The Dependence on Mean Stress and Stress Amplitude of the Fatigue Life of Elastomers

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This paper describes the dependence on test parameters of the fatigue resistance of EPDM. Fatigue was investigated using dumbbell specimens under load control at 1Hz until failure. Tests were made in order to create a common Wöhler-(S-N)-curve while increasing the stress amplitude and also to show the influence of increasing minimum stress at constant stress amplitude on fatigue properties. The results of these tests confirmed the well-known amplitude dependence of fatigue life in filled rubbers. An additional significant influence on fatigue life is seen to be the minimum stress in the cycles applied to these materials. Fatigue life is not dependent on strain crystallisation in EPDM as it is for Natural Rubber (NR). The results of this research give component designers the opportunity to increase the fatigue lives of components made from this material.

1. Introduction

Although elastomeric materials exhibit very high strains for relatively small stresses, making them appropriate for many automotive applications, they still have behaviour in common with other materials. In particular they a limiting strength and tend to fatigue. Mechanical fatigue of elastomers is manifested in a progressive reduction of the physical properties as a result of crack propagation during continuous dynamic excitation. Well founded research into metals[1,2] has shown that fatigue results from atomic and molecular processes. Similar research for elastomers is at a very early stage, because of the complex interaction between polymers, fillers, softeners and other additives. Predictions of the fatigue properties of elastomeric materials and components are currently partly of an empiric nature. Though there are levels of stress or strain below which elastomers will not suffer fatigue damage, such limits are not well established. There are few Wöhler curves[3] in the literature for rubbers due to the inordinate amount of time required to collect the data. Hence a precise understanding of the durabillity of rubber does not exist. Producing durable rubber automotive components, despite the increasing use of Finite Element Analysis (FEA), remains a challenge. The question of determining a sole criterion for predicting elastomeric fatigue is unresolved. Arguments have been made that fatigue resistance is dependent on stress, strain and also dynamic strain energy per unit volume[4-7].

When characterising crack propagation and fatigue properties, there are two problems unique to elastomers that must be surmounted for a computer simulation to model fatigue:

- Fatigue properties of rubber are not only dependent on the basic chemical composition of the polymer, but also on individual considerations like the particular cross-linking system and the ageing protection applied to it.
- Elastomers behave with sensitivity to the application of different loading modes, frequencies, strain rates, wave-forms and temperatures as a result of their hyperelastic and viscoelastic properties.

Each of these problems proves the importance of optimising a material definition so that it can represent the physical behaviour that a component experiences in service. Additionally, component testing must realistically represent in-service behaviour to allow accurate determining of fatigue characteristics.

2. Objective

The fatigue behaviour of linear materials like metals and ceramics is well researched and described in the literature. In particular emphasis has been placed on testing of fatigue properties with varying stress amplitudes and minimum stresses and this data has been represented on Wöhler curves and Haigh diagrams. Very few fatigue analyses of elastomeric nonlinear behaviour have been carried out and these have used Natural Rubber (NR). The influence of minimum stress and stress amplitude on the fatigue resistance of NR has been studied by André et al [8] and Haigh-diagrams were used to display the data. Service life was shown to increase as minimum stresses, both compressive and tensile increased from zero, for a single stress amplitude. The improved fatigue resistance with increased minimum (and hence maximum) stresses was explained previously by Gent [9] and attributed to the strain crystallisation of NR inhibiting crack growth. A previous analysis carried out by the DIK also showed a reduction of crack propagation with increases in minimum stress for non strain crystallising rubber.

Consequently, the main objective of this work is the characterisation of the dependence of fatigue on stress amplitude and minimum stress in non strain crystallising elastomers. Additionally, it was considered necessary to include materials with and without filler in this investigation. This permits simultaneous studies on the effects of reinforcement, stress softening and Payne-effects[10-12] of filled systems. A second objective is to clarify the question of which criteria (stress, strain, energy) characterises the fatigue properties of elastomeric materials. Reliable predictions of the service life of dynamically loaded components using fracture mechanics concepts as well as FEA, depend entirely on the use of the correct criteria and characterisation.

3. Methods and Materials

Unfilled and filled EPDM vulcanisates have been used in this research programme. The unfilled rubber contains standard trade EPDM and an accelerated cross-linking system. The filled rubber contained 110 phr low active carbon black and 70 phr softener. The experiments used dumbbell test specimens of 25mm free length and 15mm diameter as shown in figure 1. This test specimen is capable of being cycled in tension and compression under uniaxial loading.

