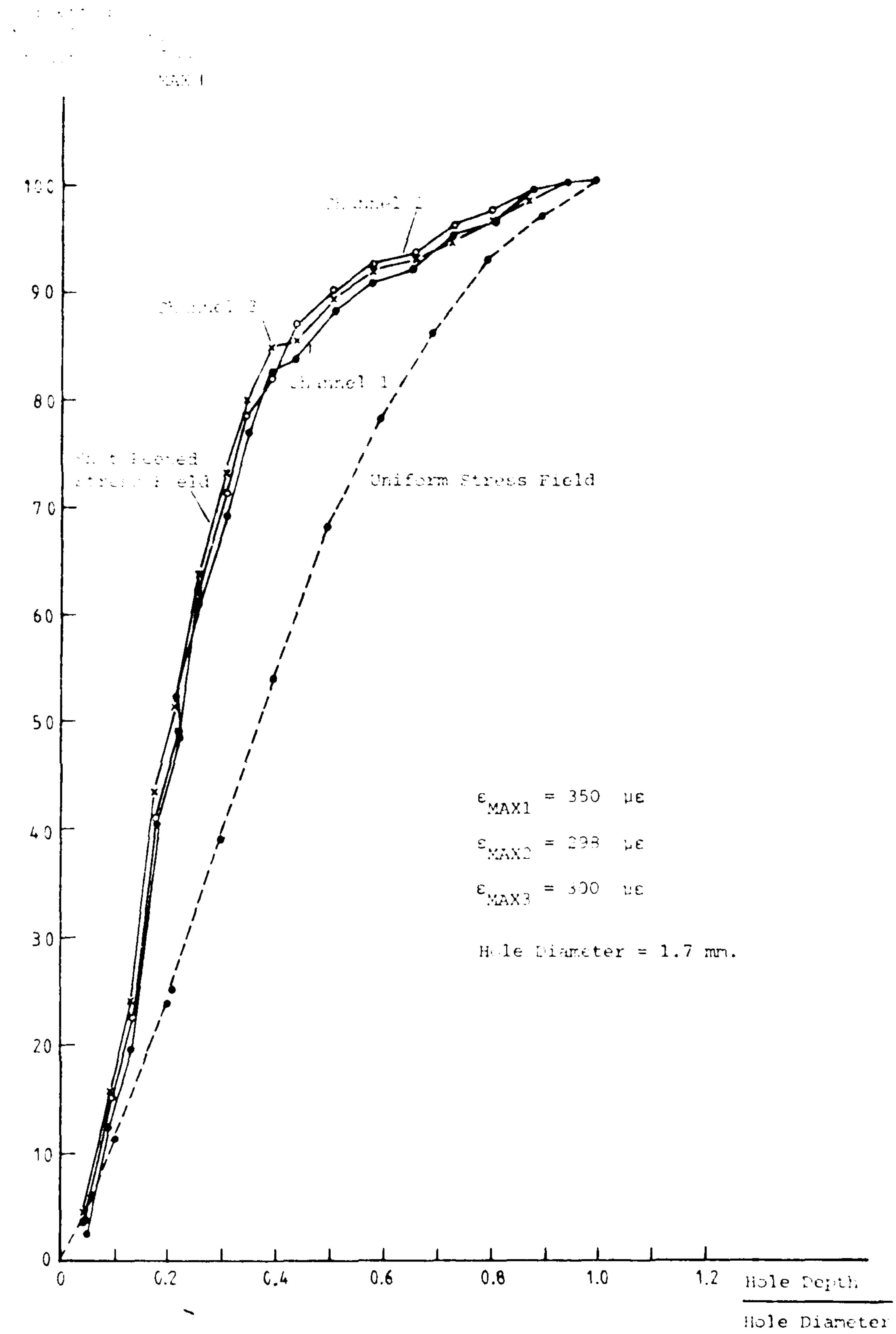


FIG. 5 BHDM MEASUREMENTS ON SHOT PEENED SPECIMEN

