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Verifying Finite Element Models of Isochoric Contact Problems

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Abstract

Accurate modelling of contact between rigid surfaces and rubber-like materials is inhibited by two factors. Often the strain energy functions employed in finite element software codes are either inadequate for a realistic specification of hyperelastic behaviour or the material data, determined from standard testing procedures cannot accurately predict complex forces and surface deformations. Also, in component assemblies and tests, contact between elastomers and surfaces that are considered to be rigid are influenced by adhesion between the two. It is reasonable to assume that the level of adhesion is affected by a number of parameters. The most significant are probably temperature, depth of indentation, rate of indentation, rubber hardness, surface finish of the rigid indenter and the influence of lubrication. Where the elastomer is used as a seal it is essential to know the effect that stress relaxation will have on adhesion between the two surfaces. It is clear that the differing viscoelastic properties of compliant materials make displacements in contact problems far more difficult to predict than those for conventional linear elastic solids.

This paper considers strategies for accurate determination of contact forces and profiles resulting from both plane strain and axisymmetric contact. Techniques for observing and recording surface deformations and adhesions are evaluated including inverse impression modelling, video microscopy and using glass indenters to permit optical analyses. Interrogating the results of these tests to provide realistic finite element modelling of contact problems is discussed. The relationship between this work and ongoing research to improve modelling, testing and computer analysis of rubber components to provide practical believable finite element analysis, is set in context.

In conclusion, the required test procedures for obtaining data which allows sensible material properties to be used in hyperelastic analysis and the appropriateness of competing strain energy functions are briefly considered.

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1.0 Introduction

Research into using hyperelastic finite element analysis to recognise components from contact stresses and strains when tactile sensing, requires determination of accurate surface profiles resulting from rigid indentation. Preliminary indentation tests used rigid punch indenters with test grade, medium hard, filled rubbers. These tests were employed to benchmark finite element analyses of contact problems. (Jerrams, Johannknecht and Hookes [1]) and showed that load / displacement curves were far more linear than classical Boussinesq equations [2] or finite element analysis predicted. However, adhesion between punch and rubber occurred in the tests. This could not be modelled by a simple two term strain energy function using Mooney-Rivlin constants and is difficult to model using higher order functions for reasons discussed later. Also the influence of a number of variables is unknown. This difficulty gives rise to a question of fundamental importance to designers of rubber components:- how can the predicted contact between a rubber part, say an 'o' seal or a door trim, be believed and consequently how can we ensure that it fulfills its function?

If we assume contact to take place at ambient temperature and elastomers remain in the rubbery state, the variables that would seem most likely to control the amount of surface adhesion in a rubber / metal contact problem are

- the rubber hardness
- the surface condition and finish of the metal and elastomer
- the rate at which the rigid surface displaces the rubber.

Sliding friction in the rubbery state has been thoroughly investigated and it was Ariano [3] who first demonstrated that friction forces increase with sliding velocity, before Roth, Driscoll and Holt carried out tests for friction with rubber sliding on glass and steel showing coefficients were also influenced by sliding distance [4]. Schallamach [5] proposed that sliding velocity was an exponential function of the tangential force and that friction of rubber-like materials is molecularly activated. However, it was Bartenev [6] who established that friction force linearly depends upon temperature and the logarithm of the sliding velocity. In the rubbery state, if decreasing friction force is plotted against increasing temperature, the resulting straight line can have its slope changed by changing the contact area as shown diagrammatically in figure 1. This, of course, suggests that friction must increase continually as an indenter feeds into a test-piece. Adhesion occurs because chain segments on a polymer surface jump in a disorderly manner when travelling over a smooth rigid surface, from one adhesive point or junction to another. The time between successive jumps is termed the relaxation time.

