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Research on the Performance of Sealing Materials for Low-Temperature Valve Insulation Layers

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Abstract: As a country with high energy consumption, Chinese demand for clean energy has been increasing due to the gradual improvement of the economy and the living standards of its citizens. Natural gas is one of the most widely used clean energy sources, and the country has vigorously promoted its use to alleviate environmental issues. As a result, China has invested heavily in the construction of LNG receiving terminals and plants in coastal areas. This has led to the rapid development of the LNG industry and placed high demands on the safety and efficiency of LNG-related cryogenic equipment. Due to the extremely low temperature of LNG, it is necessary to consider heat loss and heat intrusion in the design of LNG-related cryogenic equipment. In this study, high-density polyethylene was chosen as the low-temperature sealing material with the aim of controlling heat loss and reducing heat intrusion. Compression, compression rebound, and hardness tests were conducted on high-density polyethylene at temperatures of 25 ℃, -29 ℃, -50 ℃, -110 ℃, -162 ℃, and -180 ℃. The maximum stress values, compressibility, resilience, and hardness of high-density polyethylene at different temperatures were analyzed.

1. Introduction

With the rapid development of our country's economy, the demand for energy is increasing. In recent years, the government has been vigorously promoting the conversion from coal to gas, resulting in a growing demand for natural gas. China is a large consumer of energy, and domestic natural gas resources alone cannot meet the demand, so a significant amount of natural gas relies on imports from abroad. The common method of natural gas importation is to compress and cool the gas produced from gas fields to its boiling point (approximately -161.5 ℃) to transform it into a liquid form. Typically, liquefied natural gas (LNG) is stored in low-pressure containers at around 0.1 MPa and -161.5 ℃, and it is transported using specialized LNG ships or tanker trucks. Throughout the process of liquefaction, fractionation, storage, and transportation, various low-temperature valves are required for control.

Low-temperature valves refer to a type of valve in which the internal medium temperature is below 233K (-40 ℃) [1]. During the operation of low-temperature valves, the temperature at the bottom of the valve body and valve cover is approximately the same as the temperature of the low-temperature medium, while the external surface of the valve is exposed to the atmosphere. The temperature difference between the two is generally around 200K. Under such a large temperature difference, heat loss is highly likely. In order to prevent significant heat loss, ensure the efficiency of transporting low-temperature media, prevent heat absorption and expansion of the internal low-temperature medium, and avoid accidents caused by a rapid increase in pressure, it is necessary to install insulation layers on the valve body and the bottom of the valve cover. Additionally, the outer surface of the insulation layer should be kept dry. Therefore, the temperature of the outer surface of the insulation layer should be higher than the dew point temperature of water vapor in the air. Otherwise, condensation and moisture absorption on the surface of the insulation layer can easily increase thermal conductivity and lead to insulation failure. For the valve cover, it is desirable to have a relatively high heat transfer capacity to ensure that the bottom of the packing remains above 0 ℃, preventing freezing and potential damage to the valve stem, which could result in serious leaks [2].

The sealing performance of ultra-low-temperature valves depends on the mechanical properties of the sealing materials at low temperatures. To ensure good sealing performance, it is required that the selected polymer materials exhibit suitable compressibility and resilience at extremely low temperatures, with a glass transition temperature lower than the working temperature at low temperatures. Therefore, this paper focuses on the loss of cooling capacity of low-temperature valves and designs a low-temperature sealing material using high-density polyethylene. Compression performance, compression resilience, and hardness of high-density polyethylene at 25 ℃, -29 ℃, -50 ℃, -110 ℃, -162 ℃, and -180 ℃ were tested. Through the analysis of the experimental data and a comparison of the mechanical properties of high-density polyethylene at different temperatures, this study provides references for low-temperature sealing materials.

2. Experimental Method

2.1 Ultra-High Molecular Weight Polyethylene

Ultra-high molecular weight polyethylene (UHMW-PE) is a thermoplastic polyolefin material that is copolymerized from ethylene and butadiene monomers under the action of a catalyst (Figure 1). It has an average molecular weight of over 2 million and appears as white particles or powder, non-toxic, and odorless. The density ranges from 0.920 to 0.965 g/cm^3; the thermal deformation temperature (0.46 MPa) is 85 ℃, and the melting point is 130-136 ℃. It exhibits stable chemical properties and has excellent wear resistance, toughness, and self-lubrication. Its comprehensive performance allows for long-term use in ultra-low temperature conditions. The main characteristics of ultra-high molecular weight polyethylene are as follows [3, 4].