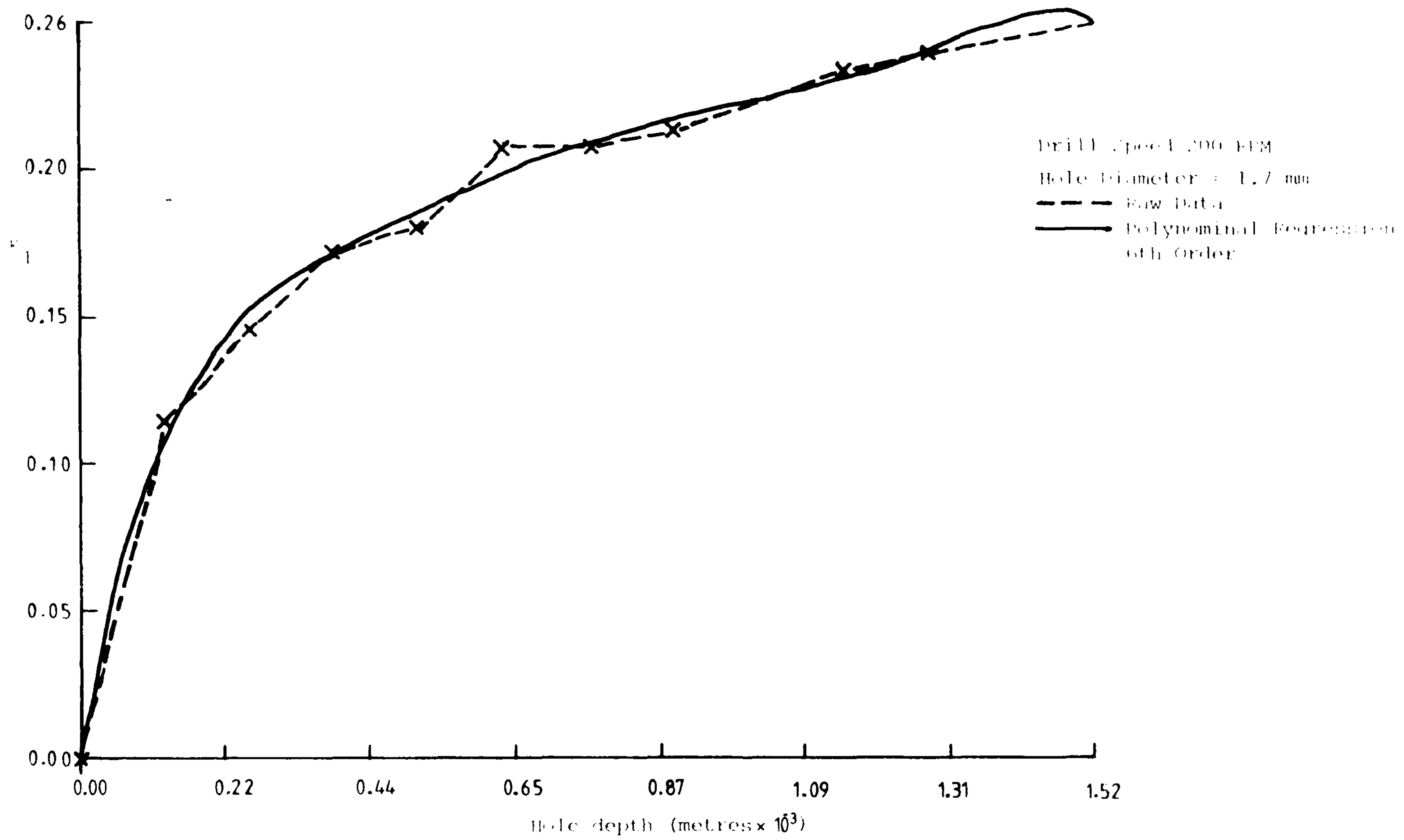


FIG. 6 VARIATION OF K_1 WITH HOLE DEPTH.

