A novel 8-element gauge for residual stress assessment using the high speed centre hole drilling method[1]

P.J. McGrath[2] D.G. Hattingh[3] M.N.James[4]

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Many researchers and scientists have contributed, over the years, to the development of residual stress assessment technology since it was first reported by Mathar in 1933. Despite such work, a commonly held view is that residual stress analysis using strain gauges is a technique whose use is restricted to homogeneous and isotropic materials. Texturing and plastic deformation are felt to lead to a significant lack of repeatability in the data. This lack of certainty has had a negative impact on beneficial uses of residual stresses in optimising fatigue and fracture performance through manipulating and controlling their magnitude. The work reported in this paper demonstrates an improvement in repeatability of residual stress measurement via strain gauges, in the presence of plastic deformation and texturing effects.

NOMENCLATURE

CW,ACW	Clockwise and anti-clockwise
DPS	Dual phase steel
HSLA	High strength low alloy
PCD	Pitch circle diameter
RS	Residual stress
YS	Yield strength
TS	Tensile strength
G1,G2	Strain gauge element numbering sequence
$\overline{A}$,$\overline{B}$	Blind hole drilling calibration constants
$\overline{a}$, $\overline{b}$	Dimensionless blind hole drilling calibration constants
α	Angle measured clockwise from G1 to the maximum principal stress direction
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	Relieved strain values, where 1,2,3, refer to the element number
$\sigma_{max}, \sigma_{min}$	Maximum and minimum relieved principal stresses

1. The concept of this novel strain rosette is subject to a South African Patent application: 2000/2042.

2. Researcher and Principal Lecturer, Department of Mechanical Engineering, Port Elizabeth Technikon, Private Bag X6011, Port Elizabeth, 6000 South Africa. (mcgrath@petech.ac.za)

3. Head, Department of Mechanical Engineering, Port Elizabeth Technikon. MSAIMechE.

4. Professor of Mechanical Engineering, University of Plymouth, England. (mjames@plymouth.ac.uk)

INTRODUCTION AND BACKGROUND

Residual stress assessment by means of the hole drilling technique is still regarded by many analysts as being restricted to isotropic and homogeneous materials,[2] despite advances in technology achieved since the work of Mathar in 1933.[1] The work reported in this paper developed from multiple analyses of industrial components, in which the maximum residual stresses were found to vary substantially under nominally constant evaluation conditions, e.g. maintaining the same reference plane for grid/element G1 (refer to Fig. 1), applying the rosette to similar locations, and constant drilling method and procedure.

Upon closer inspection of such drilled holes it was clear that a slight ovality[1,3] of the hole was present – ovality being one imperfection encountered with hole drilling. The angular orientation of the major axis of this ovality did not lie on a common axis with respect to gauge G1, but varied from component to component. This indicated that structural steels commonly used for pressed components are neither isotropic nor homogeneous in their response to residual stresses, when hole-drilling techniques are employed. The hole thus becomes ovoid with a varying orientation of major axis as a result of variability in material texture and properties because of the non-linear behaviour of the steel, as a function of position and direction.

As the direction of hole ovality is not known *a priori*, the individual elements (3 off) of a standard strain rosette[4] are unlikely to detect the maximum relieved strain. For instance, this ovality could lie in the worst case direction, perpendicular to gauge G2 (see Fig. 1). Assuming that the major axis of the oval reflects the direction of maximum relieved strain, the direction along which this occurs will remain undetected. It became clear that applying a 3-element rosette and referencing gauge G1 to a particular plane on the component would not guarantee finding the maximum value of residual stress at that particular location. Even if one does find the appropriate maximum relieved strain direction, the existence of ovality in the hole is likely to affect the strain calculation, which assumes a circular hole.

