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Multiaxial Fatigue Behavior of Cylinder Head for a Free Piston Linear Engine

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Abstract: This study was presented the assessment of multiaxial fatigue criteria of cylinder head for a free piston linear engine using finite element analysis techniques. The structural solid modeling of cylinder head was developed utilizing the computer-aided design software. The finite element modeling and analysis were performed utilizing the finite element analysis codes. The biaxiality analysis was performed to assess the multiaxial fatigue. The material parameter and Hoffmann-Seeger methods were considered to modify the uniaxial material properties. Prediction of fatigue life, effect of the stress combination for the proportional loading condition was investigated in this study. It can be seen that the biaxiality correction method gives conservative predicted life as compared to the uniaxial loading. The materials parameter correction method gives most conservative prediction with SWT criteria. It is also observed that more conservative prediction to use Signed Tresca parameter and Signed von Mises stress gives the result that lie between the absolute maximum principal and signed Tresca results. This approach shows to be quite suitable for integration with a commercial finite element code to provide for an integrated design environment for fatigue life evaluation under general multiaxial loading conditions.

Key words: Automotive component, finite element analysis, strain-life, biaxiality, proportional loading, aluminum alloy, stresses

INTRODUCTION

Fatigue failure of automotive components under multiaxial loading conditions is a common, since most engineering components are subjected to multiaxial cyclic stresses in service and the origins of multiaxiality are generally due to the external loading, geometry or residual stresses (Carpinteri *et al*., 2008; Li *et al*., 2009). Multiaxial fatigue estimation is a very complex task. In comparison to simple load states, which are more or less satisfactorily solved by widely used uniaxial methods, there is an increased number of degrees of freedom due to the enhances complexity of the interactions (Papuga and Ruzicka, 2008). Many automotive industrial components such as wheels, suspension arms, butt welds, connecting rods, steel wires, train suspension springs contain defects of different sizes and geometries (Karolczuk *et al*., 2008). Some of these components are classified as safety components and thus they have to be subjected to particular attention during fatigue design in order to guarantee an appropriate in-service durability with light-weight design. Hence, the problem of high-cycle fatigue life estimation of components containing defects is of great importance from a social, scientific and industrial point of view. The fatigue process of mechanical components under service loading is variable amplitude in nature. Life prediction and durability assessment is still a challenging problem extensive process made in the past decades. Many critical mechanical components experience the multiaxial cyclic loadings during their service life. Different from the uniaxial fatigue problem, the multiaxial fatigue problem is more involves due to the complex stress states, loading histories and different orientations of the fatigue crack in the components. In recent decades, numerous attempts to develop multiaxial fatigue damage criteria and fatigue damage modeling have been reported. Several reviews and comparison of existing multiaxial fatigue models can be found elsewhere (Bernasconi *et al*., 2006; Chamat *et al*., 2007; Liu and Mahadeven, 2007; Ninic and Stark, 2007). Understanding of multiaxial fatigue problem is essential for the reliability assessment under realistic service conditions and is valuable for the design

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and maintenance against fatigue failure. Although, there are many proposed models for multiaxial fatigue damage modeling and most of them are limited to specific materials and loading conditions. Some of them cannot predict the initial crack orientation, which is another distinct characteristic of multiaxial fatigue damage compared with the uniaxial fatigue problem. To the author's knowledge, there is no existing multiaxial fatigue damage model is universally accepted. As it is well-known, actual time varying loadings on mechanical components are often experiences the multiaxial fatigue, however, it is usual to rely on uniaxial fatigue test parameters for life predictions of such structures, due to the complexity and expense involved in multiaxial fatigue experimental tests. Several criteria proposed during the last decades to predict whether the fatigue failure under multiaxial loading may occur or not (Garud, 1981; You and Lee, 1996; Papadopoulos *et al*., 1997; Carpinteri and Spagnoli, 2001; Wang and Yao, 2004). Criteria based on the critical plane approach for multiaxial fatigue evaluation have been gaining popularity (Leese and Socie, 1989; You and Lee, 1996). According to the critical plane approach, fatigue evaluation is performed on one plane across a critical location in the component. This plane is called the critical plane, which is usually different for different fatigue models. Jiang (2000) proposed a damage parameter based on linear combination of shear stress amplitude and maximum normal stress acting on the critical plane.

The research on multiaxial fatigue can be divided into three main approaches. For stress-based approach including the maximum principal stress, Tresca (maximum shear stress) or von-Mises are used to compose the multiaxial fatigue parameter. This approach is often used to predict high cycle fatigue. Some approaches (McDiarmid, 1991) are based on shear and normal stresses associated with the critical plane. Only the shear and normal stresses in this plane are considered in formulation of the fatigue damage parameter. This idea is supported by various experimental observations of physical mechanism of the fatigue damage process (Fatemi and Socie, 1988; Brown and Miller, 2007). However, many experiments and observations showed that the fatigue cracks usually initiate in the plane of maximum shear strain amplitude which should be the plane of maximum damage. Therefore, some theoretical approaches suggested that the parameter governing fatigue life are related to the maximum shear stress and stress normal to the plane of maximum shear strain. For the strain-based approach, the octahedral strain has been used to formulate the classical fatigue failure criteria. Recently, this approach is often considered the shear strain and normal strain in the critical plane to be the governing multiaxial fatigue parameter (Fatemi and Socie, 1988). For the energy-based approach, the strain-energy density per cycle has been used to form the fatigue parameter which is related to the fatigue life. In automotive industries, cylinder heads are one of the most critical components and function is of vital importance in human safety. The cylinder head manufacturers have been taking increasing attention to lightweight designs by new materials and manufacturing technologies in contradiction to durability concerns due to the complex loading conditions on head (Socie and Marquis, 2000; Rahman *et al*., 2007a). The purpose of this study is to investigate the multiaxial fatigue behavior on cylinder head of the free piston engine based on strain-life model under proportional loading using the finite element analysis technique.

MATERIALS AND METHODS

This study was conducted at high computing laboratory, Automotive Excellence Centre, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Kuantan. The duration of the project is September 2008 to August 2009. There are number of safety-critical components of the free piston engine. The cylinder head is one of the most important and safety-critical component in the free piston engine (Rahman *et al*., 2006; Rahman *et al*., 2007b). A cylinder head of the free piston engine is considered as an example parts in this study. There are several contact areas including the cylinder block, gasket and hole for bolt. Therefore, constraints are employed for the following purposes: (1) to specify the prescribed enforce displacements, (2) to simulate the continuous behavior of displacement in the interface area, (3) to enforce rest condition in the specified directions at grid points of reaction (Leese and Socie, 1989). Three-dimensional model of cylinder head was developed utilizing the CATIA® software. A 10 nodes tetrahedral element (TET10) was used for solid mesh. Sensitivity analysis was performed to obtain the optimum element size. These analyses were performed iteratively at different element global edge lengths until the solution obtained appropriate accuracy. Convergence of the stresses was observed as mesh size was successively refined. The element size of 1.25 mm was finally considered. A total of 289142 elements and 454335 nodes were generated with 1.25 mm element length. A pressure of 7.0 MPa was applied on the surface of cylinder head chamber generating a compressive load. A pressure of 0.3 MPa was applied on bolt-hole surface generating a preload. This preload is obtained according to the RB and W recommendations (Shigley *et al*., 2004). In addition, 0.3 MPa pressure was applied on the gasket surface.