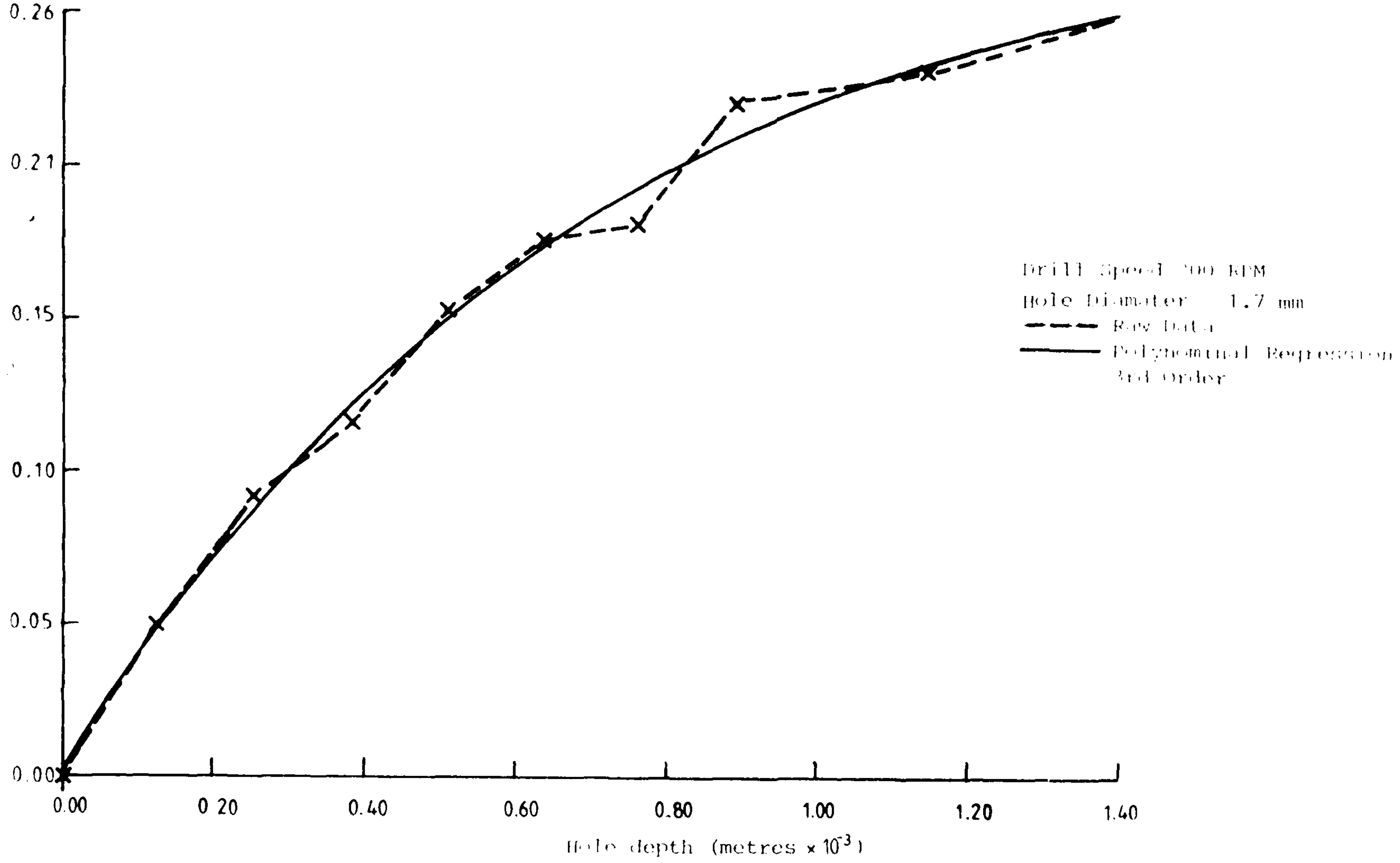


FIG. 7 VARIATION OF K_2 WITH HOLE DEPTH

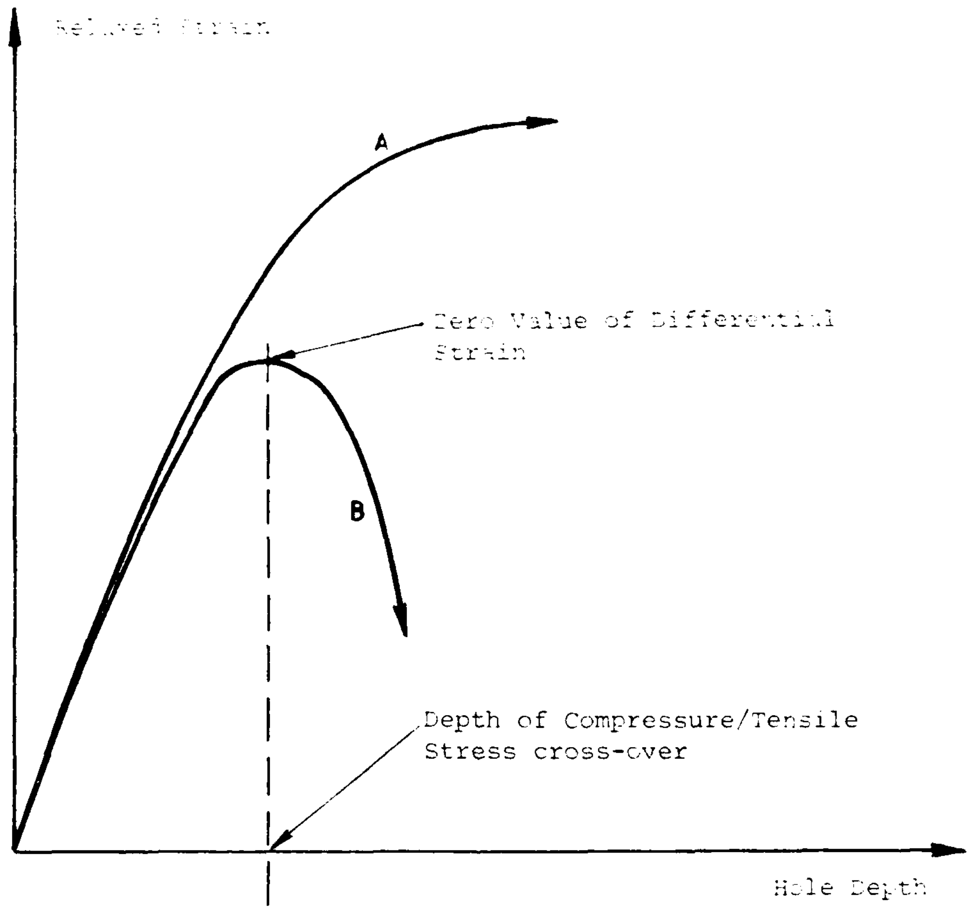


FIG. 8 SHOT PEENED STRAIN RELAXATION
CURVE A - EXPERIMENTALLY DETERMINED RELAXED STRAIN
CURVE B - RELAXED STRAIN PREDICTED BY EQUATION 2

