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**A Correlation between Experimental Characteristics and Stress Analysis Modeling for
Recycled Silicone Rubber**

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Abstract

In this paper we present a correlation between the experimental results obtained in the characterization process and the results from stress analysis modeling using Autodesk Inventor Professional 2009 for Recycled Silicone Rubber samples obtained by mechanical grinding from fiberglass rod. We used Scanning Electron Microscopy for the morphological characterization of the obtained samples, which was correlated with Atomic Force Microscopy, in order to evaluate a transversal section of a sample. The Dynamic Mechanical Analysis results were in concordance with the results obtained from the Stress Analysis Modeling.

Keywords: recycled, silicone rubber, stress analysis

Introduction

Silicone Rubber is an elastomeric material with excellent mechanical properties [1] and [2], proving thermal [3] and chemical stability [4] and insulating capability [5]. Due to these facts, the applications of this material are various, emerging from industrial [6] and [7] to medical field [1], [8], [9], [10] and [11].

The physical and chemical characteristics of Silicone Rubber require mechanical operations for the recycling process, in order to maintain its initial properties [12]. In this study, we characterized several samples obtained from Recycled Silicone Rubber using a mechanical grinding operation from a fiberglass rod [13].

Materials and methods

The morphological characterization was obtained using a scanning electron microscope (SEM) TESCAN-VEGA 5136 LM and the surface topography of the samples was determined using the Alpha300 S Scanning Near-field Optical Microscope for atomic force microscopy characterization (AFM).

For the Dynamic Mechanical Analysis (DMA) a Nano Indenter G200 - Nanomechanical Characterization Equipment from Agilent Technologies was used in order to study the viscoelastic properties of the obtained samples. The functioning applied method is Erik's CSM Berkovich Storage and Loss Modulus.

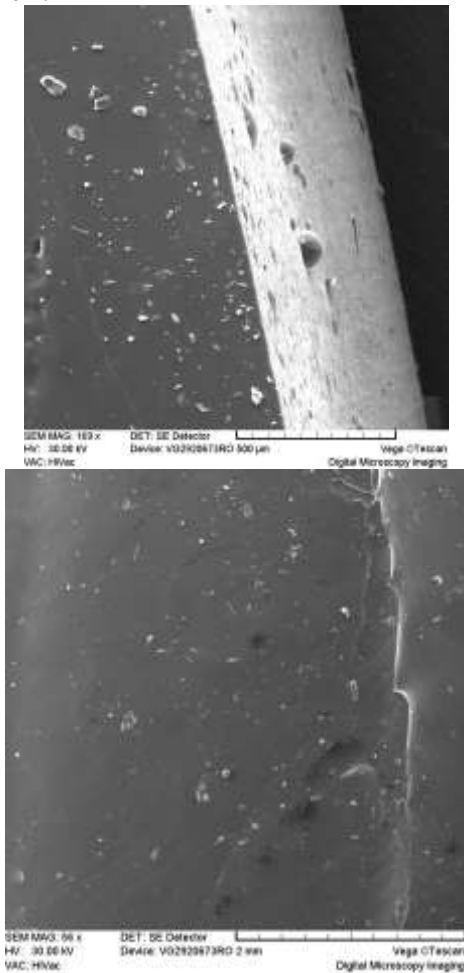
The Stress Analysis Modeling using Finite Element Simulation was implemented using Autodesk Inventor Professional 2009. Finite Element Analysis is a computerized method used for predicting the behavior of solids to mechanical stress. Here, the Relevance of the mesh geometry was set to the default value zero, in order to obtain certain results, with short solution times. The material behavior is based upon the assumptions of linearity, temperature-independent properties, homogenous and isotropic properties. The resulting parameters are based upon the equivalent stress failure theory for ductile materials like von-Mises-Hencky theory, octahedral shear stress theory and maximum distortion energy theory. [14]

Results and discussion

Morphology characterization

Regarding the morphological aspect of the obtained Recycled Silicone Rubber samples, we can tell that there is a rough surface, relatively having a uniform aspect, excepting few inclusions of maximum 100 μm (figure 1, top). The aspect of the rupture is sleek; here, we can observe the characteristic aspect of a compact polymeric structure. There are several inclusions of impurities and several micrometric-sized pores which can affect the mechanical properties of the sample.