The above observations led to an investigation into developing a reliable method to detect the maximum relieved

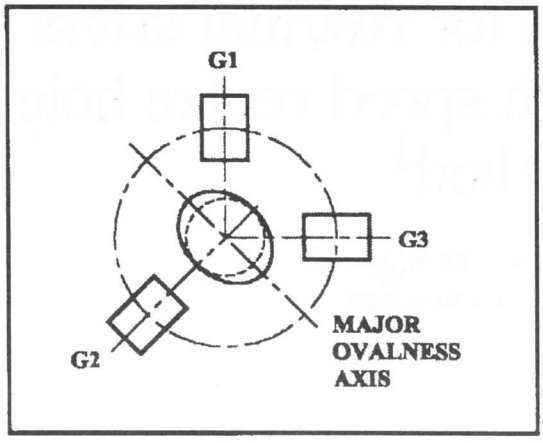


Fig. 1. Schematic of a standard clockwise RS strain rosette showing hole ovality

residual stress and, in so doing, minimize repeatability problems often associated with residual stress assessment by the strain gauge technique. The method developed uses a customised 8-element strain gauge rosette.

Material

The material used in this investigation was Dual Phase Steel[5] Plate (DPS600 – local manufacturer's designation). This is an HSLA steel developed in the mid-1970s, whose microstructure consists of islands of martensite (about 20% by volume) in a ferritic matrix.

Component

The components used for residual stress analysis during this investigation were rolled DPS plate, 4.1 mm thick, and automotive wheels pressed from the same plate. The residual stress assessments were undertaken on the centre disc region of the wheel, between the cup and hat radii, as indicated in Fig. 2.

TABLE I
Chemical composition of DPS600

Element and % chemical composition		
C	0.05	0.12
Mn	0.50	1.30
P	0.01	0.09
S	Max	Max
Si	Max	0.65
Al	0.02	0.06
Cr	Max	0.90
Ni	Max	0.25
Ti	Max	0.015
Mo	Max	0.05
Cu	Max	0.35

TABLE II
Mechanical properties of DPS600

Designation	DPS600	
Yield strength (YS) MPa	Min 300 Max 470	Actual 427
Tensile strength (TS) MPa	Min 550 Max 700	Actual 664
Elongation %	28	

Residual stress measurement

The hole-drilling method of residual stress measurement used in the present work, involves the drilling of a blind hole into the surface of a component. This changes, locally, the internal stress equilibrium through material removal. The change in local strain state resulting from the hole drilling is recorded by specially designed strain gauges mounted on the surface, concentrically with the hole, in a 90 and 120 rosette arrangement (see Fig. 1). The equipment used for this work is the HBM RESTAN (REsidual STress ANalysis) system.

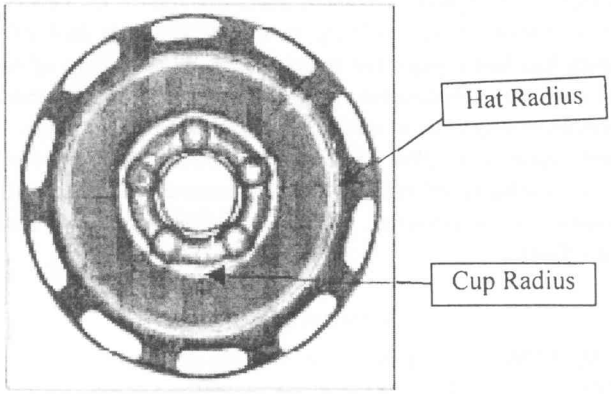


Fig. 2. Wheel centre disc showing hat and cup radii

Customised strain gauge rosette

For investigating the effect of hole ovality, a customised 8-element strain rosette was developed using three (3) Micro-Measurements CEA-06-062-UM-120 edge-type strain rosettes.

Fig. 3 illustrates the layout of the customised 8-element strain rosette. These strain rosettes were successively superimposed on one another utilising the drilling location circles for concentric alignment.

Excess carrier material was removed and the three sections were joined to form the 8-element strain rosette. This technique will lead to slight misalignment errors reflecting the skill of the operator. However, concentric alignment is possible to within 0.15 mm, which is less than the hole ovality recorded in these components (typically 0.24 mm). Concentricity misalignment will produce much lower errors in recorded strain values than will the hole ovality. Table III indicates typical misalignment errors due to the customisation process.

