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Innovation in Seal Production: Novel Additive Manufacturing for High-Performance PU Seals

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Our study unveils a groundbreaking additive manufacturing (AM) technology poised to redefine the standards of polyurethane seal production. By meticulously merging the precision of AM with the robustness of injection-molded TPU, this technology not only promises to bridge existing manufacturing gaps but also to set new benchmarks for seal performance and durability. Our rigorous evaluation underscores the technology's superior design flexibility, enabling the creation of custom, high-performance seals that surpass traditional capabilities in both efficiency and environmental sustainability. The results of our comprehensive testing and validation process reveal a significant leap forward, offering not just an alternative but a superior solution in seal manufacturing. We propose this AM technology as a transformative force capable of revolutionizing industry standards and paving the way for innovative applications across sectors. This is not just an advancement; it's a call to reimagine what's possible in seal manufacturing.

1 Introduction

The sealing industry continually seeks advancements to improve the performance and longevity of seals used in diverse applications. This paper explores the utilization of additive manufacturing (AM) techniques for producing high-performance PU seals, offering a detailed analysis of the benefits and challenges associated with this innovative approach.

1.1 Background

Polyurethane seals are widely recognized for their exceptional mechanical properties and resistance to wear and chemicals. Traditional manufacturing processes for PU seals typically involve molding techniques, which may limit design flexibility and increase costs for small series. Additive manufacturing, also known as 3D printing, offers a transformative alternative that can overcome these limitations by enabling complex geometries and material customization. [1]

This paper focuses on polyurethane technology by comparing traditionally produced polyurethane seals with their additively manufactured counterparts. Additive technologies available to produce polyurethane parts include solid extrusion or selective laser sintering (SLS) of TPU resins, utilizing filament extrusion (FDM), pellet extrusion, or SLS processes involving TPU powders. Additionally, reactive extrusion technology is highlighted, where a reactive liquid two-component system consisting of an isocyanate and a polyol component reacts during the printing process to form crosslinked polyurethane resin.

In this paper, we will exclude comparisons to other additive manufacturing technologies that cannot process pure polyurethane materials. Examples include solid extrusion-based methods, where a solid plastic or thermoplastic elastomer is processed into a filament. These filaments are often composed of the same plastic formulations as those used in traditional injection molding processes. The idea behind this process is that using similar polymers with a novel method to build the structure would result in a part with comparable mechanical properties. Unfortunately, while operating at similar temperatures to traditional injection molding, solid extrusion-based processes lack the pressures needed to entangle polymer chains. This results in lower material strength in the build direction of the production process, often up to 50% less, making them unsuitable for high-performance applications.

Even if this drawback can be overcome, solid extrusion-based processes involve placing a heated, flowable, but highly viscous polymer bead on top of an already cooled and solid polymer. Due to the high viscosity of the flowable bead, the contact areas between beads always contain voids, forming channels in the movement direction of the printhead. These voids create two problems: they are starting points for mechanical failure and contribute to crack propagation, and they allow fluids in the form of gases or liquids to travel through the part.

In powder processing technologies similar to solid extrusion, there is no applied pressure to ensure polymer chains entangle to achieve the same tensile strength as traditionally manufactured parts. Additionally, these processes depend on applying melted material onto solidified polymer resin, creating similar channels. While there are methods to post-process or soak surfaces to close voids or channels, these often involve coating with a different material that might not be compatible with the sealing application.

In conclusion, solid extrusion and powder melting processes have the drawbacks of non-isotropic material properties, as well as voids and channels that allow fluids to pass through, which is a significant issue for sealing applications. Reactive extrusion technology, though similar in processing to solid extrusion methods, distinguishes itself by combining the two components needed to make polyurethane during the form-giving process. No heat is applied, and no pre-reacted polymer is melted in the process. The closest comparison to traditional production processes is casting, where polyurethane is made by mixing an isocyanate and a polyol component in liquid form before filling the liquid into a mold. Chemically, the only difference between PU casting and PU reactive extrusion processes is the absence of a mold.

If the reactivity and print parameters are chosen carefully, the material will flow as a liquid bead onto the solidified layer below. The solidified layer and the new bead will have unreacted isocyanate and polyol groups on the surface, allowing for interlayer and interbead adhesion to provide isotropic material properties. High-performance PU materials tailored to the reactive extrusion process will enable the production of high-performance seals.