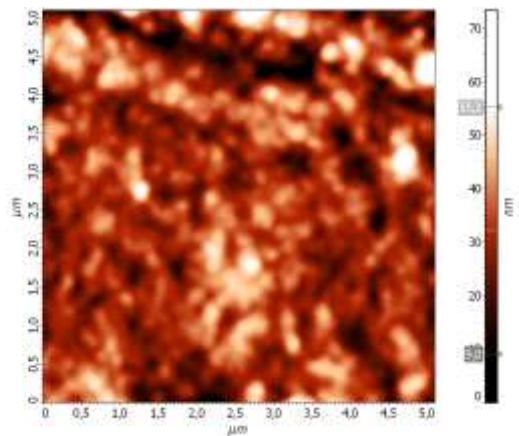
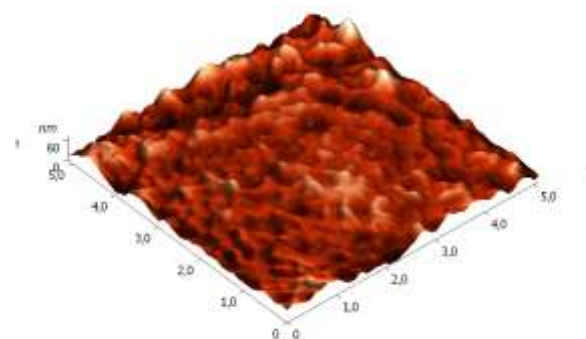
Figure 1:



SEM images of: on the top-side view of a fracture made on one of the obtained Recycled Silicone Rubber samples; on the bottom-the aspect of the fracture made on the Recycled Silicone Rubber Sample;

Topography characterization

Figure 2:



AFM images of: on the top- 3D image of the topography of the Recycled Silicone Rubber sample; on the bottom- 2D image of the same sample; (both images were acquired at 5 µm penetration depth);

From the AFM topography characterization, made for transversal sections in the sample, there can be observed the roughness of the surface, which is situated at an average value of 6,867 nm, while the maximum reaches up to 74,697 nm.

Dynamic Mechanical Analysis

The DMA measurements were made for three times on each sample (we characterized two samples using this method), in order to obtain more precise information regarding the elastic behavior of the Recycled Silicone Rubber samples. Thereof, we obtained values for parameters like Storage Modulus, Loss Modulus and Loss Factor, and the Loss Factor, to verify the viscoelastic behavior of the samples and the variation of those parameters depending on frequency of the applied oscillating strain (figure 4).

In DMA, for viscoelastic polymers, the sinusoidal force (stress, σ) applied to the testing material and the measured strain (ϵ) present a phase lag (δ), according to equations (1) and (2) [15].

