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Selection and Characterization of a Flexible Seal to Allow Sheet Flow during Superplastic Forming †

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Abstract: The auto industry aims to deliver cost-effective, efficient vehicles to meet customer needs. They are utilizing aluminum to lower expenses, enhance durability, and lighten vehicles. Currently, the industry is developing a high-speed blow forming (HSBF) technique—a faster version of the aluminum thermoforming process, superplastic forming (SPF). HSBF allows the rapid creation of aluminum bodywork or structural parts at high temperatures using pressurized gas. It can produce up to 25 parts per hour, significantly faster than SPF, which only produces 4 parts per hour. The primary objective of this project is to select and characterize a seal that can increase the production rate to 120 parts per hour by allowing the sheet to flow into the mold, especially during the initial stages of the forming process, where most of the deformation occurs. Several test benches were developed to assess the performance and durability of the selected high-temperature seals under conditions that imitate the HSBF process. During the tests, low air pressures are applied to a gasket-enclosed cavity and the resulting mass-flow leakage is measured. The temperature of the mold is kept constant at approximately the superplastic temperature of the aluminum alloy. Through testing, we derived leakage mass flow curves based on cycle count, showcasing the superior sealing ability and longevity of packing seals in HSBF conditions. The seals displayed good durability and sealing performance under HSBF operational conditions, sustaining over 3000 cycles. Moreover, the seals attained a leakage mass flow rate of around 0.3 g/s·m·bar, nearly ten times below the target application limit of 2 g/s·m·bar, confirming their superior performance.

Keywords: aluminum; seal; sealing; aluminum; life span; wear

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1. Introduction

Over the past five decades, the use of aluminum in the automotive industry has steadily increased, leading to a gradual replacement of mild steel. The amount of aluminum used in a car has increased from less than 38 kg to 180 kg [1]. By 2026, the amount of aluminum contained per vehicle will further increase by 12% compared to 2020 levels [2]. Several manufacturing techniques are used to produce aluminum automotive parts including stamping, bending, and low- and high-pressure gravity casting [3]. Air-vacuum-assisted casting is a technique that produces parts of high quality and integrity, and these are used in structural applications. Other processes such as hydroforming and thermoforming are also used, but on a smaller scale.

The high cost of production compared to steel is one of the main factors limiting the growth of aluminum use in the automotive industry. The production of aluminum is a process that requires a large amount of energy and time, which can increase its cost of production compared to other materials [4]. Additionally, producing automotive-grade aluminum requires advanced technology and high precision, which can also add to the cost. The cost of production of aluminum is higher than that of steel, and this situation is unlikely to change in the short term [5]. This reality may curb the growth of aluminum use in the automotive industry, as automakers often seek to reduce production costs to maintain market competitiveness.

The innovative "High-Speed Blow Forming" (HSBF) technique aims to efficiently create complex, high-strength aluminum structures from sheet materials [6]. This groundbreaking method, a combination of crash forming and gas blow forming, found its initial application in electric car manufacturing [7]. Notably, HSBF can produce up to 25 parts per hour, significantly outperforming traditional superplastic forming methods [8], which typically produce 4 parts per hour [9–11]. Particularly suited for bodywork and aluminum structure part manufacturing, this method shows great promise. The ultimate goal of the HSBF process is to enhance production efficiency by achieving a production rate of 120 parts per hour. This can be achieved by integrating a compliant seal in the process, which allows flow of material into the cavity, increasing the quantity of material available for forming. This increase is set to expedite the incorporation of aluminum alloys in vehicle body design through a more streamlined formation of aluminum sheets [12]. The strategy to increase the production rate revolves around eliminating current process bottlenecks, namely (1) the acceleration of sheet heating, and (2) the facilitation of sheet flow during the preliminary forming phase.

This study directs its focus on the latter task, specifically managing the sheet metal flow during the low-pressure forming phase. The challenge arises if the sheet metal fails to "flow" past the sealing bead and into the mold while undergoing stretching. In such instances, excessive thinning can occur, potentially leading to cracks and part failure. The objective of this study is to enhance the movement of the aluminum sheet by employing a seal to avoid any blockage of sheet flow into the mold during this phase. Hence, it is crucial to identify and utilize a seal that can effectively mitigate air leaks while permitting the material to smoothly transition into the mold.

