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Theoretical study of pressure distortions in a mechanical seal

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ABSTRACT

Nowadays, in various industries such as aerospace, atomic energy, chemical industries, refineries, petrochemical industries, and others, there is a need to use high-pressure mechanisms to enable and complete related processes. The increase in pressure occurs within a cylindrical chamber, and as a result, such an area must be sealed against fluid leakage from the inside to the outside. As the pressure rises, numerous problems related to fluid leakage arise because, as the process progresses, the pressure difference between the inside and outside of the system increases, consequently increasing the fluid's tendency to leak. The container becomes like a bomb where the slightest disturbance in the sealing system can cause leakage, even explosion, and irreparable damage. Therefore, for carrying out such processes (high-pressure processes), safe sealing is one of the most essential needs. This research focuses on designing a high-pressure seal based on the Bridgman design, in such a way that the sealing operation is performed reliably using the fluid pressure and its increase by the sealing assembly. To evaluate the performance of the seal, simulation using Abaqus software is utilized. Various sealing rings are examined, and ultimately, the ring that can not only create sufficient pressure (more than the fluid pressure) but also provide a more uniform pressure distribution (to prevent seal damage) is selected. In this research, PA6, UHMWPE-glass, UHMWPE-ceramic, NBR, and silicone are used for the high-pressure seal. PA6, UHMWPE-glass, and UHMWPE-ceramic exhibit elasto-plastic and time-dependent behavior. Therefore, for their simulation, elastic and viscoelastic models are used. NBR and silicone exhibit hyperelastic and time-dependent behavior, and for their simulation, hyperelastic and viscoelastic models are used.

Keywords: Sealing, High Pressure, Bridgman, Polymers, Hyperelastic

1. INTRODUCTION

Seals are used to limit or prevent the leakage of fluids. A sealing assembly typically includes a rubber ring and a gland. The gland is a groove made on metal or another hard material to hold the rubber ring.

Polymers are long artificial molecules formed by the bonding and linking of thousands of small molecular units called monomers. The process of linking molecules together is called polymerization, and the number of these small molecular units in a long chain is referred to as the degree of polymerization. Changing the size of the molecule also changes the properties of the polymer. The melting point, strength, and other physical properties of the polymer depend on the size and dimensions of the molecule (chain length).

Many polymers are named simply by adding the prefix "poly" to the name of the monomer they are derived from. For example, polypropylene and polystyrene are derived from propylene and styrene monomers, respectively.

The structure of polymers, with their long chain-like molecules, is completely different from metals. Natural materials such as silk, natural rubber, proteins, and cellulose have such molecular structures. However, significant progress in synthetic polymer materials did not begin until the nineteenth century, when efforts were made to produce artificial polymer materials. One of these new polymer materials, created by its inventor Alexander Parkes, was named Parkesine, although it was not readily marketable and eventually led to the creation of celluloid.

In the early twentieth century, there was considerable interest in new synthetic polymer materials. In 1909, phenol formaldehyde resin, known as Bakelite, was developed. During World War II, materials such as nylon, polyethylene, and acrylic, known as Perspex, were introduced to the world.

Elastomers

Rubbers are another member of the polymer family because they are composed of long chain molecules. These chains are irregular, twisted, and intertwined, giving the material high flexibility and the ability to undergo significant deformation. Rubbers, in their raw and unvulcanized state, do not completely return to their original shape after being deformed extensively; the molecules slide irreversibly past each other. To prevent this slippage between molecules, they undergo a process called vulcanization, where they are heated in a special manner. This causes the molecules to cross-link with each other, forming a network. These cross-links do not affect the initial disorder present in the rubber molecule's structure, whether it is spherical or has twists and bends. When we subject rubber to deformation, the molecules stretch and expand but do not slip over each other. Therefore, when we remove the applied force causing the deformation, the rubber immediately returns to its original state. Rubber manufacturing requires careful and precise operations, as well as considerable energy for heating and shaping.

A key property of elastomers is their elastic behavior after deformation under pressure or tension. For example, an elastomer may stretch up to ten times its original length, but upon releasing the tension, under ideal environmental conditions, it returns to its original shape and length. Moreover, elastomers exhibit characteristics such as high strength and hardness under dynamic or static stresses, excellent resistance to abrasion, flexibility even at low temperatures, impermeability to air and water, and in some cases, high resistance to swelling in solvents and chemical resistance. These properties are exhibited at room temperature and higher temperatures, and they maintain these qualities under severe weather conditions and in ozone-rich environments.

Elastomers also have the ability to adhere to textiles and metals. When combined with materials such as rayon, polyamide, polyester, or glass, elastomers gain significant tensile strength due to the reinforcing properties of these elements, while their elongation ability decreases. This capability considerably expands the range of applications for rubbers. For instance, bonding elastomers to metals results in a product that combines the elasticity of the elastomer with the hardness of metals.

Rubbers do not have a transition range to a plastic state because they have turned into three-dimensional networks that prevent the movement of macromolecular chains. Therefore, these materials can only deform plastically after undergoing certain physical or chemical structural changes due to wear, degradation, molecular rearrangement, or after physical or chemical cleavage of cross-links.