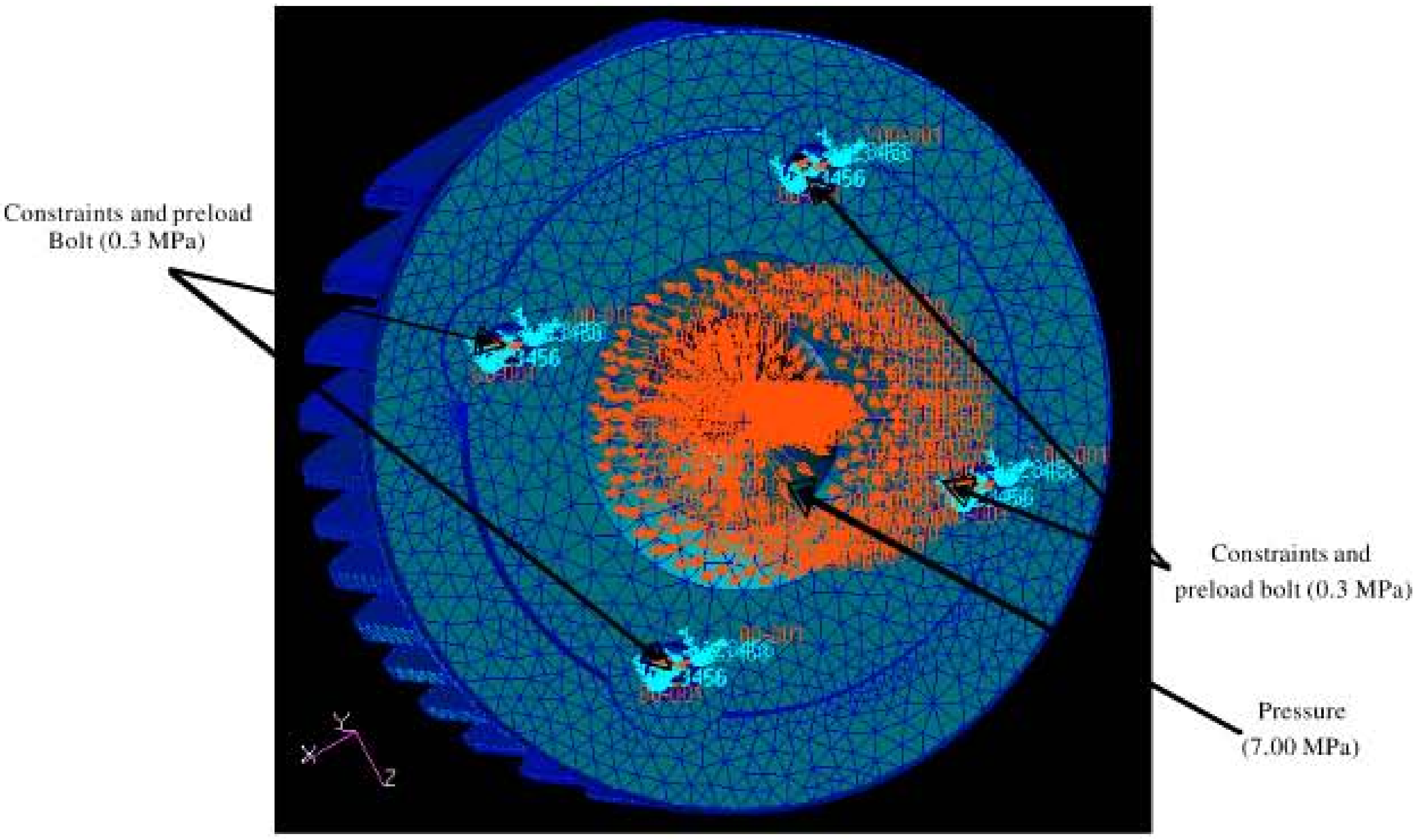

Fig. 1: Three-dimensional finite element model, loading and constraints

Multi-Point Constraints (MPCs) were applied on the bolt-hole surface for all six degree of freedom. Multi-points (Rahman *et al*., 2007b) were used to connected parts through the interface nodes. These MPCs were acting as an artificial bolt and nut that connect each parts of the structure. Each MPC's was connected using a Rigid Body Element (RBE) that indicates the independent and dependent nodes (Schaeffer, 2001). The configuration of the engine is constrained by bolting between cylinder head and cylinder block. In the condition with no loading configuration, the RBE elements with six-degrees of freedom were assigned to the bolts and hole on cylinder head. The independent node was created on the cylinder block hole. Due to the complexity of the geometry and loading on the cylinder head, a three-dimensional finite element model, loading and constraints is shown in Fig. 1. The applied loading state on the internal bore of cylinder was assumed that due to a fluctuating piston of a variable amplitude loading. This loading state of course give rise to cyclic fluctuating stresses in the global circumferential (tangential), radial and longitudinal direction of the cylinder cross section. However, it is assumed that the thickness in the radial direction is thin relative to the tangential and longitudinal directions such that an approximate biaxial stress and strain state is experienced in the cylinder head. The aluminum alloys are considered as a material of the cylinder head.

Several types of variable amplitude loading history including the tensile, compressive and bracket mean were selected for Finite Element (FE) based fatigue analysis. It is important to emphasize that these loading sequences are not intended to represent standard loading spectra in the same way that Carlos or Falstaf (MSC, 2005) was performed. However, they have been done containing many features, which are typical of automotive industries applications and therefore, are useful in the evaluation of the life estimation methods. The detailed information about these histories is given in the literature (Tucker and Bussa, 1975; Rahman *et al*., 2007b). The variable amplitude load-time histories are shown in Fig. 2a-c. The terms of SAETRN, SAESUS and SAEBRKT represent the load-time history for the transmission, suspension and bracket, respectively.