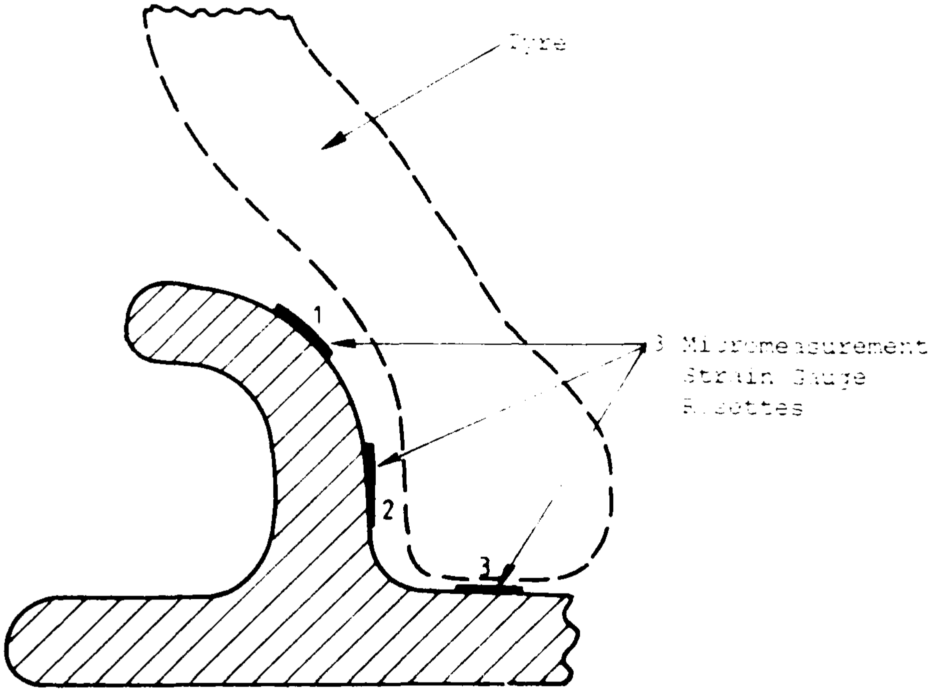
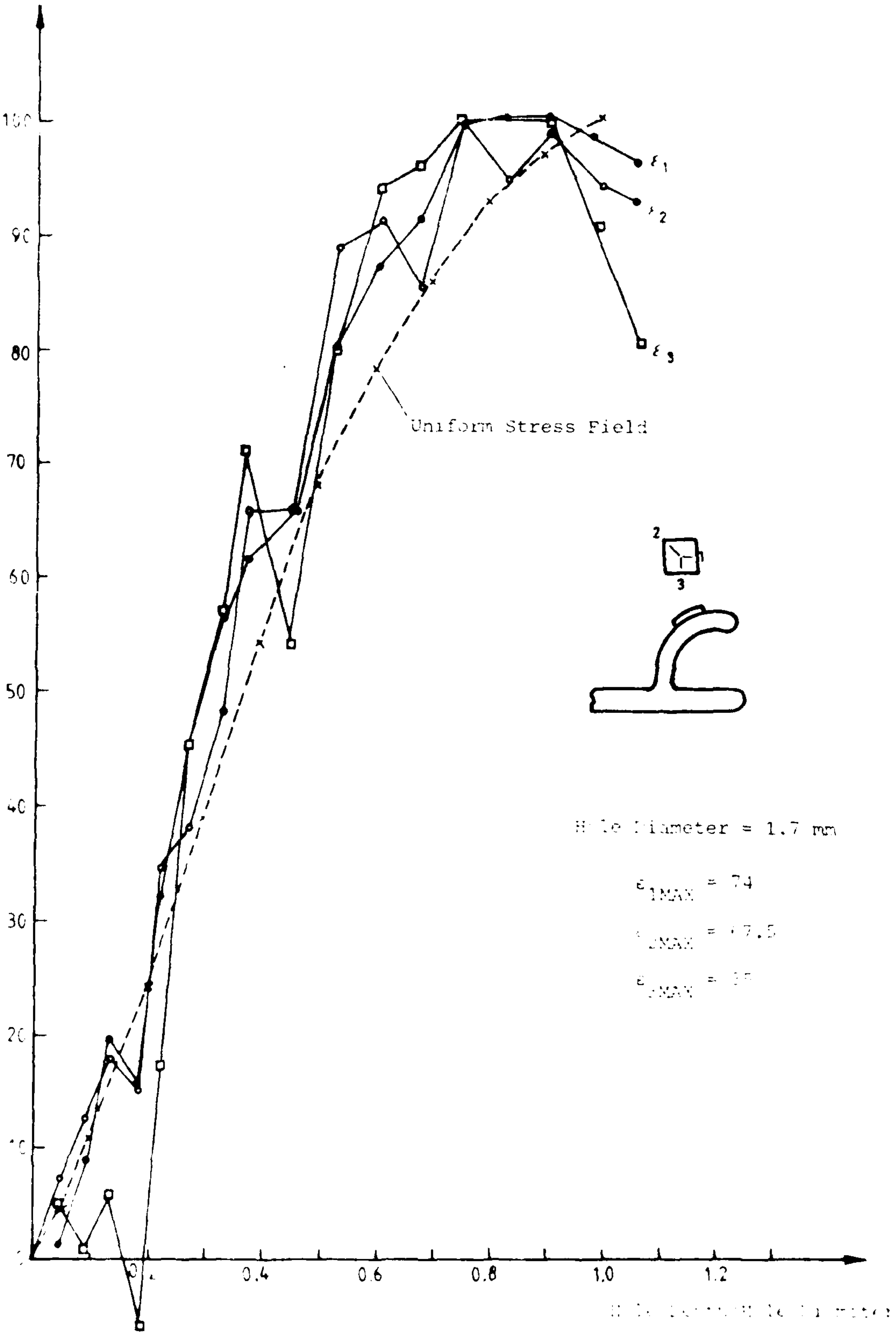


