On the Prediction of Fretting Wear of Heat Exchanger / Steam Generator Tubing

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Abstract

The phenomenon of tube *fretting wear* in Nuclear Steam Generator Tubing is of significant importance to Canadian nuclear industry, as well as to other users of heat exchangers. It occurs due to the *Flow Induced Vibration* of the tube bundle due to flow on the shell side of a heat exchanger or steam generator. Fretting wear of tubes results in the reduction in the thickness of the tube wall, leading ultimately to failure of the tubes. This type of failure is observed in the regions of U-bend supports and tube supports. It requires the plugging of tubes which in turn requires significant down time and cost to the operators. In the present study, a predictive model for simulating the wear that occurs in the tubing is developed. The results of the model are compared against experimental values obtained for identical contact configuration and from other experimental studies where a similar experimental setup was used. The predictive models incorporate the concepts of surface statistics, contact mechanics and fracture mechanics to calculate wear particle geometry and the number of cycles to failure through specific failure modes. The cyclic strains developed on the wearing surface is used for estimating wear by considering two distinct wear mechanisms, namely *cyclic fatigue* and *ratcheting.* The resulting wear volume and the number of cycles to failure are calculated by the history of strain cycling and tangential work equivalence for low cycle fatigue mechanism and by analyzing the history of strain cycling for ratcheting failure. Subsequently, it is shown that under relatively low normal loading levels over a range of friction coefficients, either no plastic deformation results or the plastic zone is contained within the subsurface, far below the wearing surface. But experiments conducted for identical situations show crack growth and wear particle formation. Thus a predictive model is developed based on the principles of fracture mechanics simulating *crack growth and particle detachment.* Finite element techniques are utilized for the simulation. The values of wear volume and aspect ratio of wear particles from the numerical studies are compared against wear volume and crack growth measured experimentally. It is seen that the experimental values agree well with the numerically computed values from the predictive wear models. This model is proposed to be expanded to study the fretting wear of tubes by incorporating the actual geometry and material combinations involved.

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1.0 Introduction

Wear is typically regarded as any process that would cause removal of material from a surface. In situations where there is no observable removal of material, there is still a possibility of considerable damage to the micro-surface in the form of material deformation and subsurface crack propagation [Rigney 1978]. The phenomenon of reciprocating sliding wear involves near surface elastic-plastic deformation of contacting bodies at relatively high normal loads [Johnson and Shercliff 1992]. These deformations are caused by normal loading and frictional traction at the contact interface due to the sliding contact of asperities of the mating surfaces [Rigney and Hirth 1979]. It is therefore imperative that any models of friction and wear particle formation processes account for near surface plasticity effects, in addition to the elastic deformations for predicting sliding wear or fretting wear when the sliding length is relatively small.

The development of mathematical models to predict wear (i.e., to calculate the volume of wear during a prescribed number of cyclic loading) will not eliminate wear, but in the design phase, these models can be used for designing components that would be subjected to minimum wear. A numerical model of wear process would allow for proper evaluation of the effects of a design change thereby offering sufficient inputs for rational design decisions for extended service life. Wear models can be similarly used in many areas of industrial design, wherever there are contacting components with relative motion between them. However the input parameters must be carefully correlated with the developed model to arrive at the correct wear mechanism.

2.0 Application of the Predictive Wear Model

An area of considerable importance in the Steam Generator industry, where the predictive wear model could be applied is the prediction of fretting wear of tubes in the U-Bend region and tube / tube support areas of the steam generator. Several experimental programs, e.g., [Ko 1984; Magel 1990] have been setup to study this phenomenon. Empirical results derived from such experimental program are still widely used in the industry. The present paper focuses on developing a mathematical model for reciprocating sliding wear that predicts the wear volume and particle geometry. The model is verified by experiments conducted under controlled experimentation, simulating the exact geometric and material combinations used in the modeling, validating the model. The model is further proposed to be applied to the steam generator tubing wear by incorporating the actual geometry and material combinations of the wearing bodies involved in tube wear. This aspect of the application of the model to the tube wear is currently in progress. The present paper focuses on the finite element modeling and analysis that are instrumental in developing the predictive wear model. Experiments run at the National Research Council labs at Vancouver [Magel 1990 ; Knowles 1994] along with the experimental work conducted as part of this research are utilized for comparison of numerical results.

3.0 Mathematical Modeling of Sliding Wear

Most of the studies on plastic deformation due to sliding contacts rely on microscopic observations of worn metallic surfaces [Knowles 1994]. Similar observations have enabled researchers to measure residual strains after a single pass of a slider over the surface [Kennedy 1982] or after several cycles of loading [Dantzenberg and Zatt 1973]. These studies have pointed towards the development of plastic zone in the sub-surface of the contacting bodies. The effects of elastic-plastic stress-strain field on the microstructural changes are critical in understanding the near surface phenomenon of sliding wear. Therefore, it becomes imperative to develop mechanical models that can enable the observed plastic deformation, along with the factors affecting it, to be analyzed. Such models would improve friction and wear prediction capabilities. It would also help in approaching the eventual goal: quantitative prediction of the wear rates.

The schematic illustration in Fig.1 explains the method of solution adopted in the present research for the development of a mathematical model for predicting sliding wear. For the purpose of this present paper, the mechanisms of ratcheting, cyclic fatigue under shakedown conditions and crack growth leading to particle detachment (Delamination wear) are presented and discussed. The results for the mild abrasive wear situation under wet sliding conditions are not presented.