2. Seal Selection Study

In order to select the most appropriate seal to improve the flow of aluminum sheet into the mold, several small-scale experimental trials were conducted. These tests are aimed at characterizing the seals under conditions similar to those of the manufacturing procedure. Importantly, it should be noted that the experimental laboratory tests were conducted at ambient temperature.

A first test rig, shown in Figure 1, allowed preliminary selection of the most promising seal candidates. Compressed air was supplied to a cavity, the flow rate of which was manually controlled by a flow controller. A pressure transducer was used to measure the pressure in the cavity. All the sensors were connected to a data acquisition card (NI USB 6008) to collect data for each sample. A LabVIEW interface was developed to monitor all variables during the experimental tests.

The seals were placed between an aluminum plate containing the cavity and the aluminum sheets. This configuration allowed for the measurement of leakage against cavity pressure for seals having a length of 0.5 m. To ensure uniform distribution of the force applied to the gaskets, the two plates were clamped together with four bolts, connected by two rigid steel rods. Under these two rods, two load cells were installed, each capable of measuring a maximum force of approximately 100 kN, in order to provide an accurate measurement of the force applied on the joints.

Multiple seal families were tested, such as packing seals, tadpole seals, and ceramic rope seals. All seals were heat treated before testing by placing them in an oven at 500 °C for 24 h. By analyzing test results from these various seal types, the most promising candidates for high-temperature applications were chosen. Figure 2 displays normalized leakage rates as correlated to the linear force exerted on the seal. The red lines denote the permissible range for leakage levels and the applied force to the gasket that will secure the aluminum sheet, thus providing an estimation of maximum leakage and force parameters for a given system. The results show that packing seals outperform others in terms of sealing and withstanding high temperatures, allowing us to further focus our study on these seals.

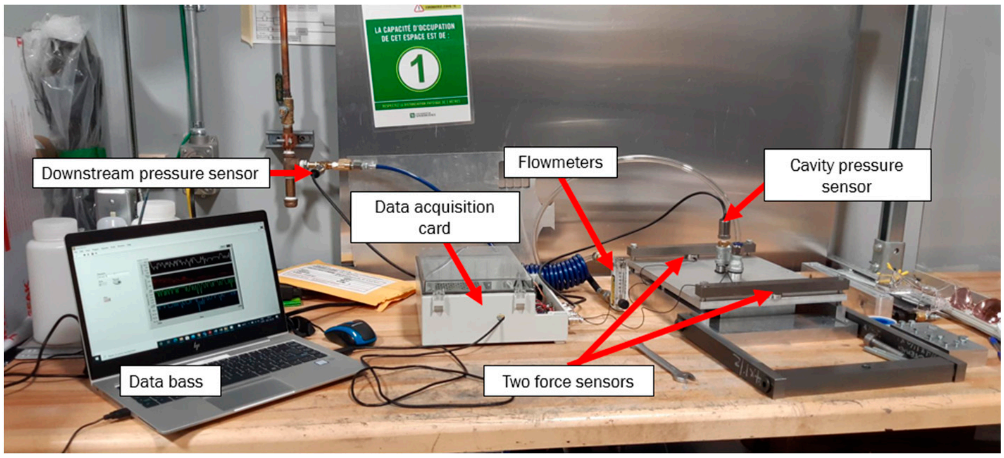


Figure 1. Global view of the test bench to evaluate the air leakage.