(1) Wear resistance: Ultra-high molecular weight polyethylene has much stronger wear resistance compared to general metal materials, with an average annual wear rate of only 0.58 mm.

(2) Impact resistance: Ultra-high molecular weight polyethylene is one of the engineering plastics with the highest impact toughness and its ability to resist impact increases as the temperature decreases.

(3) Self-lubrication: Ultra-high molecular weight polyethylene has better inherent lubricity than metal materials lubricated with oil, and it exhibits excellent dry lubrication performance, enabling smooth movement and protecting related components from abrasion. Its friction coefficient is only 0.05-0.11.

(4) Low temperature resistance and aging resistance: Due to the low content of unsaturated groups in the molecular chain and its high molecular weight, ultra-high molecular weight polyethylene has excellent resistance to aging and a strong service life. It can work for a long time even at low temperatures.

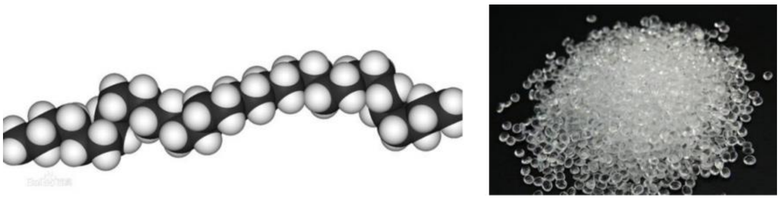


Figure 1: Polymeric polyethylene

2.2 Experimental Design

In order to verify the sealing performance of ultra-high molecular weight polyethylene (UHMW-PE) at low temperatures, this study mainly tests its compressibility and resilience at low temperatures. Additionally, the change in material hardness at low temperatures can also affect the sealing performance. Most materials tend to increase in hardness at low temperatures, which can potentially cause scratches on metal components and lead to leakage issues. Therefore, compression tests, compression resilience tests, and hardness tests need to be conducted.

Taking into consideration the operating conditions of LNG ultra-low-temperature valves, a comparison will be made between the compressibility, resilience, and hardness of UHMW-PE at low temperatures and room temperature. The selected temperatures for testing are 25 ℃ as the room temperature reference, -29 ℃, -50 ℃, -110 ℃, -162 ℃, and -180 ℃, with -162 ℃ being the working temperature of LNG low-temperature valves. The test samples of UHMW-PE are relatively thin and have a soft texture. Therefore, the samples will be processed by water jet cutting and then polished using a polishing machine to remove any burrs or irregularities on the sample surface, ensuring they do not affect the test results.

3. Experimental Results and Discussion

3.1 Compression Test

3.1.1 Experimental Setup

The purpose of the compression test is to determine the compressive stress at which ultra-high molecular weight polyethylene (UHMW-PE) fails at low temperatures, to prevent excessive pressure that could crush the material, and to establish the pressure range for using UHMW-PE at different temperatures. The dimensions of the compression test samples were determined according to the requirements of GB/T1041-2008 "Determination of Compression Properties of Plastics" to minimize experimental errors and account for differences in the testing equipment. The dimensions of the compression test samples are given in millimeters (mm).

The compression test and compression resilience test were conducted using a Shenzhen Sansi Zongheng WGDN-18300L high and low-temperature test chamber and a UTM-5205X electronic universal testing machine. Liquid nitrogen was used to provide the low-temperature environment. The UTM-5205X electronic universal testing machine is used for measuring the mechanical properties of materials, such as compression, bending, and tensile properties. It has a maximum test force (Fmax) of 200 kN, a precision level of 0.5, a test force error within ±5% of the indicated value, a resolution of 1/300000 of the maximum test force (approximately 0.67 N), and a constant test process resolution. The temperature control range of the WGDN-18300L high and low-temperature test chamber is -180 ℃ to 300 ℃, with temperature fluctuations within ±1 ℃ and temperature deviations within ±2 ℃. The temperature control display accuracy is within 0.1 ℃. Prior to the test, the specified temperature was set, and the liquid nitrogen tank was connected to the high and low-temperature control chamber via an electromagnetic regulating valve. After the temperature reached the specified value, the sample was allowed to cool down to the specified temperature for 30 minutes to ensure sufficient cooling before conducting the relevant tests.