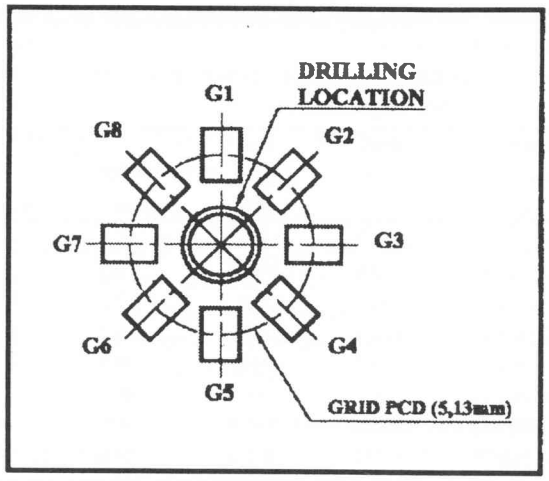


Fig. 3. Layout of 8-element strain rosette

It is still possible to use the same data reduction techniques, as for the standard three-element rosettes, by combining the three relevant elements. The various possible CW, ACW and edge gauge combinations are indicated in Table IV.

Residual stress calculation method

The principal relieved residual stresses were determined according to the ASTM 837-94(a) method of calculation,[4] as follows:

Principal stresses:

$$\sigma_1, \sigma_2 = \frac{\varepsilon_c + \varepsilon_a}{4\overline{A}} \pm \frac{\sqrt{(\varepsilon_c - \varepsilon_a) + (\varepsilon_c + \varepsilon_a - 2\varepsilon_b)^2}}{4\overline{A}}$$

TABLE III
TYPICAL MISALIGNMENT ERRORS

Gauge pairing	Distance between gauge edges (mm)	Grid length (mm)	PCD of gauge pairing (mm)	Error in PCD (%)
		Rosette 1		
1 - 5	3.27	1.97	5.24	2.14
2 - 6	3.13	1.97	5.10	-0.58
3 - 7	3.17	1.97	5.14	0.19
4 - 8	3.27	1.97	5.24	2.14
		Rosette 2		
1 - 5	3.24	1.97	5.21	1.56
2 - 6	3.10	1.97	5.07	-1.17
3 - 7	3.18	1.97	5.15	0.39
4 - 8	3.26	1.97	5.23	1.95
		Rosette 3		
1 - 5	3.21	1.97	5.18	0.97
2 - 6	3.14	1.97	5.11	-0.39
3 - 7	3.11	1.97	5.08	-0.97
4 - 8	3.14	1.97	5.11	-0.39

Principal angle:

$$\tan 2\alpha = \frac{\varepsilon_a + \varepsilon_c - 2\varepsilon_b}{\varepsilon_c - \varepsilon_a}$$

where: ε_a, ε_b and ε_c = measured strain values, with a, b, and c, for example, corresponding to the CW combination 1, 6, and 3, as indicated in Table III.

$\overline{A}$ and $\overline{B}$ = geometrical constants as determined using ASTM 837-94(a).

TABLE IV
GAUGE COMBINATIONS CORRESPONDING TO A 3-ELEMENT ROSETTE

CW	ACW	Edge
1,6,3	3,6,1	1,2,3
2,7,4	4,7,2	2,3,4
3,8,5	5,8,3	3,4,5
4,1,6	6,1,4	4,5,6
5,2,7	7,2,5	5,6,7
6,3,8	8,3,6	6,7,8
7,4,1	1,4,7	7,8,1
8,5,2	2,5,8	8,1,2

EXPERIMENTAL RESIDUAL STRESS MEASUREMENTS

DPS plate specimen

The maximum values of relieved principal residual stresses measured in the DPS plate specimen by each gauge combination are shown in Fig. 4. This figure shows that the values of maximum RS magnitudes of the 8-element *vs* the 3-element rosette differ by approximately 6%. The reference element of the 3-element rosette, G1 illustrated in Fig. 1, was aligned in the same direction as that of the 8-element rosette, as shown in Fig. 3. When undertaking RS measurements by the strain rosette technique, this may be considered an acceptable variation. The result from the 3-element rosette resides within the range of results, as assessed by the 8-element rosette with respect to the depth at which the bulk stress was relieved, i.e. 0.91 mm (see Fig. 4). This is indicative that the results obtained using an 3-element rosette may not necessarily detect the possible maximum residual stress value.