1.2 Objectives

The primary objective of this study is to evaluate the feasibility and performance of PU seals produced using AM techniques. Specific goals include:

- Assessing the mechanical properties and durability of AM-produced PU seals.
- Comparing the performance of AM seals with traditionally manufactured seals.
- Identifying potential applications and industry benefits

2 Methodology

2.1 Materials and Equipment

Material Development and Selection: Reactive extrusion technology cannot utilized by traditional 2K PU cast systems. These systems are designed to have very low viscosity, fill all mold cavities, and be processable within minutes. However, the material requires a higher viscosity to build structure for reactive extrusion. Therefore, a completely new type of 2K PU system needed to be developed.

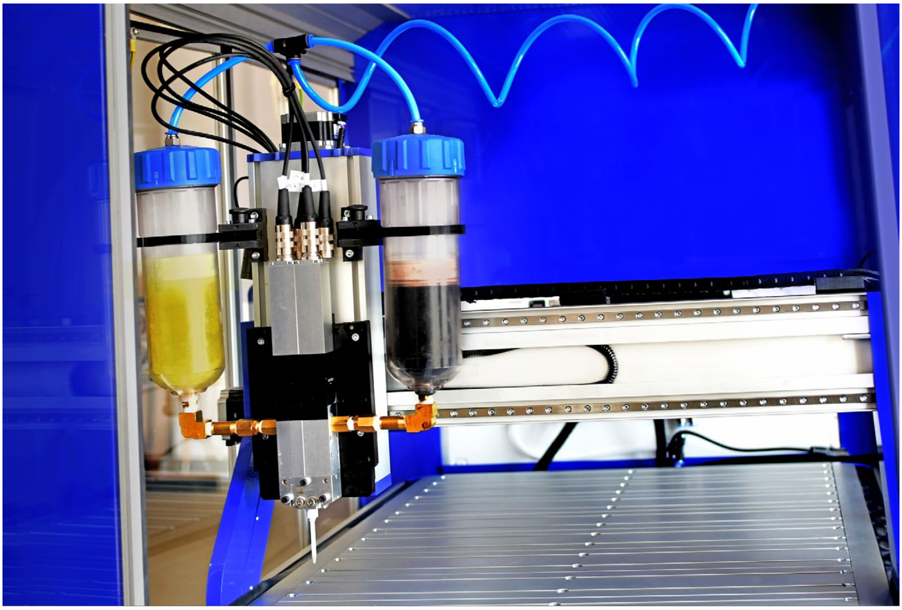


Figure 1: RX-AM 3500 printer from Chromatic 3D Material

This new system had to be created using only commercially available and registered chemicals, as this is a prerequisite for large-scale industrial applications, which are the only type of applications that will provide a payback for such material development endeavors. Several 2K PU systems are commercially available, and for these trials, ChromaLast 90 was chosen. It was developed to have a high tensile strength at a Shore A Hardness of 90, with a compression set below 30% at a temperature of 100˚C

Additive Manufacturing Software and Equipment: To create a shape using additive manufacturing, a design in the form of a CAD file has to be transformed into a machine path for the 3D printer to follow. In solid extrusion technology, commercially available slicing software such as Simplfy3D or Cura will create the tool path with the click of a button. The machine path created does not take into account the changes in viscosity and flow behavior of printing with a liquid 2-component system. Thus, next to standard slicing software, a post-processor, in this case, ChromaWare, was used to alter the tool path so that the deposited liquid could solidify into the desired shape during the printing process.