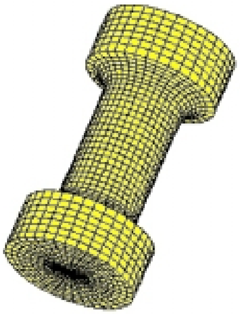

Figure 1: Model of a dumbbell test specimen

Dynamic fatigue tests have been made with a servo hydraulic test system (MTS 831.50) at room temperature and with a harmonic load of 1Hz (figure 2). The frequency was chosen to induce failure due to the initiation and growth of cracks as opposed to internal friction causing large increases in temperature and consequent thermal break-down[13]. The tests were load controlled (engineering stress controlled) to failure and at least three test specimens per test condition were used to provide sufficient data. During the fatigue tests, Young’s modulus, the loss factor and full hysteresis loops were continually recorded for later analysis.

Figure 2: The Servo hydraulic testing machine with clamped test specimen

The unfilled and the filled EPDM material was tested under various loading conditions. Tests on the filled rubber samples with increasing load amplitude from a minimum load of zero, were followed by tensile tests having two load ranges of 400 N and 500 N applied to minimum loads from zero (0 N) to 200 N. (Figures 3 and 4 respectively).

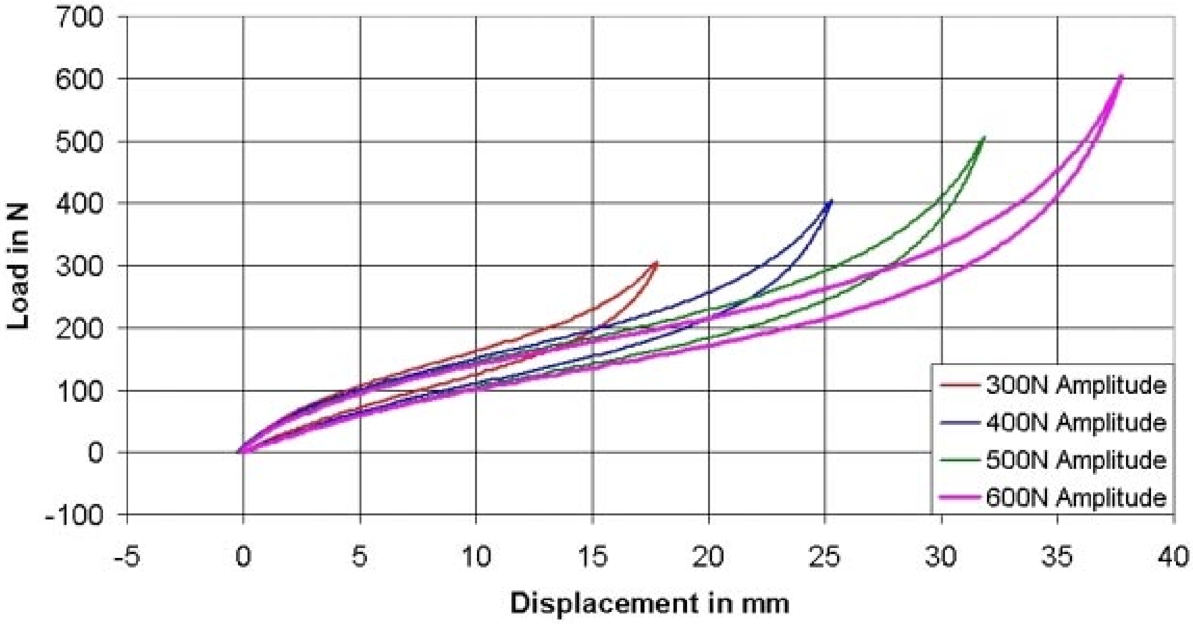

Figure 3: Diagram of four test conditions to gererate Wöhler curves (0 N minimum stress)

The test series with removal of the minimum stress (cycling back to zero load) represent an approximate full relaxation condition, as they would appear under pulse load. In the case of the series with variation of the minimum stress no full relaxation is allowed.

