3D Printing Flexible Materials: Transcending Prototyping With Industrial Manufacturing

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This paper introduces additive manufacturing techniques and their relevance in the production of seals and gaskets. Following an economic consideration of the general benefits of additive manufacturing, we will compare the application requirements and material properties of different additive manufacturing materials. We will then present an application example of a cargo-train brake membrane, including the qualification protocol for this safety-critical application. We will also discuss the isotropic material properties unique to our printing processs, as well as compression set and changes to tensile properties after aging the material in different media. The paper concludes with an outlook that considers additive manufacturing's benefits in producing other types of seals and gaskets.

1 Introduction

Additive manufacturing (AM) has the potential to revolutionize the way parts and machines are produced today [1]. To successfully enter the market, the technology either needs to compete with products in the market today or provide novel concepts that cannot be produced using traditional manufacturing approaches.

While the former will receive most attention in this paper, the latter will be highlighted in the outlook.

To produce polymeric parts via additive manufacturing, the material can either be formed during the printing process, via a chemical reaction, or melted and solidified into the desired shape. There are three categories of additive manufacturing technologies for polymers:

- Remelting in filament or powder form as preactised in fused deposition modeling (FDM), Selective laser sintering (SLS)
- Light-activated resin-based printing methods like digital light projection (DLP), Stereolithography (SLA), or Inkjetting
- Reactive-fluid deposition modeling (RAM, RXAM)

For seals or gaskets, which separate one environment from another, parts must be solid throughout and free of microchannels and voids. Furthermore, a smooth and regular sealing surface is required so that the gasket fits perfectly against the housing.

In remelting methods such as FDM or SLS, hot, liquid polymer droplets are deposited onto cold, solid polymer surfaces at ambient pressure. Given the high viscosity and the fast cooling for the polymer a perfect volumetric fill is not possible. Thus void-free production is not possible [2], nor are the resulting surfaces smooth [3]. Thus, these technologies are often unsuitable for sealing applications.

Light-activated resin-based printing, which can create parts without voids or micro-channels, depend on acrylate chemistry [4]. However, acrylates used today have limited flexibility, strength and elasticity.

While the above technologies are useful in prototyping and hard-plastic applications, they do not present an alternative to traditional manufacturing for elastomeric applications. On the contrary, deposition modeling based on a reactive fluid offers the possibility to utilize reactive chemistry and fluid processing. Parts created with reactive-fluid deposition modeling processes are solid, void free and smooth, with material properties suitable for sealing and gasketing applications [6].

A summary of properties for the aforementioned categories is presented in Table 1.

Table 1: Comparison of process and material properties of different 3D-printing technologies

Technology	Dense, solid parts	Suitable material properties
Remelting	No	Yes, ≥ Shore A 90
Light-activated resin	Yes	No
Reactive-fluid deposition modeling	Yes	Yes

Below is an economic consideration as well as an example of an application developed with a user.

2 Economic Considerations

The reality is that additive manufacturing must compete with traditional manufacturing processes in terms of product quality, availability and total cost of ownership. Assuming a similar quality (and leaving availability aside for this consideration), the total cost of ownership is usually the primary reason for switching from a current supply to a new technology.

2.1 Comparison of the production cost of additive versus traditional manufacturing

To compare additive manufacturing with traditional production methods, one must consider the costs of tooling, setup, materials, production and logistics. Given the nature of additive manufacturing, producing small quantities or larger quantities does not significantly reduce cost. Thus, the price of one part is similar or the same as the price of multiple parts.

With traditional manufacturing, the cost of a single part is an exponential decay as a function of the number of parts produced, since tooling and setup cost are shared by a larger production lot. For any given part, a comparison of the manufacturing costs as a function of production volume can be determined, and a break-even point can be defined. Figure 1 depicts this concept.