$$\sigma = \sigma_0 \cdot \sin(t \cdot \omega + \delta) \quad (1)$$

$$\epsilon = \epsilon_0 \cdot \sin(t \cdot \omega) \quad (2)$$

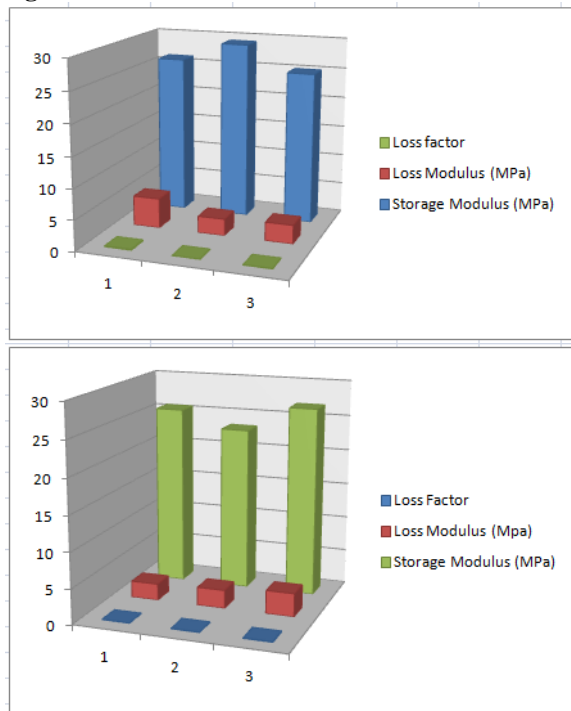
Where ω is the strain oscillation frequency and t is time.

Using the values of the applied stress, σ , and of the measured strain, ϵ , the DMA apparatus automatically calculates the values for: (1) Storage Modulus (E'), which characterizes the stored energy in the material, being a parameter proportional to the elastic portion in the tested sample; (2) Loss Modulus (E''), which determines the quantity of dissipated energy from the material, the parameter being a measure for the viscous portion of the sample; (3) Loss factor ($\tan \delta$), which is a measure for the amortization capability of the material.

$$E' = \frac{\sigma_0}{\epsilon_0} \cdot \cos \delta \quad (3)$$

$$E'' = \frac{\sigma_0}{\epsilon_0} \cdot \sin \delta \quad (4)$$

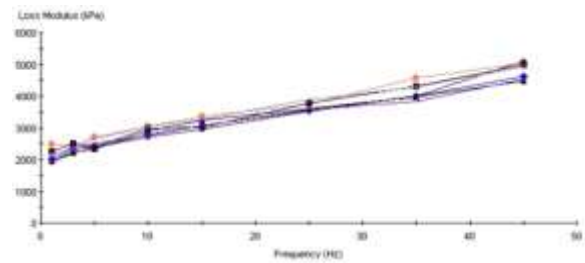
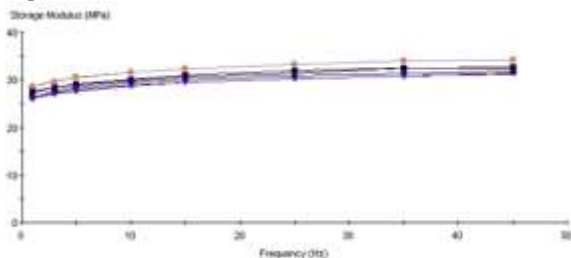
Figure 3:



DMA measurements for: on the top- the first sample; on the bottom- the second sample;

Comparing the values obtained for the two parameters Storage Modulus and Loss Modulus, we can tell that the elastic portion of the material is greater than the viscous portion of the obtained Recycled Silicone Rubber, for both samples. The amortization (given by the Loss factor) has a mean value of 0,134 for the first sample (with a standard deviation of 0,134) and 0,109 for the second sample (with a standard deviation of 0,016), which indicate the possibility of using the obtained material in the fabrication of shock absorber components.

Figure 4:



DMA characterization of the Recycled Silicone Rubber samples: on the top- Storage Modulus (MPa) as a function of frequency (Hz); on the bottom- Loss Modulus (kPa) as a function of frequency (Hz);

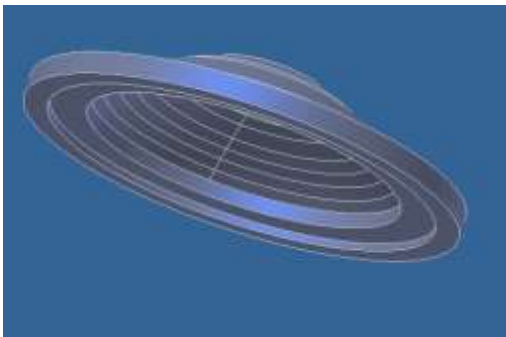
Regarding the variation of Storage Modulus, respectively Loss Modulus with frequency, we can observe a relatively linear behavior of the Recycled Silicone Rubber Samples.