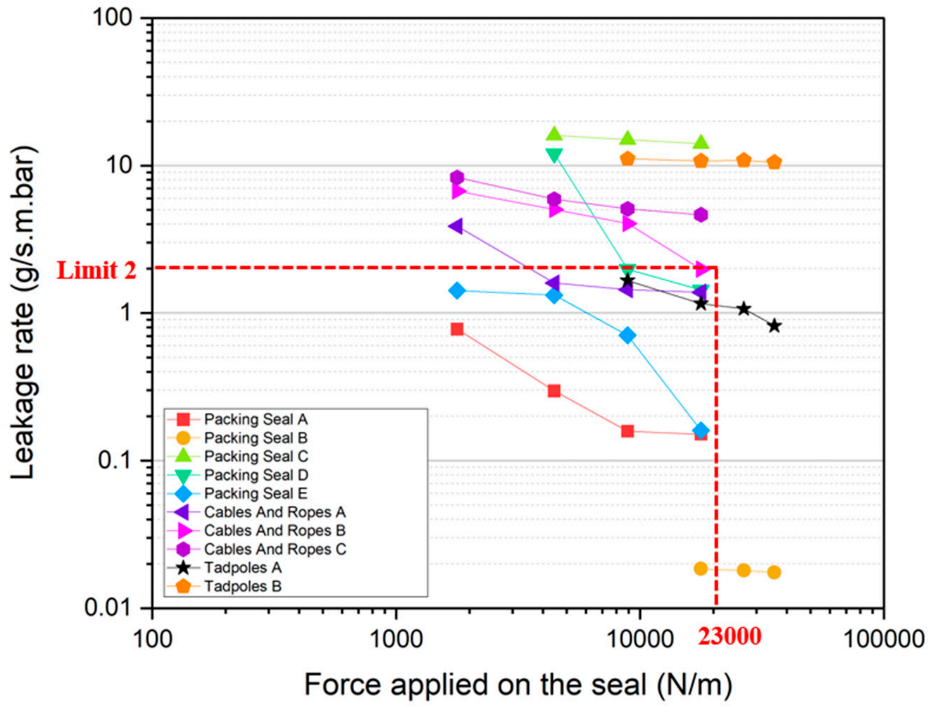
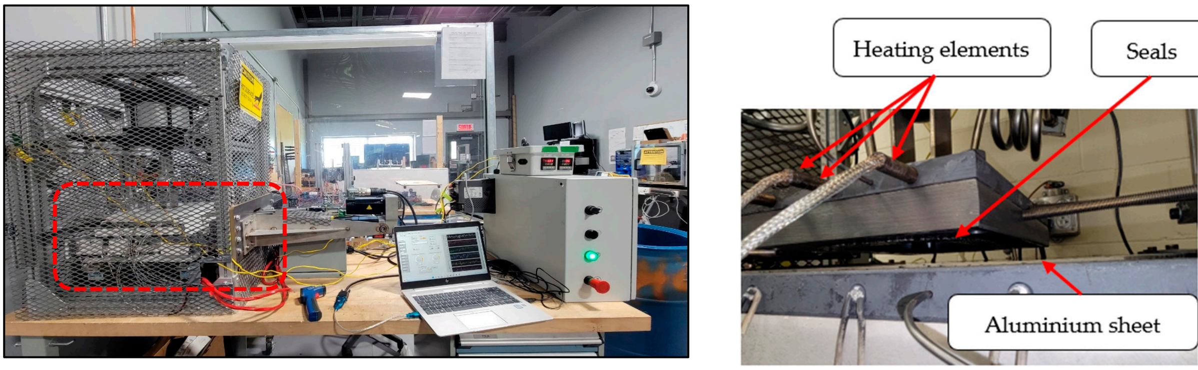


Figure 2. Data from tests conducted on various joint types.

3. Durability Test Bench

A second test rig was designed to evaluate the impact of forming conditions on the durability of selected joints, based on the manufacturing cycle. An overview of the final assembly is shown in Figure 3. A first pneumatic actuator is used to simulate the forces exerted on the seal during the thermoforming cycle, as well as the opening and closing movement of the mold during each cycle. A second electrical actuator (Kollmorgen EC5) is used to generate horizontal movement at a predetermined speed, simulating material movement at the seal by moving the bottom plate on which the sheet is attached.



(**a**) (**b**)

Figure 3. (**a**) Overall view of the test bench installed in the Lab. (**b**) Inside the rig test.

