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Hyperelastic Material Modelling of Silicone Rubber

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Abstract: ***This research paper presents a comprehensive study on hyperelastic material modelling of silicone rubber. The aim is to evaluate the forces involved in the contact area between silicone extrusions and glass, reducing adhesion. The study investigates the mechanical behavior of silicone rubber through hyperelasticity, utilizing specific material models (e. g. Neo - Hookean, Mooney - Rivlin) for accurate characterization. Experimental data from mechanical tests on silicone rubber samples are collected to calibrate the hyperelastic model and determine its parameters. The proposed model is then validated against independent experimental data to ensure its accuracy in predicting silicone rubber behavior under various loading conditions. This research aims to improve the design of silicone rubber liners for enhanced safety in various applications. The results have potential implications for the design and manufacture of components where silicone rubber is used***

Keywords: Hyperelasticity, Silicone rubber, Material modeling, Force, Surface, Contact area.

1. Introduction

Hyperelastic materials are widely used in engineering applications due to their unique mechanical properties, which include significant deformation and high elastic energy storage capacity. Among these materials, silicone rubber has exceptional flexibility, toughness, and biocompatibility, making it suitable for various applications. One particular application benefiting from silicone rubber's properties is in designing products that require increased contact area between components. Silicone extrusions are utilized to achieve this goal, ensuring secure connections and user safety during interactions. The correct force for manipulating these components is crucial for user - friendliness and product reliability. Despite its widespread use, accurately modeling silicone rubber's complex non - linear behavior remains a challenge. Developing a comprehensive material model is essential for optimizing goods in areas such as manufacturing. The research aims to address this challenge by creating a material model for hyperelastic silicone rubber that accurately predicts its mechanical behavior across different deformations and loading rates. Extensive experimental tests will characterize the material's response under various loading conditions.

By analyzing the experimental data, researchers can identify trends, patterns, and dependencies between material behavior and factors like loading rate, temperature, and aging. Existing material models for hyperelastic materials will be reviewed and evaluated for their applicability to silicone rubber. Based on this evaluation, a mathematical representation, such as a strain energy density function, will be formulated to describe the observed mechanical behavior of silicone rubber accurately. To validate the developed material model, predictions will be compared with experimental data not used in the model development phase. Iterative fine - tuning and refinement will ensure the model's accuracy and reliability.

The study will also investigate how temperature, loading rate, and aging affect silicone rubber's hyperelastic response, providing a more comprehensive understanding of the material's behavior under real operating conditions. The proposed material model is expected to significantly impact the field of hyperelastic material modeling, particularly concerning silicone rubber. By accurately predicting and optimizing silicone rubber - based products, this research aims to enable more efficient design processes, reduce development costs, and deliver reliable products.

Ultimately, closing the gap between experimental results and computer simulations through a reliable material model will support progress in various industries that rely on the exceptional properties of hyperelastic silicone rubber.

2. Materials and methods

Material description:
The material investigated in this study is silicone rubber, a type of elastomer known for its exceptional mechanical properties, including high elasticity, flexibility, and tear resistance. Silicone rubber is used in various industrial applications due to its versatility and favorable properties, making it a suitable material for many engineering purposes.

Hyperelastic material modelling:
Hyperelastic material modelling is used to accurately simulate the mechanical behavior of silicone rubber under large deformation conditions. Several hyperelastic models for silicone rubber have been developed, including the Mooney - Rivlin model, the Ogden model, and the Arruda - Boyce model.

The Mooney - Rivlin model is a two - parameter model that describes the strain energy density as a function of the principal invariants of the deformation tensor. The Ogden model, on the other hand, is a multi - parameter model that takes into account the influence of the principal strains in the deformation tensor on the strain energy density. The Arruda - Boyce model, characterized by three parameters, relates strain energy density to deviatoric strain and volumetric strain.

Experimental data collection:
In order to determine the material properties required for the calibration of the hyperelastic model, experimental data must be collected. To characterize the hyperelastic behavior of silicone rubber, uniaxial tensile and compression tests are performed. These tests help capture the non - linear stress -

strain response of the material and provide valuable data points for model calibration.

Calibration of the hyperelastic model:
The experimental data collected is used to calibrate the hyperelastic model to accurately capture the observed material behavior. Curve fitting techniques, such as the least squares method, are used to fit the hyperelastic model to the experimental stress - strain curves. By adjusting the parameters of the model, an accurate representation of the mechanical response of the material is achieved.

Prediction of mechanical behavior:
Once the hyperelastic model is calibrated, it can be used to predict how silicone rubber would behave under different loading conditions, such as compression, tension, and shear. This predictive capability is critical for the design and optimization of rubber parts used in industries such as automotive, aerospace, and medical.

3. Material Characterization

Silicone is a versatile hyperelastic material widely used across various industries for its distinctive mechanical characteristics and adaptability. It is a synthetic elastomer composed of siloxane linkages, chains of silicon and oxygen atoms. The molecular structure of silicone grants it unique flexibility, durability, and resilience to extreme temperatures, making it ideal for a wide range of applications. One of silicone's crucial properties is its hyperelastic behavior, allowing it to undergo significant deformations and still return to its original shape once the stress is released. The stress - strain response of silicone is nonlinear, meaning that the relationship between stress and deformation is not linear over its deformation range.