A finite element model for contact deformation is developed to study the sub-surface stresses /strains as a result of sliding contact between two mechanical components. The hardness of one of the wearing components is assumed to be higher in order to facilitate the studying of the contact deformations of the softer surface only. The softer surface is assumed to be perfectly smooth, devoid of any asperities. For the harder surface, surface statistics are used for quantifying the rough engineering surfaces to enable computation of stresses and strains using finite element analysis procedure, Fig. 2 - Fig. 3. A cylindrical equivalent asperity is modeled in contact with a smooth half-plane subjected to a normal load, Fig. 4 - Fig. 5. The equivalent cylindrical asperity slides perpendicular to its axis on the smooth half-plane. Several values of normal loading and interface friction coefficients are used as input parameters and a parametric study is conducted to develop the contact deformation model. A two-dimensional FE model is developed by assuming conditions of plane strain along the axis of the equivalent cylindrical asperity, Fig. 6. Surface

/subsurface cyclic plastic deformation is simulated for several reciprocating sliding loading cases using non-linear finite element analysis. Fig. 7 depicts the bi-linear kinematic hardening curve used for the deforming half space. Contact elements are employed for calculating the contact between the equivalent cylindrical asperity and the half-space. This is carried out using the finite element software, ANSYS. A detailed parametric study is undertaken and the finite element results pertaining to the contact stresses and effective strains are plotted in the sub-surface of the wearing half-space. These results are further compared against relevant experimental and analytical work.

4.0 Finite Element Analysis for Predicting Ratcheting and Cyclic Fatigue

The cyclic strains of the wearing surface elements resulting from the repeated sliding of the equivalent cylindrical asperity over the smooth half-plane are shown to accumulate during the loading cycles. Fig. 8 is shown as an example of developing ratcheting phenomenon after three reciprocating sliding cycles. It was observed that three cycles were sufficient to simulate either shakedown conditions or predictable plastic ratcheting rate. The "Post26" time-history post processor of the program is used to track the strain components of different surface /subsurface elements. The strain components are subsequently combined to calculate the effective strain or equivalent strain. This value is used in the coffin-Manson type relationship [Coffin 1970; Kapoor 1994] to calculate the number of cycles required for failure. Two distinct mechanisms of failure are utilized for this purpose. If the strain cycle was seen to be open, leading to strain accumulation per cycle, then ratcheting was used. Otherwise, shakedown was observed and the effective strain pertaining to the closed loop is used in the failure criterion to calculate the number of cycles.

- *cyclic fatigue under shakedown conditions*
- *Ratcheting failure*

These failure mechanisms had been proposed and successfully simulated in experimentation by Kapoor [1994] and Kapoor et al [1994]. The energy required to produce a given volume of worn material per cycle of reciprocating sliding, calculated through the finite element procedure, is compared with the tangential work input into the wear system to predict the volume of wear. The number of cycles for failure are calculated by the relationship

$$N_f = \left(\frac{2C}{\Delta\varepsilon_f} \right)^{1/n} \tag{1}$$

where N_f is the number of cycles to failure.

C is the strain related to the failure strain in static loading.

n is taken as 0.5 [Kapoor 1994].

$\Delta\varepsilon_f = \Delta\varepsilon_{eqv}$, the range of equivalent strain experienced by a particular element that shakes down..

Based on the tangential work equivalence, the volume of wear in N_f cycles are derived as

$$V = \frac{\mu P_N l}{0.5 K_{ult} (N_f^{1/D} \Delta\varepsilon_f)} \tag{2}$$

where P_N is the normal load.

μ is the friction coefficient.

l is the sliding length

K_{ult} is the ultimate strength of the material.

D = 1/n

Similarly, for the ratcheting failure mechanism, the effective strain is used in a predictive equation. The strain at failure under monotonic loading is divided by the range of incremental equivalent strain per cycle observed through the cyclic loading.

$$N_r = \frac{\varepsilon_c}{\Delta\varepsilon_r} \tag{3}$$

The volume of wear is calculated by observing the depth at which the ratcheting phenomenon ceases and shakedown begins beneath the surface. This depth is multiplied by the sliding length and the contact width in the direction of plane strain to calculate the volume of a delaminated sheet of material that detaches in N_r cycles. The wear volume, the number of cycles required for the worn material to detach from the parent surface are calculated for a variety of loading conditions and compared against the experimental work of Kapoor [1994], Kapoor et al [1994] and Knowles [1994]. Table 1 lists the numerically calculated values.

Table 1. predicted wear volume and number of cycles to particle detachment

CASES	Applied Pressure, P, MPa	Contact Pressure, p_0, GPa	Friction Coefficient	Mechanism of Wear	$\Delta\varepsilon_f$ or $\Delta\varepsilon_f$	Number of cycles for particle detachmen t	Wear Volume, mm^3
CASE IA	69	2.068	0.0	Ratcheting	0.01639	76	N/A
CASE IB	69	2.068	0.1	Ratcheting	0.054	23	0.226
CASE IC	69	2.068	0.3	Ratcheting	0.1101	11	0.226
CASE ID	69	2.068	0.5	Ratcheting	0.1454	9	0.226
CASE IE	69	2.068	0.7	Ratcheting	0.21	6	0.226
CASE IIA	14	0.93	0.0	Cyclic Fatigue	0.001	81000	N/A
CASE IIB	14	0.93	0.1	Cyclic Fatigue	0.00197	67310	7.2
CASE IIC	14	0.93	0.3	Ratcheting	0.00187	669	0.1
CASE IID	14	0.93	0.5	Ratcheting	0.0352	355	0.1
CASE IIE	14	0.93	0.7	Ratcheting	0.02688	46	0.1