The test rig was designed to operate at the superplastic temperature of aluminum, approximately in the range of 450 °C to 550 °C. To reach this temperature, twelve heating elements of 500 W each were installed. These elements were divided into two groups: six to heat the upper plate, which were coupled to the pneumatic actuator, and six to heat the lower plate, which were coupled to the electric actuator. The elements were controlled by two temperature controllers (REX-C100), which were connected to two thermocouples on each plate. A pressure regulator (Festo VPPM) controlled the force applied to the upper plate, while a pressure transducer was installed to measure the pressure in the pneumatic actuator, which was then converted into force. Solenoid valves were also installed to control the direction of movement of the cylinder. A mass-flow controller (ALICAT) is used to measure leakage. All these actuators and measurement devices were connected in an electrical cabinet and controlled by a NI DAQ 6008 control board, which was connected to a computer via an interface developed with LabVIEW. Figure 4 illustrates the specific steps in the test bench process.

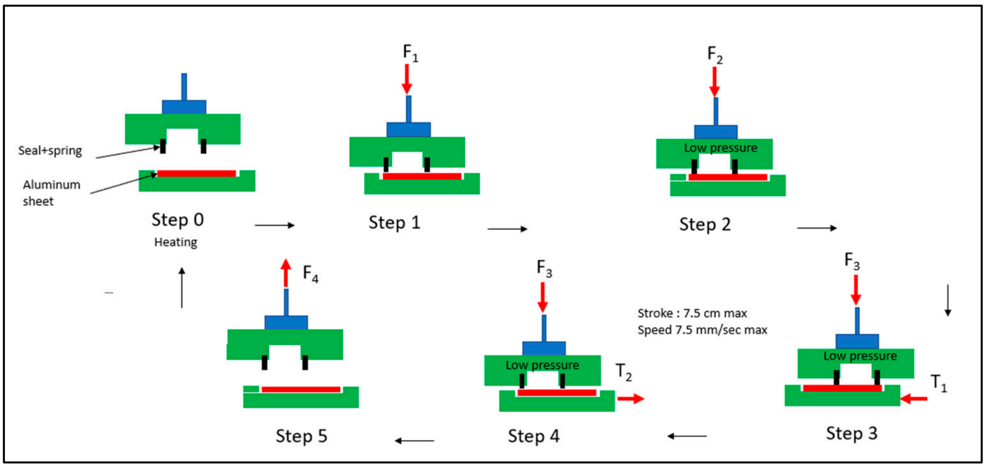


Figure 4. Test bench process phases.

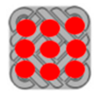
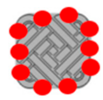
Phase 0 encompassed the process of elevating the test bench temperature to a minimum of 500 °C using 12 heating elements, each with a power of 500 W. Following Phase 0, the cycle proceeded to Step 1, which involved the application of an approximately 6.7 kN force to engage the joint. Subsequently, in Steps 2 and 3, air was introduced into the cavity at low pressure. This pressure increase induced a counter-force on the joint, generated by the opposing pressure exerted by the injected air. The subsequent activation of the linear actuator (electric cylinder) initiated a horizontal displacement of the bottom plate, resulting in a reciprocating motion. Moving to Step 4, once the complete motion cycle was accomplished, the pressure was released. Finally, the pneumatic cylinder ascended to simulate the mold's opening. To enable this entire cycle, an application developed on LabVIEW, specifically tailored for this purpose, automated and controlled the process.

This test rig had two main purposes. First, it aimed to ensure that the gasket under test can withstand extreme heat conditions and that it had an adequate service life in this situation. Second, it evaluated leakage levels, which have a significant impact on the quality of the final part. To achieve these goals, the test rig performed several measurements, including monitoring cavity pressure with a pressure transducer, quantifying leakage rate with an Alicat flow meter, monitoring temperature to ensure it is in the proper range, and applying a specific pressure to the seal.

4. Durability Results and Discussion

The top three candidates (see Table 1) were subjected to durability tests to verify their wear resistance. The preliminary durability objective is that the seals should be able to withstand at least 3000 thermoforming cycles while maintaining leakage rates below 2 g/s·m·bar.