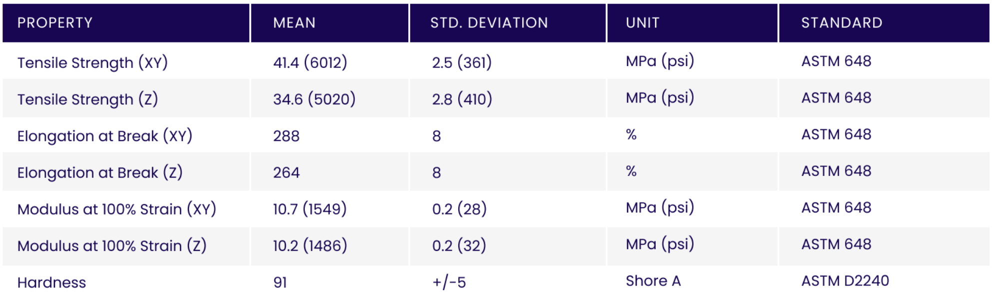
- The gaskets were printed on a 1st generation RX-AM 3500 printer from Chromatic 3D Materials equipped with a ViproDuo 5/5 printhead by Viscotec. A Sulzer Mixpac MKH 02-16S was used to combine the liquids.
- During the printing process, the print parameters were chosen, and the mixing of the two components was done within a window to allow for optimal material properties as well as inter-layer and inter-bead times that create a solid part with uniform material properties.

2.2 Experimental Setup

A series of tests were conducted to evaluate the performance of the AM-produced PU seals. These tests included:

- **Tensile Strength Test**: To measure the material's resistance to tension.
- **Compression Set Test**: To assess the seal's ability to return to its original thickness after compression.

Table 1: Mechanical Properties of ChromaLast 90



PROPERTY	MEAN	STD. DEVIATION	UNIT	STANDARD
Tensile Strength (XY)	41.4 (6012)	2.5 (361)	MPa (psi)	ASTM 648
Tensile Strength (Z)	34.6 (5020)	2.8 (410)	MPa (psi)	ASTM 648
Elongation at Break (XY)	288	8	%	ASTM 648
Elongation at Break (Z)	264	8	%	ASTM 648
Modulus at 100% Strain (XY)	10.7 (1549)	0.2 (28)	MPa (psi)	ASTM 648
Modulus at 100% Strain (Z)	10.2 (1486)	0.2 (32)	MPa (psi)	ASTM 648
Hardness	91	+/-5	Shore A	ASTM D2240

2.3 Additive Manufacturing Strategies

Alternative trials were conducted to explore the novel additive manufacturing method, testing different printing strategies and employing both 2K and 4K options. In this context, 2K refers to a single material produced by combining two components, while 4K involves using two different materials in one print, each created from two components.

Below is the list of Printing Strategies employed:

- 2 Walls: 2K Material of 90 Shore A PU
- 2 Walls + Base: 2K Material of 90 Shore A PU
- 2 Walls + Base: 4K Material of 90 Shore A Walls and 65 Shore D Base
- 1 Wall + Base: 4K Material of 90 Shore A Walls and 65 Shore D Base
- 1 Wall: 2K Material of 90 Shore A PU – Solid billet

2.3.1 2 Walls Strategy: 2K Material of 90 Shore A PU

The strategy involved printing two walls close to each other and allowing the beads to mix. However, the cross-section of the initial iterations revealed that the walls were not melding together properly. To address this, a filling extrusion (indicated by the red marker) was introduced to ensure the binding of the two walls.

The main challenge with this strategy was printing with over-dimensions to allow for machining afterward. Printing with over-dimensions required the print motions to be further apart, which meant that the beads needed to be thicker to merge properly. Increasing extrusion and speed helped with bead size, but higher speeds resulted in a less viscous extruded mixture that also did not hold its shape.

Figure 2: Cross-Section of First Iteration

To ensure the best concentricity, the print had to be done in a vase mode. Finding the optimal parameters required numerous iterations, balancing extrusion, speed, and bead thickness to achieve the desired results.

