A Numerical Investigation of Mechanical Response of Unfilled Styrene Butadiene Rubber by Static Straight Blade Indentation

B. Setiyana[1,2], R. Ismail[1], J. Jamari[1] and D.J. Schipper[2]*
[1]Laboratory for Engineering Design and Tribology,
Department of Mechanical Engineering,
University of Diponegoro,Jl. Prof. Soedharto, Tembalang,
Semarang 59275, Indonesia

[2]Laboratory for Surface Technology and Tribology,
Faculty of Engineering Technology, University of Twente,
Drienerlolaan 5, Postbus 217, 7500 AE Enschede, The Netherlands
**Corresponding author: bsetiyana@yahoo.com*

ABSTRACT

This study investigates the mechanical response of straight blade indentation on Unfilled Styrene Butadiene Rubber by Finite Element Analysis (FEA). The mechanical responses investigated were stiffness, maximum stress and indentation load. The rubber material was modeled as a hyperelastic material with the Money-Rivlin Strain Energy Function. Results were presented as a function of the blade characteristics, wedge angle and tip radius at a specified depth of indentation. Results showed that the stiffness and indenter load increase due to an increase in the wedge angle and the tip radius, on the other hand, the maximum stress decreases. Surprisingly, an approximately linear relationship between the mechanical response and the blade characteristic was found. Furthermore, the mechanical response at a specified maximum stress was also discussed.

Keywords: *Blade, Hyperelastic, Indentation*

Introduction

Rubber indentation by a straight blade indenter is usually performed in a static as well as in a dynamic manner. McCharty et al. [1, 2] investigated the

ISSN 1823- 5514, eISSN 2550- 164X

Received for review: 2016-09-01
Accepted for publication: 2016-11-17
Published: 2017-01-19

static indentation to find the deformation and load at cut formation for various wedge angles and tip radii. Moreover, static indentation can also be used to predict the elastic modulus or hardness of rubber [3]. Dynamic indentation by a straight blade is conducted by sliding indentation or abrasion [4-6]. Their results show that there are periodic wear pattern formed at the abraded rubber surface. Experimentally, Fukahori et al. [7] showed that the pattern spacing is strongly depended on the hardness of the rubber.

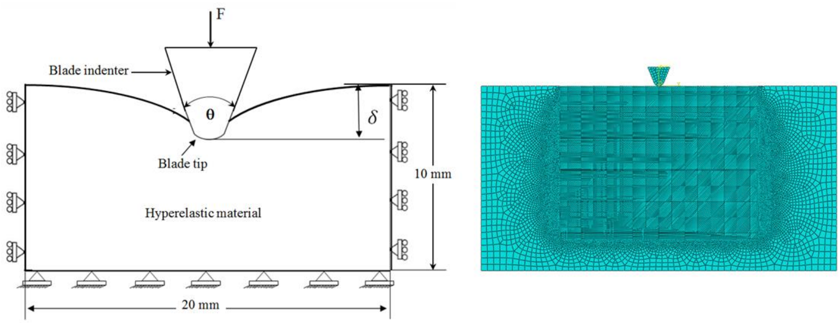
There are two important parameters at rubber indentation, i.e. the hardness of the rubber and the load at cut formation. It widely known that the hardness complies with the rubber stiffness, while the force at cut formation depends on the ultimate stress of the rubber. These parameters depend on the mechanical behavior of the rubber and blade characteristics. It is difficult to describe accurately the mechanical behavior of the rubber theoretically due to the broadness of manufacturing technology of the rubber. Therefore, it is most frequently modeled as a hyperelastic material that is constructed through phenomenological methods [8]. However, the hyperelastic material model is commonly used for describing a static indentation only, meanwhile, a viscoelastic material model is validly applied in dynamic or sliding indentation that causes a stick-slip phenomena or oscillation [9]. In general, the mechanical behavior of a hyperelastic material is modeled as Strain Energy Function (SEF) that is obtained from a tensile test. However, the hyperelastic model cannot describe the cut formation level because, the model is constructed up to a certain strain level which is lower than the ultimate strain at break. The blade characteristics can be represented by the wedge angle and tip radius.

