Numerical Investigation of the Sliding Contact of Tire Rubber Material Due to a Blade Sliding Indentation

B. Setiyana, J. Jamari, R. Ismail, S. Sugiyanto, and E. Saputra

Abstract The manufacturing technology of tire rubber material to improve its performance is still developing. Mechanical and tribological properties are considered in the rubber manufacturing. One of the important tribological properties is the braking capacity of the tire which is strongly associated with sliding contact. However, theoretical as well as experimental methods are still difficult to be applied to analyse these properties due to the unique behaviour of rubber material. This study proposes a numerical investigation of the sliding contact of rubber material due to a rigid blade sliding indentation using Finite Element Analysis (FEA). In this FE simulation, the rubber material is modelled as a hyper-elastic material with Money-Rivlin type for Strain Energy Function (SEF). There are three types of rubber material analysed, the first and second type are commonly used in vehicle tires i.e. vulcanized rubber 1 (R1) and vulcanized rubber 2 (R2), while the third type is a new product in the form of Solution Styrene Butadiene Rubber (S-SBR). Sliding indentation is carried out at a specified sliding speed with several depths and contact surface roughness. The simulation results shown are in the form of the rubber surface deformation, friction forces, and stress distribution. In general, the simulation results show that the S-SBR has a slightly higher coefficient of friction (COF) than the other types.

Keywords Blade · Rubber · Sliding · Tire

1 Introduction

The manufacturing technology of tire rubber material to improve its performance is still developing today. Parameters that need to be considered in improving rubber performance include mechanical and tribological properties [1, 2]. The use of rubber

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for vehicle tires really requires good performance, including when the tires experience braking along driving. In general, good tires are those that have a high braking capacity. Braking capacity is closely related to friction contact between the tire and the road surface which is often expressed by the friction force and the coefficient of friction. A large coefficient of friction provides a large braking capacity too.

Experimentally, research on friction contacts in tire rubber has been widely carried out by some researchers. Many valuable results were obtained from the research, both on the prototype scale and laboratory scale [2–5]. The parameters produced are generally in the form of friction force, friction coefficient and abrasion wear. In general, the total coefficient of friction (COF) consist of adhesion and deformation that is obtained by dividing horizontal force induced by vertical force. The adhesion COF depends on the contact surface roughness, meanwhile, the deformation COF depends on the elastic force on deformed rubber surface [6]. However, the phenomenon of friction contact is very difficult to be discussed theoretically because of the unique rubber behaviour that are hyper-elastic and nonlinear stress-strain relationship, therefore numerical approaches are often used [7].

Sliding phenomena on the rubber surface using multi asperities as a counterface are still difficult to be analyzed theoretically. Thus, the analytic or numeric expression is usually started by using a single asperity. Experimentally, by using on a point contact with a sharp cone as a single indenter, abrasion on the rubber surface yields to a wear pattern, however, loss volume of the rubber material caused by abrasion does not practically occur [2]. Therefore, some researchers proposed a line-contact by using a blade indenter as counterface, thus, this method is much studied experimentally and analytically [8].

This paper investigates the phenomenon of friction contact between rubber specimen and a rigid blade indenter to obtain the frictional force, the coefficient of friction, deformation and the stresses that occur during friction. The investigation is carried out numerically based on the Finite Element Method (FEA). Simulations are carried out on the two types of rubber that are commonly used for tires i.e. vulcanized rubber type 1 (R1) and type 2 (R2), and a new product in the form of Solution SBR (Styrene Butadiene Rubber). The Solution SBR was reinforced with 80 phr (parts per hundred rubber) of highly dispersible silica. The FEA output is presented in the form of stress distribution, deformation contour and friction forces that occur during sliding. The final results obtained are the maximum stress and overall coefficient of friction that occur during sliding contact for each rubber type.