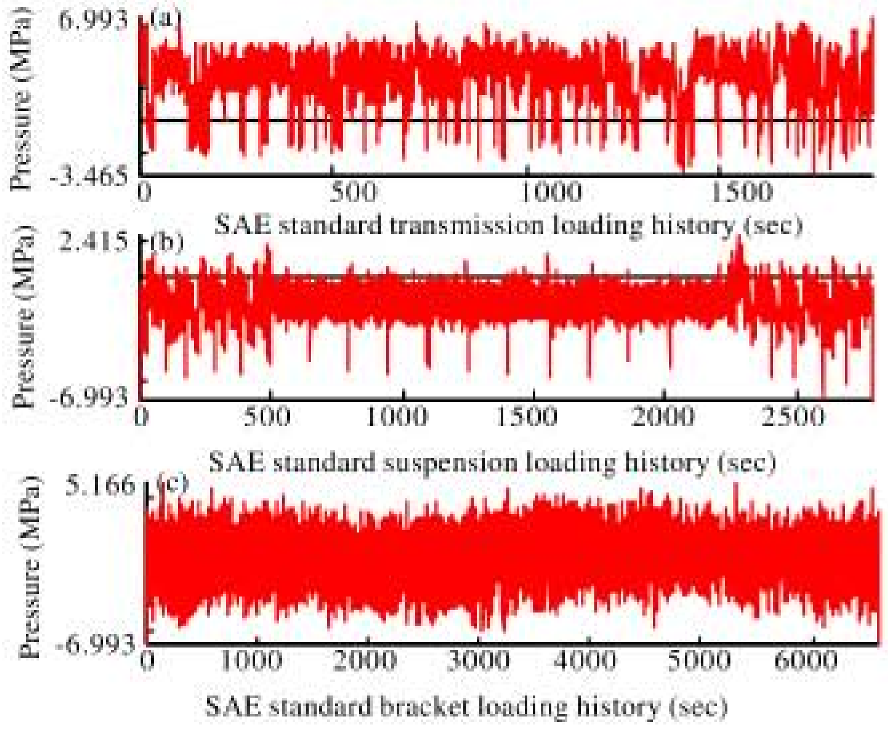

Fig. 2: (a-c) Variable amplitude load-time histories

RESULTS AND DISCUSSION

The linear static analysis was performed using MSC.NASTRAN® software to determine the stress and strain results from the finite element model. Figure 3 shows the maximum principal stresses of cylinder head with cast aluminum A356-T6 for SAETRN loading. From the acquired results, the maximum principal stresses of 642 MPa occurring at node 132171 were obtained. The results of the maximum principal stresses and strains are used for the subsequent fatigue life analysis and comparisons. The bolt-holes areas were found to experience the highest stresses.

The fatigue life of cylinder head is predicted using the Coffin-Manson method with SAETRN variable amplitude loading conditions. The result of fatigue life of the cylinder head for the cast aluminum is shown in Fig. 4. The file prediction is corresponding to 99.8% reliability. The fatigue life is expressed in terms of seconds for variable amplitude SAETRN loading histories. The fatigue equivalent unit is 3000 cpm (cycle per min) of the time history. From the results, it is observed that the predicted fatigue life of the cylinder head at most critical location (node 132171) is $10^{5.41}$ sec. It is also seen that the bolt-hole edge is the most critical positions for the cylinder head.

The multiaxiality analysis gives a better understanding of the stress state in the model and that stress state varies with time (MSC, 2005; Bannantine *et al*., 1990; Lee *et al*., 2005). It uses the surface resolved stresses and to define as the state of stress on the surface of the model should be plane stress. It is then used two in-plane principal stresses to determine the biaxiality ratio ($a_e = \sigma_2/\sigma_1$, where σ_1 is the absolute maximum in-plane principal stress and σ_2 is the other in-plane principal). A biaxiality analysis is to determine the standard deviation of the biaxiality ratio. Biaxiality ratio mean parameter is the average biaxiality ratio for every time steps in the combined loading history. The mean biaxiality ratio contours is presented in Fig. 5. It can be seen that the maximum mean biaxiality ratio value is 0.919, which is close to +1 value at critical location (node 132171). It is implied that the cylinder head experiences considerable equibiaxial. This parameter varies between minus one for pure shear and plus one for fully biaxial. Based on the above mentioned reason the multiaxial fatigue solution should be considered.