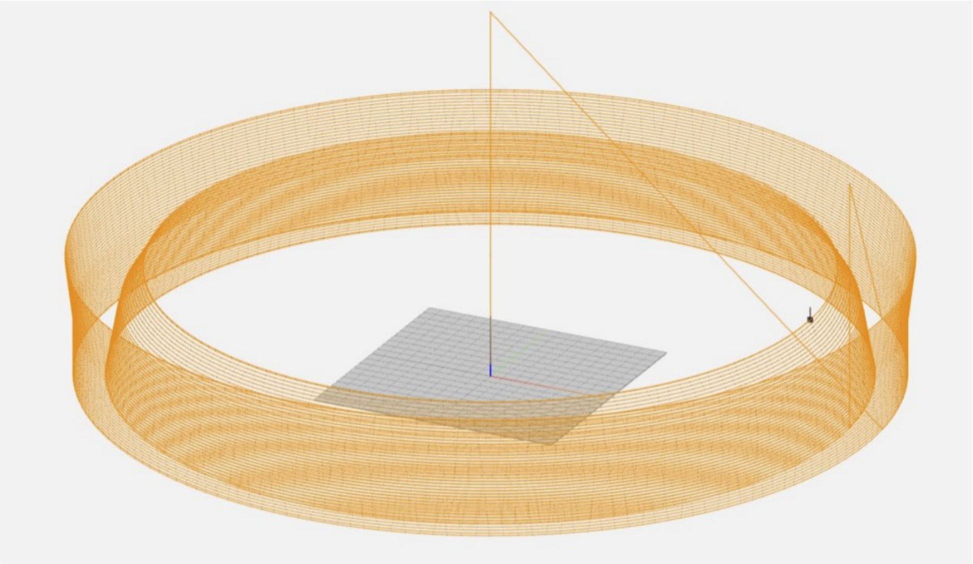


Figure 3: Printing path for 2 Wall strategy

Figure 4: Injection molded XT200 vs 2 Wall Print

2.3.2 2 Walls + Base Strategy: 2K Material of 90 Shore A PU

Printing a base increases the spread of the bead, as the surface properties of the material cause a stronger attraction to itself than to other materials. With a base, the aim is to print thicker and more homogeneous walls.

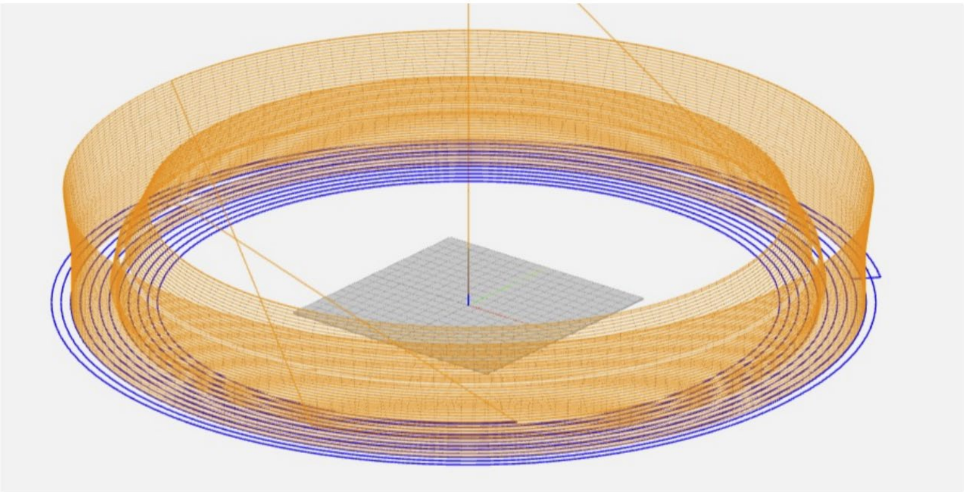


Figure 5: Printing path for 2 Walls + Base

A disc was printed to ensure a good merge at the Base of the print. Printing with more material per mm and at a faster rate increased the bead width. However, this also resulted in decreased stiffness and predictability of the material.

Figure 6: Comparison of Printed seal vs Injection Molded seal

Proper positioning of the walls, along with appropriate extrusion and speed settings, allowed for near-voidness printing. However, as the bead became saggy and easily disturbed, the shape of the cross-sections began to worsen. A suitable combination of parameters was achieved, resulting in a print with machining allowance but an irregular shape for work holding.

2.3.3 2 Walls + Base Strategy: 4K Material of 90 Shore A Walls and 65 Shore D Base

The objective of this project was to print a gasket using two different materials. Initially, the strategy involved printing the Base and the first three layers of inner and outer walls with D65 material, followed by switching to Shore A90 for the remaining walls. However, this approach resulted in a significant cavity between the walls due to the material transition. A second strategy was implemented to address this, which involved a billet-like print method. This method printed consecutive concentric circles with a smaller bead width than the wall thickness, resulting in better control and reduced voids.