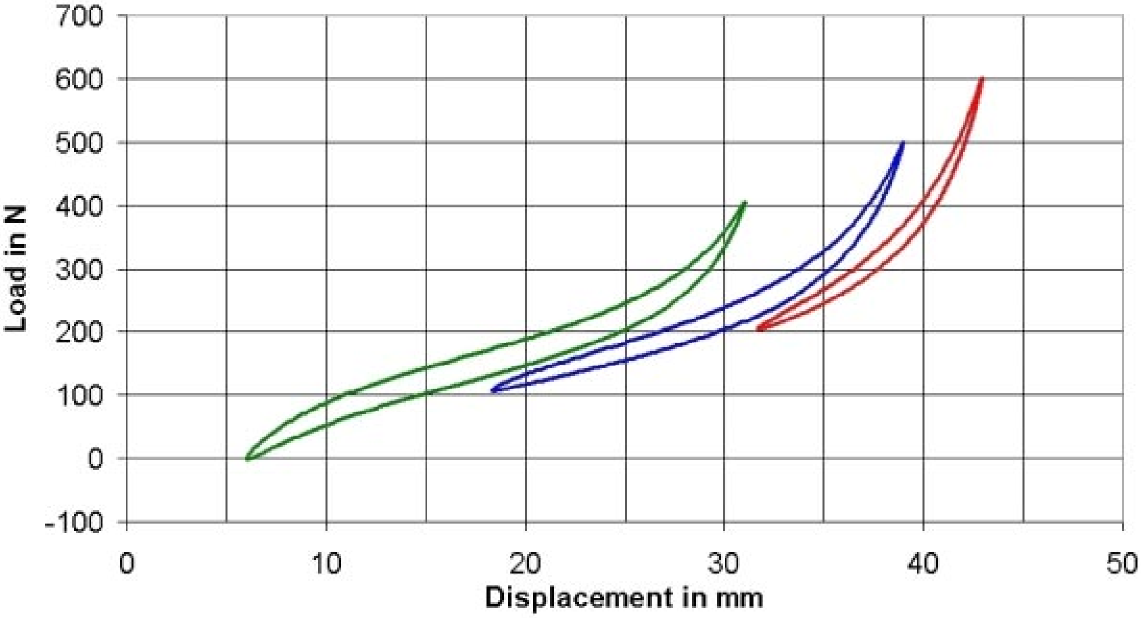

Figure 4: Diagram of four test conditions to determine the minimum stress dependence (constant stress amplitude)

Changes in maximum load (stress) resulted from varying load range and minimum load. This allowed the influence of maximum stress, as a criterion for determining fatigue resistance, to be studied.

4. Results

The results of the fatigue tests on the unfilled EPDM are plotted in figures 5 to 8.
The typical quasi-static tensile test for the unfilled material is shown in figure 5. Like the fatigue tests, a dumbbell test specimen was used for this test.

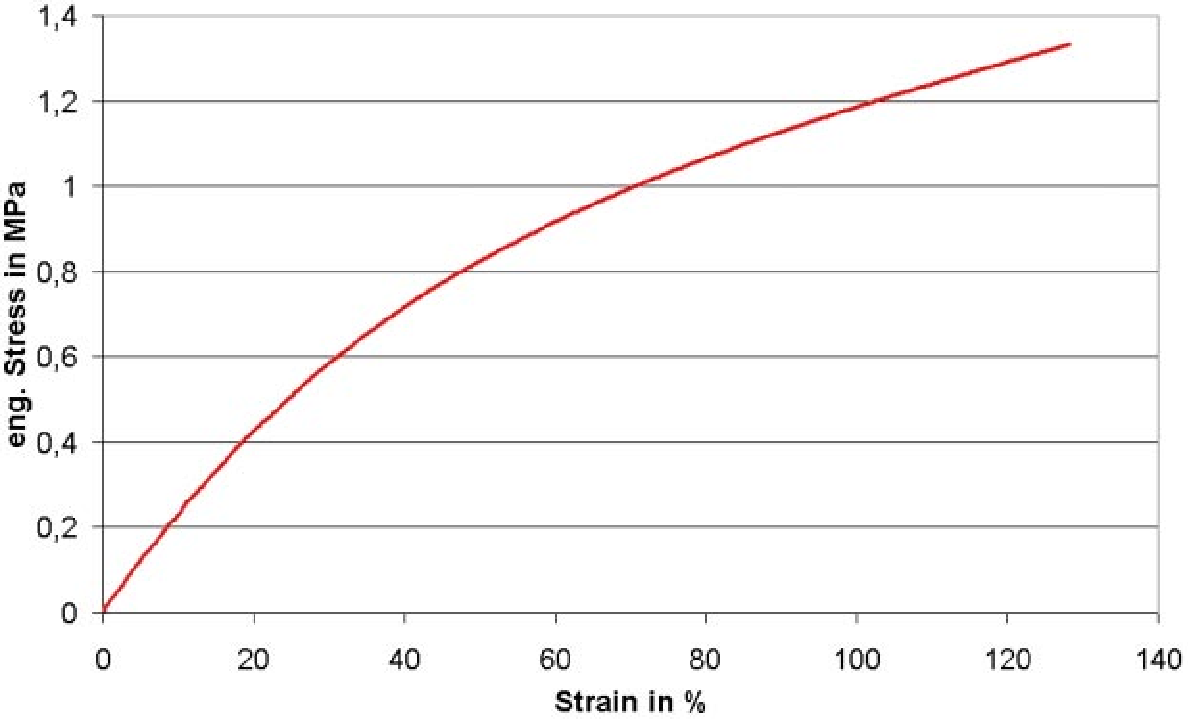

Figure 5: Tensile curve for unfilled EPDM (dumbbell test specimen)