The raw material for producing elastomers is rubber. About half of the rubber consumed worldwide is synthetic, produced from natural rubber. The raw material for producing synthetic rubber is petroleum. The range of properties obtained with elastomers primarily depends on the type of rubber, compounding, production process, and the shape and design of the product. The final properties of rubber products, which reflect the true quality of elastomers, are achieved only through proper compounding with chemicals and other additives and vulcanization systems. Depending on the type and amount of rubber, additives, and chemicals in a compound, and the degree of vulcanization, cured rubber with various properties such as hardness, elasticity, or strength can be obtained. However, the special properties of elastomers, such as their resistance to oil, gasoline, and wear, remain unchanged in different cured compounds.

Behavior of Elastic Materials

An important criterion that defines the behavior of elastic materials is their compressibility. In rubbers, this criterion is expressed by the ratio of the bulk modulus to the shear modulus. As this ratio increases, Poisson's ratio increases, resulting in less volume change of the rubber under high pressure, to the point where volume change can be approximately ignored. The maximum value of Poisson's ratio for an ideal material is 0.5. Equations (1) and (2) show the relationship between K_0/μ_0 and Poisson's ratio, and the relationship between the linear elasticity modulus with the bulk modulus (K) and shear modulus (μ), respectively. K_0 And μ_0 represent the initial bulk modulus and initial shear modulus, respectively.

$$\upsilon = \frac{3\,K_0/\mu_0 - 2}{6\,K_0/\mu_0 + 2} \qquad (1)$$

$$E = \frac{9K\mu}{(3K + \mu)} \qquad (2)$$

For incompressible materials, the linear elasticity modulus is approximately three times the shear modulus of the material. It cannot be said that the higher the bulk modulus of a material, the less compressible it is. The factor that determines the compressibility of a material is the ratio of the bulk modulus to the shear modulus. The higher this ratio, the less compressible the material becomes.

Stress-Strain Behavior of Elastic Materials

The relationship that determines the modulus of elasticity is only valid for very small strains (less than 5%) and cannot be used for higher strains. In other words, Hooke's linear relationship cannot be used to describe the behavior of rubbers because results show that rubbers behave non-linearly in the elastic deformation region. To describe the behavior of rubbers, strain energy equations are used. The model that determines the mechanical behavior of elastomeric materials is not unique, and various models have been proposed to describe their behavior. A common feature observed in all strain energy models is that they are expressed in terms of principal invariants (Equation (3)). Strain energy is a scalar quantity and is invariant with respect to material element rotation.

$$W = W(I_1 . I_2 . I_3) \tag{3}$$

The invariants can be expressed, according to Equation (4), as a function of the change in the size of the body in the principal directions.

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{4}$$

$$I_3 = \lambda_1^2\lambda_2^2\lambda_3^2$$

λ1, λ2 and λ3 are the principal stretches

Plastics

Imagining the advanced world of today without plastics is difficult. They have become a part of our lives and are used in the construction of various objects, from household items and general consumer goods to precise and complex medical and scientific instruments. Engineers and designers favor plastics due to their combination of diverse properties compared to other materials. These properties include: light weight, hardness and flexibility, resistance to corrosion, colorability, transparency, ease of molding, etc. However, there are also limitations in the application of plastics, which a good and skilled designer can minimize.

The term plastic refers to a group of materials similar to nylon, polyethylene, and Teflon (polytetrafluoroethylene), just as the term metals recalls aluminum, zinc, and steel. It is important to note that just as zinc shows completely different properties from steel within the metal group, nylon also has completely different properties from Teflon within the plastic group. Some designers may simply suggest a metal for the construction of a specific part, but such an approach with plastics is not logical at all; it requires a more sophisticated and deeper consideration. Just as steel has various grades and types, polypropylene, for instance, as a type of plastic, also has different grades and types. In both cases, a successful designer is one who selects and uses the best type of material considering factors such as moldability, toughness, chemical resistance, etc.

The terms polymers and plastics are often used interchangeably in practice, but they actually differ from each other. A polymer is a pure substance obtained from the polymerization reaction. This term is generally used as the name of a family of materials with long, chain-like molecules, and even includes elastomers. A polymer is rarely used in its pure form; it is referred to as plastic when other substances are added to it.

Plastics are divided into two general categories: Thermoplastics

In thermoplastic materials, long molecular chains are placed next to each other with weak van der Waals forces. To imagine the molecular state of these materials, one can think of a tangled wool skein. The intermolecular forces in these materials weaken with heat, causing the material to become soft and flexible, and eventually turn into a viscous melt with increasing temperature. When the material is cooled, it returns to a solid state. The process of softening with heat and solidifying with cooling can be repeated multiple times; this characteristic is the most important feature of thermoplastics and the basis of many common shaping methods. On the other hand, this feature indicates the weakness that the properties of thermoplastics are highly dependent on temperature. For example, candle-like materials repeatedly melt and soften with heat and become solid when cooled. Examples of thermoplastic materials include polyethylene, polyvinyl chloride, polystyrene, nylon, cellulose acetate, acetal, polycarbonate, polymethyl methacrylate, and polypropylene.

Thermosetting Materials

Thermosetting plastics are produced through a two-stage chemical reaction. In the first stage, long, chain-like molecules similar to those found in thermoplastic materials are formed, which still have the ability to undergo another reaction. The second stage of the reaction, which involves creating cross-links between the chains, occurs during molding operations through the application of heat and pressure. The resulting piece, once cooled, appears hard, while a dense molecular network is formed structurally within it. In the second stage of the reaction, the long molecular chains are connected to each other with strong bonds, and the material cannot become soft and fluid again when heated. If the heating is increased, the material undergoes molecular degradation and turns into charcoal. This behavior can be likened to a boiled egg that, once cooled, is hard and does not soften with reheating.