It is seen from Table 1 that the number of cycles to detach a wear particle through the mechanism of plastic ratcheting range from 77 to 6 depending upon the level of friction coefficient for the case I loading. Kapoor [1994] obtained similar values in his experimental work. (an accumulated shear strain of 0.3 and an accumulated axial strain of 0.02 to give a ratcheting strain of 0.0036 per cycle for identical loading situation). Challen and Oxley [1986] obtained between 3 and 39 cycles to failure for a ratcheting strain of 0.73 to 0.064. On comparing these values with those in Table 1, the present study predicts the ratcheting cycles between 6 and 76 cycles for a ratcheting strain of 0.21 to 0.01639. The wear groove depth obtained for cyclic fatigue is 0.014 mm for CASE I loading, which compares very well with Magel [1990] who obtained experimental values for particle depths upto 0.02 mm for similar loading levels in his experimental work (p_0 = 2.1 Gpa). For CASE II loading, the calculated depth is 0.007 mm which is normally observed in the experimental studies [Knowles 1994 ; Magel 1990]. The number of cycles calculated through experimentation for delamination wear in Knowles experimentation [1994] were 10 and 20 cycles for similar load levels (CASE I). For cyclic fatigue mechanism, long duration tests conducted by Ko et al [1992] produced a volume of 9.23 mm^3 in 60000 cycles of similar loading although the macro contact geometry was one of sphere on flat vs. cylinder on flat configuration used for the present simulation. However, their contact configuration had very similar nominal contact area and asperity density distribution as obtained in the present study. Thus the predictive model is seen to calculate the wear volume and wear particle geometry correctly for the case of ratcheting and cyclic fatigue.

5.0 Finite Element Analysis for the Prediction of Wear through Crack Growth

Experimental studies conducted as part of present research revealed that for low normal load levels and even with a high interface friction coefficient, if the hardness of the wearing surface is increased considerably, then the plastic deformation is contained within the sub-surface of the wearing half-space. Under such circumstances, the postulated mechanisms of low cycle fatigue (through plastic deformation) and ratcheting failure do not take place. But experiments conducted for identical loading situations as a part of the present research revealed the occurrence of severe subsurface cracking and crack growth leading to particle detachment. This has provided the motivation to propose that the crack growth resulting from existing micro-cracks in the wearing body is the principal reason behind wear particle formation under lower magnitudes of normal loading. In the present research, it is endeavored to simulate crack growth and wear particle formation by way of linear elastic finite element formulation.

The zone of maximum stress intensity is identified from the contact deformation analysis of a homogeneous half-space. A single crack of 30 µm (crack size is varied from 10 µm up to 50 µm insteps of 5 µm for parametric study of the model) is assumed at this location. Since the most likely situation where the crack growth is expected under the sliding load is where the zone of maximum stress intensity occurs under the contact loading in sliding wear. This is because the stress intensity factor, which is detrimental to crack growth, is maximum at the location of maximum stress intensity. The assumed crack is analyzed for the propagation, Fig. 9. For crack growth to occur, the calculated stress intensity factor must be above a threshold value (6.0 MPa $m^{0.5}$ for steel). Paris law is used for relating the range of stress intensity factor during a loading cycle and the number of cycles required to grow the crack to a specified final crack size. Further the crack growth direction is determined based on the maximum tensile stress criterion for the mixed mode fracture analysis (Mode I and Mode II). The proportion of which is determined in the analysis. This is a critical value since it governs the location of the maximum tensile stress with respect to the crack tip. Theoretical prediction for this angle under pure Mode II is 70.5° with respect to the local co-ordinate system defined at the crack tip. The finite element results correctly predict this for a predominantly Mode II crack propagating with a low value of Mode I (up to 5%). The crack thus turns from its original course towards the loading surface and detaching itself as a wear particle after two load steps, Fig. 10. This model is evaluated for a range of friction coefficients and the analysis results are presented in Table 2.

Experimental Investigation of Reciprocating Sliding Wear

A detailed experimental investigation of wear particle formation was further conducted under constant low-amplitude reciprocating sliding. The configuration of test specimens consists of a cylinder (carbon steel) sliding against a flat disc (SAE 410 stainless steel). Several tests were conducted by varying the loading, lubrication, number of wear strokes or cycles and the hardness. The wear process is carefully studied to determine the mechanisms of wear particle formation and its dependence on the governing parameters such as, the number of wear cycles, hardness, surface finish and the friction coefficient. The results of the above mentioned experimental work was then compared with the numerical prediction of wear particle geometry/wear volume through the mechanism of crack propagation leading to wear as illustrated in Fig.1. Wear volume for the detached particles were calculated based on the micrographs of the sectioned specimens for depth of the particles. The shape of the particles were triangular as seen in numerical simulation. The length and width of the particles were also measured and the volume of the triangularly shaped particles were calculated. The volume was in the range of in the range of 0.0010 mm^3 to 0.004 mm^3. The aspect ratio of the particles were seen to be in the range of 2 ~ 5. The results obtained through the predictive models agreed well with those obtained from experimentation for mass loss, number of wear cycles required to produce the wear volume and the geometry of wear particles. Thus the finite element models could satisfactorily be applied to predict the wear characteristics in similar types of wear situations that are encountered in industrial applications.

Table 2 Crack growth and particle formation
(crack length 30 µm, $p_0 / k = 2.8$)

Crack entry-angle (deg.)	dK_I Mpa.m–		dc1/dc2 µm	dθ, deg.	N, cycles	Aspect ratio*	Volume, mm^3
15	0.18	3.89	N/A	70	N_1=N/A	N/A	-
15	N/A	N/A	N/A	N/A	N_2=N/A	N/A	no particle
20	0.21	4.77	N/A	70	N_1=N/A	N/A	
20	N/A	N/A	N/A	N/A	N_2=N/A	N/A	no particle
25	0.252	6.15	15	70	N_1=116	-	
25	0.66	7.91	2.27	69	N_2=6	2.91	0.0032
30	0.297	6.4	15	69	N_1=105	-	
30	2.31	7.51	5.7	65	N_2=18	2.42	0.004
35	0.33	7.03	15	69	N_1=78	-	
35	3.57	6.86	8.9	62	N_2=40	2.1	0.0047
40	0.36	7.47	15	69.5	N_1=65	-	
40	3.63	6.26	11.9	59	N_2=53	1.9	0.00545
45	0.396	7.92	15	69	N_1=55	-	
45	3.63	5.6	N/A	59	N_2=N/A	N/A	N/A

