EFFECTS OF FORMING PROCESS ON FATIGUE PERFORMANCE OF WHEEL CENTRE DISCS

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ABSTRACT

This paper considers the effects of sheet metal forming processes on the fatigue performance of automotive wheel centre discs, manufactured from dual phase steel. Characteristics of the fatigue process for such components are crack initiation in a highly strained area, and reflect the forming deformation of the sheet and a loading mode that is predominantly bending.

This work utilises waisted hour-glass specimens, machined from centre discs taken from each stage of the manufacturing process. Attention is paid to the influence of the degree of cold working on fatigue performance, with particular emphasis on the interaction between surface hardness and induced residual stresses measured on the centre discs

The results indicate a correlation between the fatigue-tested wheels and laboratory specimens for producing their respective S-N curves. It can therefore be deduced that the fatigue testing of hourglass specimens machined from the production stages will have a similar relationship if these components could be fatigue tested under industrial conditions.

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INTRODUCTION

Sheet materials are generally characterised by a "high ratio of surface area to thickness", and the uni-axial force applied to the sheet plate during a stamping operation is mainly tensile in nature **(1)**. This applied tensile force induces residual stresses in the component that are dependent upon the shape of the component, and vary in magnitude (and sign) with position. The fact that cold working operations enhance the tensile and fatigue crack initiation strength of a material are well understood and documented **(2)** but, in terms of fatigue performance, this may be countered by the residual stresses induced during sheet metal forming operations, which achieve high tensile values. These act to increase the mean stress in fatigue cycling which will decrease fatigue strength.

Centre discs of automotive wheels are produced from sheet metal plate through a series of four cold stamping operations and a final painting and low temperature curing cycle. Centre discs relevant to a particular light passenger vehicle wheel were obtained at each stage of the wheel manufacturing process, starting with the "as-manufactured" plate. Residual stresses were measured on the discs, at each stage, in the critical crack initiation regions found from cantilever bend tests of production wheels. Hardness and microstructure were also characterised at each stage. Hourglass fatigue specimens were machined from the discs and tested in reversed bend with the same fatigue loading cycle used for the production wheels. These specimens showed decreases in fatigue life relative to the as-manufactured plate, although the trends in life did not exactly correlate with either residual stress or hardness data. The trends in fatigue life are explained in terms of the interaction between these two influences, and surface embrittlement arising from the paint bake hardening cycle.

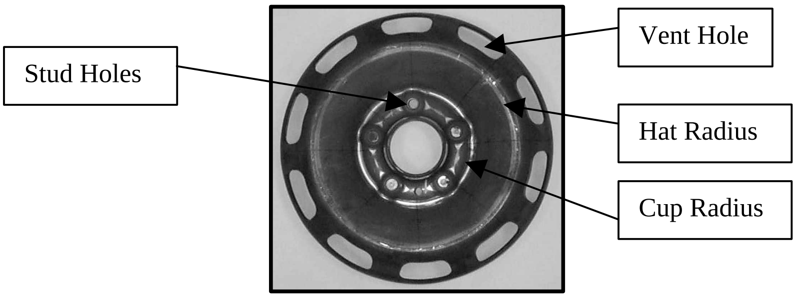


Figure 1. – Nomenclature of centre disc.

MATERIAL

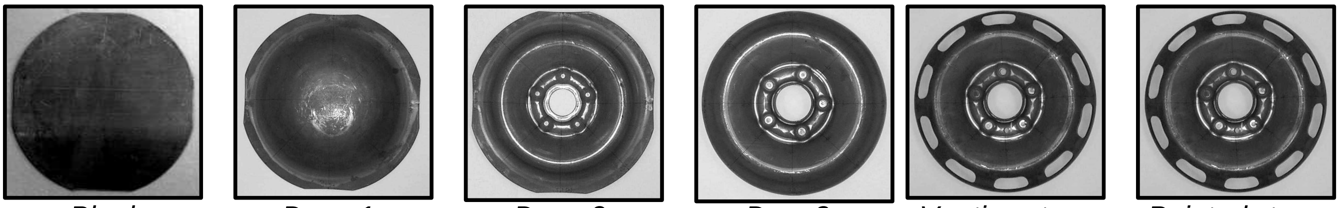
In this investigation the centre discs were manufactured from Dual Phase Steel (manufacturer designation DPS600). This type of high strength low alloy (HSLA) **(3)** steel was developed during the mid-1970's and consists of ± 20% islands of martensite within a ferritic matrix and has both good drawability and formability characteristics. It is considered superior to the conventional HSLA rim steels normally used by automotive component manufacturers. The chemical composition is given in Table 1, and the mechanical properties in Table 2.