Stress Analysis Modeling

For Stress Analysis Modeling, a copy of the membrane form figure 5 (top) was built in natural size, a pressure varying from 10-80 Barr being applied. The characteristics for Silicone Rubber have been manually inserted, according to the experimental determinations made for the obtained material. The values are given in table 1.

Figure 5:



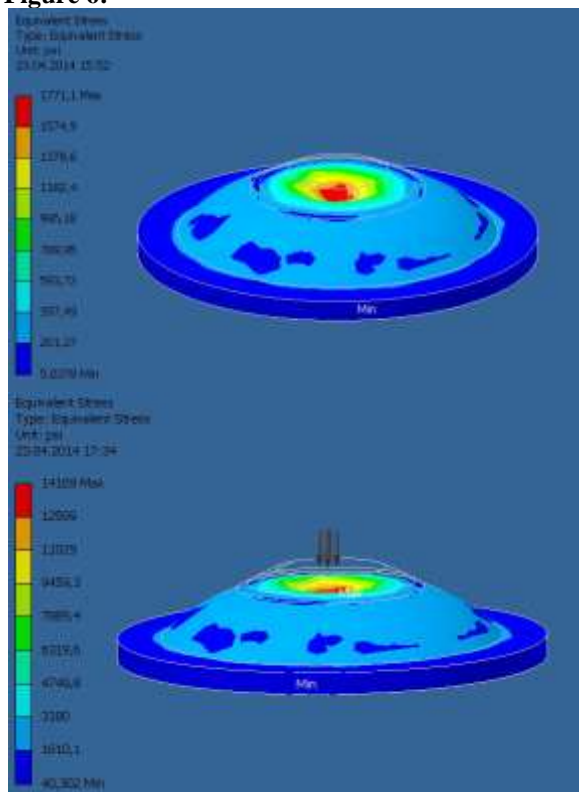


Recycled Silicone Rubber membrane: on the top- the aspect of the real object; on the bottom- top and bottom view of the reconstructed model;

Table 1. Simulation Material Data for Recycled Silicone Rubber determined from the experimental measurements;

Density	1,07 g/cm ³
Young`s Modulus	0,0255 GPa
Poisson`s Ratio	0,49
Yield Strength	5,5 MPa
Ultimate Tensile Strength	5,5 MPa
Thermal Conductivity	2,55 W/m·K
Linear Expansion	10 ⁻⁵ /m/C

Figure 6:

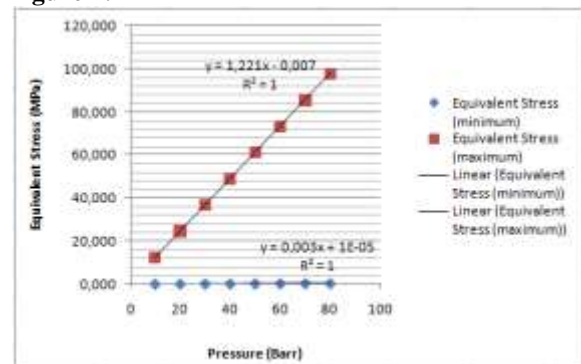


Side view of the model membrane under a certain pressure; the color bar is a measure for the variation of