Nonetheless, elimination of such random error in rosette measurements would be advantageous in ensuring higher levels of repeatability in rosette-based strain measurement.

Wheel centre discs

For the residual stress evaluation of the wheel centre discs, 27 analyses were undertaken using the 8-element strain rosette on 5 wheel centre discs at several locations. The 8-element strain rosettes were all aligned such that a line drawn through elements G1 and G5 would pass through the centre of the wheel, in a direction co-incident with the rolling direction of the steel plate.

The highest and lowest values of maximum RS for each 8-element analysis location, together with their corresponding gauge combinations are shown in Table V (CW gauge combinations were employed). Also calculated and given

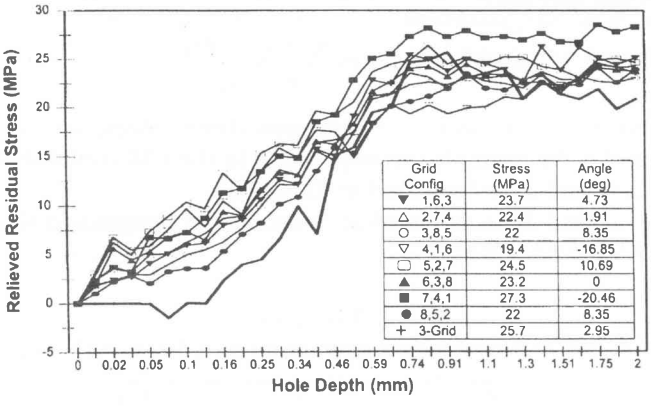


Fig. 4. Maximum relieved residual stresses, 8-element *vs* 3-element

in the table are the variation in recorded RS maxima, and the percentage variation as a function of the highest recorded maximum RS value. The percentage variation between maxima in these components range between 6.7% and 68% – see Table V. The results indicate that had 8-element strain rosettes not been employed in this study, large variations in the measured maximum RS magnitudes would have resulted. This variation, dependent on the initially unknown hole ovality, arises because recorded maxima are strongly dependent on the orientation of a standard 3-element strain rosette.

The unequal strain relaxations observed with opposite grid pairings (see Fig. 5) are considered to be a result of the ovality of the hole shape. It is assumed that this would occur because the textured DPS is neither isotropic nor homogeneous in its response to plastic deformation, which, in itself, would lead to the unequal strain response around a drilled hole. The effect of this is shown in Fig. 5, where the maximum relieved strains for a typical analysis are shown graphically with respect to their relative grid positions about the hole centre.

It was observed that the highest and lowest maximum RS magnitudes were not always indicated by the same gauge combination, even when analyses were repeated in the same relative position on similar discs. This further underlines the importance of the use of an 8-element strain rosette when seeking to obtain the maximum RS magnitude in textured steels subjected to forming operations. A further study was undertaken to establish the typical level of error that might be expected had a standard 3-element rosette been employed instead of the 8-element strain rosette. This was done by comparing the highest relieved maximum RS values, given by the 8-element strain rosette, with the maximum RS value indicated by a (constant) 1,6,3 gauge combination in the 8-element strain rosette. The 1,6,3 gauge combination would therefore represent a standard CW 3-element rosette, taken in a typical user orientation relative to the wheel centre disc. Percentage errors between maxima shown by the 1,6,3 gauge combination and the 8-element rosette were then calculated. The results of this

TABLE V

RECORDED VARIATION BETWEEN HIGHEST AND LOWEST MAXIMUM RESIDUAL STRESS MAGNITUDES FOR EACH 8-ELEMENT ANALYSIS LOCATION [RESIDUAL STRESSES IN MPa]