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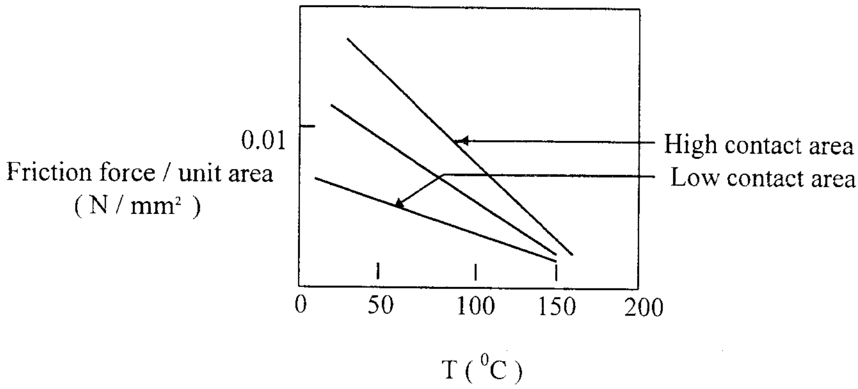

Figure 1. Relation of friction force to temperature for a typical vulcanised rubber

Other time dependent characteristics of rubber must be considered. When displaced by a rigid surface, parts made from rubber-like materials will exhibit stress relaxation - if the displacement is held the force causing the displacement will decrease with time. This prompts the additional question:- does the level of surface adhesion change with stress relaxation and what is the effect on the profile of the displaced surface away from the area of contact?

The initial axisymmetric tests used flat, conical and spherical indenters fed into a medium hard natural rubber compound (ref. no. 19066) having 68 Shore A hardness. The 'inverse impression modelling' technique, devised to model the surface profile at full indentation, exploited dental elastic impression material, hydrophilic vinyl polisilovane, to first make the impression of the deformed surface of the rubber. This method had previously been employed by Westkämper and Maskus [7] to microscopically analyse component surfaces. The impression material was chosen for its dimensional stability, minimal hardening time, ease of separation from the indented surface and lack of porosity. Each impression was itself inverse modelled to permit the production of a final permanent plaster cast of the indenter tip and the test-piece surface. All of these tests indented the rubber to a depth of 7 mm and were conducted at a constant feed rate of 7 mm/min.. Each showed adhesion between the punches and the indenter, but the possibility that the presence of the moist impression material had contributed to the level of adhesion could not be discounted. Accordingly, 'plane strain' indentations were carried out with each test recorded using a video microscope and this dispensed with the need for an impression material. The first of these tests used plate indenters of 2 mm width, having cylindrical forms on the indenting edges. The indenters had uniform surface finishes produced by shot blowing and vapour blasting.

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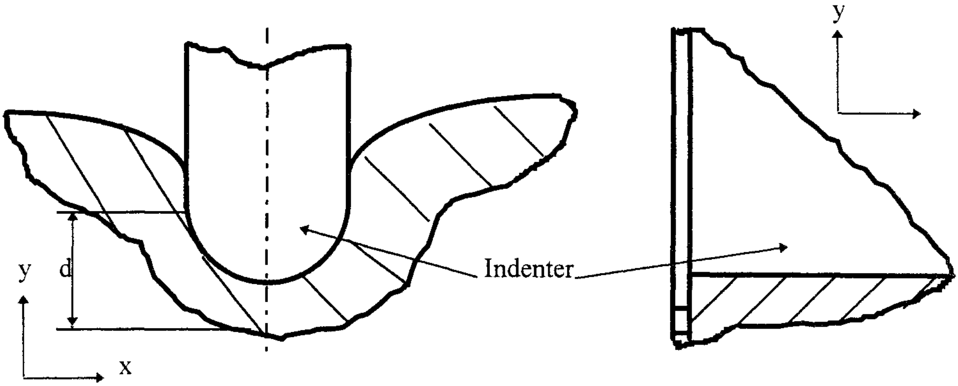

Figure 2. Cross-sections of plane strain indenter test showing typical adhesion between rubber and indenter