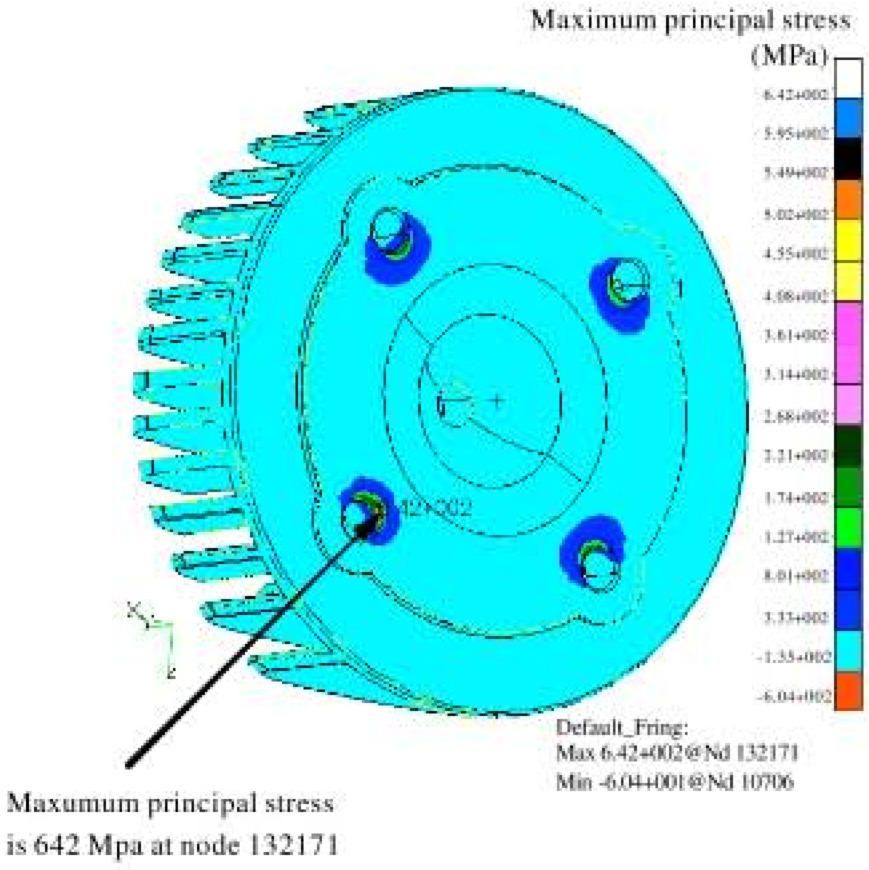

Fig. 3: Maximum principal stresses contour

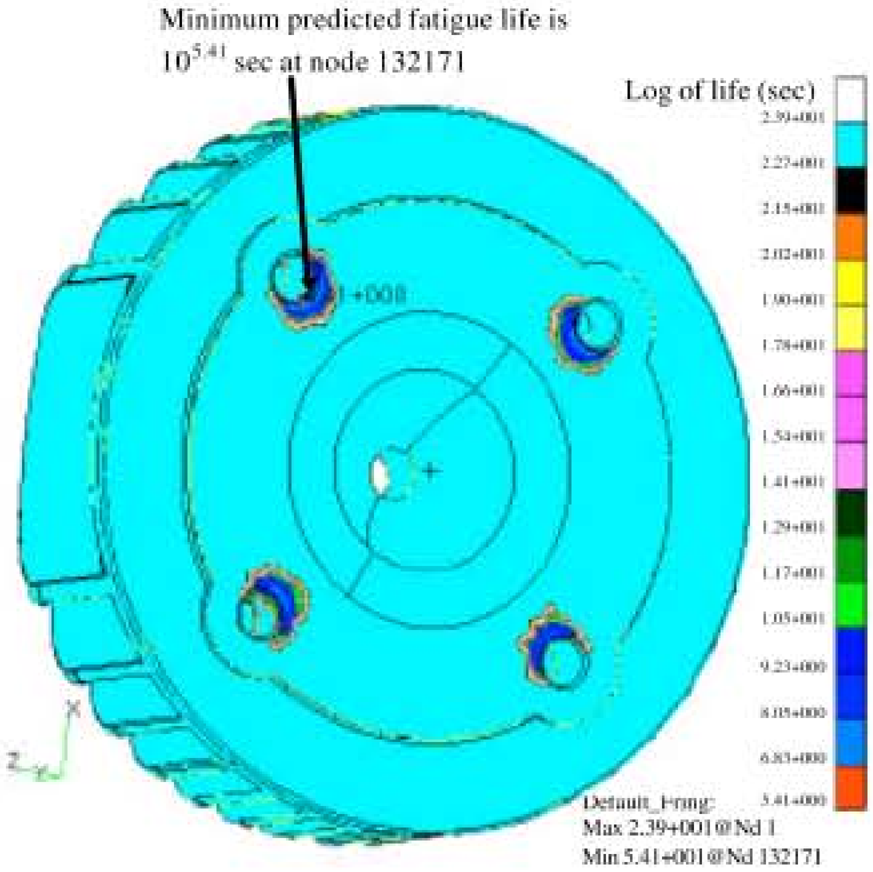

Fig. 4: Predicted fatigue life contours plotted

The biaxial parameters are calculated to loading multiaxiality present in the component due to determine the validity of the fatigue analysis. Figure 6a-e show the time variation of different multiaxiality parameters such as maximum principal stress, minimum principal stress, absolute maximum principal stress, signed von Mises stress, signed maximum shear stress for critical location (Node 132171). Biaxiality ratio defined as the ratio of the minimum and maximum principal stresses at a location on the surface of a component. Figure 7 shows the cross plot of the biaxiality ratio versus maximum absolute principal stress at the critical location (Node 132171). It can be seen that the biaxiality ratio straight lineup vertically at a particular ratio (0.5329) and non-zero. It is also implied that the cylinder head experiences considerable equibiaxial. Figure 8 shows the cross plot of the angle versus maximum absolute principal stress at critical location (Node 132171). Again note that tend the