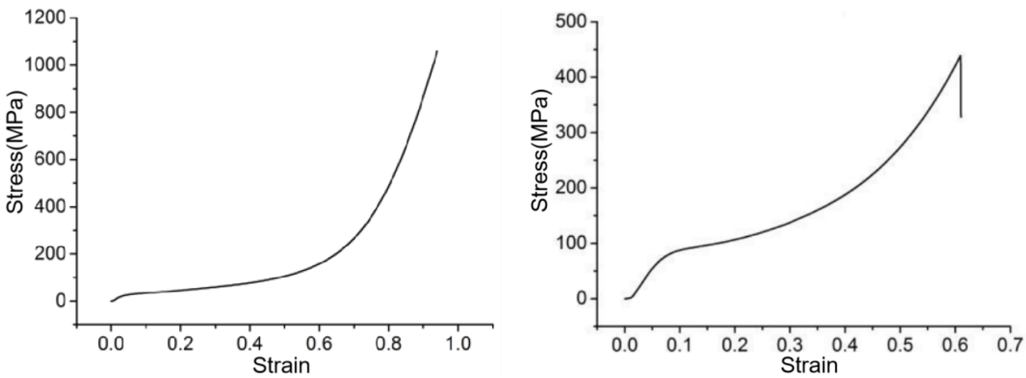
3.1.2 Data Analysis and Discussion

Compression test procedure: The sample was compressed along the axial direction (thickness) at a constant rate until failure occurred [5]. According to the requirements of GB/T1041-2008 "Determination of Compression Properties of Plastics", five samples were tested at each temperature. The compression was continued until the samples failed. The force-displacement data obtained from the equipment were processed to obtain the stress-strain curve.

As the compression pressure increased, at room temperature (25 ℃), the five samples experienced plastic deformation when the pressure reached the maximum load capacity of the testing machine (190 kN), as shown in Figure 2a. However, at low temperatures, except for two samples at -29 ℃ that did not crush, the remaining 23 samples were all crushed (Figure 2b). This indicates a decrease in toughness of UHMW-PE at low temperatures. Figure 3 shows the stress-strain curves of the compression test. At room temperature, the compression curve showed no sudden change and the samples underwent plastic deformation (Figure 3a). At low temperatures, the compression curve exhibited a distinct inflection point, which corresponded to the compressive stress at failure (Figure 3b) [6].

(a) Plastic deformation sample (b) Broken sample

Figure 2: Samples after test



(a) Room temperature (b) Low temperature

Figure 3: Compression curves of polymer polyethylene at different temperatures

Plotting the stress-strain curve of the compression test allows us to determine the compressive stress at the point of curve inflection, which corresponds to the stress at failure. The average compressive stress at failure was calculated for five specimens at each of the six different temperatures, as shown in Table 1.

Table 1: Compressive stress of specimen at failure

Temperature/ ℃	Damaged Compressive Stress					Average/MPa
25	undamaged					
-29	undamaged		766	701	788	751.67
-50	577	683	644	625	586	623
-110	672	583	603	638	655	630.2
-162	436	444	417	389	422	421.6
-180	379	366	342	406	351	368.8

From the observed change in stress values at specimen failure during the compression test, it can be seen that at room temperature, the specimens remained intact even when compressed to the maximum load of the testing machine. This indicates that the high polymer material exhibited a decrease in toughness and an increase in brittleness with decreasing temperature, leading to specimen failure. The compressive stress at failure decreased further as the temperature decreased (Figure 4).