Comb. [High/ Low]	High Max. RS	Low Max. RS	RS variation	% variation
[3,8,5][2,7,4	166.1	155	11.1	6.7
[1,6,3][7,4,1]	113.6	101.1	12.5	11
[3,8,5][7,4,1]	186	161	25	13.4
[3,8,5][8,5,2]	298.3	249	49.3	16.5
[7,4,1][6,3,8]	113.2	94.3	18.9	16.7
[4,1,6][8,5,2]	239	198.4	40.6	17
[1,6,3][5,2,7]	346.8	280.8	66	19
[4,1,6][5,2,7]	381.7	305.3	76.4	20
[4,1,6][8,5,2]	217.2	163.9	53.3	24.5
[8,5,2][4,1,6]	363.5	263.5	100	27.5
[5,2,7][1,6,3]	144.3	104.3	40	27.7
[2,7,4][1,6,3]	156.4	111.3	45.1	28.8
[2,7,4][5,2,7]	415.6	280.4	135.2	32.5
[3,8,5][6,3,8]	130.3	85.4	44.9	34.5
[5,2,7][6,3,8]	181.4	118.4	63	34.7
[3,8,5][7,4,1]	159.1	101.4	57.7	36.3
[1,6,3][5,2,7]	109.3	68.4	40.9	37.4
[4,1,6][8,5,2]	152.5	91.1	61.4	40.3
[5,2,7][1,6,3]	158.4	92.4	66	41.7
[1,6,3][5,2,7]	188.6	106.5	82.1	43.5
[5,2,7][1,6,3]	173.3	92.7	80.6	46.5
[4,1,6][8,5,2]	384.1	182.3	201.8	52.5
[8,5,2][4,1,6]	468.7	202.7	266	56.8
[4,1,6][8,5,2]	406.4	164.2	242.2	59.6
[3,8,5][7,4,1]	−296.9	−111.7	185.2	62.4
[5,2,7][2,7,4]	−265.7	−99.7	166	62.5
[3,8,5][4,1,6]	−264.9	−84.8	180.1	68

comparison are shown in Table VI. Note that 'Gauge HRS' indicates which gauge combination revealed the highest maximum RS magnitude. All RS magnitudes are given in MPa.

Only 4 of the 27 results would have yielded the same maximum RS magnitude. The largest difference between the 8-element and 3-element gauges was found to be 60.7%. Of concern is the fact that more than half of the analyses would have yielded differences greater than 25%. For purposes of component design and repeatability of measurement, such large variations in results of residual stress analysis are not acceptable. For each analysis the angle of action of the principal relieved residual stresses, or principal angle, was determined for all gauge combinations. The calculated principal angles revealed by each gauge combination showed good correlation, with all values lying within a range of 10°. However, in a similar fashion to the observed variation in stress data found considering the various 3-element gauge combinations, the principal angle variation depended on the gauge orientation with respect to the major axis of the oval hole. Typical data for variation of prin-

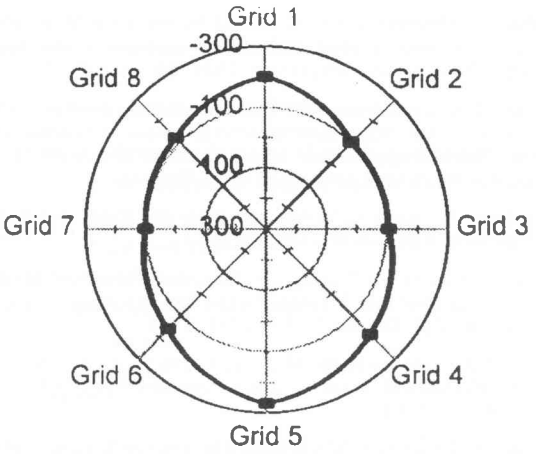


Fig. 5. Example of uneven strain relief distribution on opposite sides of the hole, units in micro strain

cipal angles observed by an 8-element rosette are given in Table VII.

Discussion

When attempting to measure the relieved residual stresses by the hole-drilling technique a question arises as to the direction along which element Gl should be aligned, and which type of rosette is required to obtain the maximum RS magnitude. This concern has previously been raised by users of this technique.[6] The information presented in this paper goes some way towards resolving some of these difficulties.