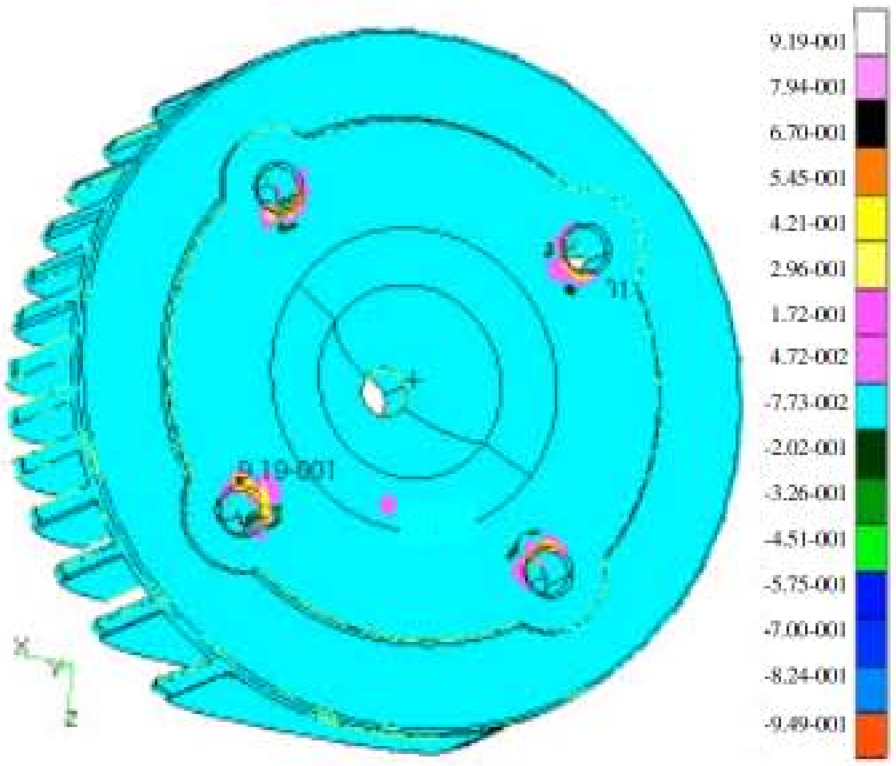

Fig. 5: Mean biaxiality ratio contours

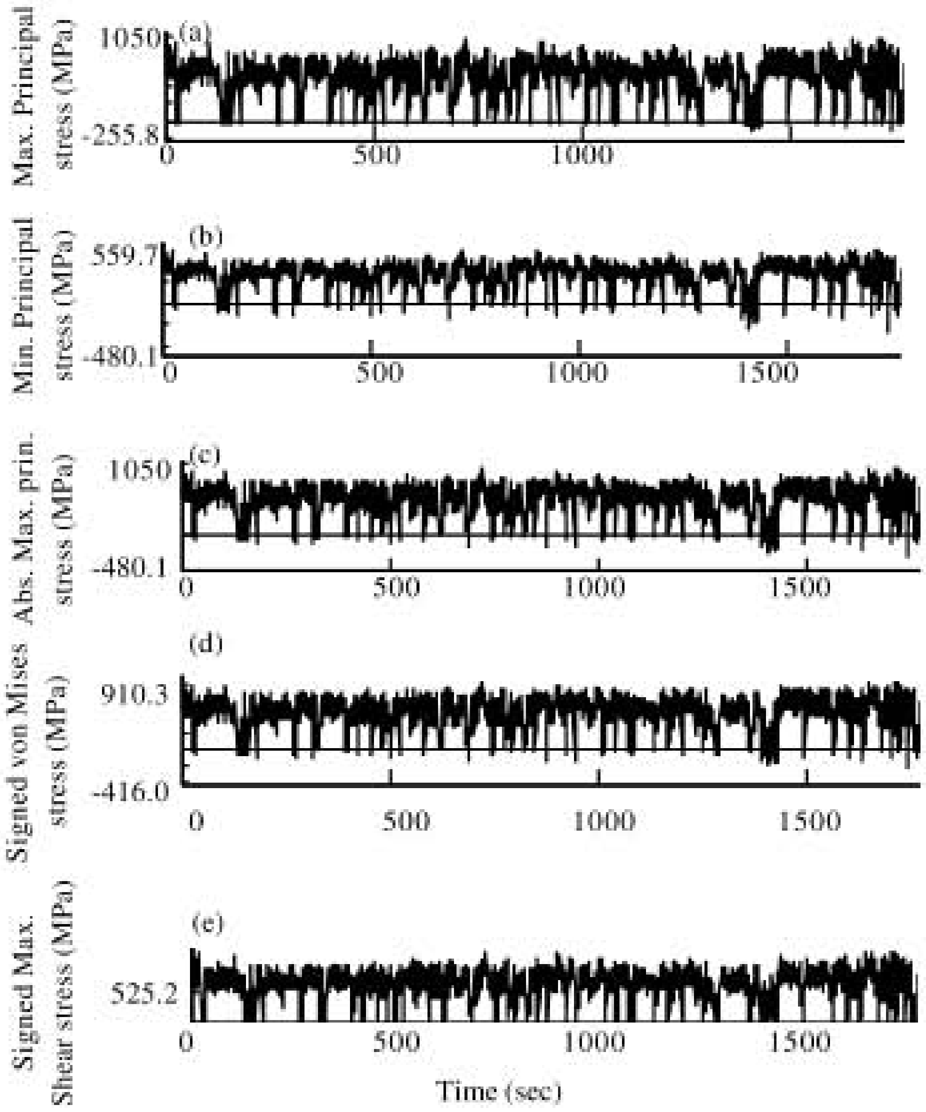

Fig. 6: Time variation of all the multiaxial assessment parameters: (a) maximum principal stress, (b) minimum principal stress, (c) absolute maximum principal stress, (d) signed von Mises and (e) signed maximum shear stress

angle straight lineup vertically at a particular angle of -53.67. It is implied that the mobility is minimal and uniaxial conditions exist. The gate value (0 MPa) is properly check for mobility, which excludes small stress/strain cycles that may mislead in the interpretation of the angle spread.

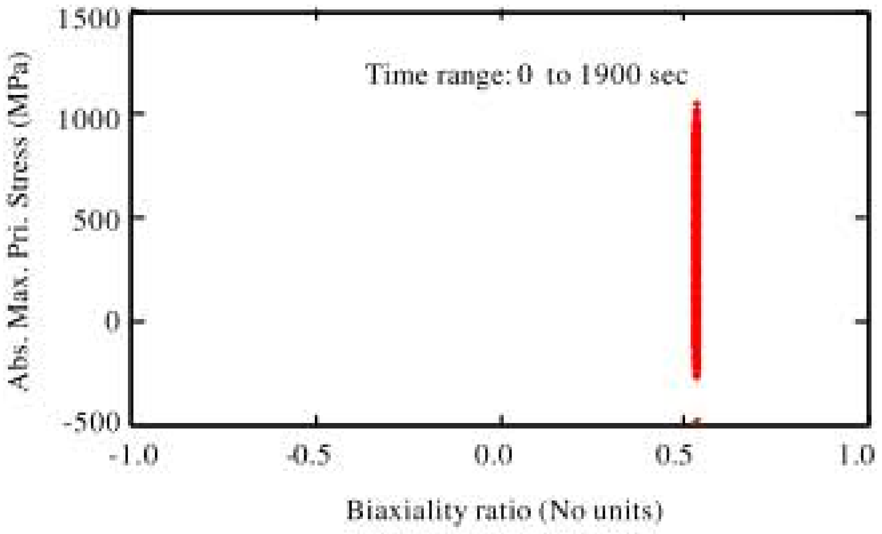

Fig. 7: Cross plot of the biaxiality ratio against the maximum absolute principal stress

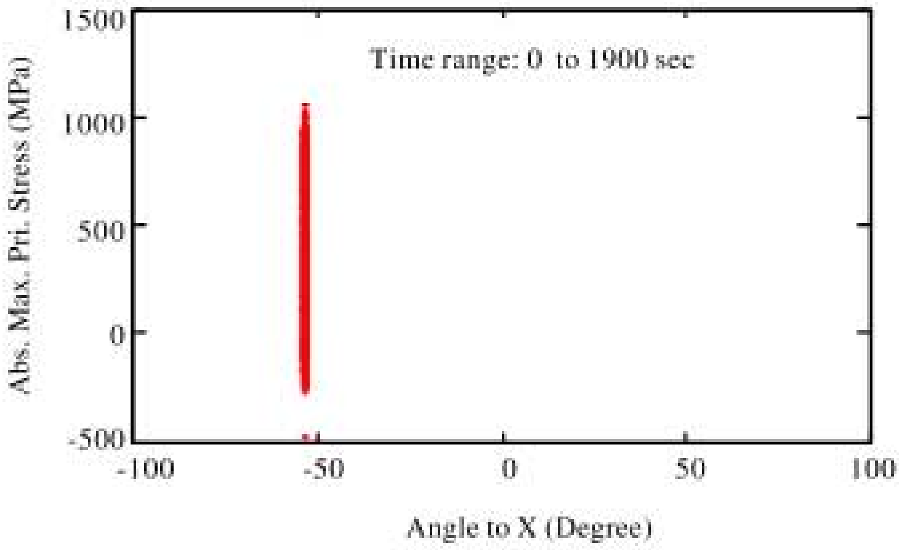

Fig. 8: Cross plot of the angle against the maximum absolute principal stress

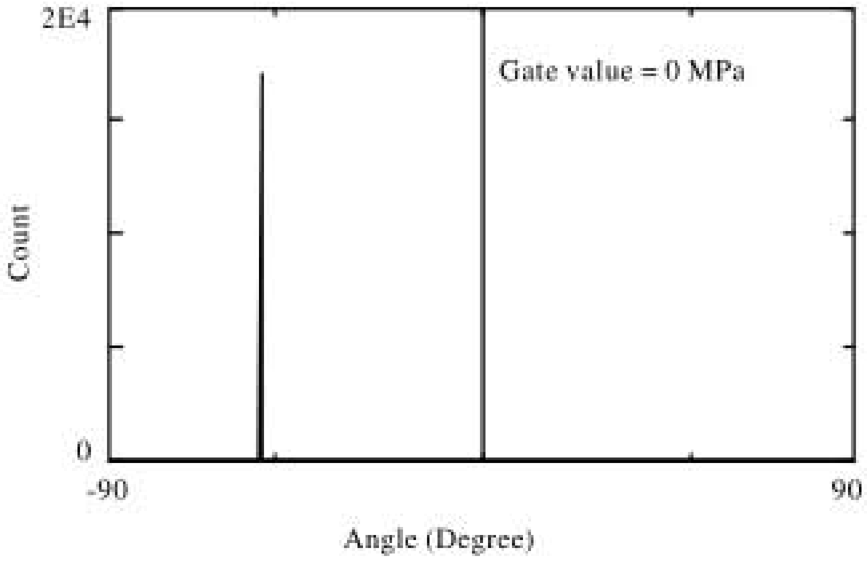

Fig. 9: Distribution of the angle versus the number of times encountered throughout the time series

Figure 9 shows the stress tensor mobility, which illustrates the number of times each angle appeared during the loading sequence. A spike indicates the predominate angle (-53.67). Gate (0 MPa) in stress units is stress level below, which biaxiality is ignored regardless of what the principal angles are done.