* Ratio of (length of wear particle/ maximum depth of wear particle).
N/A - No particle formation since the SIF was below the threshold value.
(dK_I is the change in SIF per reciprocating cycle ; dc1 & dc2 are crack extensions ; dθ is the crack turn angle ; N1 and N2 are the number of cycles required for the extension)

6.0 Conclusions and Future Scope of Work

A Predictive model for reciprocating sliding wear is developed and shown to calculate the characteristics of wear particles observed through experimentation. This model branches into one of several mechanisms depending on the type of contact configuration and loading conditions. The finite element technique is used for simulating the mechanisms of plastic ratcheting, cyclic fatigue and crack growth leading into distinctly different wear mechanisms. This model is proposed to be expanded to study the fretting wear of tubes in the nuclear steam generator. The exact geometry (asperity level) and material combinations need to be input to the model and the results could thus be compared to the experimental values. The numerical simulation part of this work is currently in progress.

Acknowledgement

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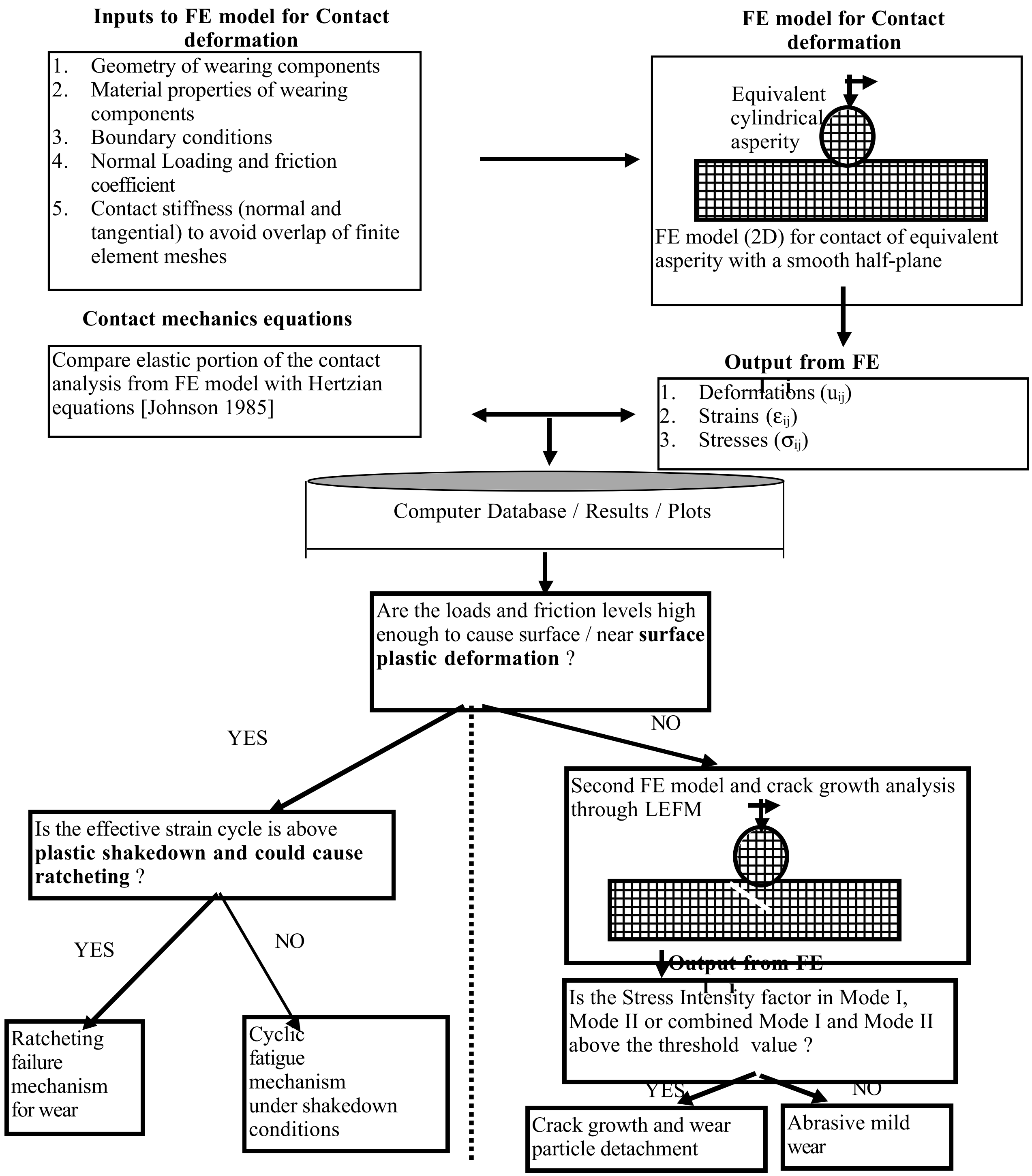


Fig. 1 Proposed model for predicting sliding wear of mechanical components.