Finite Element Analysis (FEA) is a numerical method that is a useful tool to analyze the tribo-system with dry contact as well as lubricated contact [10]. By using FEA, the aim of the present study is to investigate the mechanical responses of a static straight blade indentation on Unfilled Styrene Butadiene Rubber (SBR-0). The main mechanical responses investigated are stiffness of the rubber, maximum stress and indentation load as a function of the blade characteristics, wedge angles and tip radii. In addition, the mechanical responses are presented at a specified depth of indentation.

Methods

The finite element analysis of the present work was performed using a commercial finite element software package, ABAQUS 6.11 [11] with a built-in strain energy function (SEF) model for a hyperelastic material. The SBR-0 (Unfilled Styrene Butadiene Rubber) with the Mooney-Rivlin strain energy function is used and the material is assumed as an incompressible material. The SEF data were adopted from Liang's experiment [12] obtained from a uniaxial tensile test up to approximate 5.5 MPa stress and 300% strain in elastic condition.

Figure 1(a) shows a schematic illustration of a straight rigid blade indenting a rubber surface. The symbol F represents indenter load, δ represents the depth of indentation and θ represents wedge angle of the blade indenter. Boundary conditions of the indentation system are depicted schematically in this figure as well. The rubber specimen of 10 mm high, 20 mm wide and 10 mm thick was modeled in plane strain. For analysis, the chosen blade wedge angles θ are 30, 45 and 60 degrees for a sharp blade (tip radius is 0 mm) which are often used in abrasion testing [3-6], and the chosen tip radii are 0.3, 0.4, 0.5 mm for a 45 degrees wedge angle. The finite element mesh of the indentation is presented in Figure 1(b). A finer mesh is applied at the middle part of the material for obtaining more accurate results for deformation and stress around the indenter.



(a)

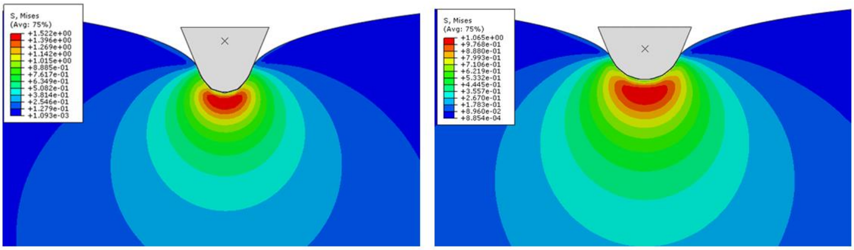
(b)

Figure 1: (a) Schematic illustration of the indentation model; a rigid blade indenting a rubber surface and (b) the generated FEA mesh for the indentation model.

The mechanical responses are presented in the form of indentation load and maximum stress of the rubber at a specified blade displacement or depth of indentation (at δ = 1 mm and 2 mm, see figure 1a) for various blade characteristics.

Result and Discussion

Figure 2 demonstrates an FEA output of the von Mises stress field and the deformation contour surface of SBR-0 by blade indentation. The FEA output with the 45 degrees wedge angle of 0.3 and 0.5 mm tip radius are depicted in these figures respectively. These figures show that the highest contact stress and surface deformation are located at the indenter's blade tip.



(a) (b)

Figure 2: An example of FEA output; stress distribution by blade indentation at $\delta = 1$ mm (a) 45 degrees wedge angle and 0.3 mm tip radius, (b) 45 degrees wedge angle and 0.5 mm tip radius.

In general, the stress field, indenter load and blade displacement can be obtained from a FEA output. In order to predict the rubber stiffness by blade indentation, it requires a relationship between indenter load and depth of the indentation. At a specified depth of the indentation, the higher wedge angle and tip radius of the blade indenter require a higher indenter load as shown in Fig 3 and 4. These figures reflect that the indenter's load approximately increase quadratic with respect to the depth of indentation. These trend lines were also obtained numerically as well as experimentally for polyurethane rubber indentation [2].