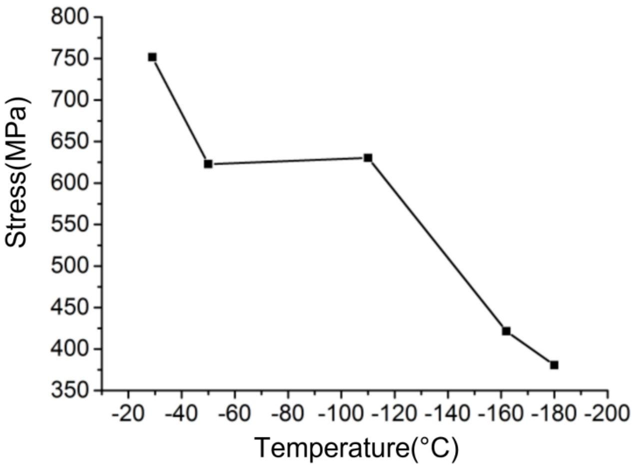


Figure 4: Compressive stress of specimen failure at different temperatures

3.2 Compression Rebound Test

3.2.1 Test Setup

The deformation characteristics of sealing gaskets during loading are important factors for their initial sealing ability. The key indicators to measure the deformation characteristics are compression ratio and rebound ratio. Both too small and too large compression ratios can have adverse effects on sealing. A too small compression ratio requires a larger preload force during installation, making it difficult to achieve a proper seal. On the other hand, a too large compression ratio can cause gasket failure under normal installation preload. Therefore, high polymer materials with suitable compression ratios at low temperatures can achieve better sealing effects. The rebound ratio measures the gasket's ability to recover elasticity after unloading, and a higher rebound ratio indicates better compensating ability and sealing effectiveness. Generally, the principle for evaluating the quality of sealing gaskets is that, under a suitable compression ratio, a higher rebound ratio is preferable. Therefore, to determine the deformation characteristics of high-density polyethylene at low temperatures, a compression rebound test needs to be conducted [6]. The dimensions of the compression rebound test specimens are referenced from GB/T 20671.2-2006

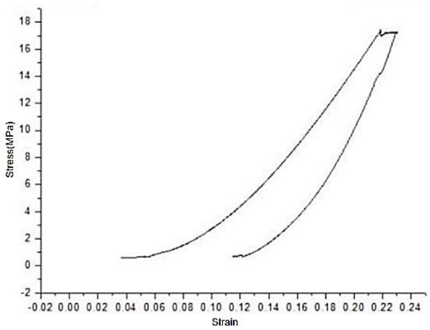
"Test Method for Compression and Rebound of Gasket Materials". Considering the thickness of the gaskets used in the ultra-low temperature valves, actual processing conditions, and experimental errors, the specimen dimensions are determined accordingly. The test load is set at 17.25 MPa, and the corresponding load for this test is calculated using the equal pressure method, as shown in Table 2.

Table 2: Compressive rebound test load

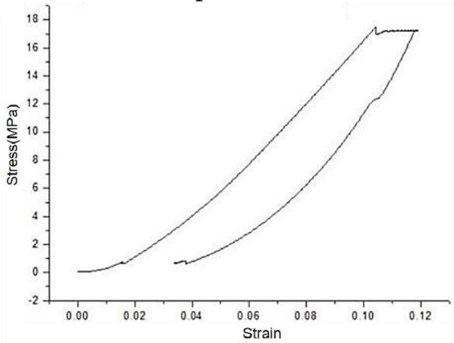
Initial Load F_1/N	**Primary Load F_2/N**	**Total Load F/N**
224	5384	5608

3.2.2 Experimental Data Analysis and Discussion

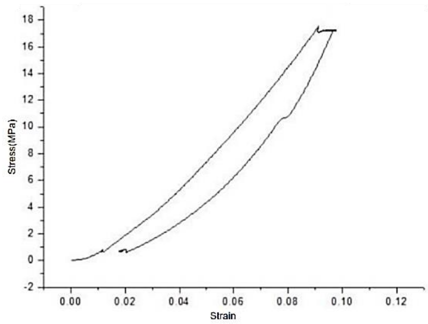
The force-displacement data obtained from the computer output were processed to obtain the stress-strain curves for the compression rebound test specimens. After processing the data, the compression rebound stress-strain curves for the six different temperatures are shown in Figure 5.



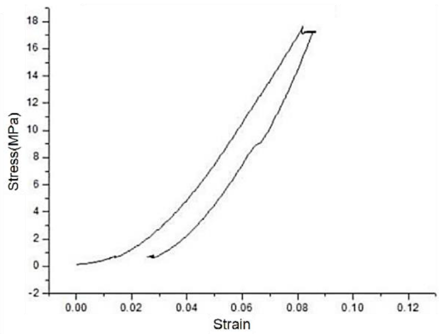
(a) 25°C



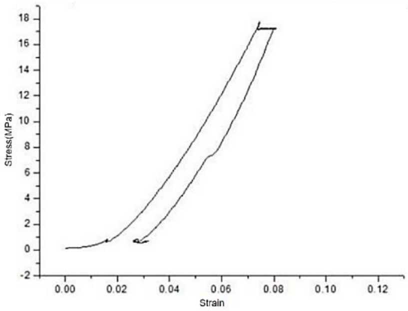
(b) -29°C



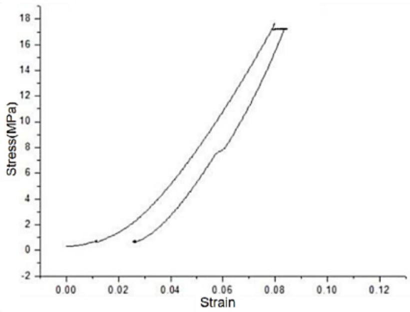
(c) -50°C



(d) -110°C



(e) -162°C



(f) -180°C

Figure 5: Stress-strain curves of compressive rebound tests at different temperatures