The cross-links between the polymer chains are strong chemical bonds; hence, thermosetting materials have two prominent characteristics: hardness and mechanical properties that are independent of temperature. Phenol formaldehyde, epoxies, and some polyesters are considered thermosetting materials.

Mechanical Properties of Plastics

Due to the wide variety of polymer materials and additives, each plastic exhibits significantly different properties compared to other plastics. However, when plastics are categorized into groups, they generally share similar properties when compared to other materials. Among these properties, low density of plastics, ease of shaping and processability, high coefficient of thermal expansion, good thermal and electrical insulation, high specific strength and low modulus of elasticity, dependence of mechanical properties on time, loading rate, and temperature, resistance to corrosion and some chemicals (such as acids, bases, etc.) can be mentioned.

The properties of a plastic are a combination of the properties of the polymer and additives present in the polymer matrix, thus knowledge of both polymer and additives properties is essential. Polymer properties play a crucial role in determining the properties of the plastic, highlighting the importance of understanding polymer properties. Quality control of products, predicting their service life, and designing them require determining specific properties, especially mechanical and thermal properties. Each of these aspects necessitates specific testing according to standardized procedures. While simple, cost-effective, and repeatable tests are necessary for quality control of products, determining the required properties for product design needs to cover a wide range of variables.

Mechanical properties involve examining and determining the behavior of a material under stress. The response of a material to applied stress not only depends on the type of stress and temperature but also on the type of bonds, arrangement of atoms and molecules, and internal defects within the material.

2- MATHEMATICAL MODELS OF VISCOELASTIC BEHAVIOR

Over the years, significant efforts have been made to simulate the behavior of viscoelastic materials. These endeavors aim to facilitate the analysis of plastic product behaviors, advance interpolation and extrapolation methods from test results, and reduce the need for extensive and time-consuming creep tests. The most successful mathematical models are based on spring and dashpot elements, representing the elastic response and viscosity of plastic materials, respectively. Some of these models are further examined below.

Maxwell Model

The Maxwell model consists of spring and dashpot elements arranged in series (Figure 1). This model is analyzed as follows:

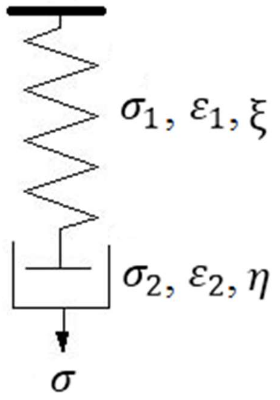

Fig.1. Maxwell Model

Stress-Strain Relationships

The spring exhibits elastic behavior and follows the relationship given by Equation (5).

$$\sigma_1 = \xi, \varepsilon_1 \qquad (5)$$

In which σ1 and ε1 are stress and strain, respectively, and ξ is a constant coefficient.
The dashpot represents viscous fluid behavior expressed by the relationship (6), where stress σ_2 is proportional to the strain rate, $\dot{\varepsilon}_2$.

$$\sigma_2 = \eta, \dot{\varepsilon}_2 \qquad (6)$$

η is a constant value for the material in question.

Equilibrium equation

With the assumption of constant area, the equation of force equilibrium is expressed by equation (7).

$$\sigma = \sigma_1 = \sigma_2 \qquad (7)$$

The geometry of the strain equation

As shown in equation (8), the total strain(ε), equals the sum of strains occurring in the two components of the model.

$$\varepsilon = \varepsilon_1 + \varepsilon_2 \qquad (8)$$

$$\dot{\varepsilon} = \frac{1}{\xi}, \dot{\sigma}_1 + \frac{1}{\eta}, \sigma_2 \qquad (9)$$

$$\dot{\varepsilon} = \frac{1}{\xi}, \dot{\sigma} + \frac{1}{\eta}, \sigma \qquad (10)$$

Equation (10) is the governing equation of the Maxwell model. Subsequently, the response of this model to creep phenomena, stress relaxation, and recoverability has been investigated.

Creep

If a constant stress σ_0 is applied to the body, equation (10) transforms into the following form (11):

$$\dot{\varepsilon} = \frac{1}{\eta}, \sigma_0 \qquad (11)$$

This indicates the constant rate of strain increase over time.

Stress relaxation

If the strain is held constant, equation (12) is derived from equation (10).

$$0 = \frac{1}{\xi}, \dot{\sigma} + \frac{1}{\eta}, \sigma \qquad (12)$$

Solving this differential equation with initial conditions at ($t = t_0$) and ($\sigma = \sigma_0$) yields the following results.

$$\sigma(t) = \sigma_0 e^{\frac{-\xi}{\eta}t} \quad (13)$$

$$\sigma(t) = \sigma_0 e^{\frac{-t}{T_R}} \quad (14)$$

"$T_R = \eta/\xi$ represents the relaxation time. Equation (14) expresses stress relaxation exponentially with the time constant η/ξ.

3- REVERSIBILITY

According to equation (10), when stress is removed, strain recovery is zero; hence, reversibility does not exist. As observed, although the stress relaxation behavior of this model provides an acceptable approximation of real material behavior, its prediction of creep and reversibility is inadequate.