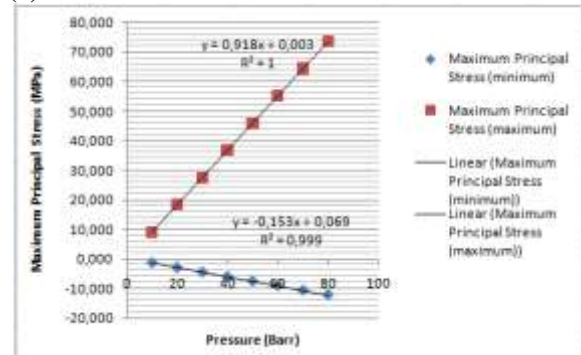
the Equivalent Stress on areas with different loadings: on the top- it is applied a pressure of 10 Barr; on the bottom- it is applied a pressure of 80 Barr;

The results of the mechanical simulation are illustrated in the graphics from figure 7. All of the recorded parameters (Equivalent Stress, Minimum Principal Stress, Maximum Principal Stress and Deformation) have a linear variation with the applied pressure, except for the Safety Factor, whose value has a significant drop from 0,425 to 0,210 for 10 Barr, respectively 20 Barr. The variation of the Safety Factor with the applied pressure is an exponential decay. This behavior can be determined by the elastic feature of the material.

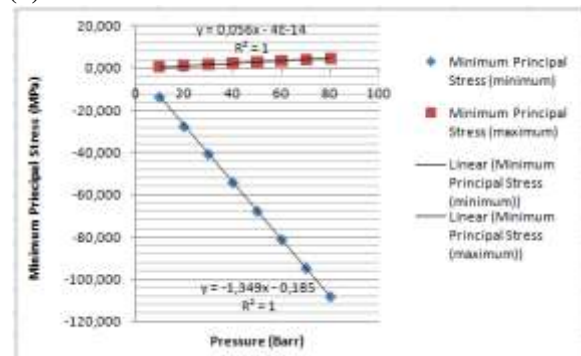
Figure 7:



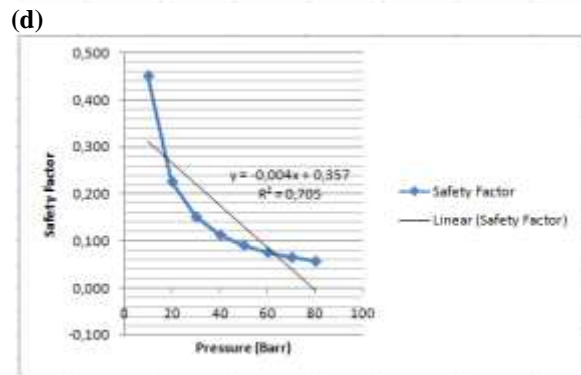
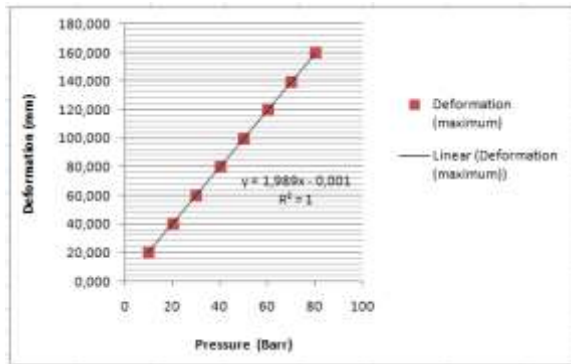
(a)



(b)



(c)



(e) The results of the mechanical simulation for the Recycled Silicone Rubber membrane: (a) the variation of Equivalent Stress (MPa) with the applied pressure (Barr); (b) the variation of the Maximum Principal Stress (MPa) with the applied pressure (Barr); (c) the variation of the Minimum Principal Stress (MPa) with the applied pressure (Barr); (d) the variation of the Deformation (mm) with the applied pressure (Barr); (e) the variation of the Safety Factor with the applied pressure (Barr);

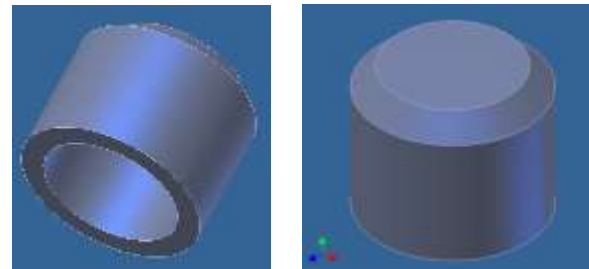
Another part was designed to function as an insulating element, its features being improved starting from previously obtained components (figure 8). The model insulating element is illustrated in figure 9.