Using **Education (1) and (2)** provided in GB/T 20671.2-2006, the compression ratio and rebound ratio for each temperature were calculated and are presented in Table 3.

compression ratio and rebound ratio

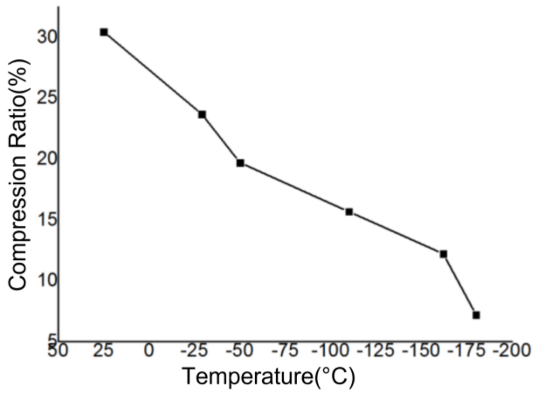
$$\mathrm{C(Compression\ ratio)} = \left(\frac{\mathrm{P-M}}{\mathrm{P}}\right) \times 100\% \tag{1}$$

$$\mathrm{R(Rebound\ ratio)} = \left(\frac{\mathrm{R-M}}{\mathrm{P-M}}\right) \times 100\% \tag{2}$$

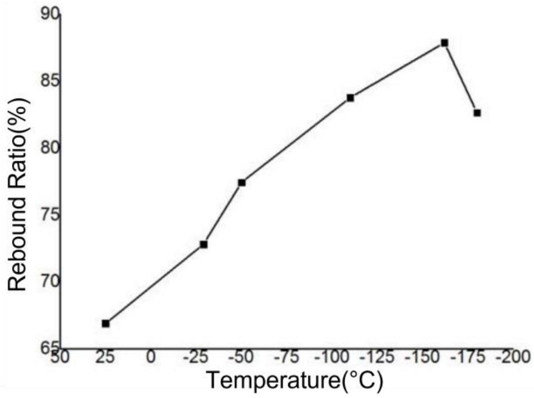
Table 3: Compress the rebound test data

Temperature /℃	**P/mm**	**M/mm**	**R/mm**	**Compression Ratio/%**	**Average Compression Ratio/%**	**Rebound Ratio/%**	**Average Rebound Ratio/%**
25	1.0304	0.7586	0.9136	26.38	30.46	65.31	66.91
	1.0513	0.72	0.9512	31.51		69.79	
	1.0420	0.693	0.9220	33.49		65.62	
-29	1.2941	0.9823	1.2079	24.09	23.68	72.35	72.84
	1.2780	0.9842	1.1997	22.99		73.45	
	1.2843	0.9767	1.2004	23.95		72.72	
-50	1.3016	1.0477	1.2443	19.51	19.70	77.43	77.44
	1.3202	1.0702	1.2623	18.94		76.84	
	1.3144	1.0429	1.2548	20.66		78.05	
-110	1.3486	1.1244	1.3134	16.62	15.68	84.30	83.78
	1.3582	1.1472	1.3267	15.54		85.07	
	1.3613	1.1588	1.3248	14.88		81.89	
-162	1.3987	1.2048	1.3797	13.86	12.22	90.20	87.88
	1.4007	1.2360	1.3804	11.76		87.67	
	1.4020	1.2473	1.3800	11.03		85.78	
-180	1.4144	1.3040	1.3937	7.81	7.18	81.25	82.65
	1.4204	1.3160	1.4015	7.35		81.90	
	1.4121	1.3219	1.3984	6.38		84.81	

The average values of the compression ratio and rebound ratio from Table 3 were taken, and the trends of compression ratio and rebound ratio with temperature were plotted in Figure 6. From Figure 6, it can be observed that the polyethylene exhibits higher compression ratio at room temperature, which gradually decreases as the temperature decreases. According to GB/T 9129-2003, the compression ratio of polytetrafluoroethylene should be between 15% and 25% at a preload-to-pressure ratio of 35 MPa. The high-density polyethylene, at temperatures of -110 ℃ and above with a pressure of 17.25 MPa, maintains a compression ratio of 15% or above, indicating good compression performance. However, at -162 ℃ and -180 ℃, the compression ratios decrease to 12.22% and 7.18% respectively, failing to meet the standard's requirements for compression ratio. Additionally, at all six test temperatures, the rebound ratios of the high-density polyethylene are higher than the requirements specified in the standard. Based on the above analysis, the suitable operating temperature range for high-density polyethylene as a sealing gasket is from room temperature to -110 ℃.