Relaxation Simulation

The stress-strain behavior of polymeric materials is strongly time-dependent. Hydraulic seals are subjected to sudden pressure changes and may be held at a constant pressure level during loading cycles, hence viscoelasticity can significantly affect the pressure distribution at the sealing surface. The viscoelastic behavior of materials is highly important at high pressures, and understanding how materials achieve stability requires knowledge of stress relaxation. Relaxation tests according to ISO 6914 standard were conducted on NBR and silicone samples, with the respective results shown in Figure2 and Figure3.

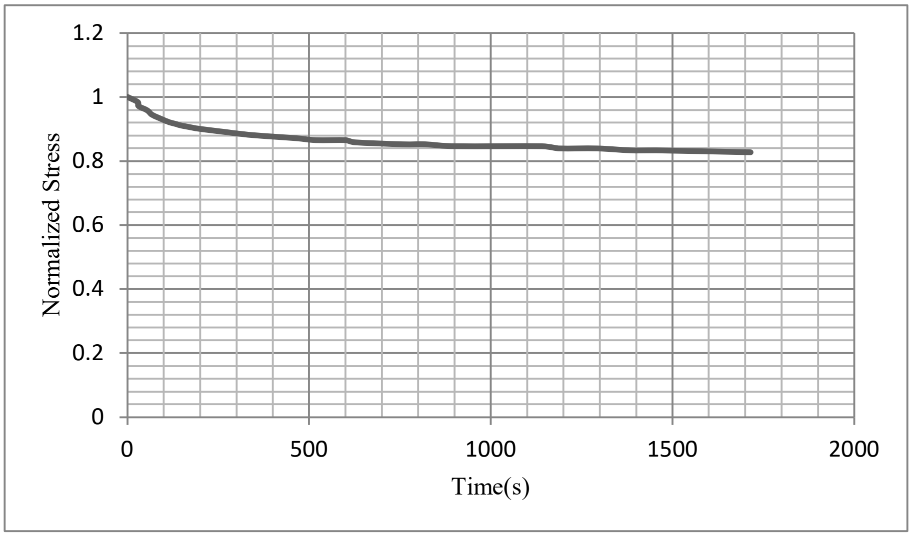

Fig.2. shows the stress relaxation curve obtained from the NBR sample test

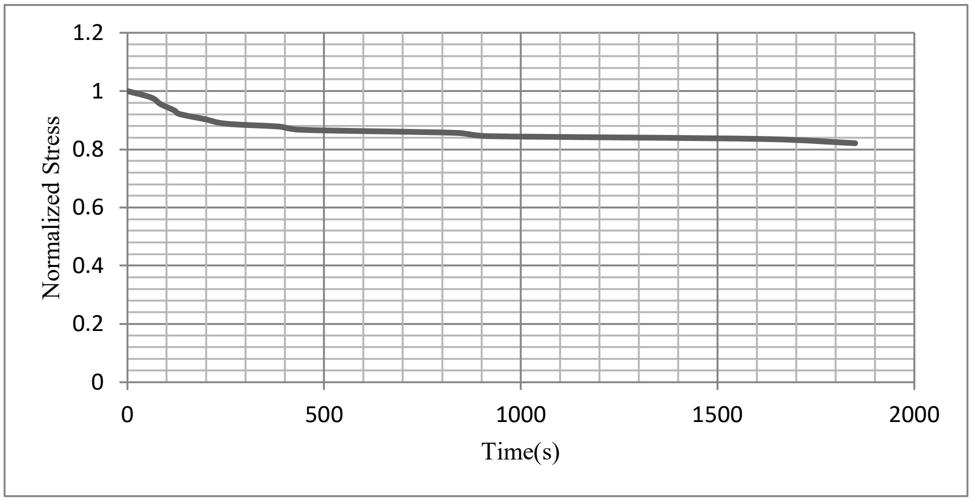

Fig.3. depicts the stress relaxation curve obtained from the silicone sample test

Figures 4, 5, and 6 respectively depict the results of stress relaxation tests on samples of PA6, UHMWPE-glass, and UHMWPE-ceramic with various initial strain conditions.