2 Method

This work is carried out numerically using a legal version of commercial finite element software package, ABAQUS 6.11 [9]. Rubber material is modeled as hyperelastic and considered in compressible. An experimental test for rubber material is required for obtaining Strain Energy Function (SEF) for FE simulation input data. The SEF data were constructed on Money-Rivlin version. It was obtained from stress-strain diagrams based on the results of tensile tests under elastic conditions. Therefore, the maximum stress generated in this study is presented in an elastic level so that crack initiation has not occurred yet.

Schematic illustration of a rigid blade that sliding on the rubber surface is depicted in Fig. 1a. Rigid blade indenter with 0.5 mm of tip radius slides on the rubber surface (elastomer). The boundary condition of the schematic drawing indenting system is depicted in this picture as well. Rubber specimens as high of 10 mm, width 20 mm, and thickness of 10 mm are modeled in the plane strain model. FE simulations are carried out in a constant sliding speed of 5 mm/s, maximum horizontal displacement of 4.0 mm with several data inputs namely rubber type, indentation depth and surface roughness. Rubber type is vulcanized rubber 1, vulcanized rubber 2 and solution SBR meanwhile the indentation depth selected is 0.5, 1.0 and 2.0 mm. Surface roughness is represented by the adhesion coefficient of friction (adhesion COF) and the given value is 0.0 and 0.5.

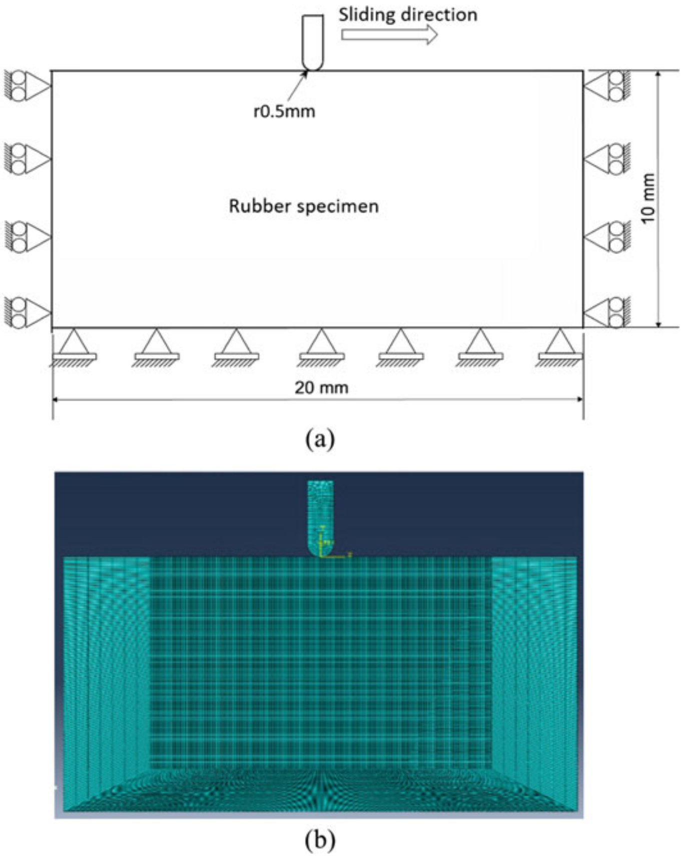

Fig. 1 Initial model of the rubber sliding. **a** Schematic model. **b** Generated mesh of FE

The FEA simulation is evaluated in three steps of indenter movement, namely starting in a stationary position (initial state), then continued in a moving state (sliding state) and finally in a stopped state (final state). The FEA output is presented in the form of stress field, contour deformation and the friction forces that occur during sliding. From this result, the maximum stress and coefficient of friction can be observed and identified. Finally, the maximum stress generated and friction coefficient can be described graphically with respect to various input data.

3 Results and Discussions

Regarding to the mechanical properties of rubber material, the tensile test results are given at Table 1 in the form of tensile strength and extension ratio when the test specimen is broken. The tensile test procedure was carried out based on ISO 37 Standard (1993 and 2015). The rubber analyzed is vulcanized rubber type 1 (R1), vulcanized rubber type 2 (R2) and Solution SBR (S-SBR). From the Table, it can be seen that the tensile strength of each material has difference value that may not very large. This is different to the extension ratio for the solution SBR that it has a very large value, therefore it has a more hyper-elastic behaviour.