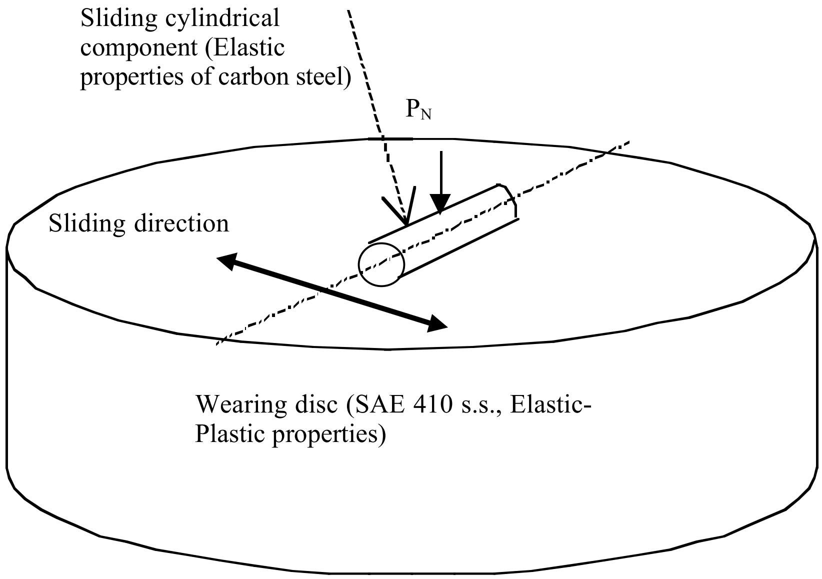


Fig. 2 A cylindrical component in contact with a wearing disc.

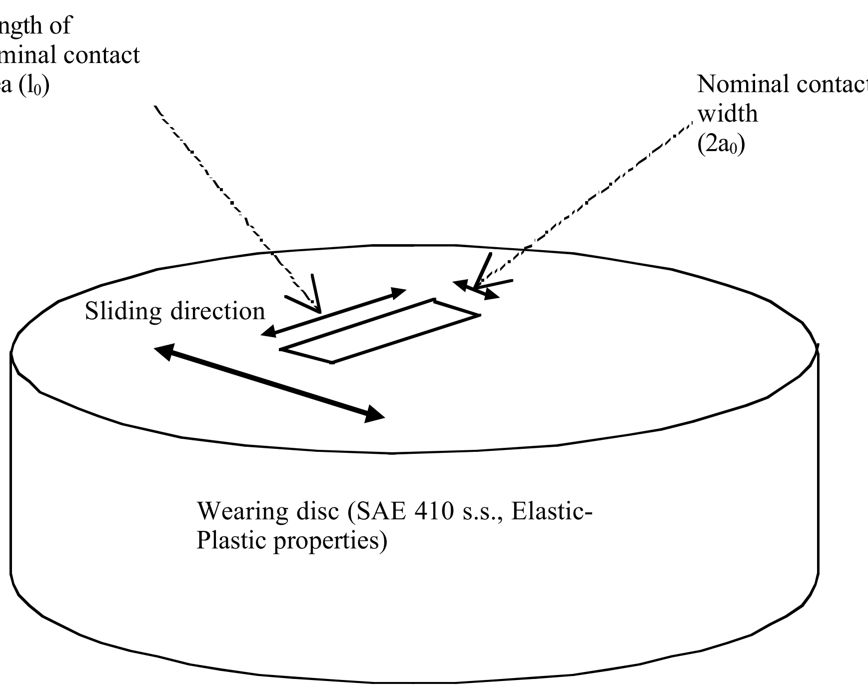


Fig. 3 A schematic depicting the nominal area of contact.

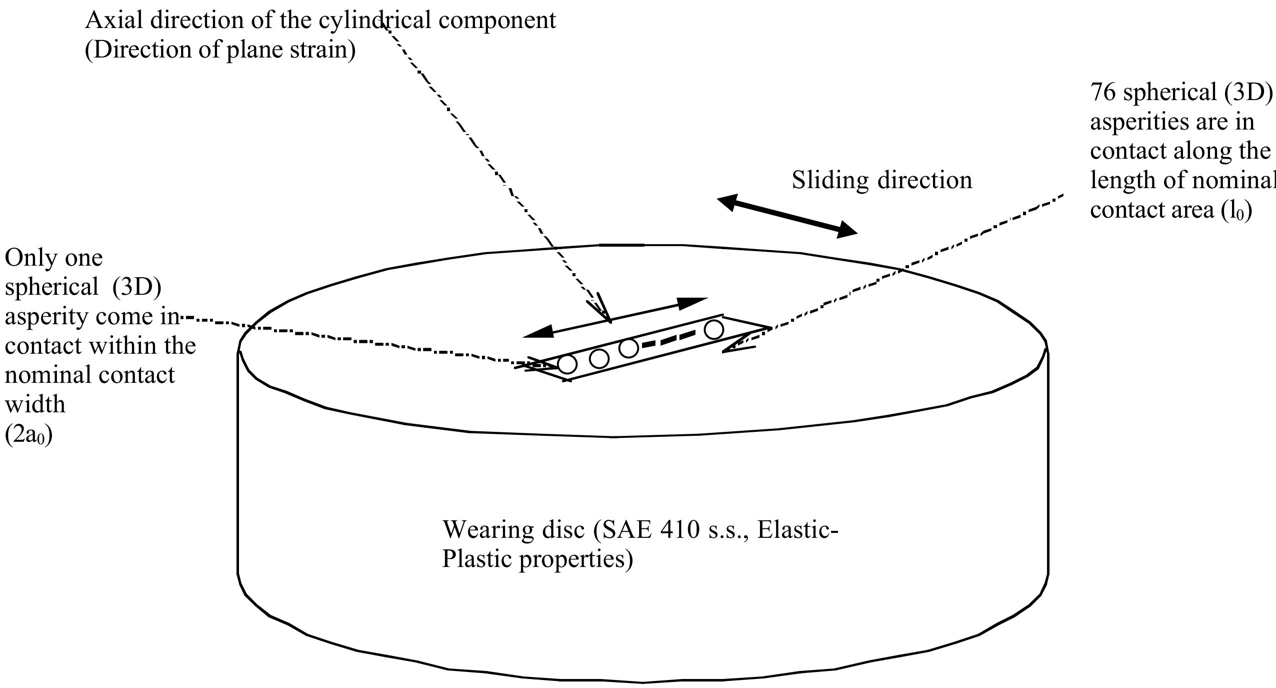


Fig. 4. A schematic illustrating ***one asperity in contact along the sliding direction*** and 76 asperities in contact along the length of the cylinder (plane strain direction).