Figure 7: Cavity in the base plate of 65 Shore D material

The billet-like print method improved printing by eliminating voids and providing better dimensional control. However, printing numerous layers created a rough axial surface texture, so the Base was printed oversized to compensate. Additionally, the viscous nature of the material caused the corners of the printed parts to round, requiring the Base to be printed oversized for a flatter surface. Despite these adjustments, cross-sections of the prints showed inconsistencies, with varying degrees of sagging and voids. However, samples for testing were created successfully despite the difficulties.

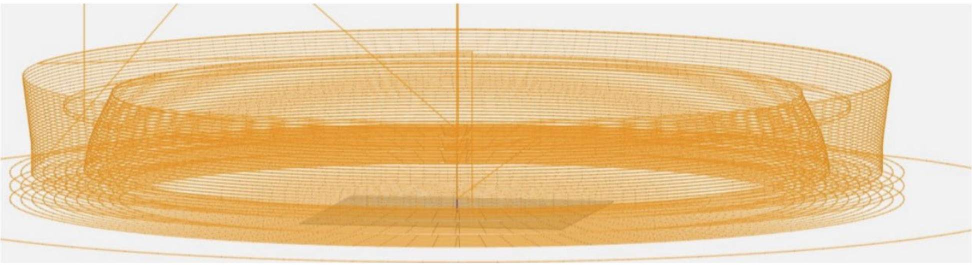


Figure 8: Printing path for 4K material

Using a base material with a Shore D hardness of 65 enabled further machining without the need for clamping rings, thanks to the high hardness of the base material. Additionally, this choice improved the extrusion resistance of the seal during high-pressure testing.

2.3.4 1 Wall + Base: 4K Material of 90 Shore A Walls and 65 Shore D Base

The strategy involved laying concentric beads from the outside to the inside to create a disc of 65 Shore D, then repeating this process to stack discs on top of each other. At a height of 3mm, the Shore A90 material was primed, and the printing continued. This method produced a raw material that could be fully machined to shape the gasket.

Figure 9: 4K material into near-net-shape billet

Cutting the billet revealed a print without voids. However, different materials have different printing properties, so using the same print parameters resulted in varying dimensions. Print speed and extrusion were adjusted for each material section to achieve the desired dimensions. To facilitate further tests of entirely shaped gaskets before developing a near net shape multi-material print and sent for machining.

2.3.5 1 Wall: 2K Material of 90 Shore A PU – Solid Billet

Another strategy we tested involved printing long billets directly to machine seals. This approach allowed us to prepare billets without the need for molds, streamlining the production process. By continuously extruding material to form elongated billets, we were able to produce a uniform and consistent raw material. This method provided greater flexibility in manufacturing and reduced the time and costs associated with mold preparation. The long billets could then be machined to the precise specifications required for high-performance seals, ensuring both efficiency and quality in the final product.

Figure 10: 2K 90 Shore A Billet

3 Results

All the samples were tested on the test rigs of Kastas Sealing Technologies R&D Test Center. Two sets of test runs will be presented on paper from the seals acquired with different print strategies.

3.1 Results of Test Group I

The first group of seals was tested for 10 km at a pressure of 50 bar, followed by another 10 km at 240 bar. The seals failed before completing the second 10 km at the higher pressure due to significant leakage. Upon disassembly, the seals exhibited excessive extrusion and a high level of deformation. These results indicate that the 90 Shore A 2K PU material, combined with the initial set of strategies, was insufficient to meet the demands of standard hydraulic applications.

Tested seals are listed below:

- Sample 1B: 2 Walls: 2K Material of 90 Shore A PU
- Sample 1A: 2 Walls + Base: 2K Material of 90 Shore A PU
- Sample 2A: 2 Walls + Base: 2K Material of 90 Shore A PU

Three samples were tested using the test parameters below in the first test group.