Related to the mechanical and tribological properties of the rubber material along sliding contact, i.e. stress, deformation, friction force and coefficient of friction (COF), the simulation results based on the Finite Element Analysis (FEA) are given below.

3.1 Stress Distribution

Figure 2 shows the FEA output from the von Mises stress distribution and the contour of deformation surface of vulcanized R1 by the blade sliding. The FEA output with a sliding depth of 0.5 mm and adhesion COF of 0.5 is illustrated in these figures at the initial state (a), the sliding state (b) and the final state (c) respectively. In general, the highest contact stress regime is below the tip of the indenter. In the initial condition, the stress distribution is symmetrical because it is still in static condition. In addition, in the sliding state, there are two locations of high stress in the direction as well as in the opposite direction of the sliding. Meanwhile, in the final condition, the location

Table 1 Results of the tensile test for various rubber material

No.	Testing parameter	Test specimen		
		Vulcanized R1	Vulcanized R2	Solution SBR
1	Tensile strength (MPa)	15.90	18.10	19.69
2	Extension ratio at break	4.80	5.08	14.15

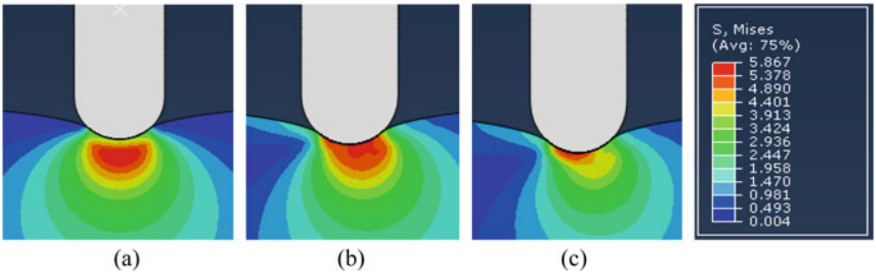

Fig. 2 The stress distribution of the rubber on the indentation depth of 0.5 mm and adhesion COF of 0.5 for vulcanizated R1. **a** Initial state. **b** Sliding state. **c** Final state

of the high stress close to the tip of the indenter that is shown in the opposite direction of the sliding. In the sliding and final state, the maximum stress is located at the back of the moving of the indenter tip.

Figure 3 shows a picture of the stress field for variations in rubber material under sliding state conditions. From the picture it can be seen that the largest stress occurs in vulcanized R1 that is equal to 5.613 Mpa and the lowest stress is in Solution SBR that is equal to 3.943 Mpa. The stress field indicates that the concentration of the high stress leads to the direction of the indenter movement.