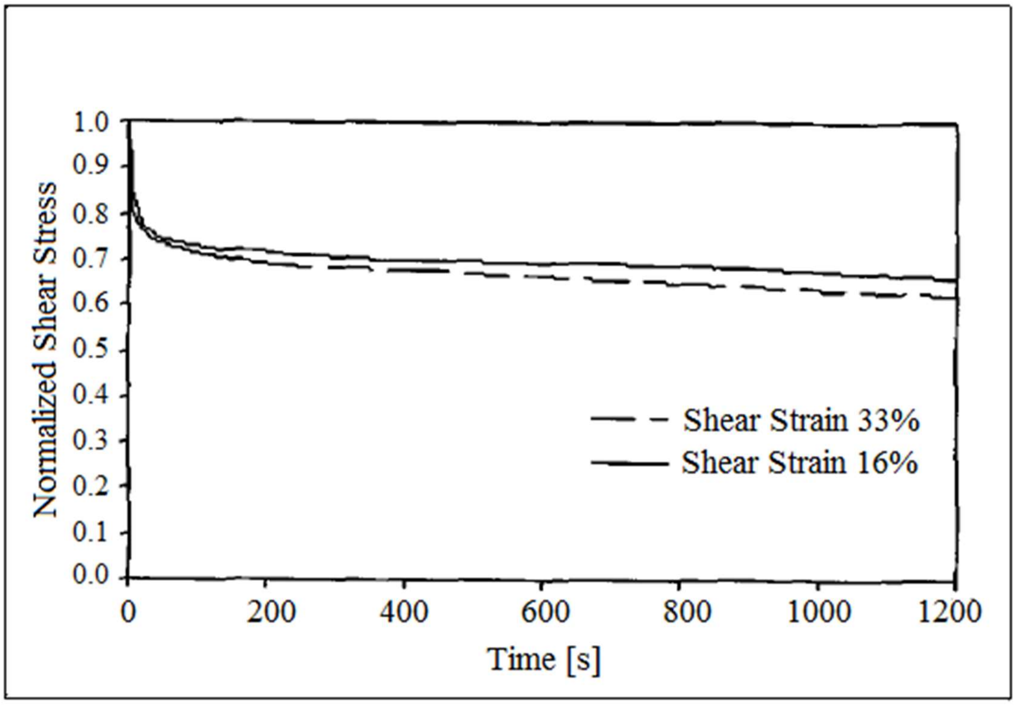

Fig.4. shows the results obtained from the stress relaxation test of the PA6 sample

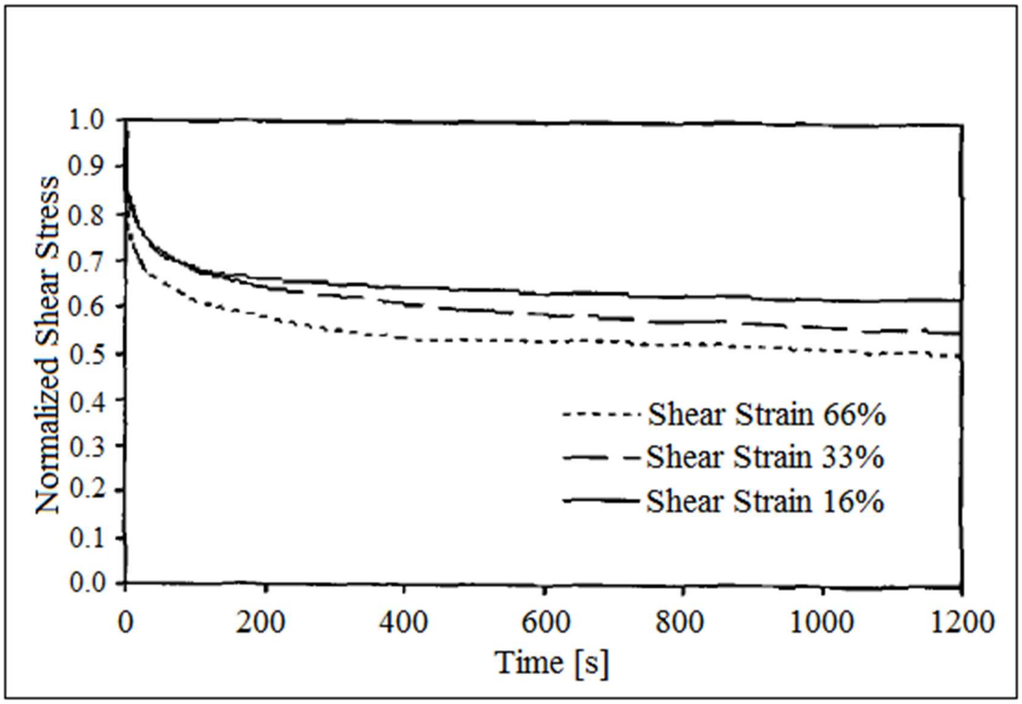

Fig.5. displays the results obtained from the stress relaxation test of the UHMWPE-glass sample