For the 45 degree sharp indenter in Fig 3, the trend line can be approximated as second order equation that can be stated as $F = 0.3086\delta^2 + 0.587\delta - 0.0283$, where F is the indenter load in N and δ is the depth of indentation in mm. The correlation coefficient of this approximation is good (close to unity), therefore, this equation can be validly applied. The stiffness of the rubber $k = dF/d\delta$ is a linear increase with respect to the depth of indentation for the 45 degree sharp indenter this is $k = 0.617\delta + 0.587$ [N/mm].

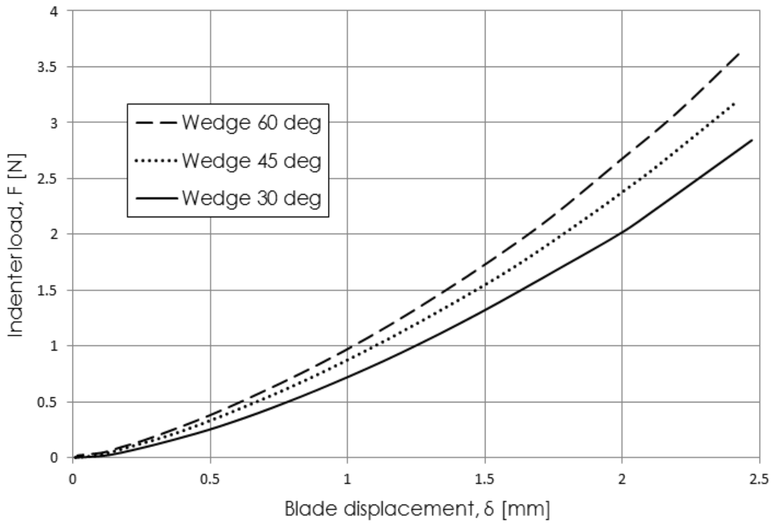


Figure 3: Applied indenter load as a function of blade indentation at various wedge angles of blade indenter at 0 mm tip radius.

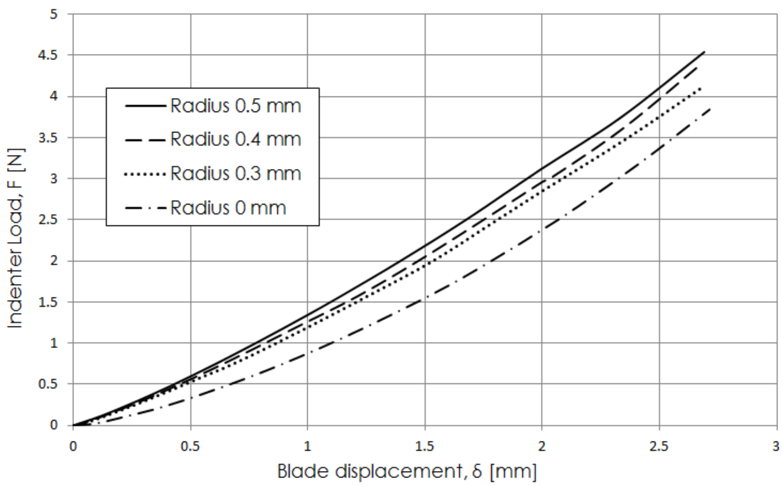


Figure 4: Applied indenter load as a function of blade indentation at various tip radii for 45 degree wedge angle blade indenter.

Based on a specified depth of indentation δ, the relationship between the indenter load and maximum stress as a function of the wedge angle and tip radius are presented in Figure 5 and 6 respectively. These figures show that the indenter load increases with increasing the wedge angle and tip radius of the blade. The maximum stress reduces due to an increase of the wedge angle and tip radius. An approximately linear relationship between the mechanical response and these blade characteristics is found (figures are on linear scale).