Figure 6 shows the well known dependence of fatigue properties on maximum stress (Wöhler-curve). It appears to be unimportant whether the maximum stress is produced by a high stress amplitude or by a high minimum stress. Relaxing and non relaxing test conditions lead to identical dependence. For unfilled EPDM the results show that the maximum stress criteria can be used for the predictions of fatigue life.

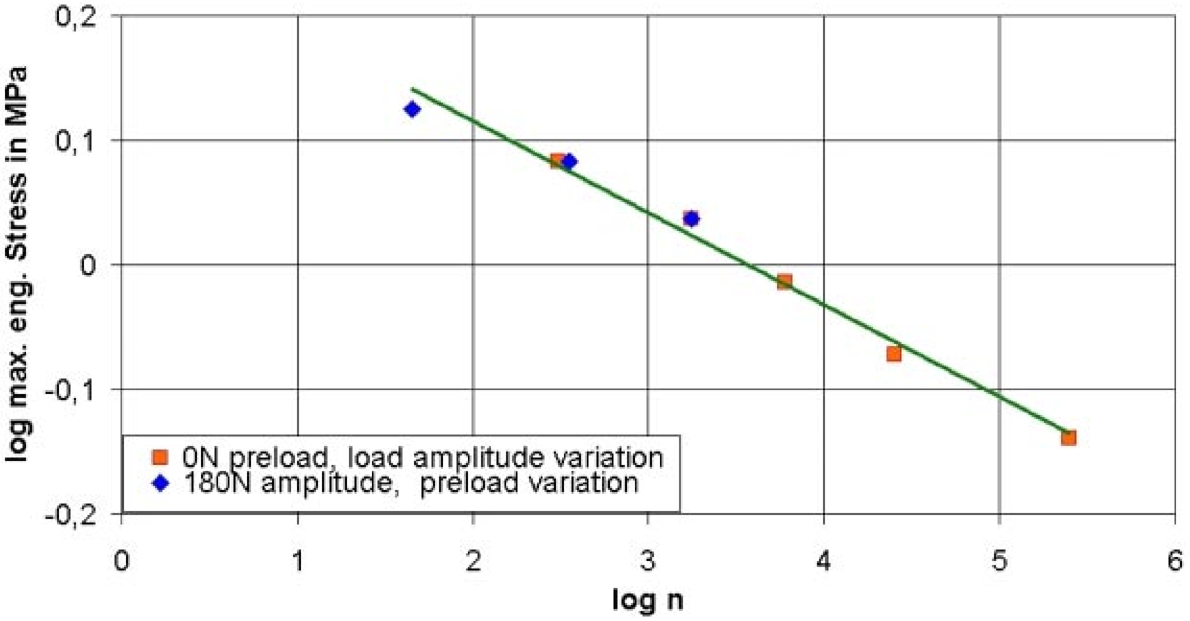

Figure 6: Fatigue properties of unfilled EPDM (maximum stress influence)

Figure 7 shows that a single curve for dynamic strain range versus fatigue life results from the tests. Hence for the unfilled EPDM, dynamic strain range could also be used as a criterion for determining fatigue resistance.