Figure 8:



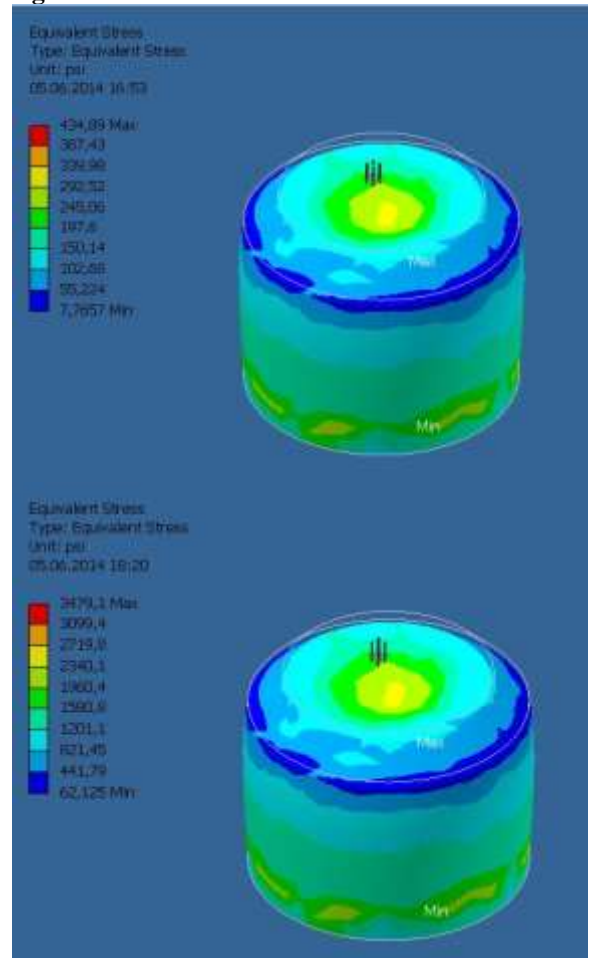
Left: coupling part; right: insulating element;

Figure 9:



The model Recycled Silicone Rubber insulating element: left- bottom view of the designed part; right- top view of the designed part;

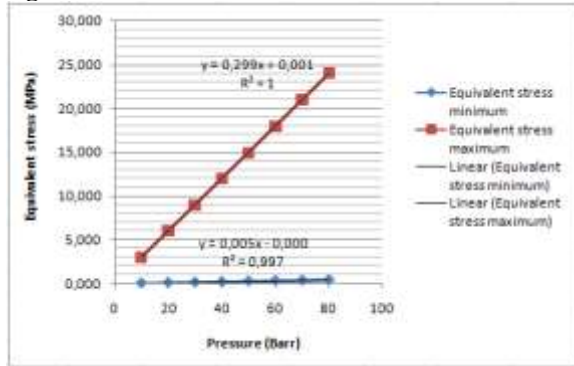
Figure 10:



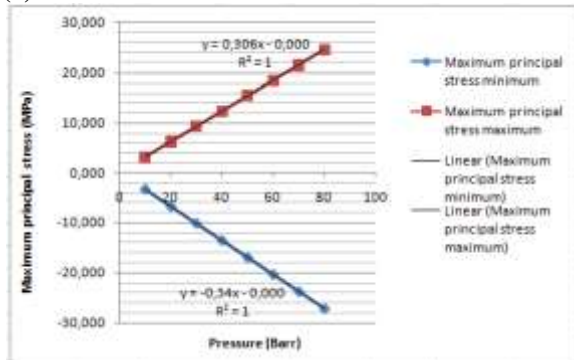
Side view of the designed insulating element under a certain pressure; the color bar is a measure for the variation of the Equivalent Stress on areas with different loadings: on the top- it is applied a pressure of 10 Barr; on the bottom- it is applied a pressure of 80 Barr;

The recorded parameters in the mechanical simulation for the designed part had similar variations to the ones recorded for the membrane. The values for the Equivalent Stress are lower in comparison to the membrane, probably because of the solid design of the part.