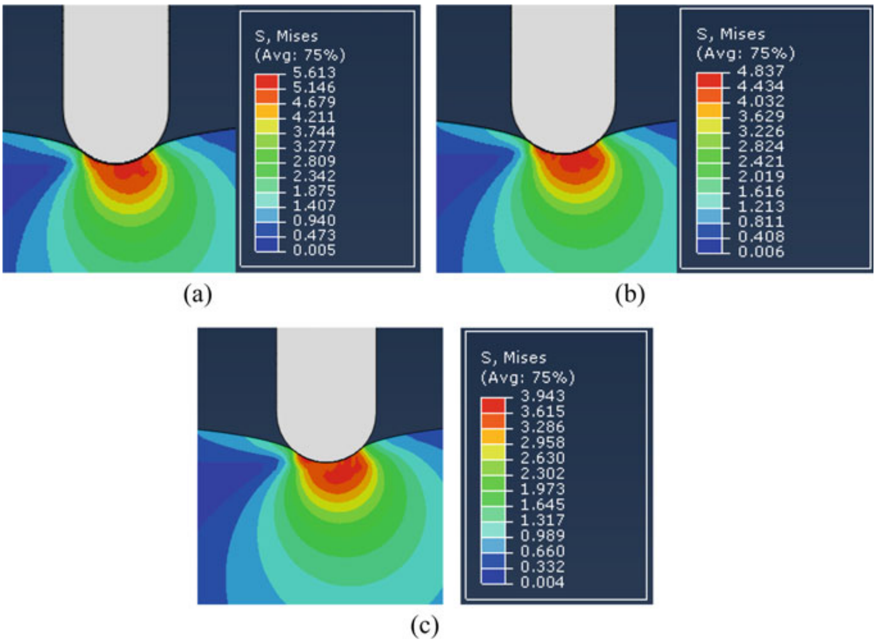

Fig. 3 The stress distribution of the rubber on the indentation depth of 0.5 mm and adhesion COF of 0.5 in the sliding state. **a** Vulcanizated R1. **b** Vulcanizated R2. **c** Solution SBR

The maximum stress data for various rubber material is given in Fig. 4. The maximum stress is presented as a function of horizontal displacement. It appears that the maximum stresses are fluctuating with respect to the horizontal displacement of the blade indenter. The fluctuation occurs because of self excited vibration along sliding contact. Force induced along sliding contact on the elastic material surface causes the self excited oscillation. In general, the largest maximum stress occurs in vulcanized R1 and the smallest maximum stress occurs in solution SBR.

Figure 5 shows the maximum stress based on the variation in indentation depth. Indentation with a depth of 2.0 mm gives a maximum stress value that is much higher than for depths of 0.5 and 1.0 mm. When the indentation depth is 2.0 mm, it appears that the stress occurs very fluctuative compared to lower depths. In general, this

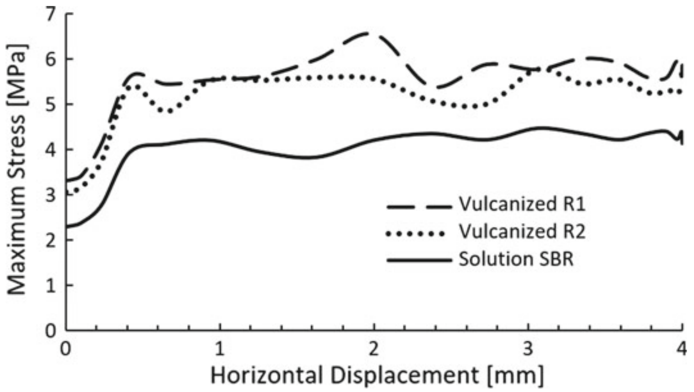

Fig. 4 The maximum stress of the rubber on the sliding depth of 0.5 mm and adhesion COF of 0.5 for various rubber material

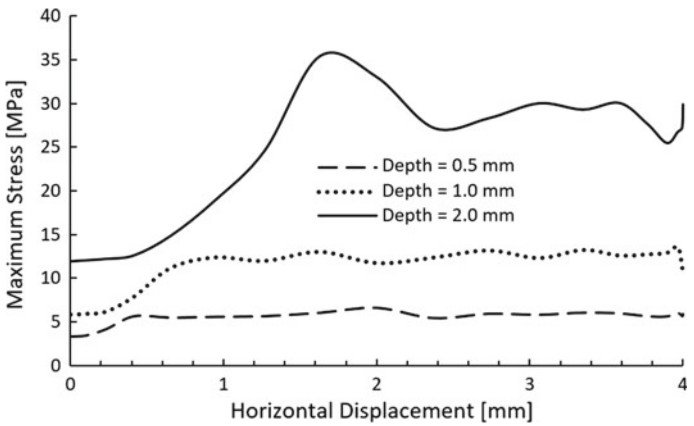

Fig. 5 The maximum stress of the rubber sliding for vulcanized R1 with the adhesion COF of 0.5 for various depth of sliding

