MECHANICAL CHARACTERIZATION AND FINITE ELEMENT MODELING OF NBR AND PDM FOR DIRECTIONAL DRILLING

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INTRODUCTION

A Positive Displacement Motor (PDM) is at the heart of the Directional Drilling (DD) operation. A recent increase in drilling of horizontal wells using PDMs has brought forth the need to understand the effects of the aggressive downhole environment on the mechanical behaviors of elastomers, Nitrile Butadiene Rubbers (NBR) in particular. Elastomers used in these applications experience elevated temperatures and pressures, abrasion and chemical attack, swelling and hysteresis, which all contribute to the degradation of the mechanical properties and the eventual power section stator failure.

This study reports the mechanical characterization of a common type of NBR and the creation of a finite element model in order to understand the stress-strain distribution in elastomer used in the cross section of an operating PDM.

EXPERIMENTAL

Materials

NBR with 30 volume percent of carbon black.

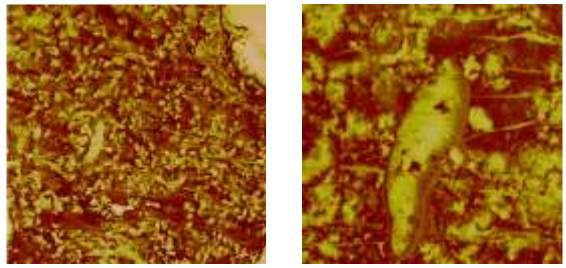
Apparatus and Procedures

For this study the following mechanical tests were performed at temperatures of 66, 93 and 121°C: uniaxial tension, equal-biaxial extension, planar tension, volumetric compression and short term stress relaxation (STSR).

Atomic Force Microscope (AFM) images were obtained using a MultiMode^{TM} SPM, Nanoscope IIIa controller, with scanner type “E”.

RESULTS AND DISCUSSIONS

Figures 1 shows the Tapping Mode Atomic Force Microscope (TMAFM) images of NBR carbon black dispersion. The approximate mean diameter of the carbon black particles is about 200 nm, which is in line with the specification of ASTM N880 standard. From the images, it can be seen that the spherically shaped carbon black particles conglomerated together to form larger irregular clusters. Single strands of polymer chains can be seen strung across the sample surface. The addition of carbon black fillers enhances performance of elastomer with modified mechanical properties, such as increased resistance to mechanical deformation. The elastomer durometer hardness was found to be around 75 Shore A.



a) b)

Figure 1. AFM micrographs of 30 vol.% carbon black distribution in NBR: a) 5x5; and b) 2x2 µm scan size.

As a comparison, Figure 2 shows the mechanical response of the NBR specimens during the uniaxial, equal biaxial and planar extension tests up to a stain of 0.4 at a loading rate of 0.1 s^{-1} and temperature of 66°C.

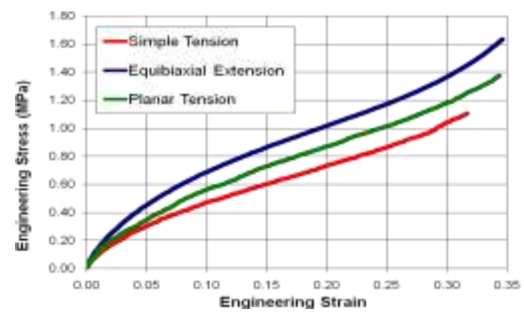


Figure 2. Comparison of mechanical stress-strain behavior of NBR/30vol. % carbon black in uniaxial, equal biaxial and planar extension tests at 66°C.

Volumetric response of the NBR in the compression tests, up to a strain of 0.08 at a loading rate of 0.1 strain per second at 66°C, is shown in Figure 3.

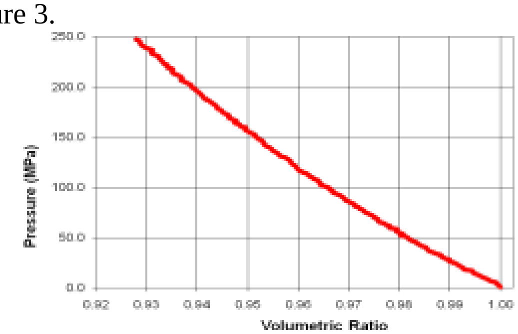


Figure 3. Stress-volume ratio behavior of NBR/30vol.% carbon black at 66°C.

The viscoelastic response of NBR preloaded to 0.4 strain is shown in Figure 4. The load was maintained for 2,000 seconds at 66°C.

For elastic, rubberlike materials, hyperelastic and

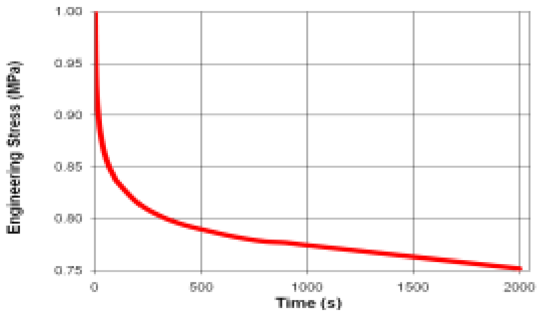


Figure 4. Normalized STSR behavior of NBR/30 vol.% carbon black at 66°C with a strain of 0.4.

viscoelastic models are usually used to predict material behaviors, as these non-linear models are well suited for large deformations. In this work, the hyperelastic Ogden[1] and viscoelastic Prony series material models were used to predict the behaviors of the NBR. Figure 5 shows Ogden N = 5 model prediction based on the uniaxial, biaxial and planar experimental data.