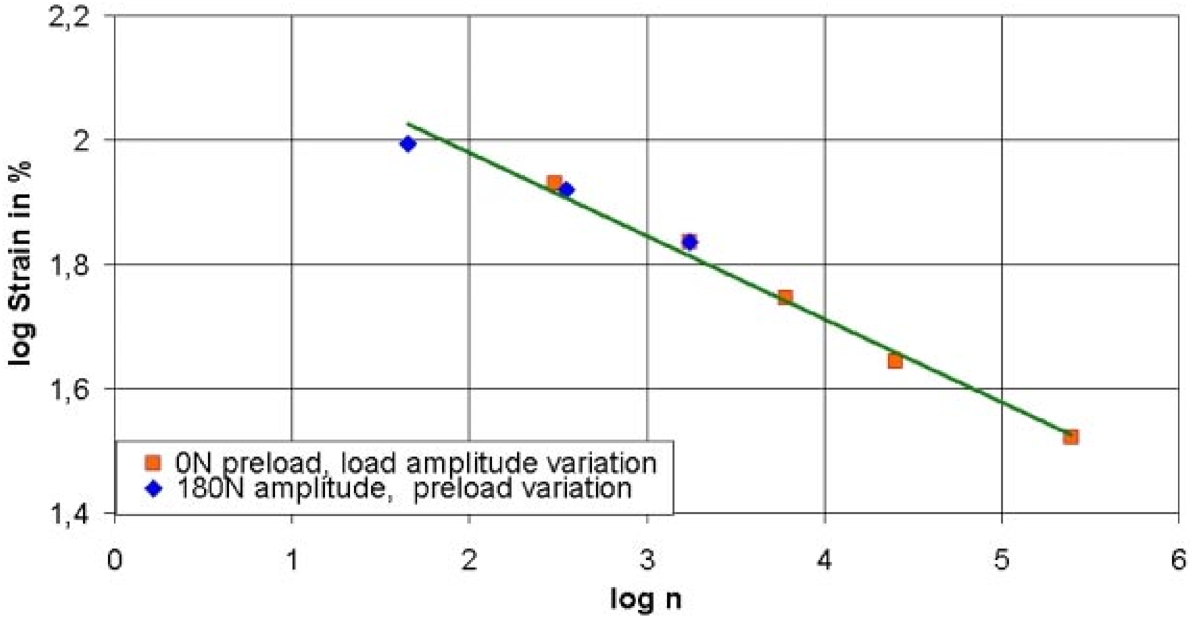

Figure 7: Fatigue properties of unfilled EPDM (strain amplitude influence)

A consideration of the detailed testing or operating conditions appear to be unnecessary for a precise prediction. In these tests it is predictable, that a plot of the fatigue dependence on dynamic strain energy is independent of the adjusted test parameters minimum stress and stress amplitude. The results form a unique picture for the unfilled EPDM relating the dynamic strain energy to fatigue life (figure 8).

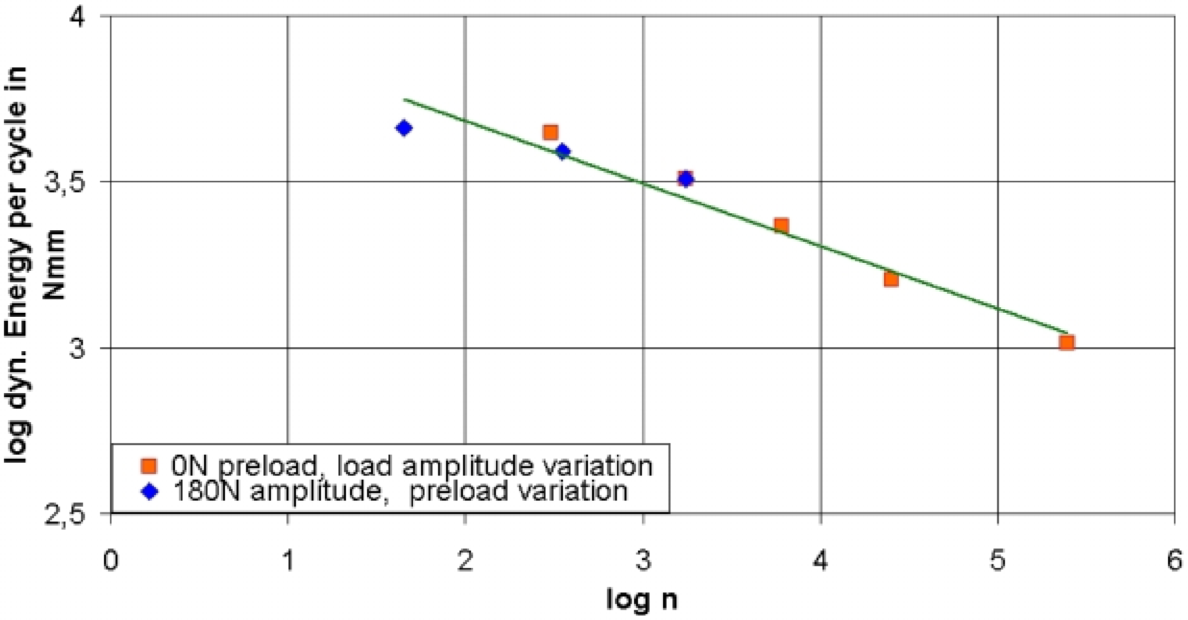

Figure 8: Fatigue properties of unfilled EPDM (energy dependency)

The behaviour of the filled EPDM differs fundamentally from that of the unfilled material (figures 9 to 12). Figure 9 shows the typical quasi-static tensile test for the filled material. The reinforcement properties of the filler are obvious when comparing figures 5 and 9. The filled EPDM also shows an upturn in the tensile curve compared with the unfilled material.