The indented test-pieces were of the same compound used in the Boussinesq tests. Again, all tests showed adhesion; the rubber bonded to the radius of the indenter and its sides as shown in figure 2. This is attributed to molecular bonding of exposed surface atoms in each material and can be seen as a thermally activated stick-slip process. However, the number of tests was too small to draw firmer conclusions than that the indentation having the slowest rate of ingress and finest indenter surface finish produced the least adhesion, whilst the highest feed and coarsest finish produced the greatest adhesion. If sensible coefficients of friction are to be provided for contact problems, then high strain indentation must be studied. Boussinesq and plane strain contact theories assume axial loading of a semi-infinite half space, but in reality the resistance encountered by a rigid indenter in test will be influenced by the depth of the test-piece and hence the proximity of a rigid base. The plane strain tests described hereafter used test-pieces 50 mm x 50 mm x 25 mm deep, held in a fixture that prevented strain in the Z direction. The process was videod through a perspex insert positioned at the front of the fixture. A range of rubber hardnesses were used and feeds, indenter surface finish and lubrication were varied. Each test was videod using a Microvision MV2100 video microscope and the level of adhesion during indentation recorded. When the indenters had reached the maximum indentation (4 mm) they were held at that depth for 10 minutes to allow stress relaxation to be monitored. The levels of adhesion and surface profiles were observed throughout the stress relaxation periods. Of necessity this paper focuses on tests of one rubber type and hardness. Similarly, results for a range of feeds for only one indenter surface finish without the presence of lubricant are described. The results and conclusions from all the tests will be presented later.

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2.0 Plane strain indentation

The tests were carried out on an Instron 8501 Dynamic Testing System and were recorded using the video microscope. The elastomer initially supplied by Robert Bosch GmbH, Stuttgart, was a 40 Shore A hardness, NBR (Acrylnitril Butadiene Rubber). Subsequently a range of hardnesses of HNBR (Hydrided Acrylnitril Butadiene Rubber) were tested using the same procedures and it is anticipated that this series of tests will establish adhesion constants that can be related to coefficients of friction for input in hyperelastic finite element analysis. Three uniform indenter surface finishes were tested at five indentation (feed) rates. The finishes and feed rates are shown in table 1.

Finishing process	polishing	vapour blasting	shot blowing
Surface finish (R_a) μm	0.26	1.06	1.88

Indentation rates mm/min	5	50	100	250	500

Table 1. Indenter finishes and feed rates for plane strain tests.

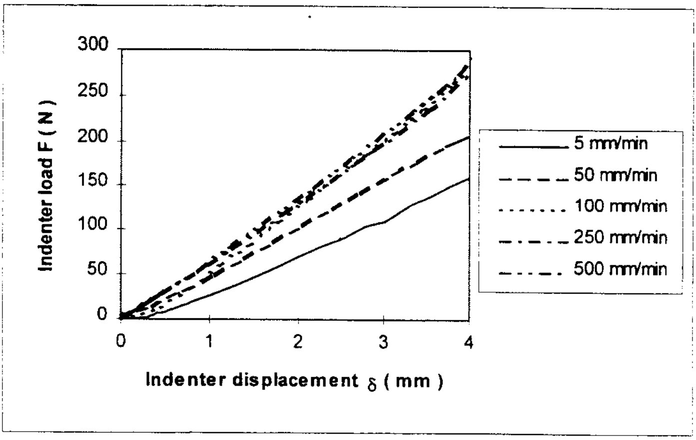

Figure 3. Variation of indentation load for the vapour blasted indenter test

Analysis of the data from the tests using the NBR and vapour blasted indenter are depicted in figures 3 to 5. The rubber had a mean surface finish (R_a) of 0.8 μm averaged from results on three test specimens, where the finish was measured both in the direction of and perpendicular to tooling marks. The force to indent to a depth of 4 mm increases with feed rate. This can be anticipated from previous research into sliding friction and also simultaneous

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stress relaxation will become less pronounced as feed rates increase. The 100 mm/min ingress and stress relaxation curves are inconsistent with the trends in the test. This result can only be attributed to the test-piece physical properties being different from the remainder of the set or a calibration error in between tests. An estimate of the indenter force for a given displacement is provided by the formula

$$F = (\alpha \ln R + \beta)\delta \qquad (1)$$

where F = Indenter force (N)
R = Feed (mm / min)
δ = Displacement (mm)
α and β are material constants

This formula produces the equation below for the NBR tests

$$F = (7.25 \ln R + 25)\delta \qquad (2)$$

giving a straight line which is reasonably accurate for medium and higher indentation rates but can be inaccurate at low indentation rates, particularly for small indentations.