The data presented in this paper indicate the difficulty of predicting hole ovality or the uneven strain relief distribution about the hole, when textured materials that have been plastically deformed are analysed. It is therefore not possible to predict in what orientation the reference grid of a 3-element rosette should be aligned in order to reveal the maximum RS magnitude. This led to the development of the novel 8-element rosette, which considerably reduces the resultant variation in RS values. This work has shed light on percentage differences in RS maxima found with the various 3-element gauge combinations contained in an 8-element rosette. This random variation reached values greater than 60%, which indicates why strain rosette measurements of residual stress can be somewhat unreliable.

Although the use of an 8-element strain rosette could still lead to variable results, even when analysing similar components at similar locations, variation is apparently much lower for the pressed steel wheel, i.e. less than 30%. Use of the 8-element rosette would therefore confer a higher confidence level when applying the results of strain-rosette-based RS analysis to component design and fatigue/fracture lifing. It would also provide a higher level of repeatability with a lower number of hole drilling analyses.

The work by Schajer[7] resulting from the development of a new 6-element strain rosette has shown that the measurement accuracy can be greatly improved, compared to the results of a conventional 3-element rosette. An interesting future study would be to compare results using the 6-element rosette to those using the 8-element rosette on plastically deformed sheet metal components.

TABLE VI

Results of comparison showing expected error as a result of rosette orientation when using a 3-element rosette

Max. RS [1,6,3]	Highest Max. RS	Gauge HRS	% difference
113.6	113.6	1,6,3	0
109.3	109.3	1,6,3	0
188.6	188.6	1,6,3	0
346.8	346.8	1,6,3	0
294.2	298.3	3,8,5	1.4
163.4	166.1	3,8,5	1.6
181.1	185	3,8,5	2.6
369.9	381.7	4,1,6	3.1
381.7	415.6	2,7,4	8.2
193.8	217.2	4,1,6	10.8
100.4	113.2	7,4,1	11.3
209.6	238	4,1,6	12.3
298.7	363.5	8,5,2	17.8
114.2	152.5	4,1,6	25.1
346.9	468.7	3,8,5	26
104.3	144.3	5,2,7	27.7
111.3	156.4	2,7,4	28.8
273.5	384.1	4,1,6	28.8
288.5	406.4	4,1,6	29
111.8	159.1	3,8,5	29.7
91	130.3	3,8,5	30.2
124.1	181.4	5,2,7	31.6
92.4	158.4	5,2,7	41.7
92.7	173.3	5,2,7	46.5
-126.3	-264.9	3,8,5	52.3
-131.6	-296.9	3,8,5	55.7
-104.4	-265.7	5,2,7	60.7

Conclusion

The present work shows that the 8-element rosette developed can reduce the variability inherent in strain rosette-based residual stress assessment, particularly where effects of anisotropy and lack of homogeneity in textured steels must be taken into account.

The data obtained from the "as manufactured" DPS plate indicate that the 3-element strain rosette would have given an acceptable maximum residual stress result. The difference being 16 MPa (see Fig. 4) compared with the maximum value as assessed by the 8-element strain rosette, as analysts using the hole drilling method regard the norm to within 20 MPa.[2] Hence, the potential now exists for substantial savings in time, effort and money through use of an 8-element strain rosette in routine component testing in industry. The present authors believe that hole oval-

TABLE VII

TYPICAL PRINCIPAL ANGLES AS REVEALED BY EACH GAUGE COMBINATION IN AN 8-ELEMENT ROSETTE AS ASSESSED ON A CENTRE DISC

Gauge combination	Principal angle α
1,6,3	4.6°
2,7,4	6.8°
3,8,5	3.3°
4,1,6	5°
5,2,7	3.5°
6,3,8	2.4°
7,4,1	6.3°
8,5,2	4°

ity is important in residual stress measurement of plastically deformed components, and strain gauge manufacturers should pursue the concept of the 8-element gauge.

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