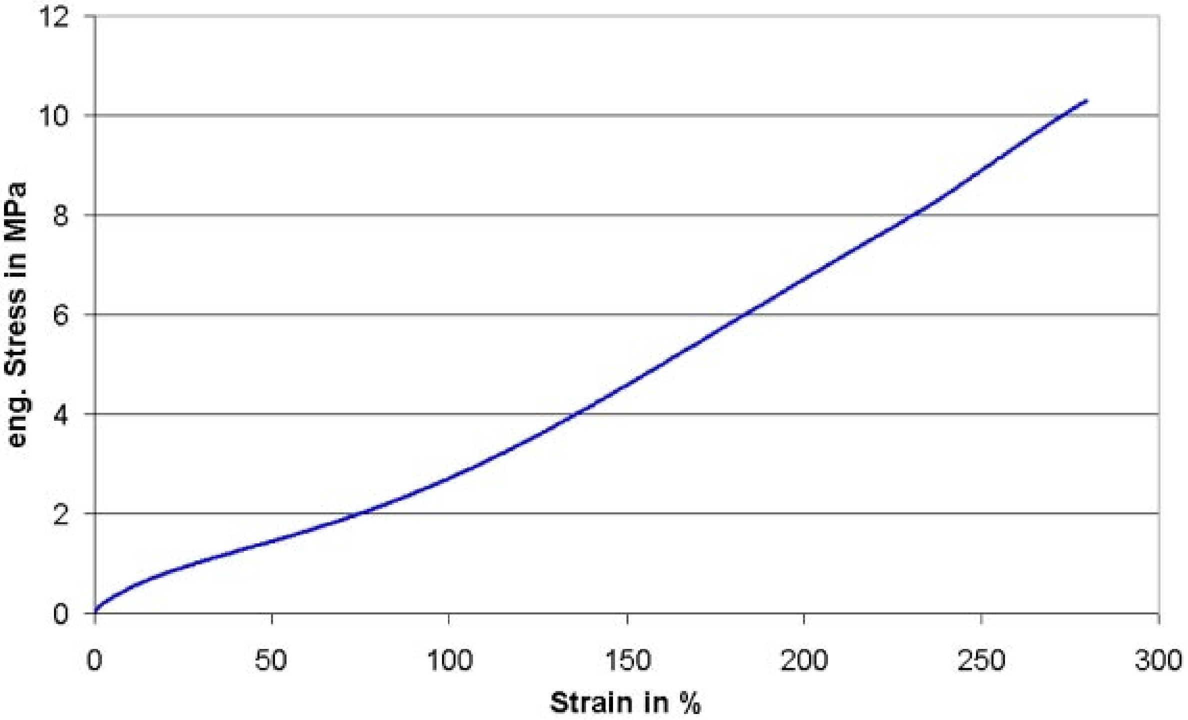

Figure 9: Tensile curve of filled EPDM (dumbbell test specimen)

With a variation in stress amplitude the fatigue life reduces as maximum stress increases, where the minimum stress is kept constant at zero, as shown in figure 10. When the maximum stress is increased and a constant stress amplitude is maintained, the service life increases in spite of an increase in maximum stress. Figure 8 shows that the same maximum stress, but with varying stress amplitude, results in very different fatigue properties. In this case the maximum stress criterion can not be used. Conversely results from the tests show, that under certain conditions an increase in maximum stress in filled rubbers can lead to an increase of the service life by a factor of more than 10.