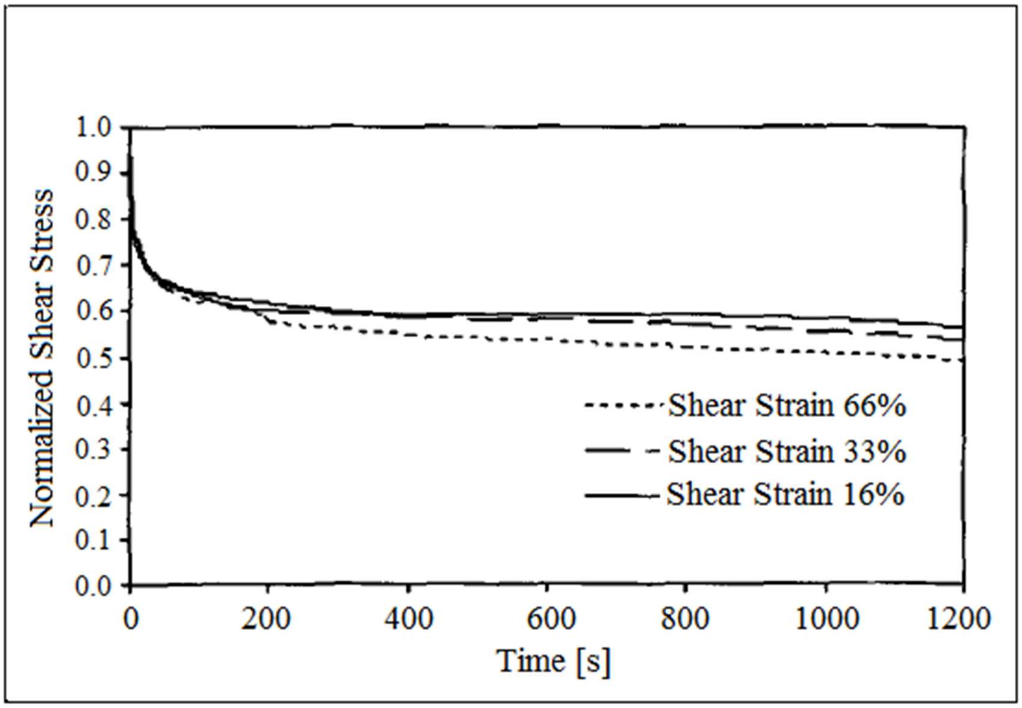

Fig.6. shows the results obtained from the stress relaxation test of the UHMWPE-ceramic sample.

The figure of the seal

The main objective of this research is to use the Bridgeham design and create a pressure greater than the fluid pressure in the seal, ensuring effective sealing. Designing high-pressure seals made of rubber in V-ring and C-ring forms is not feasible due to the significant deformation under high pressure. Figure7 illustrates the use of V-rings and C-rings for the desired design. Since the geometry of the seal, boundary conditions, and axisymmetric loading are considered, the problem is simplified in axisymmetric form. In this simulation, the cylinder is modeled as steel, V-rings and C-rings as PA6 with element CAX4R, and the piston as solid. The V-ring is subjected to a pressure load of bar700 and the C-ring to a pressure load of bar1500. For the analysis, an explicit solver is used, and contact between components is defined in a penalty manner. Consequently, the deformation of V-rings and C-rings under pressure is illustrated.

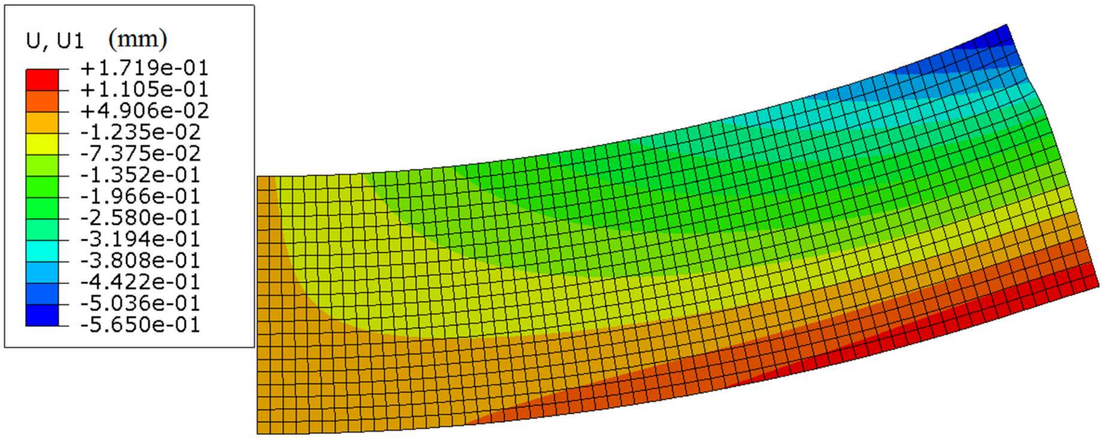

Fig.7. Piston shape change under pressure

Water Seal Pressure

In this section, the simulation results of the designed water seal made of specified materials are presented. In this simulation, NBR and silicone rubbers have been used as Enhanced options to address the Hourglass problem. Different mesh sizes for the water seal are shown. The pressure generated in the section of the water seal in contact with the cylinder wall must exceed the fluid pressure for effective sealing. Modeling results for PA6, UHMWPE-glass, UHMWPE-ceramic, NBR, and silicone are presented in these pressure versus node distance curves for nodes in contact with the cylinder wall. The length of the water seal section in contact with the cylinder wall is 5.54 mm. Node zero in these curves represents the node in contact with the piston, and the node at 5.54 mm represents the node in contact with the reinforcement. these curves, as the mesh is refined, the solutions converge, and as expected, the pressure generated in section a of the water seal exceeds the pressure in other sections and the fluid pressure (bar30