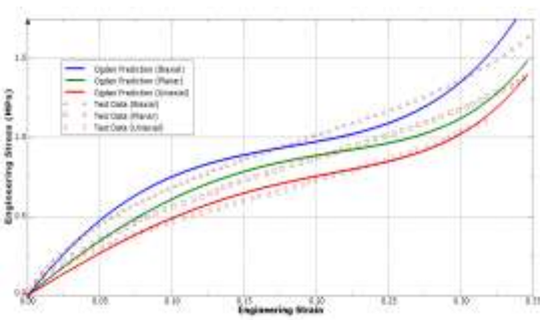
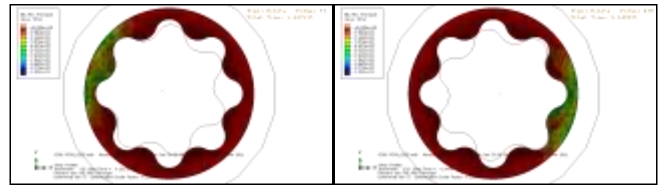


Figure 5. Ogden N = 5 model prediction based on uniaxial, biaxial and planar experimental data.

A widely used type of PDM with a 7:8 rotor/stator lobe configuration was selected for simulation. The inside diameter of the stator tube is 100.33 mm and outside diameter 127.00 mm. The major, minor, and lobe tip radius and peak-to-valley dimensions of rotor profile are 78.613 mm, 60.985 mm, 8.407 mm and 69.799 mm, respectively. Similarly, the major, minor and lobe tip radius dimensions of stator rubber profile are 87.173 mm, 69.545 mm and 8.280 mm, respectively.

Abaqus 6.10-EF was used to create the PDM finite element model. The simulation was composed of two steps: Interference Resolution and Rotor Rotation. During the first step the interference between the rotor and stator was simulated by displacing the elastomer and creating an initial stress field. In the second step, the rotor began to rotate and nutate within the stator, and displaced the elastomer, while maintaining the initial interference stress field. Figure 6 shows the rotor position and elastomer minimum principal strain in the first and third stator quadrants.

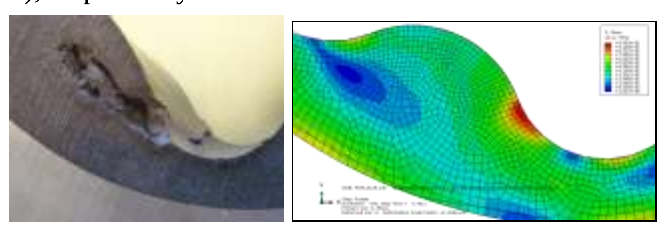
One major cause of power section failure is hysteretic heat buildup in the stator lobes. During a drilling operation at 175 rpm, each stator lobe would



a) b)

Figure 6. Rotor position and elastomer minimum principal strain in: a) the first; and b) third stator quadrants.

flex at 1225 times per minute. Due to the viscoelastic properties of rubber, some of the energy during the loading and unloading cycles of the stator lobes is released as heat (hysteresis). Since elastomers are poor conductors of heat, the temperature continues to increase within the stator lobes, inducing degradation of the elastomer. Once the temperature reaches the maximum operating temperature for NBR at about 149°C, the rubber starts to break down and voids begin to form within the stator lobes. The voids and resulting cracks continue to grow and propagate to form networks along the path of higher stress concentration, and finally reach the stator surface, resulting in splitting fracture and eventually chunking off of the lobe. Typical hysteretic failure of a stator lobe in operation and the finite element simulation of the elastomer by von Mises stress concentration prediction at the same lobe location are shown in Figure 7 a) and b), respectively.



a) b)

Figure 7. a) Stator lobe hysteretic failure photograph[2]; and b) simulation of lobe stress concentration prediction at the same location.

CONCLUSIONS

Using the elastomeric properties at the downhole operating temperatures, the finite element method was successfully used to create a two-dimensional model of a 7:8 lobe ratio positive displacement motor power section to simulate and predict the stresses and displacements in the stator elastomer due to the interference and motion of the rotor during operation.

REFERENCES

1. R. W. Ogden, "Large Deformation Isotropic Elasticity – On the Correlation of Theory and Experiment for Incompressible Rubberlike Solids", *Proceedings of the Royal Society of London*, Series A, Mathematical and Physical Sciences, Vol. 326, No. 1567, February 1, pp. 565-584, 1972.
2. M. S. Delpassand, *Technical Report*, No. 101, pp. 3, Dyna Drill Technologies, Inc.