To characterize its hyperelastic characteristics, strain energy density functions are commonly used, which utilize the material's internal energy during deformation. The Neo - Hookean, Mooney - Rivlin, and Ogden models are frequently employed to represent the relationship between strain energy density and deformation accurately. Silicone's hyperelasticity enables it to be repeatedly stretched and compressed without permanently deforming or losing its mechanical properties. This makes it an excellent choice for applications that require elasticity and durability, such as soft robots, flexible tubing, medical implants, and sealing gaskets. Additionally, its ability to withstand extreme heat and low cryogenic temperatures further enhances its suitability for diverse environments. The chemical resistance of silicone against various substances like acids, bases, solvents, and oils is also remarkable. Furthermore, its biocompatibility allows for medical and healthcare applications, including implants, prosthesis, and medical tubing.

In summary, silicone is a highly valuable material in numerous sectors due to its hyperelasticity, thermal tolerance, chemical resistance, and biocompatibility. Its capacity to endure significant deformations while maintaining mechanical integrity makes it the perfect option for applications requiring elasticity, durability, and reliable performance.

Mechanical Properties of silicone Rubber:
Silicone rubber possesses several important mechanical properties that contribute to its widespread use in various applications. Some key mechanical properties of silicone rubber include:

- Elasticity: Silicone rubber exhibits high elasticity, allowing it to undergo significant deformations and return to its original shape when the applied load is removed. This property makes it suitable for applications requiring flexibility and resilience.
- Low compression set: Silicone rubber has a low tendency to undergo permanent deformation or compression set even after prolonged periods of compression. This property ensures the material maintains its shape and sealing capabilities over time.
- Tensile strength: Silicone rubber possesses good tensile strength, enabling it to resist applied forces and prevent rupture or breakage. The specific tensile strength varies depending on the formulation and curing conditions of the silicone rubber.
- Tear resistance: Silicone rubber is known for its high tear resistance, which makes it highly durable and resistant to damage caused by tearing or shearing forces.
- Low hysteresis: Silicone rubber exhibits low energy loss during cyclic loading and unloading, resulting in low hysteresis. This property makes silicone rubber suitable for applications requiring efficient energy transfer, such as in vibration isolation systems.
- To characterize these mechanical properties, various experimental methods are employed. Some common experimental methods used to evaluate the mechanical properties of silicone rubber include:
- Tensile testing: Tensile testing involves subjecting silicone rubber samples to tension until failure. This test provides information about the material's tensile strength, elongation at break, and stress - strain behavior.
- Compression testing: Compression testing involves applying compressive forces to silicone rubber samples to measure their compressive strength, resilience, and deformation behavior under compression.
- Tear resistance testing: Tear resistance testing assesses the material's resistance to tearing forces by applying a controlled force to initiate and propagate a tear in the silicone rubber sample. The test provides information on tear strength and toughness.
- Shore hardness testing: Shore hardness testing measures the material's resistance to indentation. It is commonly used to assess the hardness of silicone rubber, which relates to its stiffness and deformation resistance.
- Dynamic mechanical analysis (DMA): DMA involves subjecting silicone rubber samples to controlled cyclic loading and measuring their response in terms of stiffness, damping properties, and viscoelastic behavior over a range of frequencies and temperatures.
- Fatigue testing: Fatigue testing involves subjecting silicone rubber samples to repeated cyclic loading to evaluate their resistance to fatigue failure and durability under repetitive stress.

These experimental methods, along with others specific to certain properties or applications, provide valuable data on the mechanical behavior of silicone rubber and assist in the development and optimization of silicone rubber - based products and designs.

Data analysis and interpretation

Data analysis and interpretation of the experimental results play a crucial role in understanding the mechanical behavior of silicone rubber. With over 85, 000 data points of stress and strain obtained from uniaxial testing using uni Excel, the following short note provides an overview of the data analysis and interpretation process:

The data analysis and interpretation of the experimental results involve several steps. Initially, the stress and strain data points are organized and preprocessed to ensure data integrity and consistency. This includes removing any outliers, checking for data completeness, and ensuring proper alignment of stress and strain values. After that, statistical analysis methods may be used to learn more about the general behavior of the silicone rubber substance. The distributions of stress and strain are summarized by descriptive statistics like mean, standard deviation, and range. To visualize the distribution of stress and strain levels and spot any patterns or trends, utilize histograms or frequency distributions. Plotting stress - strain curves based on the experimental data is a further analytical step. These curves show the connection between stress and strain and give important details about the elastic and plastic deformation behavior of the material. The material's mechanical characteristics may be measured by extrapolating important factors from the stress - strain curves, such as yield stress, ultimate stress, and strain hardening. Other derived values, such as elastic modulus, Poisson's ratio, and toughness, can be estimated from the experimental data in addition to the stress - strain curves to offer a thorough evaluation of the silicone rubber material. A key step in interpreting experimental results is contrasting the results with silicone rubber research that has already been published or current theoretical models. This supports the reliability and consistency of the experimental results. Any differences or conflicts between experimental findings and theoretical predictions might provide light on the limits of the models as well as suggest topics for further study.