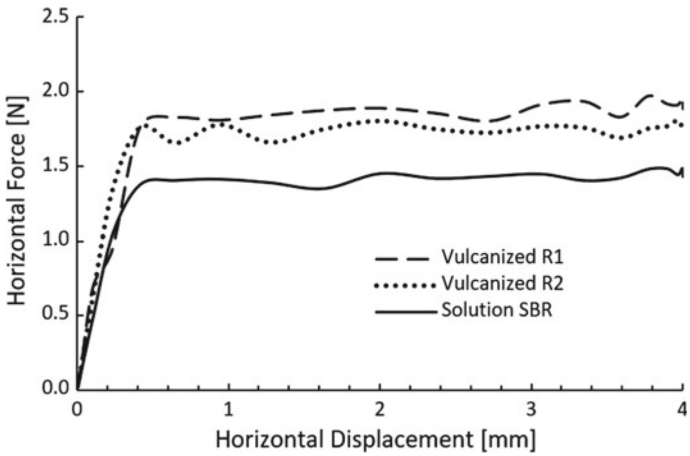

Fig. 6 The horizontal force of the rubber sliding on the indentation depth of 0.5 mm and adhesion COF of 0.5 for various rubber material

fluctuation phenomenon is related to the frictional contact nature of rubber, which is the occurrence of stick-slip [10, 11]. At first, the stick contact occurs between the rubber and the indenter until it reaches a high stress value, and then a contact slip occurs which causes the stress to drop. A peak stress of 35 MPa for a depth of 2.0 mm occurs when the indenter displaces around 1.3 mm from the initial position.

3.2 Coefficient of Friction (COF)

Figure 6 shows the horizontal force of the indenter during sliding on the rubber surface for variations in rubber material. It can be seen that vulcanized R1 has the largest horizontal force, meanwhile the solution SBR material has the smallest force. Figure 7 depicts the overall COF for the three types of material analyzed. In general, the overall COF values for the three materials have values that are not so different. The overall COF value for the S-SBR has the highest value around 0.60, while the vulcanized R1 material has the lowest value around 0.55. In general, it shows that the S-SBR material has a slightly higher overall COF than other rubber types with small horizontal or tangential force.

Overall COF with depth of indentation variations are given in Fig. 8. Overall COF for 0.5 mm depth have lower values than for 1.0 mm depth. But for indentation depth of 2.0 mm, COF values fluctuate, which is most likely due to the oscillation phenomenon of the rubber surface when under sliding contact. This phenomenon is often referred to as stick-slip occurrence which is common emerged in rubber sliding. The stick contact phenomenon occurs at the beginning of the sliding, where the tip of the indenter and the rubber surface are fused to move horizontally together before finally releasing the contact into a slip contact [11]. The figure shows that

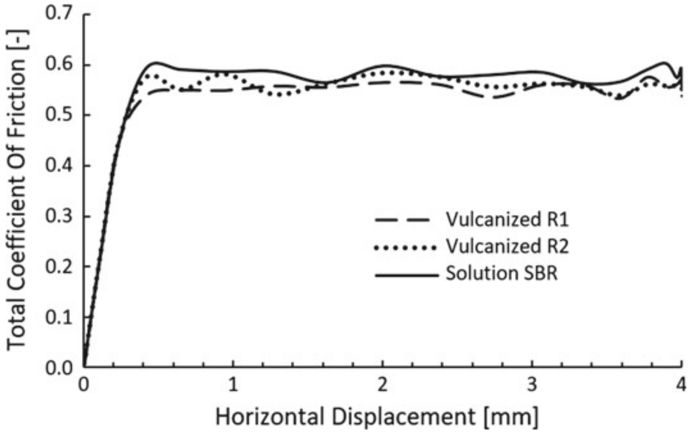

Fig. 7 The total Coefficient of Friction (COF) on the indentation depth of 0.5 mm and adhesion COF of 0.5 for various rubber material