Table 1 are listed the predicted fatigue life in seconds using different biaxiality correction method in conjunction with the crack initiation approach for A356-T6 material. In Table 1, it is observed that the biaxiality correction

Table 1: Predicted fatigue life for different loading conditions and biaxiality correction method

	Predicted fatigue life (10^6 sec) using biaxiality correction method								
	No correction			Hoffmann-Seeger			Material parameter		
Loading cond.	CM	SWT	MO	CM	SWT	MO	CM	SWT	MO
SAETRN	0.28	0.19	0.23	0.24	0.17	0.22	0.20	0.15	0.21
SAESUS	48.7	76.4	67.6	37.1	63.0	58.9	33.2	63.9	56.7
SAEBKT	3.20	2.97	3.14	3.13	2.90	3.04	2.97	2.72	2.80

CM: Coffin-Manson method; MO: Morrow's method

Table 2: Effect of stress combination with different biaxiality correction method for A356-T6 material and SAETRN loading

	Prediction fatigue life (10^6 sec)					
	Hoffmann-Seeger			Material parameter		
Stress combination methods	CM	SWT	MO	CM	SWT	MO
Absolute maximum principal	0.238	0.185	0.217	0.202	0.148	0.210
Signed von Mises	0.221	0.176	0.199	0.182	0.139	0.177
Signed Tresca	0.208	0.171	0.187	0.168	0.117	0.154

Table 3: Averaged percentage errors between the two methods predicted results

	Error based on Hoffmann-Seeger (%)		
Stress combination methods	CM	SWT	MO
Absolute maximum principal	15.12	20.00	3.22
Signed von Mises	17.65	21.02	11.05
Signed Tresca	19.23	31.57	17.65

Table 4: Predicted fatigue life for various materials for SAETRN loading, singed Tresca and SWT parameter criteria using biaxiality material parameter correction

Materials name (Aluminum alloys)	Predicted fatigue life × 10^5 sec
2014-T6-CF	2.72
5083-87-CF	1.81
5454-none-CF	2.04
6009-T6	1.12
6061-T6-80-CF	1.89
6061-T91	1.99
6070-T6	1.59
6151-T6	1.02
6262-T9	1.92
6951-T6	0.59
6061-T6-NONE-CF	3.29
7175-T73	4.79
A356-T6	1.17

method give the conservative results than with no correction. It is shown that the materials parameter gives the most conservative prediction with SWT criteria for all loading conditions. It is implied that the Hoffmann-Seeger method in conjunction with maximum absolute principal stress is method of choice when the mean biaxiality ratio tends to be zero. Otherwise, the material parameter modification method is suitable for conservative prediction of fatigue life, which is shown in Table 1.

Effect of stress combination with different biaxiality correction method for A356-T6 material and SAETRN loading are presented in Table 2. It is observed from Table 2 for $a_c \leq 1$, Signed Tresca parameter is predicted the better and more conservative results than others. The Signed von Mises stress gives results lies between the absolute maximum principal and signed Tresca. Proportional loading means that no longer have a uniaxial stress state but the relative magnitude of σ_2 to σ_1 is not changing with time, i.e., remain proportional to each other. This loading can be fully handled with the techniques of classical durability assessment using the biaxiality correction using a Singed Tresca Shear stress parameter as opposed to using maximum absolute principal stress. Averaged percentage errors between the two methods predicted results are given in Table 3. Table 4 is listed the predicted fatigue life for various aluminum alloys for SAETRN loading, singed Tresca and SWT parameter criteria using biaxiality material parameter correction. Table 4 is shown that AA7175-T73 alloy is the most superior material having with longest life among various aluminum alloys, while AA6951-T6 found the weakest material.

DISCUSSION

Due to the relatively complex geometry of the cylinder head and loading conditions, the FE method is used in the calculation of the local loads. Moreover, the transient effects during start-up are ignored and internal cylinder pressure acting on the cylinder head is modeled as a distributed loads, with a constant pressure of value 7 MPa, acting statically. Therefore, the total stress at any point of the cylinder head is assumed to be the sum of the stress due to the bolt pretension, the stress due to cylinder pressure. The linear elastic FE analyses are employed to calculate the scaling constants of pseudo stress tensor history at each material point on the cylinder head. The pseudo stress-notch strain curve employed for the stress-strain analysis of complete cylinder head is calculated for each material point, equivalent in this content to a node in the FE mesh of the head based on the

Neuber's rule as a uniaxial approximation formula. In fatigue life predictions, the strain life curve determined from the strain-controlled fatigue tests of uniaxial smooth specimen described using Coffin-Manson strain-life equation is employed. The computational fatigue analysis of cylinder head biaxial cornering fatigue tests are conducted in two steps. First, a global analysis is performed in that all material points on the surface of cylinder head are analyzed for a single test cycle. The fatigue damage distribution on the surface of the cylinder head is predicted and the fatigue cycles at a material point, equivalently the FE node in this content, is determined estimated by using multiaxial damage parameters. Next, the most critical point candidate for test failure location is analyzed and the characteristics of both stress-strain history and variation of fatigue damage per cycles are evaluated. In the global approach, the stress-strain history of all head surface nodes is analyzed for a single cycle following a pre-loading step including the bolt pre-tension and cylinder pressure. Next, assuming a cyclically stable behavior, the fatigue damage is calculated. The uniaxial cyclic stress-strain curve is frequently used in fatigue analysis of stress concentrations, under unidirectional loading. However, the stress states at critical locations in many components subject to fatigue loadings are not uniaxial. For instance, even in a simple notched cylindrical bar in tension, the constraint on transverse strain often causes considerable notch root multiaxiality. In general then, the use of the Neuber method in conjunction with the uniaxial cyclic stress-strain curve is likely to generate values of stress and strain that are misleading and when used as inputs to a fatigue analysis, potentially dangerous. Clearly, some means of taking into account the multiaxiality of stress and strains in necessary.

The following discussion addresses the description of material stress-strain responses in what will loosely be described as proportional loading. The proportional loading means that the principal stresses remain in a constant ratio and the principal stress axes remain fixed in orientation. The multiaxial loadings are very often due to constraints the stress-strain state can be described more accurately. The principal strains are in a constant ratio. For the purpose of this discussion, this condition is closer to the majority of non-uniaxial loadings that occur in practice, the method describes model deformation under constant strain ratio rather than constant stress ratio. The context of this discussion is to calculate elastic-plastic stresses and strains on the basis of linear elastic FE results, using methods based on rule by Neuber (1961). Two methods are based on the extension of the von Mises yield criterion to predict post-yield stress-strain behavior. The Hoffmann-Seeger method can reasonably be applied when the selected Strain Combination is Absolute Maximum Principal or Signed Tresca. Application when using the signed von Mises is identical to the normal Neuber method. The method assumes that the Neuber method can be applied using equivalent stresses and strains based on the von Mises values. The first step then is to take whatever parameter has been cycle counted and converted to equivalent strain. In order to deal with a random variable amplitude loading it is necessary to use a signed form of the von Mises strain.