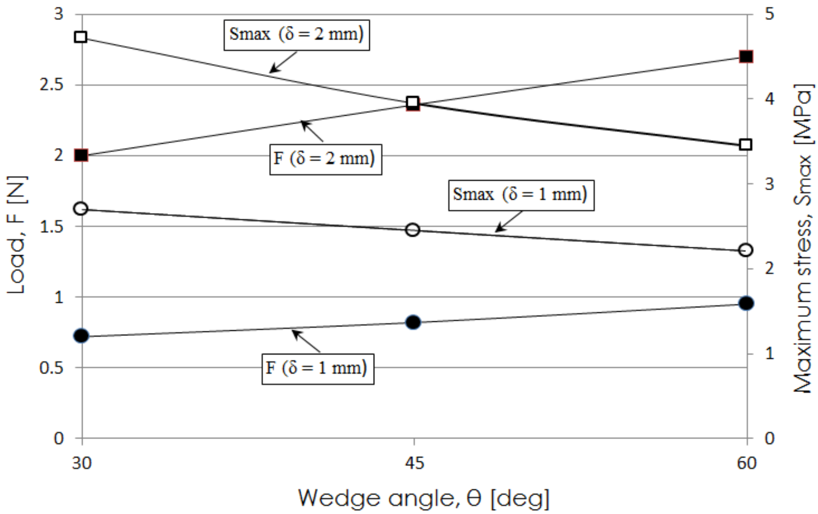


Figure 5: Indenter load F and maximum stress Smax for various wedge angles for a tip radius of 0 mm.

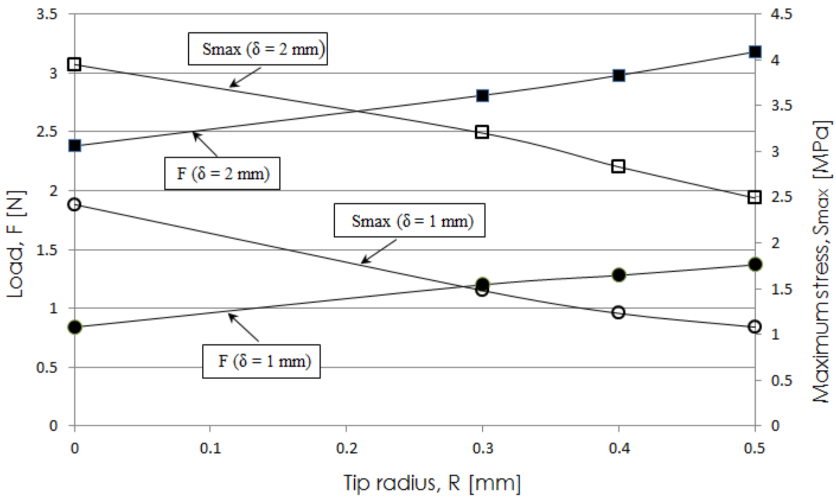


Figure 6: Indentation load F and maximum stress Smax for various tip radii for a wedge angle of 45 degrees