Chemical Element & % Content	C	Mn	P	S	Si	Al	Cr	Ni	Ti	Mo	Cu
	0.05 0.12	0.50 1.30	0.01 0.09	Max 0.006	Max 0.65	0.02 0.06	Max 0.90	Max 0.25	Max 0.015	Max 0.05	Max 0.35

Table 1. – Chemical composition of DPS600.

Designation	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% Elongation
Dual Phase Steel (DPS600)	Min. 300 Max. 470 Actual 427	Min. 550 Max. 700 Actual 662	28

Table 2. – Mechanical Properties of DPS600.



Blank | *Draw 1* | *Draw 2* | *Draw3* | *Venting* stage | *Painted* stage

Figure 2. – Production stages of centre disc manufacture.

TESTING APPARATUS

Fatigue

Fatigues testing for this investigation were performed on a purpose-built reversed bend machine. This dual-purpose computer controlled testing machine consists of three components, namely, a loading frequency controller, the reversed bend test set-up and a strain amplifier (see Figure 3) which is capable of controlling applied load via strain information under high and low cycle fatigue conditions.

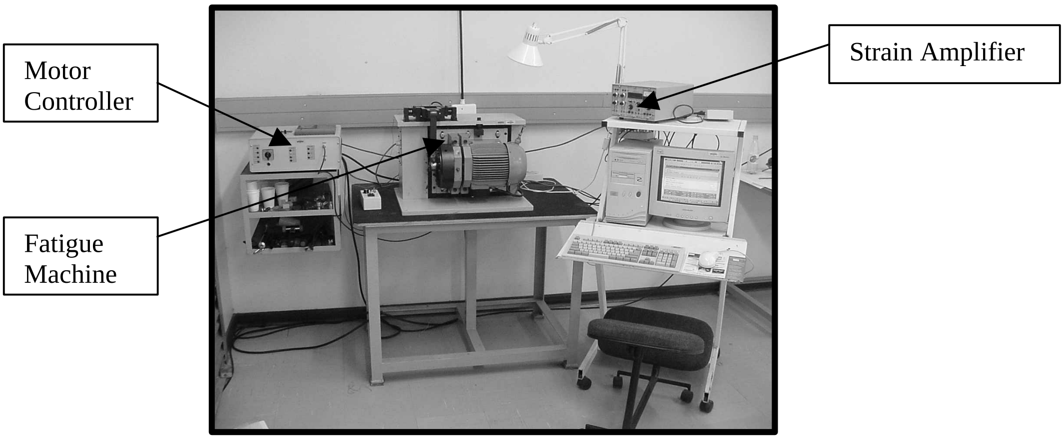


Figure 3. – Purpose-built fatigue testing system.

Residual Stress

The RESTAN hole drilling strain gauge system was employed for this work. This system is computer controlled and consists of three main devices; the electronic unit, strain amplifier and the drilling machine, see Figure 4. Once the specimen has been prepared, it is leveled and aligned with the drilling machine by means of an optical device incorporated in the drilling head and is then secured to the work table in this position. On completion of the drilling operation, the hole is measured and these measurements are input into a computer program to obtain the principal stresses and principal angles. This is carried out in accordance with ASTM 837.94(a).