As it is known, using local strain approach to predict fatigue life, one of the crucial steps is to determine the notch-tip stress and strain responses in elastic-plastic bodies subjected to cyclic loads. Although, accurate determinations of the notch-tip stress and strain response using existing techniques such as experimental measurements and numerical simulations are not intractable, they are often too expensive and time-consuming especially when components are subjected to long arbitrary multiaxial cyclic loading histories in service. For this reason, simplified analytical methods that approximate the actual elastic-plastic notch-tip material behavior are frequently preferred in practical engineering applications. So far, a number of approximate methods (Neuber, 1961; Glinka, 1985; Gu and Lee, 1997) have been proposed for determining the elastic-plastic notch-tip stress and strain. Among these, the rule originally proposed by Neuber (1961).

The biaxiality correction method was used to correct the treatment of material properties in the application of Neuber method in order to take into account the biaxiality of the loading. Uniaxial material properties can be modified by using either material parameter or Hoffmann-Seeger methods. The material parameter method basically makes a new set of parameters for each state of stress. It assumes the ratio of the principal strains remains fixed and that the von Mises stress and strain yield criteria obey the cyclic stress strain curve post-yield. It is only use with a maximum strain based combination such as maximum absolute principal. The Hoffmann-Seeger method formulates Neuber correction in equivalent stress-strain space. It predicts all the principal stresses and strains and can, therefore, be used in conjunction with any equivalent stress or strain combination parameter. The current fatigue model is based on critical plane-based model. Most of the earlier models based on the critical plane approach assume that the critical plane only depends on the stress state. This indicates that such models account the fatigue damage accumulation in the same way for different materials under the same stress state. Their applicability generally depends on the material's properties. In the current model, the critical plane does not only depend on the stress state but also on the material properties. There are some other advantages of the current model. The fatigue fracture plane is determined and directly related to the critical plane. The calculation is relatively simple. In the fatigue life prediction model, no special requirements are needed for the S-N curve function. The mean stress effect is included in the current model through a general mean stress effect correction factor.

In the present study, discussions about Hoffmann and Seeger based on Neuber's rule and Material Parameter Modification (MPM) method are mainly focused on their physical meaning based on cyclic plastic deformation. Both Hoffmann-Seeger and the MPM methods express the strain energy density, it is of a practical significance to discuss the two approximate relations from the viewpoint of energy. The above discussion concerning Hoffmann-Seeger method has been proven by the available experimental and numerical investigations regarding two approximate relations for a variety of notch geometries, materials and loading configurations (Newport and Glinka, 1990). This suggests that there may exist some inherent shortcomings of the above approximate relations in estimating the notch-tip stresses and strains in the case of elastic-plastic deformation. Therefore, in order to obtain more precise estimations of the notch-tip stress and strain responses of components subjected to multiaxial cyclic loading histories, MPM approach that can reveal the actual energy dissipation behavior of the notch-tip material element during cyclic plastic deformation. Kim *et al*. (2004) also supported these trends of the results. As mentioned by Kim *et al*. (2004), there is more scatter in life data than usually observed in the laboratory for ductile metals. This is believed to be an inherent characteristic of materials whose life is controlled by defects (Hanlon *et al*., 1997; Nadot *et al*., 1999).

As it is seen in Table 1 and 2, the two approximate methods, i.e., Hoffmann-Seeger method and MPM, predict the general trends in the elastic-plastic notch-tip strain responses. Material Parameter Modification (MPM) method tends to underestimate the fatigue life, while Hoffmann-Seeger method apparently overestimates the actual notch-tip strain histories for the all loading conditions. The averaged percentage errors between the two methods predicted results, as listed in Table 3. It is shown that there are no systematic errors in the model, for various material properties and loading conditions. It can be inferred from the present study that in comparison with Hoffmann and Seeger based on Neuber's rule, MPM method obtains better estimations of the notch-tip strains in spite of its underestimations of the measured data, which well accords with the available evaluations regarding the two approximate relations (Newport and Glinka, 1990). Since the form of the unified expression is no more complicated than that of Neuber's rule and the MPM method can be easily applied to the engineering approximate estimations of the elastic-plastic notch-tip stress and strain responses in components subjected to long arbitrary multiaxial cyclic loading histories. The proposed model is also capable of handling non-proportional mixed-mode loading. However, further experimental work is required to validate the proposed methodology.

It should be pointed out that, as discussed in the literature (Jiang and Xu, 2001) regarding the applicability of Hoffmann and Seeger based on Neuber's rule and the MPM method in analyses of the elastic-plastic notch strain and stress. The materials parameters are computed using the cyclic stress-strain curve of the material and are mainly influenced by the cyclic deformation characteristics. Jiang and Xu (2001) proposed a general method in the computation of material parameters in the Armstrong-Frederich type of back stress evaluation and this approach is employed in this study. Bannantine and Socie (1992) suggest using two different models for different failure modes and choosing the better prediction as the final result. Similar methodologies are used by other researchers (Chen *et al*., 1999; Liu and Wang, 2001). Park and Nelson (2000) reviewed the two-model methodology suggested by Socie and Marquis (2007) and stated that the failure modes depend on the materials. It appears that the failure mode depends not only on the material properties but also on the stress state (Lee *et al*., 2003).

CONCLUSION

The multiaxial fatigue problem is much more complex compared to commonly study uniaxial fatigue. The proposed fatigue life prediction methodology was based on the local strain-life approach and used available models for multiaxial cyclic plasticity, notch analysis, multiaxial damage estimation. A cyclic plasticity model using nonlinear kinematic hardening rule is integrated with an approximation method for notch stress-strain analysis. It was demonstrated that for the biaxial loading states were considered. Pseudo stress coefficient histories are calculated utilizing linear static finite element analysis. The proposed fatigue life prediction methodology was based on local strain-life approach. Fatigue life and crack initiation locations of an aluminum alloy cylinder head in biaxial analysis are presented for various loading conditions and aluminum alloys. It is concluded from the results that Signed Tresca, SWT criteria and SAETRN loading conditions give conservative predicted fatigue life with materials parameter biaxiality correction method. Conventional multiaxial fatigue damage criteria (like von Mises) based on equivalent stress has made non-conservative life under proportional multiaxial loading.

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REFERENCES

Bannantine, J., J. Comer and J. Handrock, 1990. Fundamentals of Metal Fatigue Analysis, 1st Edn. Prentice Hall, New Jersey, ISBN-10: 013340191X.

Bannantine, J.A. and D.F. Socie, 1992. A Multiaxial Fatigue Life Estimation Technique. In: Advances in Fatigue Life Predictive Techniques, Mitchell, M.R. and R.W. Landgraf (Eds.). American Society for Testing and Materials, Philadelphia, pp: 249-275.

Bernasconi, A., M. Filippini, S. Foletti and D. Vaudo, 2006. Multiaixal fatigue of railway wheel steel under non-proportional loading. Int. J. Fatigue, 28: 663-672.