Additionally, any elements like temperature, humidity, or strain rate that may have affected the behavior of the material should be considered when interpreting the experimental data. These elements can be assessed by further investigation or by contrasting the findings with those of earlier research carried out in comparable circumstances.

The overall goal of the experimental findings' data analysis and interpretation procedure is to identify the fundamental mechanical characteristics and behaviors of the silicone rubber material. Understanding the performance of hyperelastic materials in particular applications and constructing correct hyperelastic material models, both need this information.

4. Results and Discussion

4.1 Experimental validation and material characterisation:

Nine tests were conducted to experimentally validate the hyperelastic behavior of silicone rubber material. The stress - strain data obtained from these tests were compared to simulation results using the Mooney - Rivlin five - parameter model in ANSYS Workbench.

The comparison between experimental and simulated results displayed a strong correlation, with an R - squared value of 0.98 from correlation coefficient test and an estimated correlation coefficient of 85%. This high level of agreement indicates that the chosen hyperelastic model accurately represents the material's mechanical response under various loading conditions. The calibration of the Mooney - Rivlin five - parameter model allowed the determination of key material properties, including the initial shear modulus (c10), softening or stiffening behavior (c01), and volumetric response (c11). These material parameters are crucial for predicting the behavior of silicone rubber under different loading scenarios.

4.2 Hyperelastic modelling and simulation accuracy

The Mooney - Rivlin five - parameter model implemented in ANSYS Workbench effectively captured the complex hyperelastic behavior of silicone rubber. The stress - strain curves obtained from the simulation closely matched the experimental data, exhibiting similar patterns and characteristic features. The simulation accurately represented the yield point, strain hardening behavior, and initial linear range.

A quantitative analysis was conducted to assess the consistency between the experimental and simulated data. Statistical measures, including the mean absolute error, mean square error, and coefficient of determination, were computed. The results indicated strong agreement between the two datasets, confirming the accuracy and reliability of the simulation approach.

Moreover, a sensitivity analysis was performed on the hyperelastic model, demonstrating its robustness. Even slight variations in the parameters of the Mooney - Rivlin model led to minimal differences between the simulated and experimental stress - strain curves. This finding further validated the precision and stability of the selected model in predicting the mechanical behavior of silicone rubber.

4.3 Predictive capabilities and practical applications:

The validated hyperelastic model shows promise for practical applications in engineering design and optimization. The simulation approach accurately predicts the mechanical behavior of materials under various loading scenarios, making it a valuable tool for improving the design and functionality of components. The accurate prediction of forces ensures that the components hold securely in position. This not only increases user safety but also prevents accidental slippage of the lining when the component is removed.

5. Conclusion

Future research directions

Although the Mooney - Rivlin five - parameter model captured the hyperelastic behaviour of silicone rubber with excellent accuracy, there are potential opportunities for future research. Exploring other hyperelastic models or refining the existing model could further improve its accuracy and applicability in different scenarios. In addition, studying the viscoelastic behaviour of silicone rubber and evaluating its long - term durability can provide valuable insights for applications that require longer material performance.

In summary, the successful validation of the Mooney - Rivlin five - parameter model to accurately represent the hyperelastic behaviour of silicone rubber represents an important milestone in materials modelling research. The simulation results show a remarkable level of agreement with the experimental data and confirm the model's ability to accurately predict the mechanical response of the material under various loading conditions.

The reliability and accuracy of the hyperelastic model hold immense potential for engineering applications. With the ability to accurately predict mechanical properties, designers can ensure that materials perform reliably and consistently, reducing the risk of failure and increasing the overall safety of the end - user.

In addition, the validated hyperelastic model provides a powerful tool for optimizing the design and functionality of silicone rubber - based products in industries such as automotive, aerospace, and medical. Engineers can make informed decisions based on the simulation results, leading to more efficient design processes, lower development costs, and improved product performance.

The importance of this research lies not only in its successful validation but also in the opportunities it opens up for further exploration. As the field of material modelling continues to advance, there is an opportunity to explore other hyperelastic models and refine the existing model to improve its accuracy and applicability to a wider range of silicone rubber compositions and loading scenarios.

In addition, future research can explore the viscoelastic behaviour of silicone rubber and investigate its long - term durability, providing valuable insights for applications that require long material performance and structural integrity.

In summary, the successful validation of the Mooney - Rivlin five - parameter model to faithfully represent the hyperelastic behaviour of silicone rubber represents a significant advance for materials modelling science. The improved understanding and predictive capabilities gained through this research offer promising prospects for optimizing silicone rubber - based designs, ultimately leading to safer, more efficient, and reliable products in a variety of engineering fields. As the technology continues to evolve, it is certain that the results of this study will serve as a cornerstone for future advances and applications in the exciting field of silicone rubber material modelling.

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Footnotes:

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