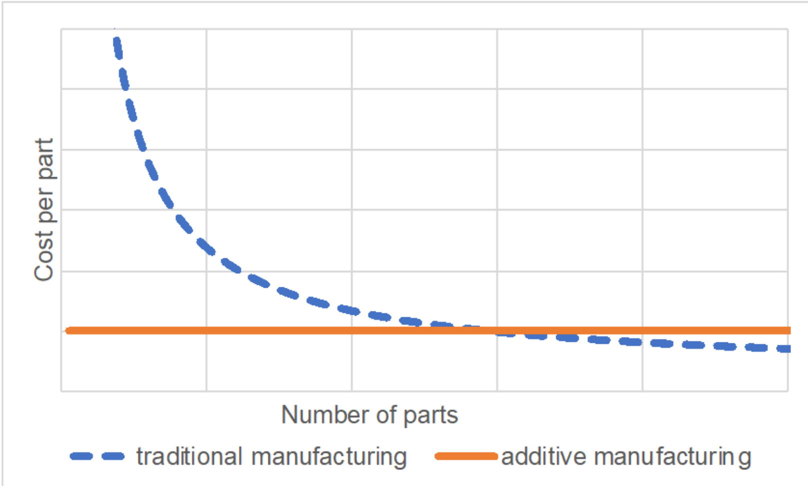

Figure 1: Cost comparison of a single part as a function of production volume for both traditional and additive manufacturing, with intercept marking the break-even point

2.2 Comparison of the qualification cost of additive versus traditional manufacturing

Generally, if the new technology offers a significant price advantage, a user will consider a change. An additional factor to consider is the cost of qualification for a part produced with a new technology in a given application. Generally, the higher the risk, the larger the qualification effort. This can be significant and may easily offset the the cost of manufacturing of traditional methods.

In safety-critical applications, such as the membrane of a train brake, qualification of a single part number will destroy the underlying financial incentive to switch technologies. In a case with a high qualification cost, a given application needs to have not only have a small number of parts per part number but also a large number of part numbers for the same function, which can be qualified in unison. For example, the rail industry has many use cases where this applies due to the large variety of rolling stock and low quantity of each specific vehicle type.

3 Application Example: Brake Membrane of a Cargo Train

Train bakes are air-pressure actuated. They operate at a maximum pressure of 5 bars, which keeps the brake open. A pressure reduction in the system actuates the brake. The lower the pressure in the system, the stronger the brakes actuate. Membranes in the brake system open and shut valves that regulate airflow from the locomotive to individual brake pistons. They determine if and how hard an individual rail car brakes. In the worst case, a failed membrane might lead to the actuation of a brake at full speed, which could derail an entire train.

Figure 2 shows a brake membrane in its valve housing.

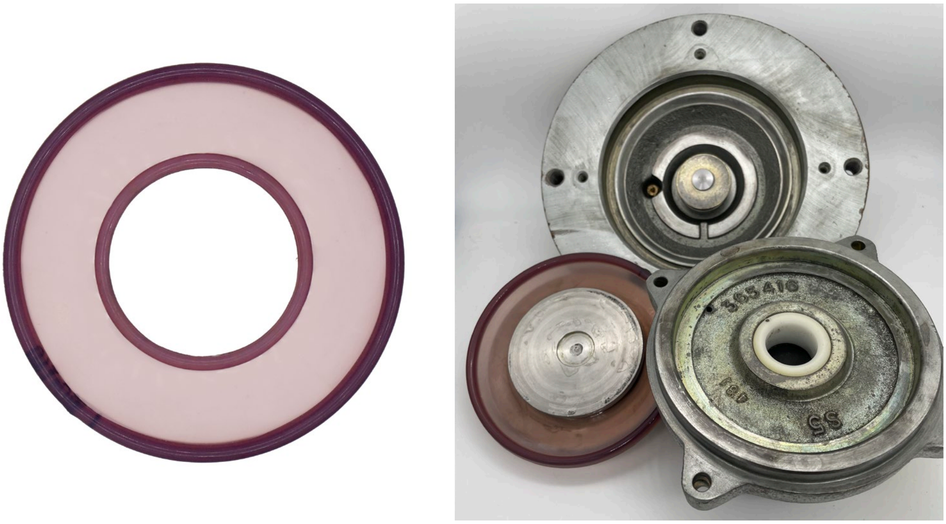

Figure 2: Additive manufactured brake membrane and in-brake valve assembly

The membrane is 125 millimeters in diameter and 1.0 millimeter thick in the membrane area. Further geometric requirements are a smooth surface, to reduce the induction of vibrations when air passes by, as well as an accuracy of ≥0.1mm in all directions.

The membrane needs to be airtight and able to withstand 5 bars of air pressure, yet flexible enough to react quickly to changes in pressure to open or shut the valve.

Table 2 summarizes the basic requirements.

Table 2: Basic membrane requirements

Requirement	Value	Unit
Shore hardness	55-60	Shore A
Tensile strength	16	N/mm^3
Minimum temperature	-30	˚C
Maximum temperature	70	˚C
Compression set at 70˚C	13	% at 25% deflection

Neither remelting technology—FDM or SLS—yielded a membrane that met the requirements for surface quality or airtightness. Furthermore, the available material grades are of a hardness of Shore A 90 or higher, making them unsuitable for the application.