Brown, M.W. and K.J. Miller, 2007. High temperature low cycle biaxial fatigue of two steels. Fatigue Fract. Eng. Mater. Struct., 1: 217-229.

Carpinteri, A. and A. Spagnoli, 2001. Multiaxial high cycle fatigue criterion for hard metals. Int. J. Fatigue, 23: 135-145.

Carpinteri, A., A. Spagnoli, S. Vantadori and D. Viappiani, 2008. A multiaxial criterion for notch high cycle fatigue using a critical-point method. Eng. Fract. Mech., 75: 1864-1874.

Chamat, A., M. Abbadi, J. Gilgert, F. Cocheteux and Z. Azari, 2007. A new non-local criterion in high cycle multiaxial fatigue for non-proportional loadings. Int. J. Fatigue, 29: 1465-1474.

Chen, X., S. Xu and D. Huang, 1999. A critical plane-strain energy density criterion for multiaxial low-cycle fatigue life under non-proportional loading. Fatigue Fract. Eng. Mater. Struct., 22: 679-686.

Fatemi, A. and D.F. Socie, 1988. A critical plane approach to multiaxial fatigue damage including out of phase loading. Fatigue Fract. Eng. Mater. Struct., 11: 149-165.

Garud, Y.S., 1981. Multiaxial fatigue: A survey of the state of the art. J. Test Evol. ASTM., 9: 165-178.

Glinka, G., 1985. Calculation of inelastic notch-tip strain-stress histories under cyclic loading. Eng. Fract. Mech., 22: 839-854.

Gu, R.J. and Y.L. Lee, 1997. A new method for estimating nonproportional notch-root stresses and strains. J. Eng. Mater. Technol. Trans. ASME., 119: 240-245.

Hanlon, D.N., W.M. Rainforth and C.M. Sellars, 1997. The effect of processing route, composition and hardness on the wear resistance of chromium bearing steels in a rolling-sliding configuration. Wear, 203: 220-229.

Jiang, Y., 2000. A fatigue criterion for general multiaxial loading. Fatigue Fract. Eng. Mater. Struct., 23: 19-32.

Jiang, Y. and B. Xu, 2001. Deformation analysis of notched components and assessment of approximate method. Fatigue Fract. Eng. Mater. Struct., 24: 729-740.

Karolczuk, A., Y. Nadot and A. Dragon, 2008. Non-local stress gradient approach for multiaxial fatigue of defective material. Comput. Mater. Sci., 44: 464-475.

Kim, K.S., K.M. Nam, G.J. Kwak and S.M. Hwang, 2004. A fatigue life model for 5% chrome work roll steel under multiaxial loading. Int. J. Fatigue, 26: 683-689.

Lee, B.L., K.S. Kim and K.M. Nam, 2003. Fatigue analysis under variable amplitude loading using an energy parameter. Int. J. Fatigue, 25: 621-631.

Lee, Y.L., J. Pan, R.B. Hathaway and M.E. Barkey, 2005. Fatigue Testing and Analysis: Theory and Practice. 1st Edn., Butterworth Heinrahmanemann, New York, ISBN: 978-0-7506-7719-6.

Leese, G.E. and D. Socie, 1989. Multiaxial Fatigue: Analysis and Experiments. Society of Automotive Engineers, Warrendale, PA.

Li, B., L. Reis and M. de Freitas, 2009. Comparative study of multiaxial damage models for ductile structural steels and brittle materials. Int. J. Fatigue 10.1016/j.ijfatigue.2009.01.006

Liu, K.C. and J.A. Wang, 2001. An energy method for predicting fatigue life, crack orientation and crack growth under multiaxial loading conditions. Int. J. Fatigue, 23: S129-S134.

Liu, Y. and S. Mahadevan, 2007. A unified multiaxial fatigue damage model for isotropic and anisotropic materials. Int. J. Fatigue, 29: 347-359.

MSC. Fatigure, 2005. User manual. Los Angles: MSc. Software Corporation. http://mscsoftware.com/.

McDiarmid, D.L., 1991. A general criterion for high cycle multiaxial fatigue failure. Fatigue Fract. Eng. Mater. Struct., 14: 429-453.

Nadot, Y., J. Mendez, N. Ranganathan and S. Beranger, 1999. Fatigue life assessment of nodular cast iron containing casting defects. Fatigue Fract. Eng. Mater. Struct., 22: 289-300.

Neuber, H., 1961. Theory of stress concentration for shear strained prismatic bodies with arbitrary non-linear stress-strain law. ASME. J. Applied Mech., 26: 544-550.

Newport, A. and G. Glinka, 1990. Effect of notch-strain calculation method on fatigue-crack-initiation predictions. Exp. Mech., 30: 208-216.

Ninic, D. and H.L. Stark, 2007. A multiaxial fatigue damage function. Int. J. Fatigue, 29: 533-548.

Papadopoulos, I.V., P. Avoli, C. Gorla, M. Filippini and A. Bernasconi, 1997. A comparative study of multiaxial high cycle fatigue criteria for metals. Int. J. Fatigue, 19: 219-235.

Papuga, J. and M. Ruzicka, 2008. Two new multiaxial criteria for high cycle fatigue computation. Int. J. Fatigue, 30: 58-66.

Park, J. and D. Nelson, 2000. Evaluation of an energy-based approach and a critical plane approach for predicting constant amplitude multiaxial fatigue life. Int. J. Fatigue, 22: 23-39.

Rahman, M.M., A.K. Ariffin, N. Jamaludin and C.H.C. Haron, 2006. Influence of surface treatments on fatigue life of a free piston linear generator engine component using random loading. J. Zhejiang Univ. Sci. A., 7: 1819-1830.

Rahman, M.M., A.K. Ariffin, S. Abdullah and N. Jamaludin, 2007a. Finite element based durability assessment of a free piston linear engine component. Struct. Durability Health Monit., 3: 1-13.

Rahman, M.M., A.K. Ariffin, S. Abdullah and R.A. Bakar, 2007b. Effect of nitriding treatment on fatigue life for free piston linear engine component using frequency response method: A finite element approach. Struct. Durability Health Monit., 3: 197-210.

Schaeffer, H.G., 2001. MSC. NASTRAN Primer for Linear Analysis. MSC. Software Corporation, USA.

Shigley, J.E., C.R. Mischke and R.G. Budynas, 2004. Mechanical Engineering Design. 7th Edn., McGraw Hill, New York, ISBN 978-0072520361.

Socie, D. and G. Marquis, 2000. Multiaxial fatigue. 1st Edn., Society of Automotive Engineers, Washington DC., pp: 244.

Tucker, L. and S. Bussa, 1975. The SAE cumulative fatigue damage test program. Soc. Automotive Eng., 6: 1-53.

Wang, Y.Y. and W.X. Yao, 2004. Evaluation and comparison of several multiaxial fatigue criteria. Int. J. Fatigue, 26: 17-25.

You, B.R. and S.B. Lee, 1996. A critical review on multiaxial fatigue assessments of metals. Int. J. Fatigue, 18: 235-244.