Table 2: Test Group I - Test Parameters

Test Parameter	1st Period	2nd Period
Pressure (Bar) :	50	240
Speed (m/s):	0,3	0,3
Target Distance (km):	10	10
Temperature (°C):	60	60
Range of Extrusion Gap (mm):	0.15	
Media:	Vg 46 Hydraulic Oil	

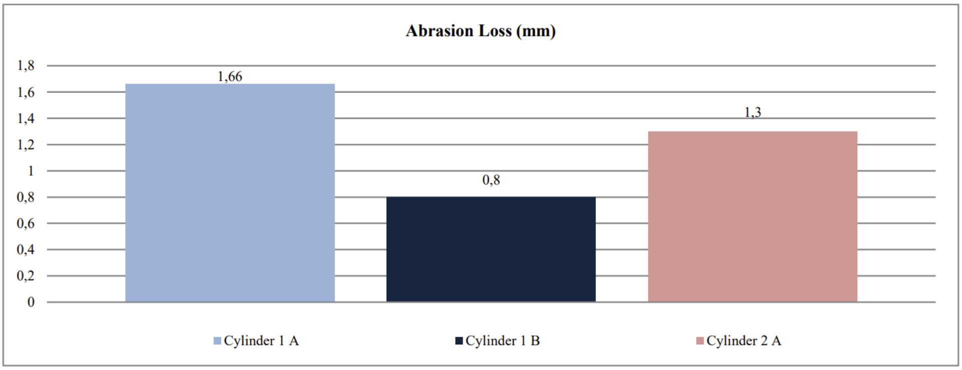


Figure 11: Abrasion loss results for Test Group 1

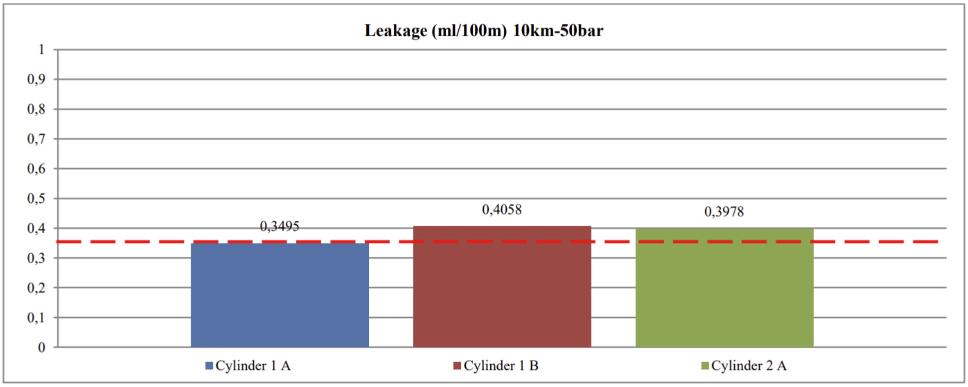


Figure 12: Leakage results for Test Group 1

Sample 1A: 2 Walls + Base: 2K Material of 90 Shore A PU

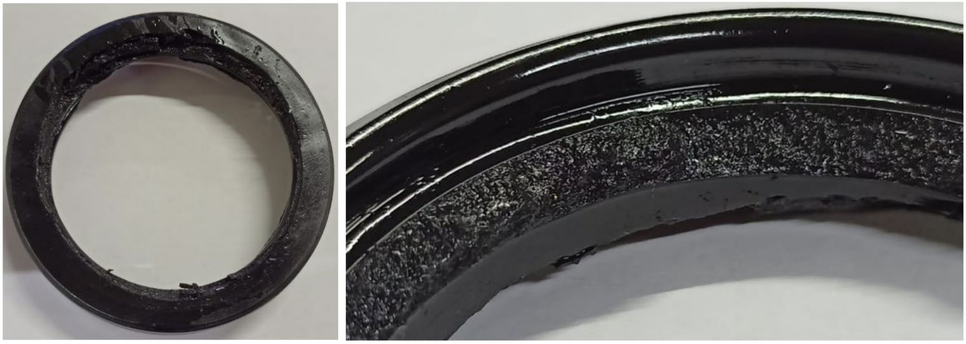


Figure 13: Sample 1A After testing

Sample 1B: 2 Walls: 2K Material of 90 Shore A PU

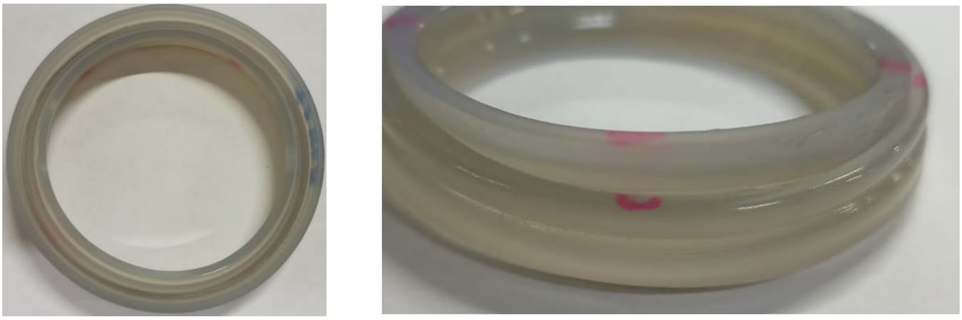


Figure 14: Sample 1B After Testing

Sample 2A: 2 Walls + Base: 2K Material of 90 Shore A PU

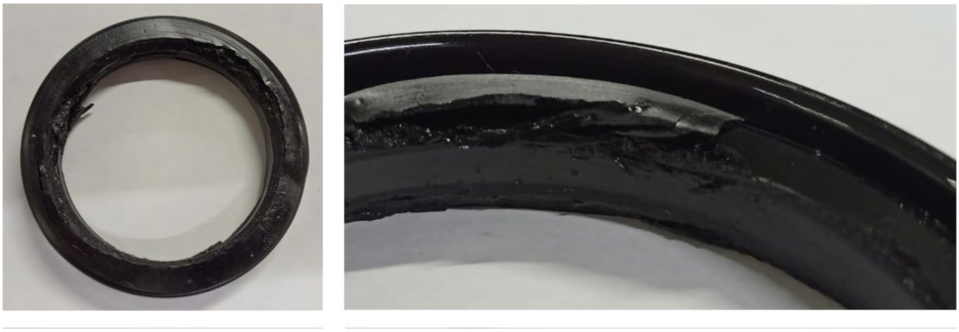


Figure 15: Sample 2A After testing

3.2 Results of Test Group II

Improved printing strategies were employed for the second set of tests, enabling higher pressure testing over a longer duration of 80 km or 220,000 cycles. The seals withstood the testing, although they exhibited higher-than-usual levels of leakage and visible extrusion, except for the 4K material with a 65 Shore D base, which performed more reliably.

Tested seals are listed below:

- Sample 2A: 2 Walls + Base: 2K Material of 90 Shore A PU
- Sample 2B: 2 Walls + Base: 4K Material of 90 Shore A and 65 Shore D PU
- Sample 3A: 1 Wall: 2K Material of 90 Shore A PU – Solid billet

Table 3: Test Group II - Test Parameters

Test Parameter	1st Period	2nd Period
Pressure (Bar) :	50	240
Speed (m/s):	0,3	0,3
Target Distance (km):	10	70
Temperature (°C):	60	60
Range of Extrusion Gap (mm):	0.15	
Media:	Vg 46 Hydraulic Oil	