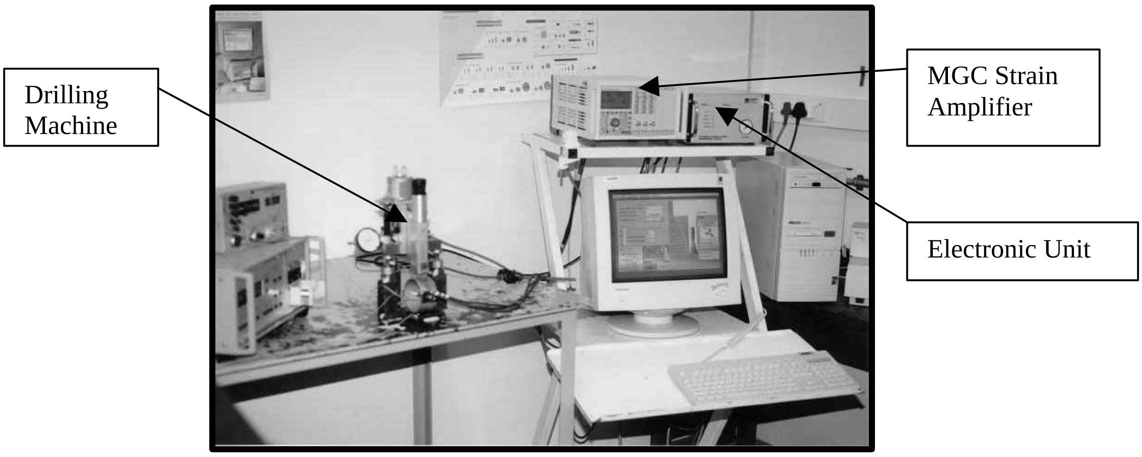


Figure 4. – Residual Stress System.

SPECIMEN PREPARATION

Fatigue

Waisted hour-glass specimens were machined from centre discs taken from each stage of the wheel production process using a CNC milling machine (Figure 5). On completion of the machining process the specimens were assigned an identification mark, de-burred and flapper ground to remove machining marks.

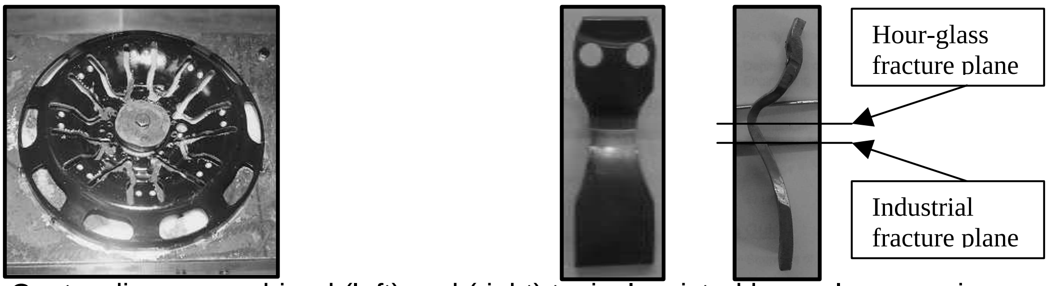


Figure 5. – Centre disc as-machined (left) and (right) typical waisted hour-glass specimen.

Because of the shape of the centre discs, specimens required jigging in the fatigue testing machine to duplicate their test conditions under cantilever bend in the dynamic wheel testing machine used commercially. This was done in an endeavour to match crack initiation and fracture planes in the specimen and the production wheels. Hence specimens were placed in a mould and a cold curing resin (Lecoset 7007) cast around them to ensure a flat seating (see Figure 6) of the specimen ends in the test grips, and the correct orientation of the specimen in the test machine. This orientation is such that the predominant fracture plane position in the centre disc, as observed under industrial fatigue testing conditions (just above the cup radius area, see Figure 1), is coincident with the axis of rotation of the fatigue testing machine. All specimens were machined to ASTM E468-82.

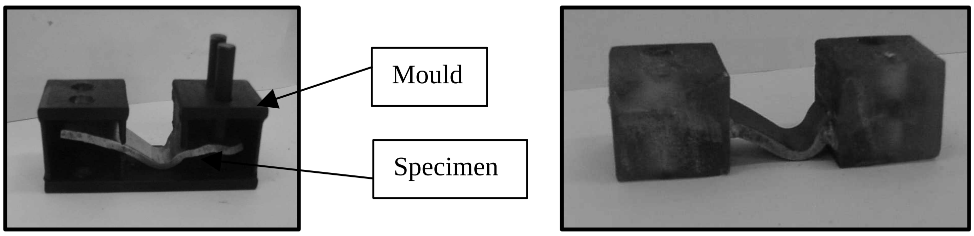


Figure 6. – Mould (left) for producing spacers (right).

Finally a strain gauge (Micro Measurements type EA-06-062-AK-120) was attached to the specimen perpendicular to the axis of rotation plane to allow for the applied load setting.

Residual Stress

Centre discs from each stage of the production process were used for assessing the residual stress magnitudes. Measurement locations considered were that above the cup radius area as mentioned above. For this investigation a customised eight-element strain rosette* was employed (see Figure 7) using three Micro Measurements type CEA-06-062-UM-120 strain rosettes for assessing the maximum arithmetical principal stresses and corresponding principal angles.