Resin-based processes using lithography, such as DLP or SLA, have technical difficulties producing a flat surface with a large surface area due to diffusion issues. Therefore, the membrane needed to be produced at an angle in reference to the light source. This required the use of a support structure, which cannot be removed without damaging the surface. Furthermore, the tensile strength of the materials available will not withstand the pressure and would lead to a ruptured membrane.

A closer look at reactive additive manufacturing yields two possible materials that may be suitable for the application: silicone and elastomeric polyurethane. Both technologies offer a smooth printing surface as well as a solid, void-free part—the prerequisite for a successful gasket or seal. However, we were unable to find a silicone with tensile properties as depicted in Table 2 at the Shore hardness requested. In subsequent tests, the silicon-based membranes did not withstand the air pressure that was applied.

This left elastomeric polyurethane and RXAM as the only suitable technology for the brake-membrane application.

4 Elastic Polyurethanes Deposited By RXAM Technology

In the reactive liquid-mixing process, known as Reactive Extrusion Additive Manufacturing (RXAM), two reactive liquids are pumped through a mixing tip, where they react, yielding a durable, crosslinked elastomeric polyurethane. The print process is conducted at ambient temperatures and pressures, and the curing of the reactive liquids relies on the reaction of an isocyanate with a polyol. Seals can be printed under similar conditions compared to casting, with the same resulting material.

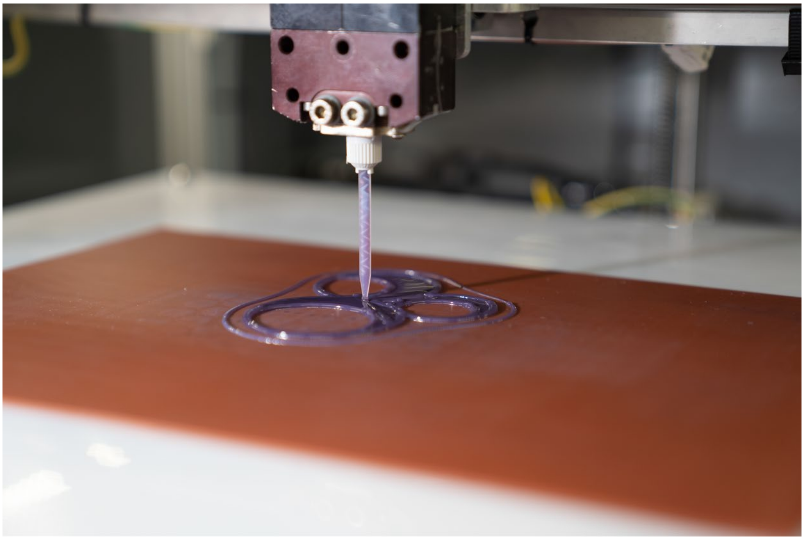

Figure 3: Printing a multi-layer design with RXAM technology

Unlike most 3D-printed components, Chromatic's seals exhibit long-term stability without warping or breaking and can withstand high pressure as well as high and low temperatures (up to 150 degrees Celsius and as low as -40 degrees Celsius). Materials range from Shore A 50 to Shore A 90, with tensile strength ranging from 4.5 megapascals to 18 megapascals. Elongation at break can be as high as 550 percent.

4.1 Isotropic properties of RXAM printing process

Isotropic properties are vital for the application. To qualify the printing process and material properties, we first tested tensile properties along the different print axes. Samples printed all three directions were tested stamped out at an ISO Type 2 dye and tested according to ISO 34. Samples were printed perpendicular to the pull in X direction and parallel to the pull in Y direction, in the form of sheets. The printing parameters of flow, layer height and beat width were representative of the final part. We also printed specimens in Z direction, which pulled perpendicular to the printed layers and were cut from a wall that was printed 2 millimeters wide and 46 millimeters tall. Test results for tensile strength and elongation at break for ChromaLast (the material chosen for the application) are shown in Table 3. Notably, print direction has no influence on the strength of a part.