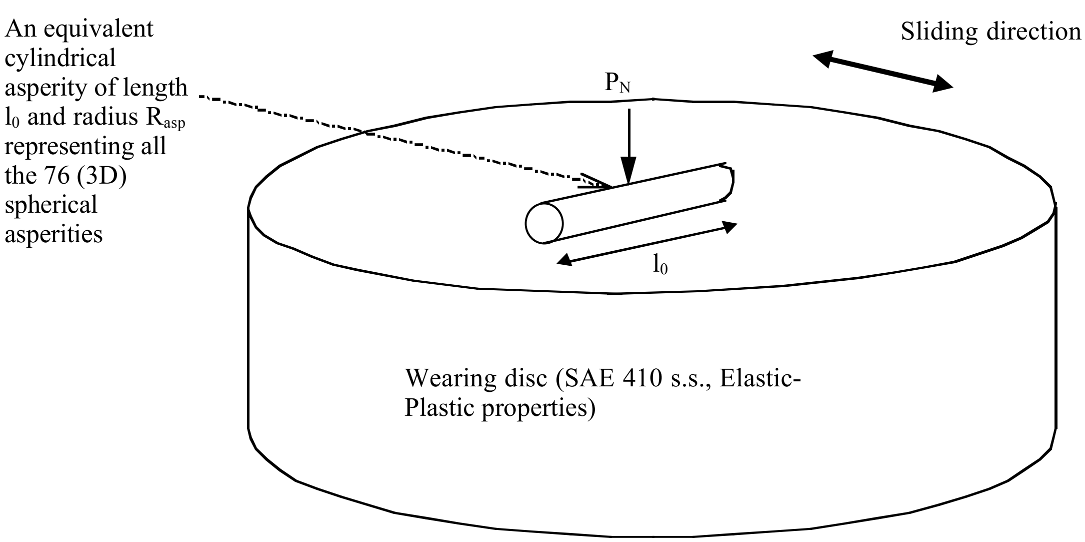


Fig. 5. A schematic illustrating the concept of ***equivalent cylindrical asperity*** representing 76 spherical asperities making circular contacts.