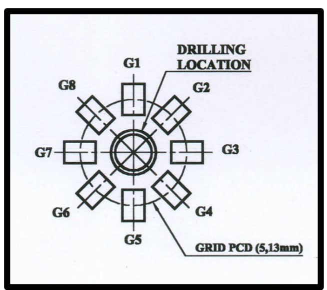


Figure 7. – Illustration of customised eight-element rosette layout.

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* The concept of the customised strain rosette used for the residual stress investigations in this work is subject to a South African patent application No. 99\2855.

TESTING PROCEDURES

Fatigue

The strain amplitude was set at 1300 micro-strain (this being equivalent to 260 MPa) at the predominant industrial fracture plane (Figure 5) and a test frequency of 33 Hz. In the event this endeavour was unsuccessful, because the cross-sectional area of the specimen corresponding to the cup radius region was smaller than that corresponding to the fracture plane under industrial testing of the wheels. This region is also offset both vertically and horizontally from axis of bend (rotation) of the fatigue-testing machine. This implies that the bending stresses in this region are different to those along the predominant fracture plane in the wheel and hour-glass specimens, under similar applied load conditions.

The applied load cycle (strain ratio) gave maximum and minimum values of -1540μ strain and +1420μ strain at the fracture plane (through apex of cup radius). This assessment was fundamentally important with a view of having to fatigue test plate (*blank*) and d*raw 1* specimens. The fatigue testing procedure of the production stages commenced with the *painted* stage and finished with the plate (*blank*) specimen. It must be remembered that the cup radius region is present from *draw 2* thru *painted* specimens and it is through the apex of this region that failure occured. Both the plate (*blank*) and *draw 1* specimens (which do not have this cup radius region) were aligned such that the narrowest cross-section of the hour-glass shape corresponded with the axis of bend of the fatigue machine. Failure of these specimens would thus occur through this region. Therefore, all the production stages were fatigue tested at the same applied load cycle (strain ratio) corresponding to their respective fracture planes.

Residual Stress

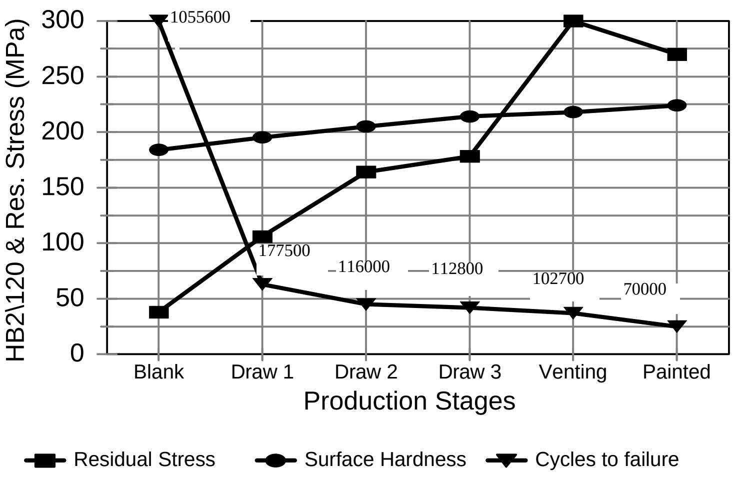
In order to align the drilling location on the component to the drilling head it was necessary to extend the feet of the drilling machine, this was achieved by manufacturing a rigid framework from 20 mm solid square bar to which the feet and the machine was attached. For this investigation a 2 mm deep hole was drilled using the polynomial drilling method with 30 increments and a delay time setting of 10 seconds between each increment. Prior to commencing the drilling operation the end mill is brought into contact with the metal component, causing a short circuit between component and end mill. This position of the end mill is taken as datum and the drilling operation can commence.

Surface Hardness

Due to the peculiar shape of the components, Brinell hardness measurements were made using a 2 mm ball indenter and a 120 kgf load on the same components used for the residual stress measurements. Measurement locations were adjacent to the residual stress analysis positions.

RESULTS

For this exploratory investigation five fatigue specimens were cut from centre discs from each production stage and tested at the mean strain ratio as observed at the hour-glass fracture plane.



Prod. Stages	**Fatigue Life** (Nf)	**Hardness** (HB2\120)	**Residual Stress** (MPa)
Blank	1055600	184	38
Draw 1	177500	195	106
Draw 2	116000	205	164
Draw 3	112800	214	178
Venting	102700	218	300
Painted	70000	224	270
Wheel	72500	226	320

Figure 8. – Results of the residual stress, hardness and fatigue analysis.