FIG. 4 [illegible] TEST SPECIMEN


100
90
80
70
60
50
40
30
20
10
0
0.4
0.6
0.8
1.0
1.2
ε1
ε2
ε3
Uniform Stress Field
2
1
3
Hole Diameter = 1.7 mm
ε1MAX = 74
ε2MAX = 7.5
ε3MAX =

[illegible]

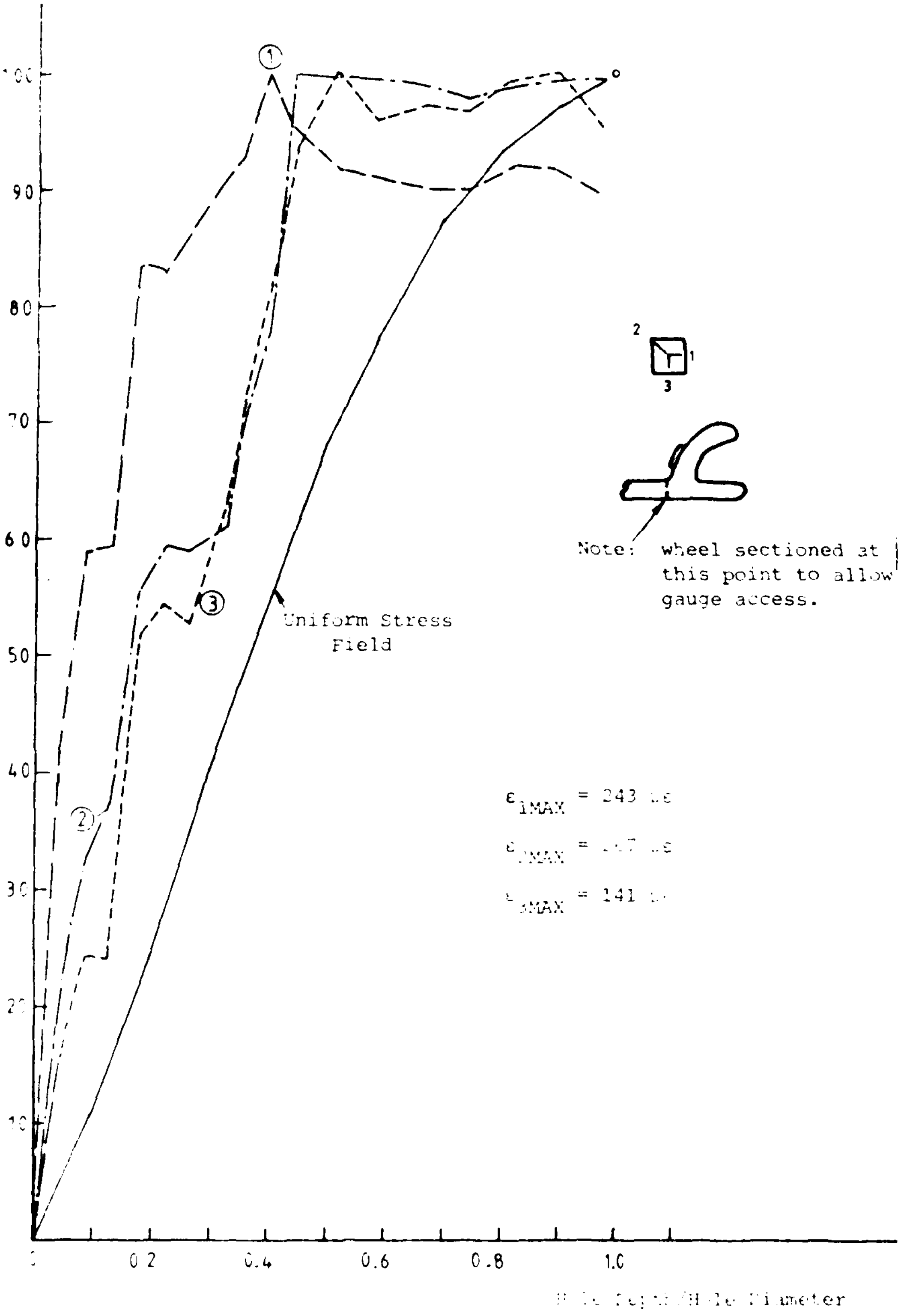


FIG. 11 MEASURED STRAIN RELIEF FOR POSITION 2 ON BOEING WHEEL

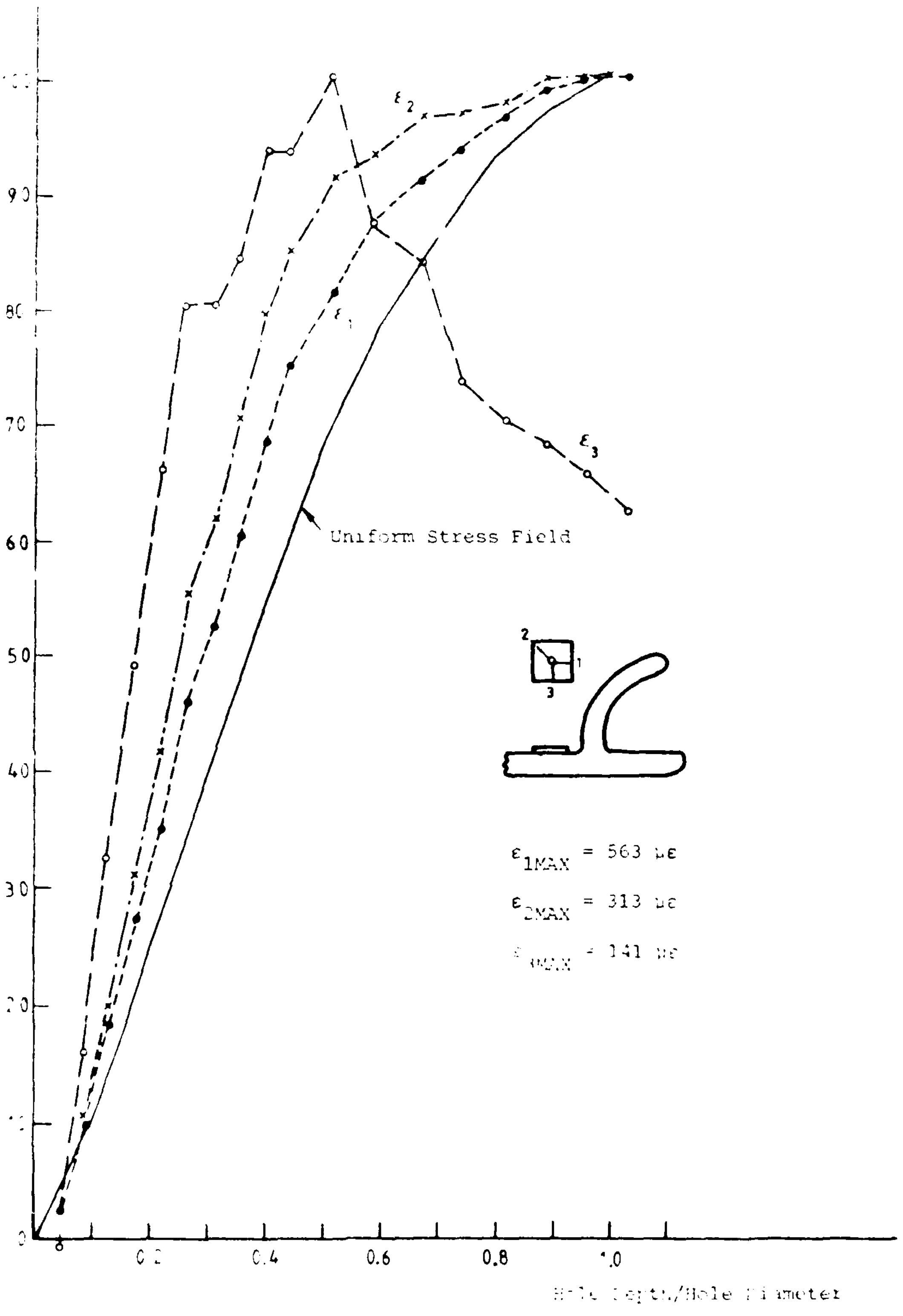


FIG. 12 MEASURED STRAIN RELIEF FOR POSITION 3 ON ROLLING WHEEL