Table 3: Tensile strength and elongation at break for ChromaLast printed X direction (perpendicular to pull), Y direction (parallel to pull) and Z direction (vertical box printed 2 millimeters wide)

Print direction	Tensile strength (N/mm^2)	Elongation at break (%)
X	18.4	618
Y	17.8	605
Z	20.0	657

The results show that the tensile strength matches or exceeds the required 16.3 megapascals in all print directions. The elongation of more than 600 percent shows excellent elastomeric properties and is also within the expected ranges and accuracies for this type of measurement.

4.2 Compression set for ChromaLast

The compression set for ChromaLast was measured in triplicate at two different temperatures, 70° Celsius and 100° Celsius, for 22 hours. The method used was ISO 815-1 Type B Method A, except that a higher deflection was used, adding additional stress to the system.

The test involves fabricating a compression-set button from the material to be tested. The button is placed in the compression-set apparatus and compressed when the plates are tightened up against the spacer. (The button has a height higher that the spacer.)

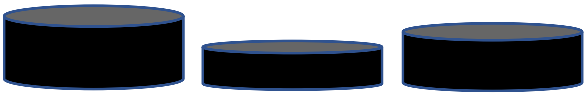

Figure 4: Button height before test (A), during compression (B), and after test (C)

The percent defection is equal to the difference between button and spacer height, divided by the button height, multiplied by 100. The expected button height changes are depicted in Figure 4.

Table 4: Compression set measured after 22 hours

Test temperature (°C)	**Deflection (%)**	**Compression set (%)**
70	33.8	14.7
100	33.2	35.4

The results are shown in Table 4. A low compression set of 14.7 percent with 33.8 percent deflection was obtained after 22 hours at 70° Celsius. Compression set was 35.4 percent at 33.2 percent deflection after 22 hours at 100° Celsius. Both values show deflections equal to or better than the requirements.

To our knowledge, this represents the first time an additive manufactured material combines elastic properties with the strength required for industrial application and the compression set needed for longterm use.

4.3 Tensile strength and hardness after conditioning treatments in media and heat

To qualify for an application, it is not only the virgin properties of a material that matter. The aging of the material must also be considered in the context of the environment and media it will most likely touch. In the case of the membrane, these are a hydraulic oil, a heat-transfer oil and a heat-aging treatment of 72 hours at 100° Celsius. Gasoline is not relevant for the application, but it was tested as a comparison to the material currently used.

Tensile strength, hardness, weight and volume changes were measured after these conditioning treatments.

The treatments were performed according to ISO 1817 and the measurements according to ISO 34. The reported value is the average of three tested specimens, which were all printed in the Y direction.

ChromaLast's tensile strength declines for all tested conditions, but within the window specified by the application. The lower the strong decrease of tensile properties in gasoline is not very relevant for this application since the currently used material loses more than 50 percent of its initial strength under these conditions, which renders them both not suitable for use in gasoline.

Table 5: Tensile strength of specimens that were immersed in different media and subjected to heat treatment

Conditioning treatment	**Temperature (˚C / time in hrs)**	**ChromaLast tensile strength (N/mm2)**	**ChromaLast Shore A hardness**
Control		18.4	60
Heat treatment	100 °C / 72 h	17.9	64
Hydraulic oil	100˚C / 168 h	14.6	54
Shell heat-transfer oil	100˚C / 168 h	17.2	58
ASTM oil 2	100˚C / 72 h	16.8	59
Gasoline	RT / 24 h	2.8	53

The comparison of the Shore A hardness of the different materials shows them to perform within the expected boundaries of technical relevance for both.

5 Conclusion and Outlook

After careful economic consideration, the potential of additive manufacturing for industrial parts is clear. Significant value can be added by switching from traditional production technology to additive manufacturing in instances when there are a variety of different part numbers for the same functional application. Furthermore, this can be an appealing business case even in safety-critical allocations that have a high cost of qualification.

After comparing different additive manufacturing technologies and discussing the technical requirements of a train-brake application, Reactive Extrusion Additive Manufacturing appears to be the only suitable production method from both a material and printing-process perspective.

An in-depth study of Chromatic 3D Materials' ChromaLast material shows isotropic tensile and compression set properties of 17.6 megapascals and less than 15 percent at 70˚ Celsius, respectively. These figures qualify the virgin ChromaLast material for the application. Furthermore, an aging study proved that the material is stable in an environment of various hydraulic and lubricating oils. Stability in gasoline is not given, as it is not required for the application.

In conclusion, we have presented the first additive manufacturing process suitable for producing such seals and gaskets. Further developments will provide a wider range of materials, allowing the use of additive manufacturing to penetrate other application areas.

6 References

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