The residual stress and hardness measurements were averaged from two centre discs from each stage, as the results obtained were of similar magnitude.

DISCUSSION

It is well known that cold working operations increase the ultimate tensile and yield strengths of steels. If a component is subjected to a shot peening or cold rolling operation the fatigue performance will be enhanced by the compressive residual stresses induced as a result. These compressive residual stresses are beneficial in terms of fatigue. However, if the component is subjected to cold drawing operations carried out under tensile conditions, such as is the case in sheet metal forming, the residual stresses induced will be tensile in nature and will have the opposite effect in terms of fatigue performance. The fatigue performance may also be impaired due to void formation **(4)** along grain boundaries see, for example, Figure 9 (x3865).

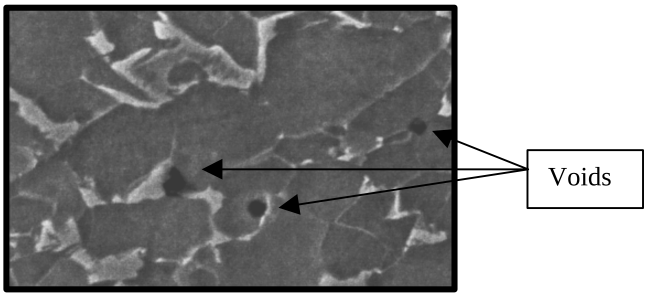


Figure 9 – Voids (near top surface) resulting from operations carried out under tensile conditions.

The trends indicated in Figure 8 for surface hardness, residual stress and fatigue performance were to be expected in terms of the cold working operations, with the exception of the residual stress and fatigue life for the *painted* stage. The substantial decrease in fatigue performance between plate (*blank*) and *draw 1* specimens is largely attributed to the tensile residual stresses and the onset of void formation within the microstructure due to the tensile natured plastic deformation. Further plastic deformation (tensile) experienced by *draw 2* components resulted in a similar increase in residual stress magnitude, and the voids being more pronounced increases the fatigue notch sensitivity resulting in a less significant decrease in fatigue life. A less pronounced decrease in fatigue life and a corresponding increase in surface hardness is observed from *draw 2* up to and including the *venting* stage. From Figure 2 it is evident that the volume of material differs between the various production stages. In terms of volume of material, the stages can be classified into the following groups:

- *Blank* and *draw 1;*
- *Draw 2* and *draw 3;*
- *Venting* stage and *paint* stage.

This is important to note since the residual stress magnitude of the *venting* stage is considerably higher than *draw 3* stage. This significant increase in magnitude can be attributed to the decrease in volume of material (punching of vent holes) leading to the re-distribution of internal energy (residual stress) to attain new equilibrium conditions.

The paint curing process is of low temperature (around 200°C) and the observed small reduction in residual stresses is to be expected. Such a reduction should be beneficial to fatigue life, as should the increase in hardness observed for this stage. However, the fatigue life actually decreases slightly after this process. It was only after microstructural analysis was carried out that this behaviour was clarified. It was found that carbonitrides had precipitated along the grain boundaries on the surface of the *painted* stage centre discs, which has a significant effect on surface hardness as reported by Okita et.al. **(5)**. The martensite grains also show a change to a more acicular structure. The net result of these fairly subtle microstructural changes during paint baking, is that the surface is slightly 'embrittled' thereby increasing the notch sensitivity. Hence the fatigue life is reduced in this stage of the process.

The residual stress analysis was undertaken on complete production components and not on the waisted hour-glass specimens, in which the residual stress field would have been largely eradicated by the specimen manufacturing process. Fatigue data from these specimens can, however, be correlated with hardness results (which would be the similar in centre discs and specimens) and with the residual stress data from the centre discs, as indicated in Figure 10. A calibration of the residual stress information and the fatigue results can be effected by considering the difference between lives for the complete wheel and specimens cut from the *painted* and baked centre disc. This implies that if production stages could be fatigue tested under industrial conditions then the same trend as indicated in Figure 8, would apply, but that the number of cycles to failure would be in accordance with the relationship which exists at a load cycle of 260 MPa.