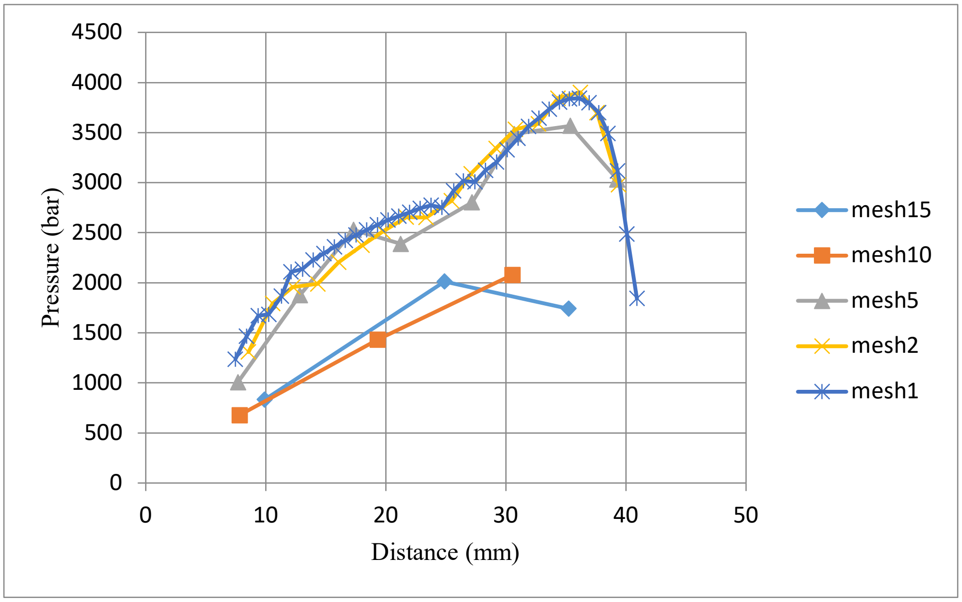

Fig.8. Water pressure resistance for PA6

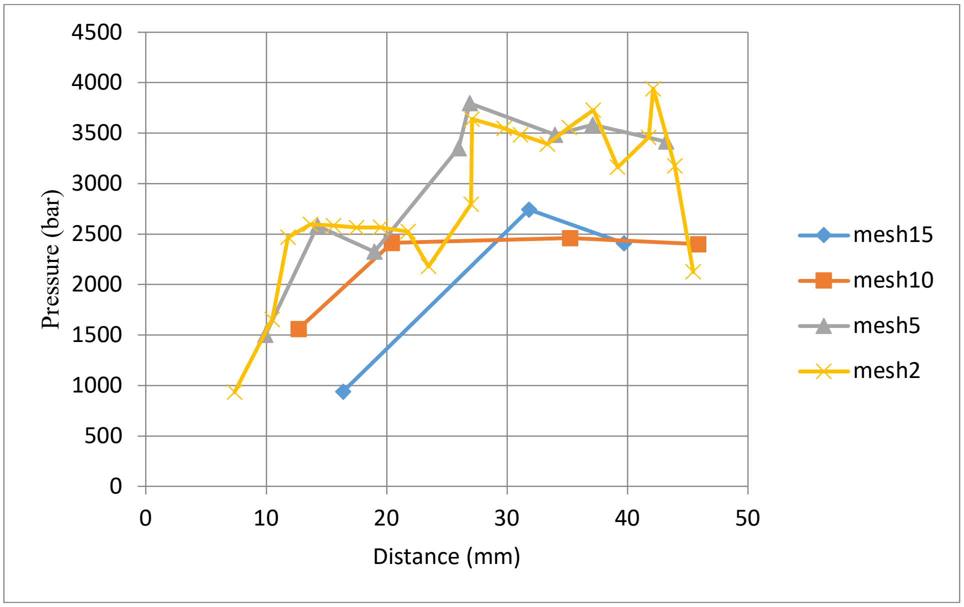

Fig.9. Water pressure resistance for UHMWPE-glass

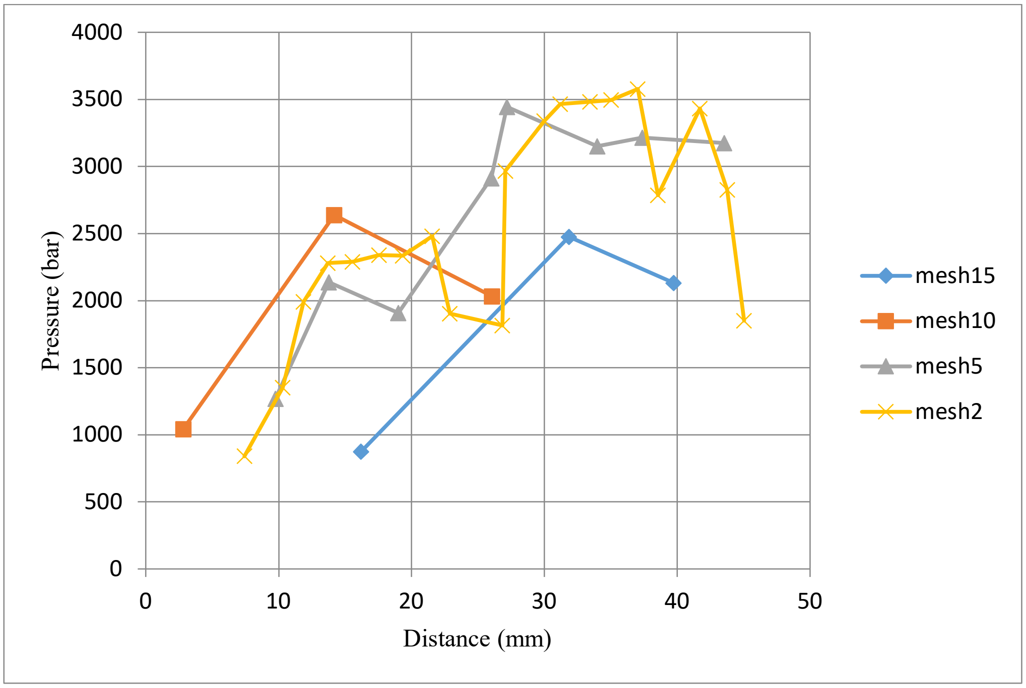

Fig.10. Water pressure resistance for UHMWPE-ceramic

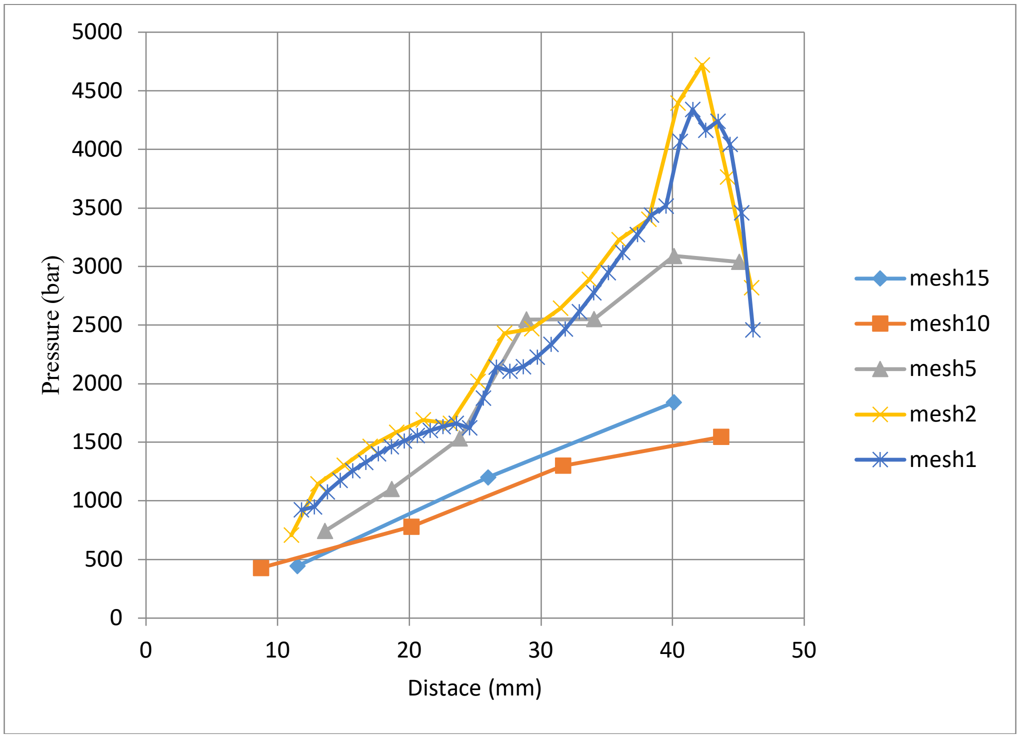

Fig.11. Water pressure resistance for NBR

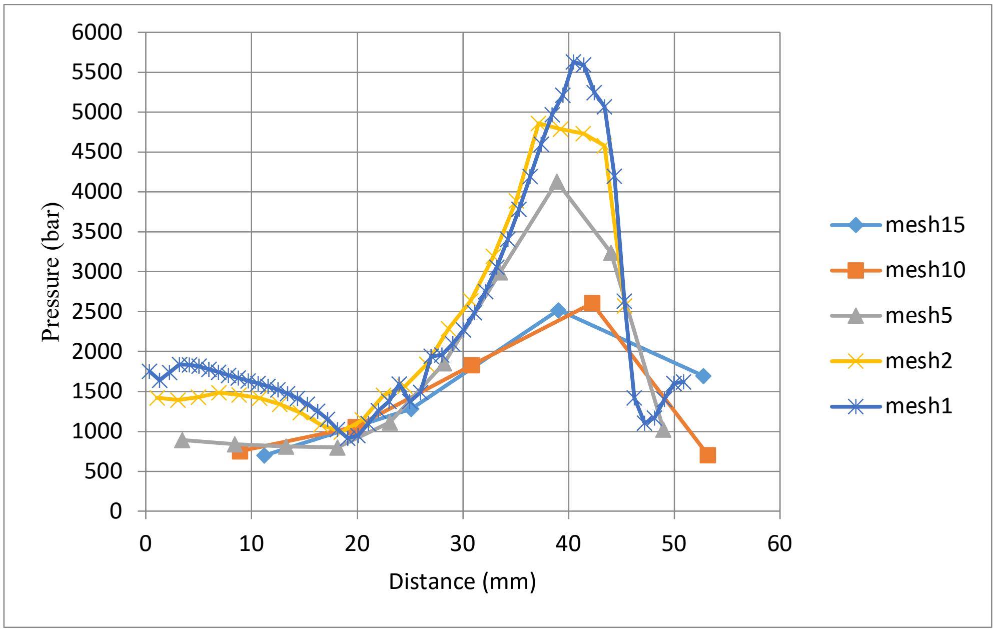

Fig.12. Water pressure resistance for silicone

4- CONCLUSION

For reliable sealing in systems, the Bridgman design can be employed. This design creates a pressure greater than the fluid pressure that needs to be sealed, thereby forcing the seal into the sealing surface. The hydrostatic pressure compresses the polymeric seal towards the sealing surface, filling in surface irregularities. Consequently, the contact stress at the sealing interface exceeds the fluid pressure, ensuring effective sealing.

The design presented in Chapter Five can be utilized for sealing high-pressure systems (up to 3000 bar). It generates high pressure intensification for sealing in the portion of the elastomer in contact with the desired surface, thereby achieving fluid sealing. Certain polymers can be used to produce high-pressure seals. With increased pressure, the hardness and yield stress of polymers also increase, allowing them to withstand and transfer the high pressures generated to the desired surface.

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