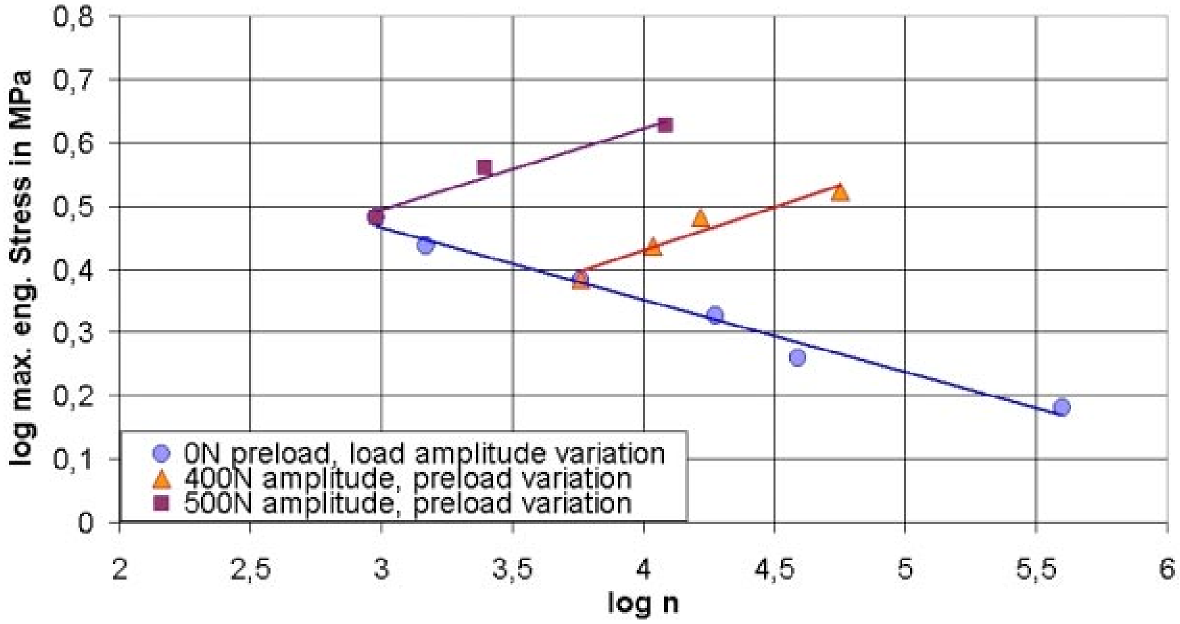

Figure 10: Fatigue properties of filled EPDM (maximum stress dependency)

The graph showing the influence of the dynamic strain range on the fatigue properties (figure 11) confirms the same trend as that for stress dependency. The variation of the amplitude leads to a Wöhler curve similar to that in figure 10. However, when the minimum dynamic strain is varied, a sensible curve cannot be fitted to the data, making a strain criterion for predicting fatigue life inappropriate for the filled EPDM.

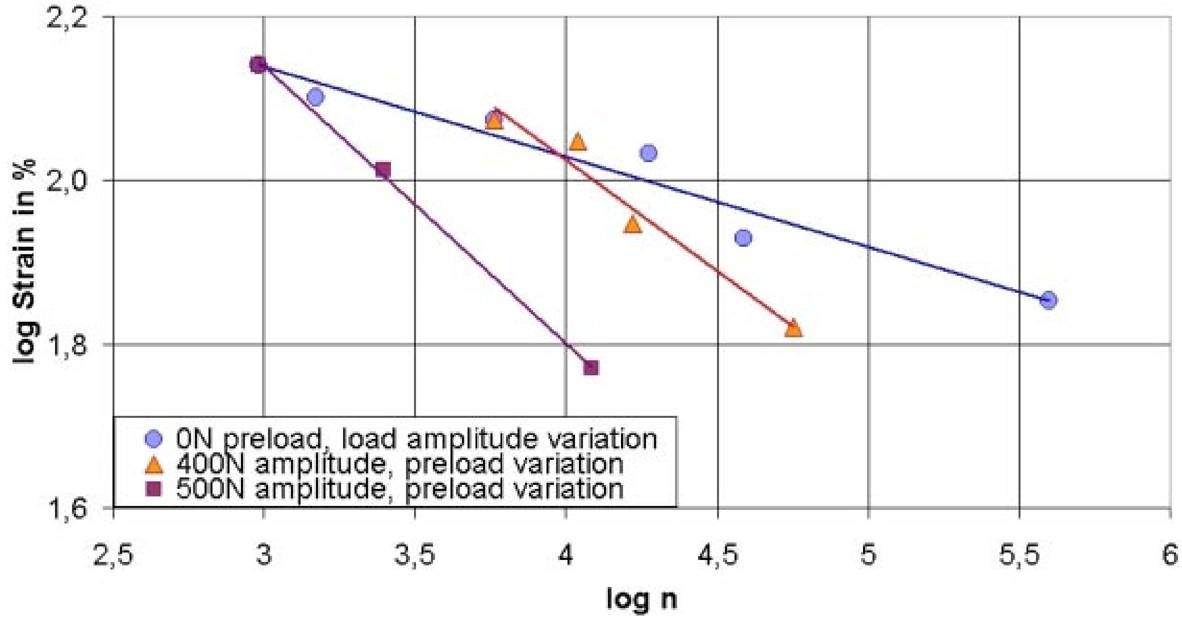

Figure 11: Fatigue properties of filled EPDM (strain dependency)