Table 1. Packing seal candidates for durability testing.

Type of Seal	Description	Schematic
Seal A	Packing seal, no reinforcement	
Seal B	Packing seal, internal metal reinforcement	
Seal C	Packing seal, external metal reinforcement	

The results of our study, shown in Figure 5, indicate promising results for two seal candidates: Seal A and Seal B. Both of these candidates showed considerable resilience and durability, meeting our target of 3000 cycles. More precisely, the leakage rate for these two candidates did not exceed our set limit, remaining below 0.3 g/s·m·bar, well below our maximum authorized threshold of 2 g/s·m·bar. This suggests that Seal A and Seal B have suitable sealing capabilities that can maintain the desired performance levels over extended operational cycles. On the other hand, Seal C presented contrasting results. During the cycling tests, it exhibited rapid degradation and loss of sealing capability. Seal C could not meet the 3000-cycle target, showing significant signs of failure after only 650 cycles. The quick deterioration observed in Seal C, leading to the exposure of metal reinforcement wires and creation of a leakage path, suggests possible issues with its durability and operational lifespan. Based on these test findings, Seal C may not be a suitable choice.

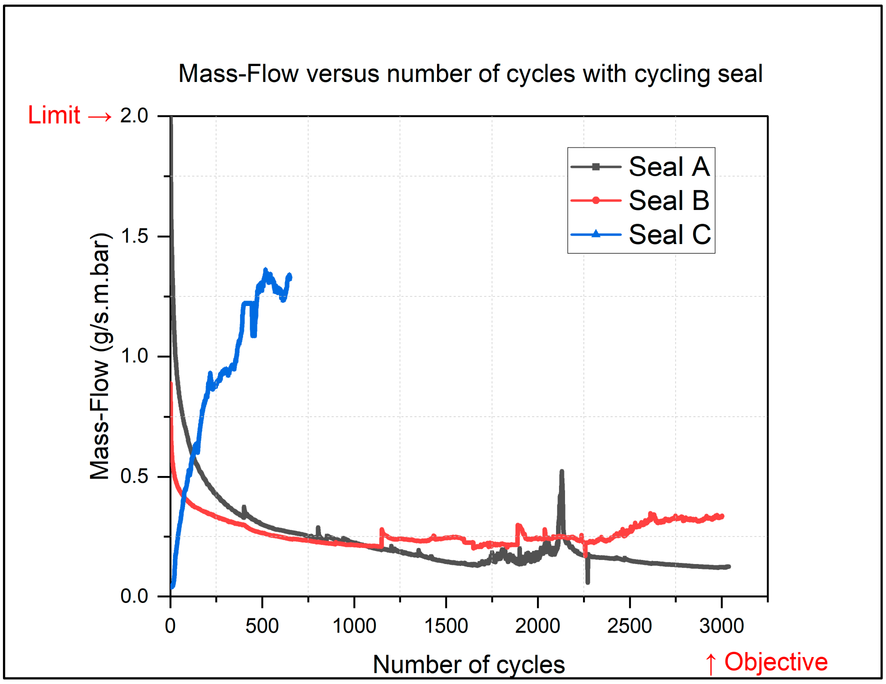


Figure 5. The variation of the mass flow according to the number of cycles performed.

5. Conclusions

Packing seals surpass the sealing demands set for the initial stage of high-speed blow forming, especially under high temperature conditions. Following rigorous testing, two suitable candidates, either with internal metal reinforcement or without any reinforcement, were identified. These candidates can endure up to 3000 thermoforming cycles, while achieving a low leakage rate of 0.3 g/s·m·bar, almost 10 times lower than the acceptable limit. However, a contrasting pattern emerges with outer metal-reinforced seals. Their rate of degradation far surpasses other packing seals, leading to a significant decrease in their performance and longevity. As a result, they are deemed less suitable for integration into the new process.

These insights, derived from testing and analysis, provide valuable data that can guide the optimization of the design and material selection for future seal candidates. Utilizing this knowledge could greatly enhance the durability and efficiency of future seals, thereby ensuring they meet the demanding specifications required for aluminum superplastic forming.

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