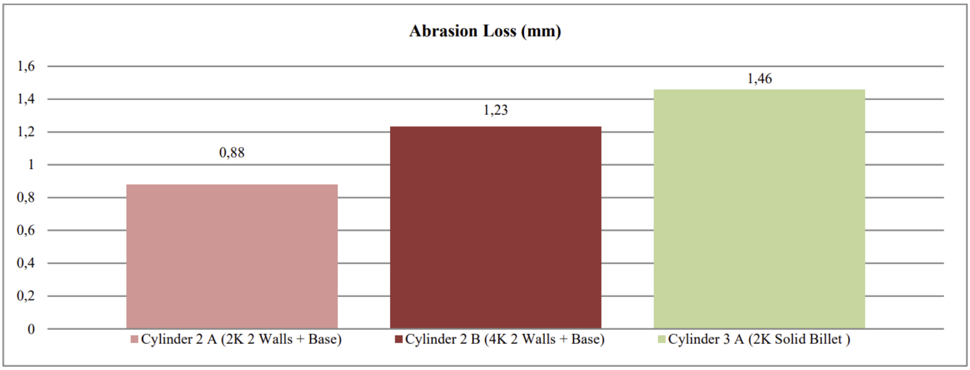


Figure 16: Test Group II – Abrasion Loss

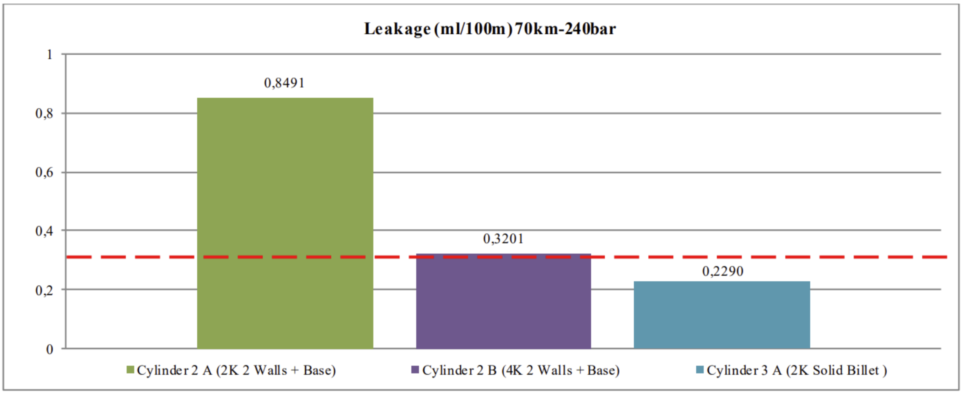


Figure 17: Test Group II – Leakage

Sample 2A: 2 Walls + Base: 2K Material of 90 Shore A PU

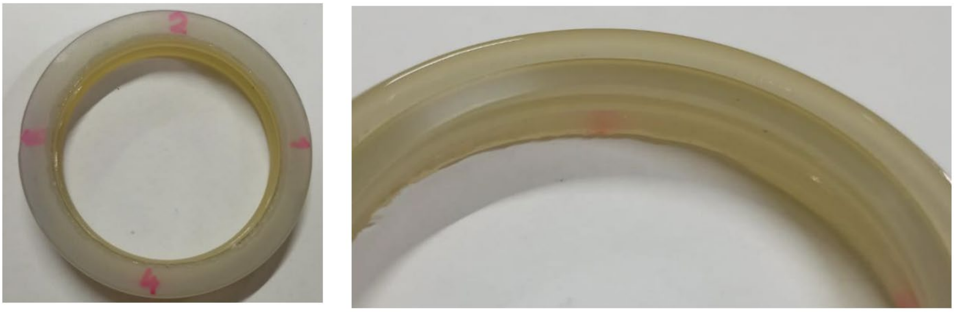


Figure 18: Sample 2A After testing

Sample 2B: 2 Walls + Base: 4K Material of 90 Shore A and 65 Shore D PU

Figure 19: Sample 2B After Testing

Sample 3A: 1 Wall: 2K Material of 90 Shore A PU – Solid billet

Figure 20: Sample 3A After testing

4 Summary and Conclusion

This study explores the innovative use of additive manufacturing (AM) technologies to produce high-performance polyurethane (PU) seals. By merging the precision of AM with the robustness of injection-molded TPU, the research aims to bridge existing manufacturing gaps and set new benchmarks for seal performance and durability. The comprehensive testing and validation results indicate that while the initial strategies using 90 Shore A 2K PU material were insufficient for standard hydraulic applications, subsequent strategies demonstrated improved outcomes.

Introducing a billet-like print method and using 4K materials with a 65 Shore D base showed significant improvements in extrusion resistance and overall seal integrity under high pressure. Despite some challenges with leakage and dimensional consistency, the refined strategies allowed for better control over the final dimensions and reduced void formation.

In conclusion, the novel AM technology presents a transformative solution for the seal manufacturing industry, offering enhanced design flexibility, material customization, and environmental sustainability. The findings underscore the potential for AM technologies to revolutionize industry standards and pave the way for innovative applications across various sectors. Further research and optimization of print parameters and material combinations are recommended to fully realize the benefits of this approach in large-scale industrial applications.

Further printing strategies should be explored to fully exploit the design freedom provided by the AM method, maximizing the potential of this technology. Future trials will include such design instances to bring additional value to the finished seals. By continuously refining and expanding these strategies, we can enhance AM-produced seals' performance, durability, and applicability, ensuring they meet and exceed industry demands.

5 References

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