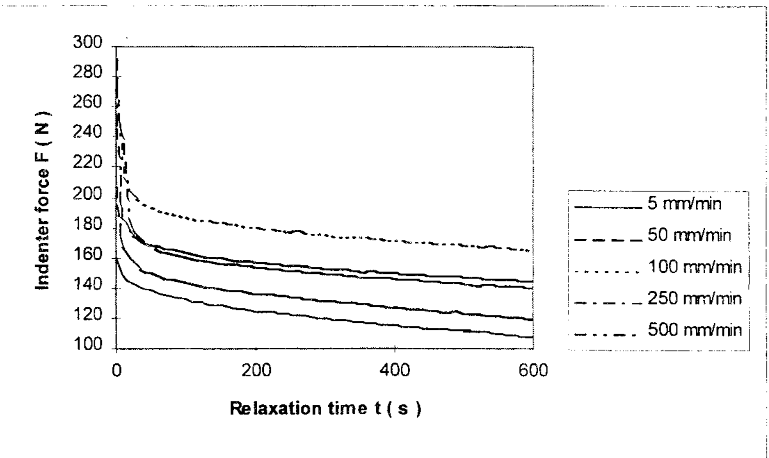

Figure 4. Stress relaxation at constant depth for vapour blasted indenter test

Figure 4 shows that although stress relaxation is most pronounced in the first minute after ingress in each test, it is still underway after 10 minutes. The curves are noticeably similar to those achieved from micro-hardness tests.

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Since the curves are not converging, one of the physical characteristics leading to a fundamental limitation of existing hyperelastic finite element analysis is highlighted; that stress and deformation in a loaded component are a function of its loading history. Consequently, two components of the same material and dimensions, subject to identical loading at an instant, can and often do possess different states of stress and strain.

After the first minute of stress relaxation the curves for indenter load against time can be approximated by the equation

$$F' = (a \ln R + b) F_{max} e^{-ct} \qquad (3)$$

where F' = Force after t sec. relaxation time (N)
R = Indenter feed rate (mm / min)
F_{max} = Indenter force at relaxation time 0 s (N)
t = relaxation time (s)
a, b and c are constants

giving an expression for load reduction resulting from stress relaxation for the 40 Shore A NBR in plane strain of

$$F' = [-0.0522(\ln R) + 0.953] F_{max} e^{-0.0005t} \qquad (4)$$

This formula cannot represent the rapid load relaxation at its start, but is reasonably accurate when predicting loads after a relaxation time of one minute. It will be inaccurate if used in conjunction with (3) for low feeds and indentations. Figure 5 indicates that the greater the indentation rate the greater is the subsequent stress relaxation. It can be seen that as relaxation time increases the load variation is far less pronounced, but each test-piece will not ultimately stress relax to the same load.

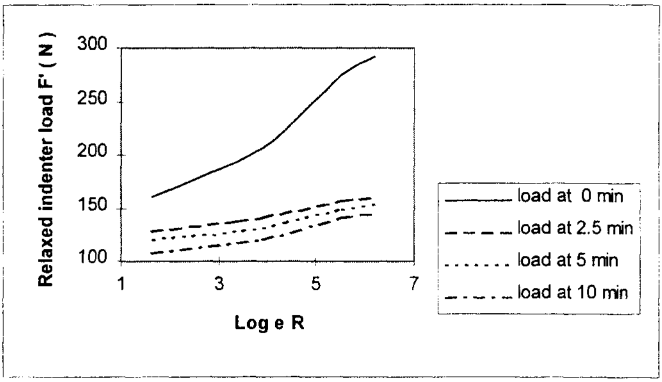

Figure 5. Variation of load with feed rate at different relaxation times

2.1 Change in surface profile and levels of adhesion

In all the tests on the NBR, irrespective of indenter surface finish, the video recordings showed that the level of adhesion (dimension 'd', figure 2) and the surface contour on the indented face did not change with time and hence did not change with stress relaxation. Hence it appears that friction forces tangential to the indented surface are greater than the indentation force. This conclusion is consistent with the experiments of Roth, Driscoll and Holt referred to earlier. Clearly the friction force is retained as stress relaxation takes place in the body of the rubber, suggesting that intermolecular strains between the rubber and indenter are unchanged after indentation to full depth.