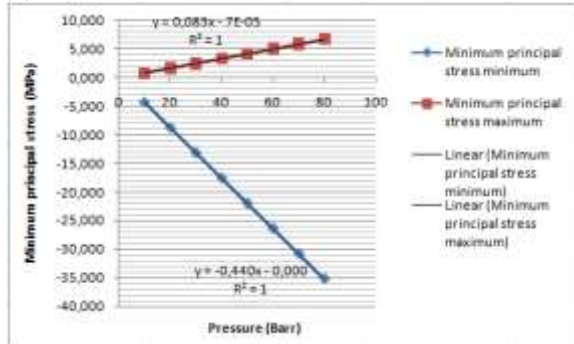
Figure 11:



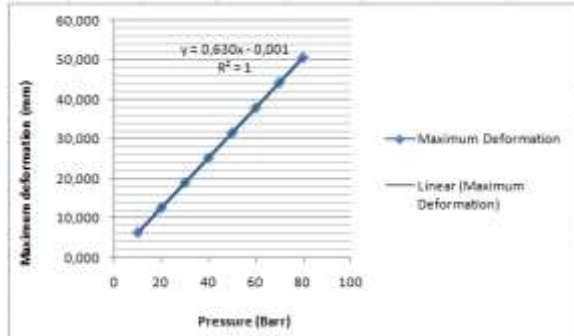
(a)



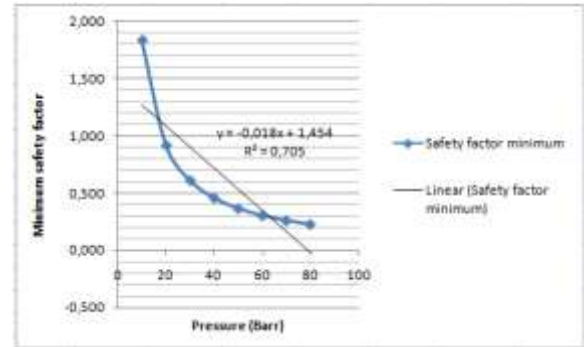
(b)



(c)



(d)



(e)

The results of the mechanical simulation for the designed Recycled Silicone Rubber insulating element: (a) the variation of Equivalent Stress (MPa) with the applied pressure (Barr); (b) the variation of the Maximum Principal Stress (MPa) with the applied pressure (Barr); (c) the variation of the Minimum Principal Stress (MPa) with the applied pressure (Barr); (d) the variation of the Deformation (mm) with the applied pressure (Barr); (e) the variation of the Safety Factor with the applied pressure (Barr);

Conclusion

From the experimental characterization and the stress analysis modeling, we can conclude the following: (1) regarding the morphological features of the Recycled Silicone Rubber, the samples have a nearly homogenous surface, with few inclusions, that exceed 100 μm; the interior of the samples is sleek with few impurities and small porosity; (2) the topography of the transversal sections made on Recycled Silicone Rubber samples is relatively uniform, and does not exceed 75 nm, being in concordance with the morphological characterization for the rupture section; (3) the dynamic mechanical analysis shows an elastic comportment of the Recycled Silicone Rubber and its suitable amortization properties; (4) the mechanical simulation confirms the elastic behavior of the Recycled Silicone Rubber models and a linear dependence of the predicted stress with the applied strain; the part geometry highly influences the resulting stress.

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