Finally figure 12 shows the correlation between dynamic stored energy and fatigue for the filled EPDM material. A unique curve results from both a variation of the minimum stress and the stress amplitude. This suggest that energy is the most promising criterion for the prediction of fatigue of components made from EPDM, irrespective of the load cases and service conditions.

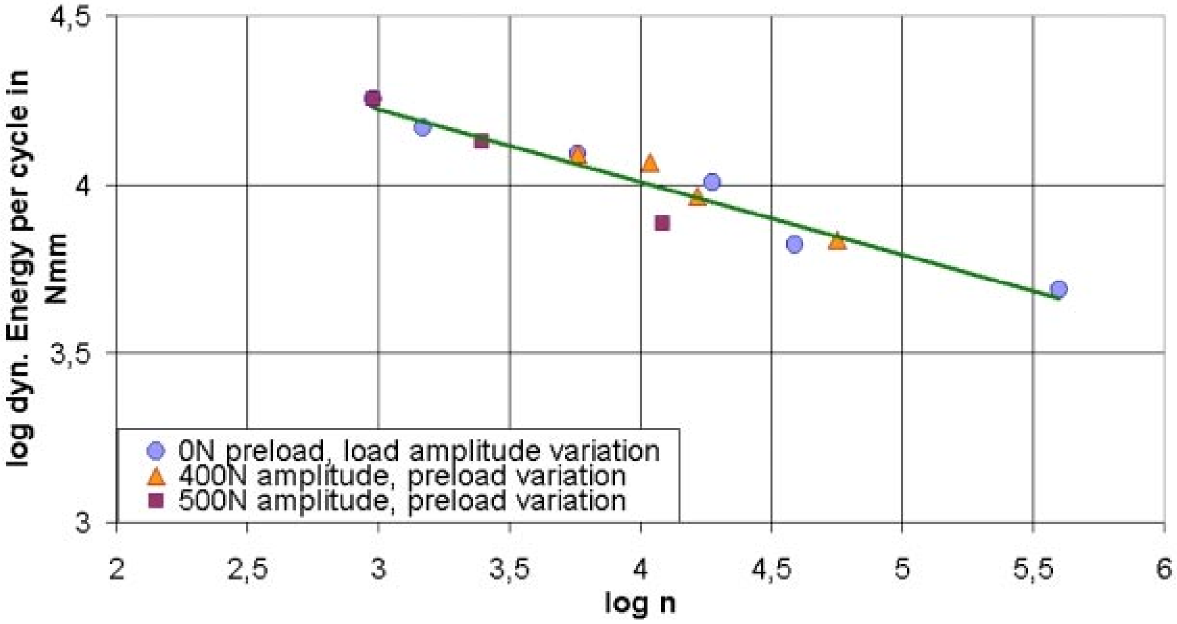

Figure 12: Fatigue properties of filled EPDM (energy dependency)

This result supports the early theories developed to apply fracture mechanics concepts based on energy to fatigue resistance [14-19].

5. Summary

The experimental results of this work show that the dynamic fatigue properties of filled elastomers under equal conditions of temperature and frequency (etc) depend on the applied stress amplitude as well as minimum stress. Increasing minimum stresses with constant strain amplitude could increase the service life by a factor greater than 10 despite increasing maximum stresses. These effects do not apply to unfilled rubber. Because of the use of EPDM, strain crystallisation cannot explain the increase in service life. It is evident that the phenomenon of increased fatigue life with increased maximum stress is related to the properties of the rubber filler system.

The improvement of the fatigue properties under minimum stress can be used constructively to increase the service life of components, or put simply, pre-loading EPDM components increases fatigue life. This necessitates an accurate simulation of service life, most probably aided by Finite-Element-Analysis, using the criteria and characteristics of fatigue determined in this research.

The maximum stress criterion and the strain criterion should be regarded with scepticism. However, the energy criteria are superior, because they create a unique picture of fatigue dependence on both the minimum stress and the stress amplitude.

In the future it is planned to investigate the crack propagation under similar test conditions and also to test under pulse loading conditions. Clearly the results should be confirmed for other non strain crystallising rubbers materials.

6. References

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