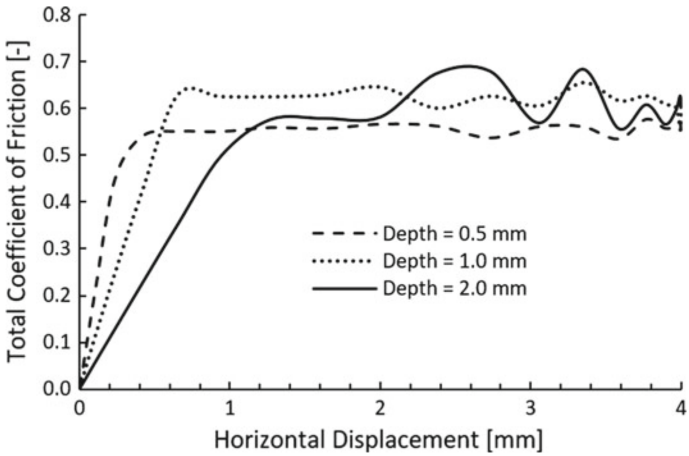

Fig. 8 The overall coefficient of friction of the vulcanizated R1 with the adhesion COF of 0.5 for various of depth of indentation

the larger depth of indentation also causes the larger sliding distance of the initial stick contact. This occurs because when a large indentation depth provides a large normal force and consequently require a large tangential force as well. This makes the sliding displacement during the initial stick contact becomes larger.

The overall COF values based on variations in surface roughness are given in Fig. 9. Smooth surface is expressed with adhesion COF of 0 and rough surfaces is expressed with adhesion COF of 0.5. For smooth surfaces, the overall value of COF is very small and does not fluctuate so much. Here the overall COF value is only influenced by the deformation COF. For rough surface, the overall COF highly

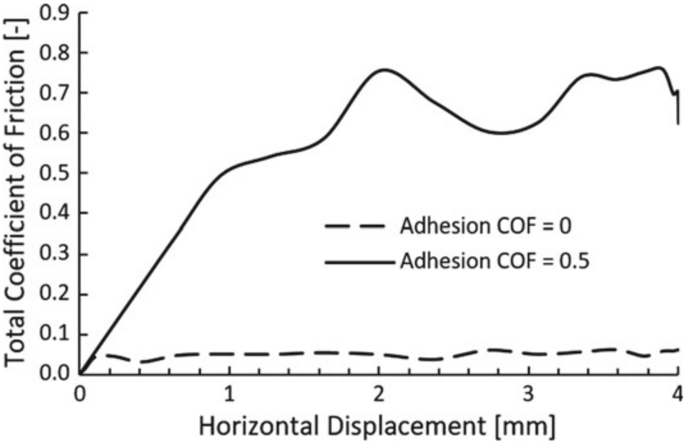

Fig. 9 The total coefficient of friction of the vulcanizated rubber type 2 with the depth of indentation 2.0 mm for various of adhesion COF

fluctuates which is started with stick contact. It is indicated by the overall value of the COF which increases linearly with respect to a sliding displacement of up to 1.0 mm. The rough surface provides a fluctuating value for the overall COF and the stick-slip phenomenon appears here, as is common emerged on the sliding contacts in rubber [11].

Based on the analysis results above, there are some results to note, namely that the solution SBR has more hyper-elastic behaviour than vulcanized material R1 as well as R2, but the value of the tensile strength is not so much different. Stress simulations show that for the same sliding indentation conditions, vulcanized R1 materials have the largest stress, while solution SBR have the lowest stresses. Likewise, the tangential force that occurs during sliding indentation, that the frictional force of vulcanized material R1 has the high friction force and SBR material solution has a low value. Stress simulations show that the deeper sliding indentation causes the larger stresses, however the stresses that occur during deep indentation have fluctuating values.

Regarding the overall coefficient of friction, the type of material does not have a significant difference in value. The coefficient of friction is closely related to the braking capacity of the tire, where a large coefficient of friction provides a large braking capacity as well. However, for SBR solution materials, despite having a slightly larger coefficient of friction than other materials, this material is very hyper-elastic so it has a very large deformation. This needs to be considered if this material will be applied as a vehicle tire.