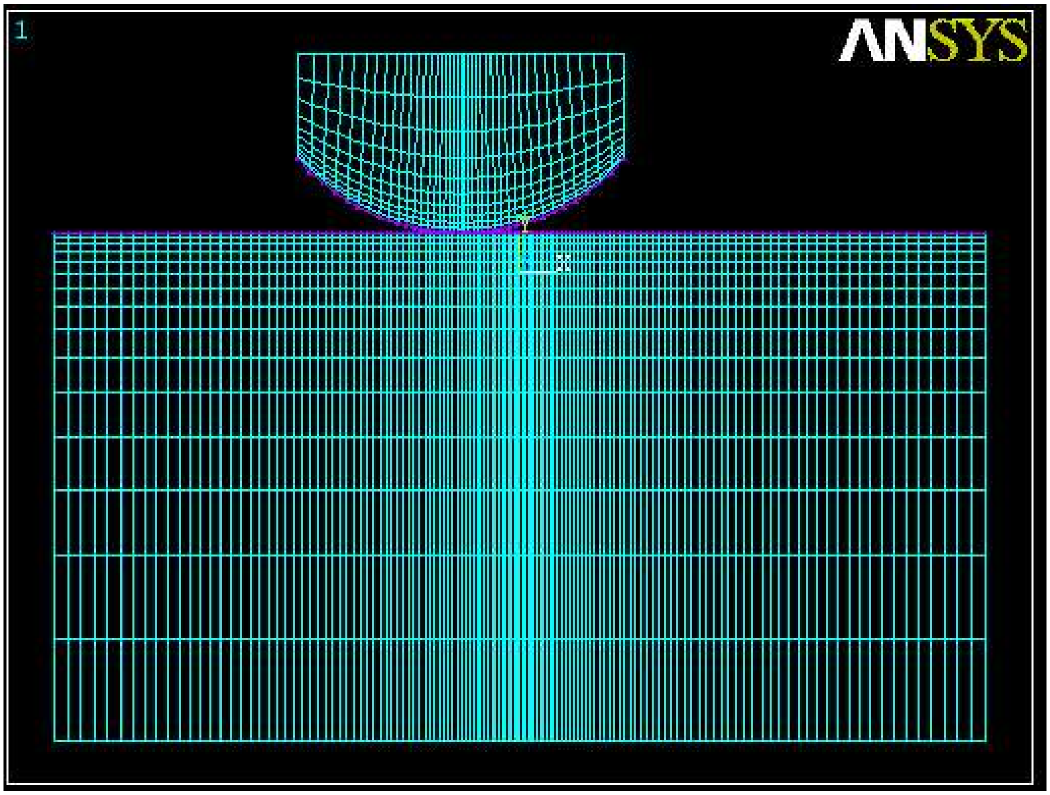


Fig. 6 Finite element mesh employed for the simulation of contact deformation

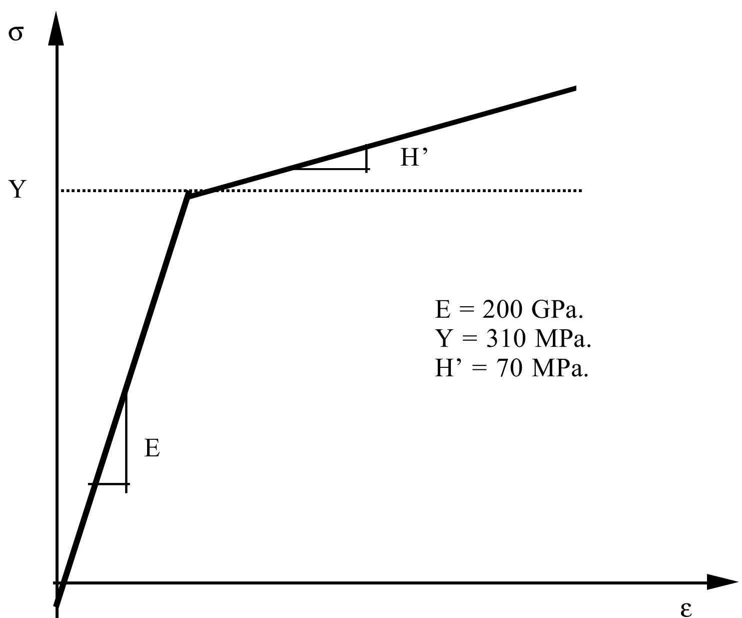
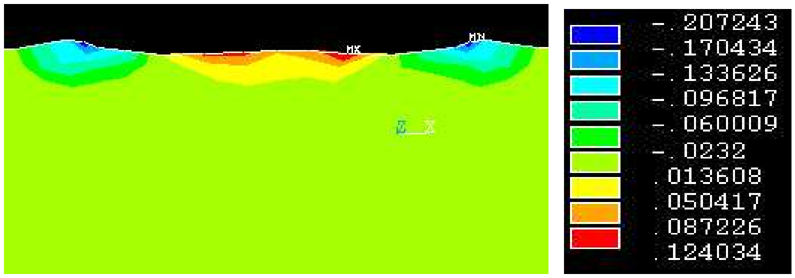
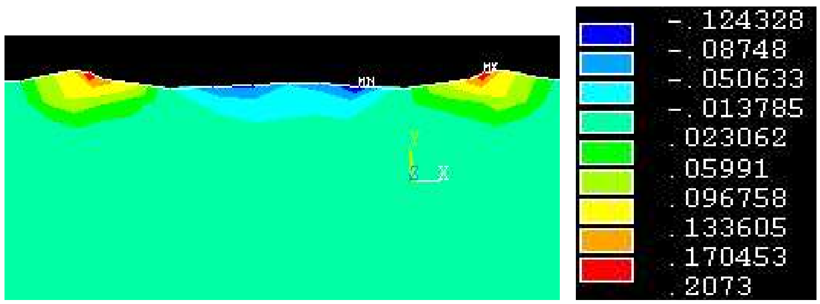


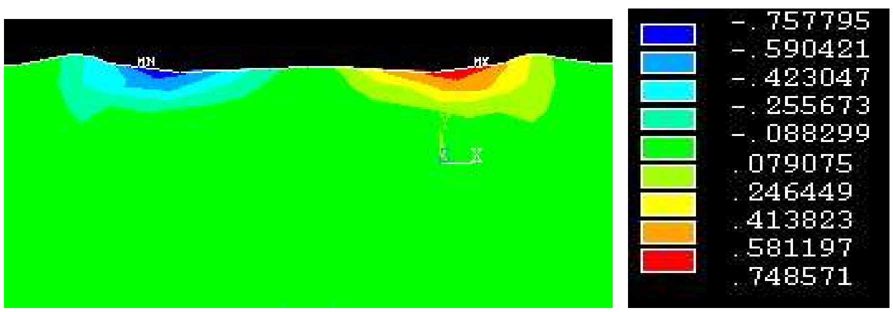
Fig. 7. Stress- Strain response curve for the modeled elastic-plastic half-space.



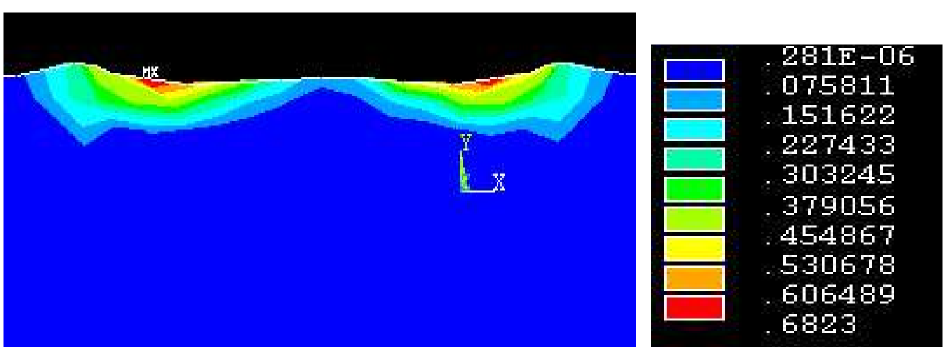
(a) Contours of ε_{xx}



(b) Contours of ε_{yy}



(c) Contours of ε_{xy}



(d) Contours of equivalent strain ε_{eqv}

Fig. 8. Contours of strain components at the end of five fretting wear cycles ($\mu = 0.5$; $P_0 / k = 7.6$)