(a) Compression Ratio



(b) Rebound Ratio

Figure 6: Curve of compression and resilience with temperature

3.3 Hardness Test

3.3.1 Test Apparatus

When selecting sealing gaskets for low-temperature applications, hardness should also be taken into consideration. This is because, for most materials, decreasing temperature leads to an increase in hardness. Excessive hardness of the sealing gasket can potentially cause scratching of metal components and leakage issues during operation. Therefore, hardness testing is necessary to determine the hardness of the gasket at low temperatures and ensure sealing effectiveness.

According to the relevant requirements of GB/T 2411-2008 [7] "Determination of Indentation Hardness (Shore Hardness) of Plastics and Hard Rubber Using Hardness Testers", combined with the actual conditions of low-temperature testing, the dimensions of the Shore hardness test specimens were determined. To maintain the desired test temperatures, the thickness of the specimens for low-temperature testing was not stacked, except for the ambient temperature (25 ℃) specimens. In this experiment, high-density polyethylene is classified as a rigid plastic, and the D-scale Shore hardness tester was used.

3.3.2 Experimental Data Analysis and Discussion

The hardness test data is recorded in Table 4, and the trend of hardness variation with temperature is shown in Figure 7.

Table 4: Hardness test data polymer polyethylene

Temperature /°C	**Average Hardness/HD**					**Average Hardness/HD**
	Sample 1	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	
25	64.2	65	64.4	65.2	63	64.36
-29	66.2	67.8	68.2	68.6	68.4	67.84
-50	68.8	68.6	68.6	67.4	69	68.48
-110	68.4	68.2	69.2	69.2	69	68.8
-162	69.8	70.2	68	69.2	70.4	69.52
-180	70.4	68.6	70.8	71.6	71.4	70.56

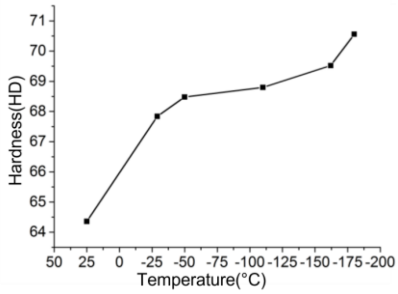


Figure 7: The trend of hardness with temperature

From Figure 7, it can be observed that the Shore hardness of high-density polyethylene gradually increases as the temperature decreases. The curve slope indicates a relatively rapid increase in the range of 25 ℃ to -50 ℃, and as the temperature further decreases, the rate of increase in Shore hardness becomes slower. When the temperature decreases from 25 ℃ to -180 ℃, the Shore hardness (HD) increases from 64.36 to 70.56, which is a 9.63% increase. From a microscopic molecular structure perspective, as the temperature decreases, the internal molecular motion of the high-density polyethylene slows down, resulting in increased material stiffness and hardness. As the temperature continues to decrease, the rate of change in molecular motion decreases, leading to less significant changes in hardness. Therefore, when the temperature decreases from -29 ℃ to -180 ℃, the hardness increases by 4.2%. The maximum hardness of high-density polyethylene at -180 ℃ was measured as 70.56 HD. The hardness of high-density polyethylene at low temperatures is suitable and will not cause damage to sealing surfaces and valve components.

4. Conclusion

In this study, the mechanical properties of high-density polyethylene material at low temperatures were analyzed through experiments, and the suitable operating temperature range for high-density polyethylene at low temperatures was determined. By analyzing the experimental data, the appropriate working temperature range for high-density polyethylene at low temperatures was obtained. The compression test provided the compressive failure stress of high-density polyethylene at different temperatures. The results of the compression test indicated that the compressive stress of high-density polyethylene decreases as the temperature decreases. The results of the compression rebound test showed a decrease in compressibility and an increasing trend in resilience with decreasing temperature. The hardness test results showed that high-density polyethylene at low temperatures has suitable hardness and will not cause harm to valve components. The comprehensive analysis of the three tests concludes that high-density polyethylene is reliable for working in low-temperature environments at temperatures above -110 ℃.

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