Large overall coefficient of friction does not change much to the depth of indentation, but for deeper indentation, the overall coefficient of friction is fluctuating, as is the phenomenon of stick-slip which is common emerged in the rubber sliding. In addition, a large depth of indentation will provide a strong stick contact which is indicated by the large sliding distance during the stick contact. The stick condition at the beginning of the sliding indentation is indicated by the increased indenter friction force linearly during sliding. The larger depth of indentation is, the larger stick's sliding distance. After the stick phase has passed, the stick-slip phenomenon will occur continuously.

The contact surface roughness effect between the indenter tip and the rubber surface is very influential on the contact phenomenon. A smooth surface with adhesion COF equals to zero provides a very small value of the overall COF and it is only affected by the deformation of the rubber surface. On the other hand, a rough surface with adhesion COF equal to 0.5 provides a large overall COF with fluctuating values and the stick-slip phenomenon occurs here.

4 Conclusion

This paper investigates the phenomenon of friction contact between rubber specimen and a rigid blade indenter to obtain the frictional force, the coefficient of friction, deformation and the stresses that occur during friction. Simulations are carried out on the two types of rubber that are commonly used for tires i.e. vulcanized rubber type 1 (R1) and type 2 (R2), and a new product in the form of Solution SBR (Styrene Butadiene Rubber) that was reinforced with 80 phr (parts per hundred rubber) of highly dispersible silica. Sliding contact is carried out with specified indenter tip radius and sliding speed with variations in indentation depth and surface roughness.

Stress simulations show that the deeper sliding indentation causes the larger stresses, but the stresses that occur during deep indentation have fluctuating values. Regarding the overall coefficient of friction, in general the three types of material do not have significant differences in value. The value of the coefficient of friction is closely related to the braking capacity of the tire, where the larger coefficient of friction causes the larger braking capacity as well. However, for solution SBR material, even though it has a slightly larger coefficient of friction than other materials, this material is very hyper-elastic so it has a very large deformation. Such behaviour should be considered if this material will be applied as vehicle tires. It has been noted that stick-slip occurrence along rubber sliding is commonly emerged, especially for large depth of indentation and in a rough contact surface.

References

1. Gent AN (1992) Engineering with rubber, how to design rubber components, 3rd edn. Hanser Publication, Cincinati
2. Zhang SW (2004) Tribology of elastomer, tribology and interface engineering series. Elsevier, Amsterdam
3. Fukahori Y, Yamazaki H (1994) Mechanism of rubber abrasion—part 1: abrasion pattern formation in natural rubber vulcanizate. Wear 171:195–202
4. Khafidh M, Setiyana B, Jamari J, Masen M, Schipper DJ (2018) Understanding the occurrence of wavy track of elastomeric material. Wear 412–413:23–29

5. Setiyana B, Ismail R, Jamari J, Schipper DJ (2018) Analytical study of the wear pattern of an abraded rubber surface: interaction model. Tribol Mater Surf Interfaces, 1–7
6. Bowden FP, Tabor D (1954) The friction and lubrication of solids, vol I. Clarendon Press, Oxford
7. MSC Software Whitepaper (2010) Nonlinear finite element analysis of elastomer. MSC Software Corporation, Santa Ana
8. Uchiyama Y, Ishino Y (1992) Pattern abrasion mechanism of rubber. Wear 158:141–155
9. ABAQUS 6.11.: Standard user's manual. Dassault Systems Simulia Corp., USA (2011)
10. Fukahori Y, Yamazaki H (1994) Mechanism of rubber abrasion—part 2: General rule in abrasion pattern formation in rubber-like materials. Wear 178:109–116
11. Setiyana B, Ismail R, Jamari J, Schipper DJ (2016) Stick-slip behavior of a viscoelastic flat sliding along a rigid indenter. Tribol Online 11(3):512–518