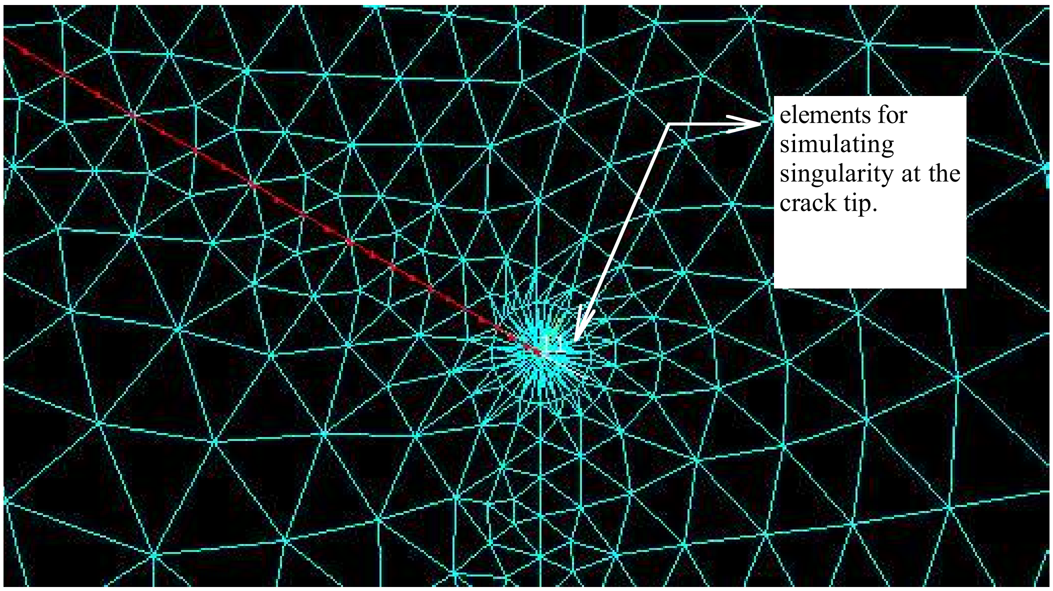
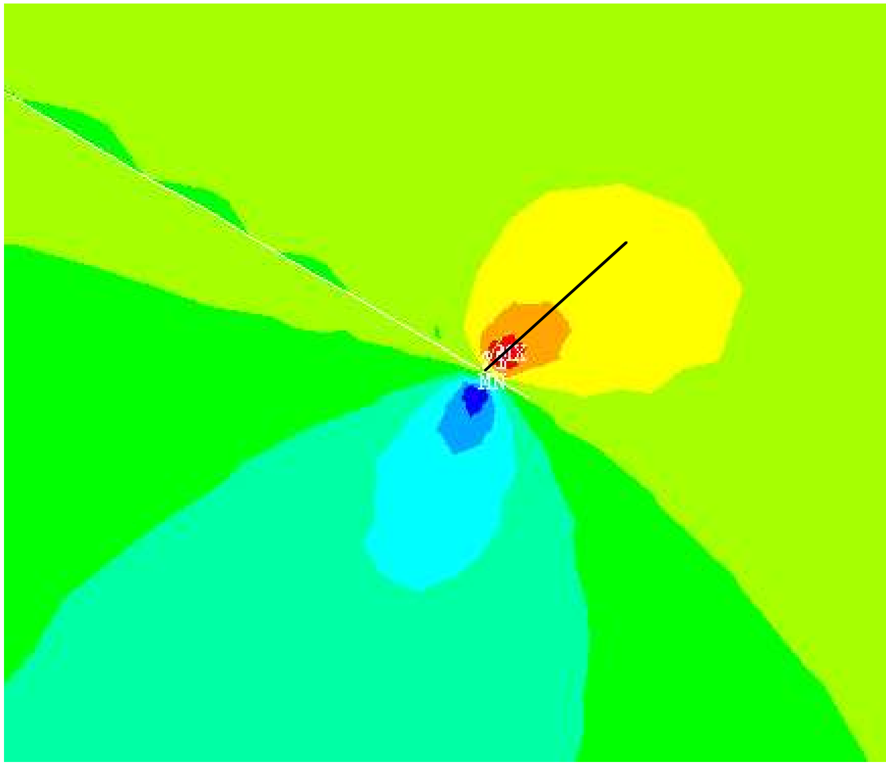
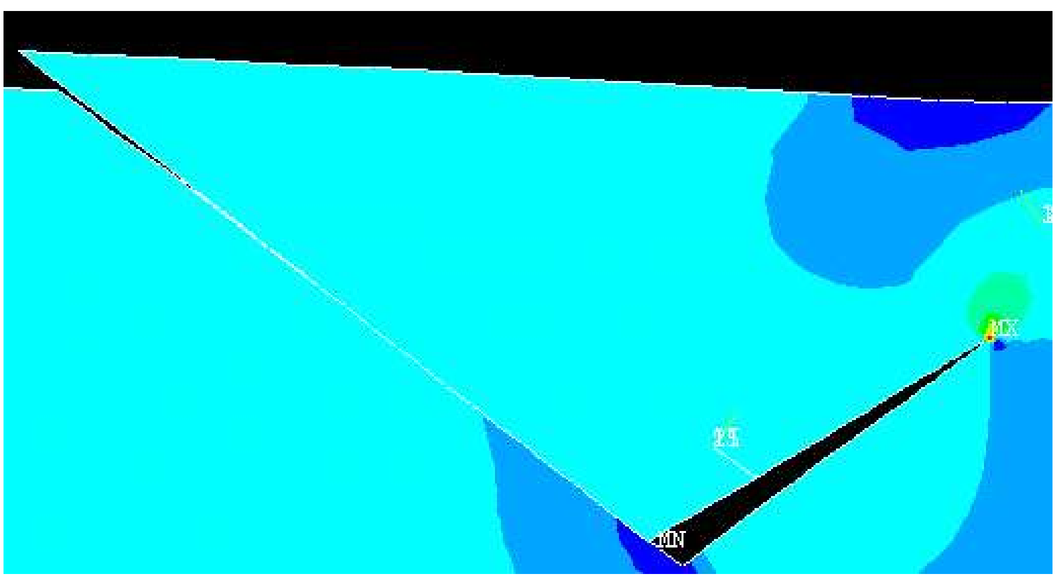


Fig.9 Elements for simulating stress singularity at the crack tip.



(a) (θ = 35 °)



(b) (θ = 35 °)

Fig. 10. Maximum tensile stress (σ_θ) in the vicinity of the crack tip for an initial crack length of 30 μm.