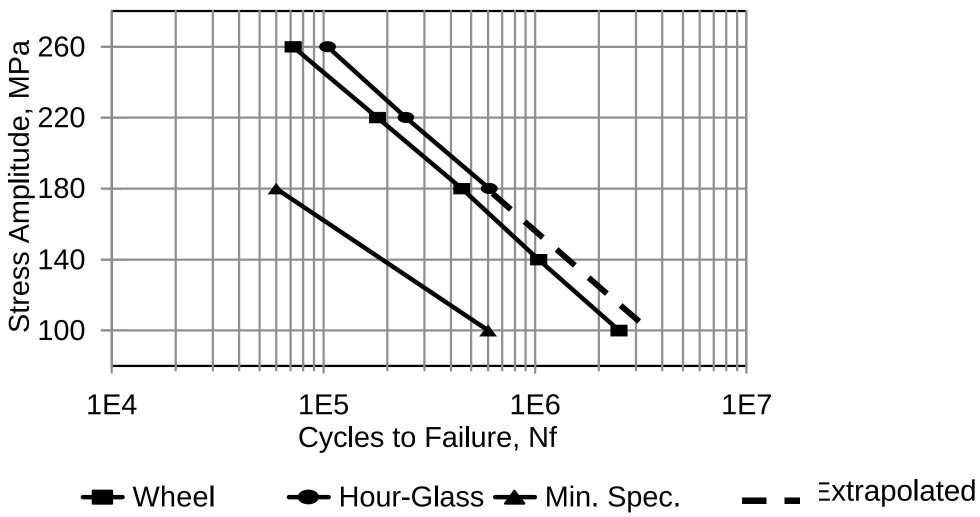


Figure 10. – Comparison of S-N curves for wheel and hour-glass specimens.

All fracture surfaces showed similar features, i.e. ratchet markings on both top and bottom surfaces, more pronounced along the top surface. It is envisaged that the crack front slows as it propagates through the elastic core region (an area around the neutral axis) where it grows laterally (secondary cracking) due to the discontinuities present in this region. These discontinuities are considered imperfections resulting from the stamping operation which cannot be removed through metallurgical or heat treatment processes. Therefore, as the crack front grows through this region (see Figure 12, x775), crack initiation commences from the bottom surface, as ratchet markings are also evident. Finally the crack fronts grow toward one another until catastrophic failure occurs which is observed by the 'fast fracture plane' evident along the lower half in Figure 11.

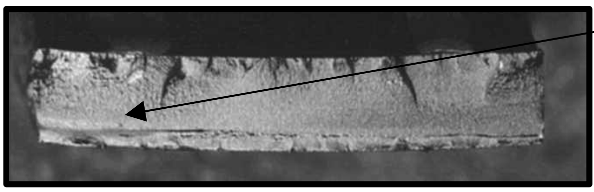


Figure 11 – Fracture Surface.

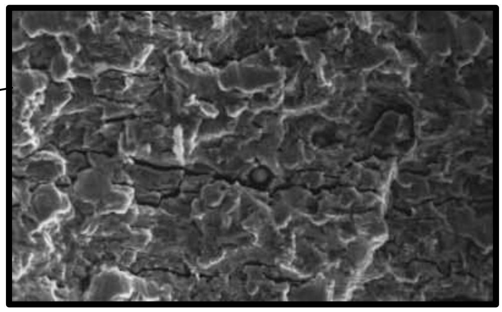


Figure 12 – Showing secondary cracking in elastic core region.

An additional interesting outcome from this work relates to the development of an eight-element strain rosette, which gives improved residual stress information when holes are drilled into a textured steel (which causes hole ovality to occur). In such cases there is no easy way of identifying, a priori, the plane along which the maximum deformation will occur when the internal strains are relieved through the drilling of a hole. The eight-element strain rosette gives improved results because the arithmetic maximum relieved residual stresses are revealed at a particular assessment location.

CONCLUSIONS

Based on the experimental results presented in this paper, the following conclusions have been drawn:

- Fatigue testing of waisted hour-glass specimens machined from the various production stages of the centre disc is an effective tool in evaluating the fatigue strength of centre discs.
- Tensile surface residual stresses appear to play a significant role in fatigue performance, as fatigue life is more closely aligned with trends in residual stress than with trends in hardness.
- The final paint baking cycle has a larger detrimental influence on fatigue life than would be expected from residual stress or hardness data. This is due to carbonitride precipitation at the grain boundaries in this dual phase steel. Small changes in chemical composition of the steel may alleviate this phenomenon.
- The eight-element strain rosette concept offers advantages in residual stress measurement in textured metals which show significant hole ovality. It should be pursued by strain gauge manufacturers.

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