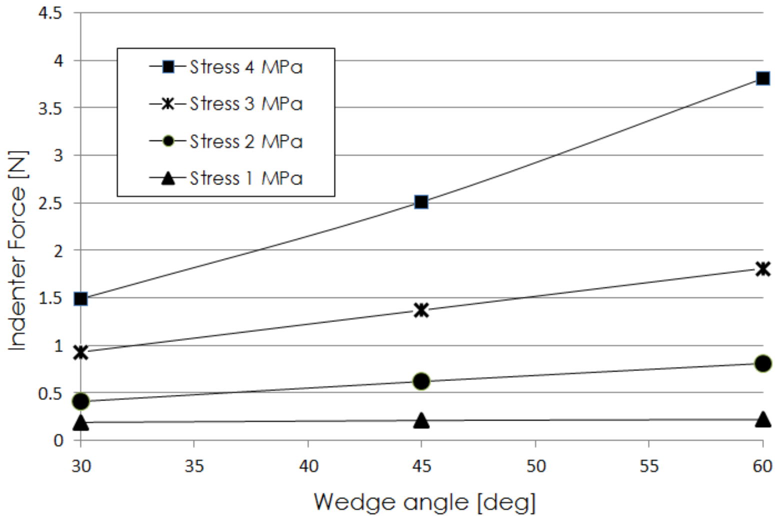


Figure 7: Indenter load at specified maximum stress for various wedge angles of sharp blade indenter (tip radius 0 mm).

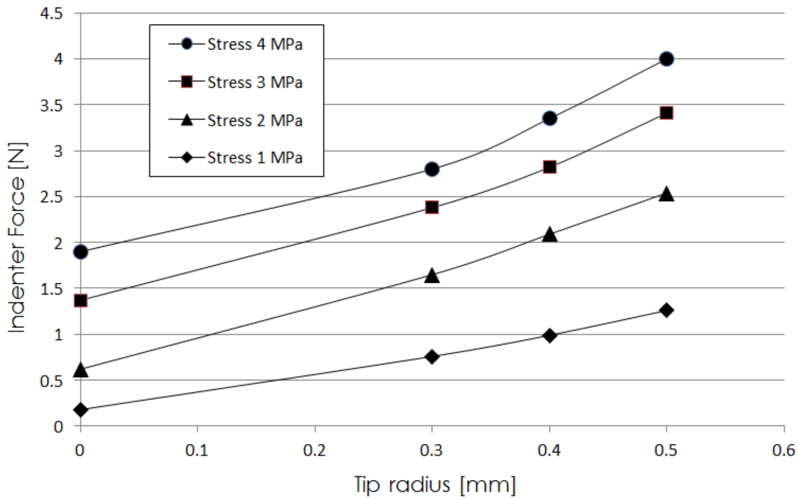


Figure 8: Indenter load at specified maximum stress for various tip radii with a wedge angle of 45 degrees blade indenter.

In addition to this, these results can also be presented at a specified maximum stress as shown in Figure 7 and 8 respectively. These figures show the relationship of the indenter load for various blade characteristics, the indenter load increases with respect to the wedge angle and tip radius. A linear relationship between indenter load and blade characteristics is found.

It should be noted that the maximum stress resulted from this analysis occurs at elastic level. The SEF input data for FE simulation is generated at elastic level, so it is not reliable to describe beyond the elastic level as for, for instance, cut formation. Cut formation on polyurethane rubber by blade indentation with various blade characteristics was experimentally conducted [2]. Results showed that a linear relationship between indenter load and blade characteristics was also found. Although by using different blade characteristic data, qualitatively, the results of this study as described in Figure 7 and Figure 8 give the same linear trend as found for polyurethane indentation at cut formation. Thus, based on the above results, it reflects that the cut formation of rubber-like materials by blade indentation can be estimated by using the method presented in this study.

Conclusion

This study investigates the mechanical response of straight blade indentation on Unfilled Styrene Butadiene Rubber by FE analysis. The analysis is carried out to investigate the rubber stiffness, maximum stress and indenter load as a function of blade characteristics, i.e. wedge angle and tip radius. It is shown that the rubber stiffness increase linearly with respect to the wedge angle and tip radius. At a specified depth of indentation, the indenter load increases and the maximum stress reduces when increasing the wedge angle and tip radius. A linear trend between indentation load and maximum stress as well as wedge angle and tip radius is found. Therefore, a linear trend between indenter load and blade characteristic is also found at a specified maximum stress.

A linear trend was also found between indenter load and blade characteristics at cut formation (or ultimate stress) on polyurethane rubber that was conducted by other researchers. Further, these results reflect that the method presented of this study can be implemented in analyzing the cut formation of rubber-like materials by blade indentation.

Acknowledgements

This article was originally accepted for and presented at MITC2015.

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