2.2 Axisymmetric contact problems

To dispense with the need to use inverse impression modelling and the attendant problems of the presence of a moist impression material in the region of contact, experiments are to be conducted using optical methods and glass indenters. Contact and adhesion between punch and indenter will be viewed along the axis of the punch and a convention for marking a grid on the deformed surface of the rubber is being developed. The outcome of this work will be correlated to plane strain indentation for a range of rubbers.

2.3 Finite element modelling of plane strain indentation

Figure 6 shows the recorded levels of adhesion for the preliminary tests on a test grade, medium hard, filled rubber. Feeds of 5, 50 and 100 mm/min were used with two indenter surface finishes and adhesion to the indenter form can be observed for each test. The results of finite element simulations using two parameter ANSYS and MARC software are superimposed on the curves. Each used hyperelastic and rigid surface elements. Coefficients of friction were varied in the ANSYS analysis with little effect, whilst the MARC analysis uses a coefficient of friction (μ) of 0.35. The Mooney-Rivlin constants for

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both analyses were derived from test as $C_{10} = 0.916$ and $C_{01} = 0.0647$. The ANSYS analysis did not model adhesion and it can be seen that the elements representing the elastomer encroach into the rigid surface despite correct element selection and specification. The MARC software was capable of modelling some adhesion though not the full amount. Attempts at inputting values of μ of unity and greater caused the analysis to fail. A comparison of indenter forces recorded at full depth indentation (4 mm) and the corresponding finite element values are shown in table 2. The ANSYS analysis under-predicts the load at 4 mm whilst MARC slightly over-predicts the indenter load when compared with the range of final loads obtained in the tests.

Test/ Analysis	Load (N) at 4 mm depth, no stress relaxation
All tests	635-759
ANSYS	548
MARC	789

Table 2 Indenter load for plane strain test on 68 Shore A hardness rubber

Levels of adhesion are shown in figure 6 and it is clear that the ANSYS analysis fails to adequately predict surface deformation. The MARC analysis gives reasonable results away from the vicinity of the indenter. Two parameter models are seen to be inadequate for modelling contact problems of this kind. Higher order models add complexity yet still prove to be inaccurate. This is because complex material behaviour contradicts the information obtained from uniaxial, equibiaxial and biaxial tests. However, parameter determination is based on these simple tests, though they do not yield the same parameters when compared with one another.

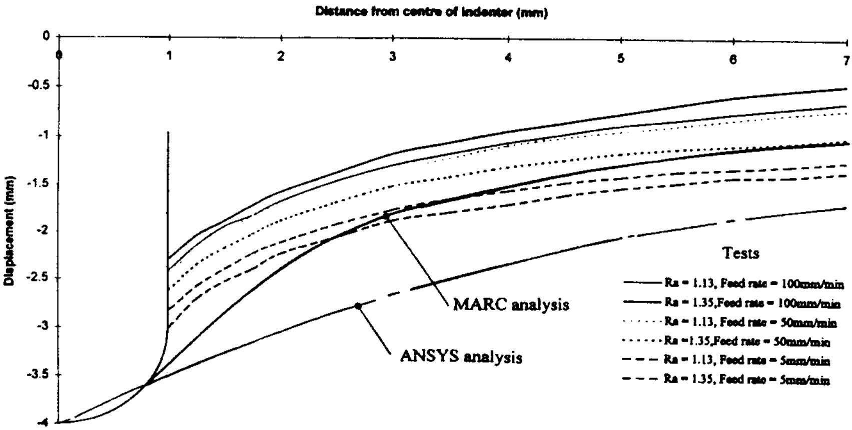

Figure 6. Adhesion and surface profiles from tests on a medium hard rubber

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3 What needs to be done

The current research programme in conjunction with Bosch and DIK is concerned with the plausibility and development of -

- existing and envisaged material models
- basic physical tests
- curve fitting procedures.

These tasks are of fundamental importance in establishing realistic models of isochoric material behaviour. Their resolution must also allow sensible modelling of contact problems because so many rubber components are required to seal or be deformed by rigid contact. Hence, adhesion, its effect on surface profile and changes due to stress relaxation must be fully understood to permit their simulation. Parameters need to be provided for a range of elastomers, with or without lubrication, that are easily determined and easily incorporated into finite element code. Until this is achieved we will continue to question whether hyperelastic finite element codes permit us to do any more than compare alternative designs.

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