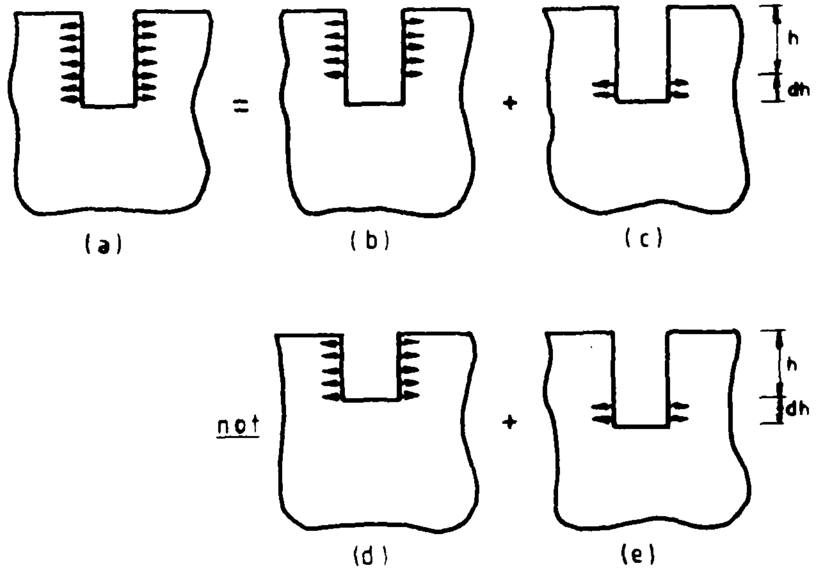


FIG. 13 SUPERPOSITION OF LOADINGS DUE TO STRESSES AT DIFFERENT DEPTH

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14 Descriptors
Residual stress
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16 Abstract

The blind hole drilling method has been employed to measure uniform residual stress fields; and an evaluation made of one approach to using this method when the stress field varies with depth. In particular stress fields generated by the application of uniaxial loads, by shot-peening and by heat treatment have been evaluated. The technique has been applied to the measurement of the residual stress field in the tyre bead seat region of a Boeing 727 main undercarriage wheel. This region has been found to have a significant level of residual stress perhaps indicative of the action of surface rolling.