Soft Elastomers for Fused Deposition Modeling

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This paper describes an ongoing effort towards extending the capabilities of the fused deposition modeling (FDM) process to soft thermoplastic elastomers (STPEs). Two thermoplastic elastomers with hardness of 72 and 78 Shore A, respectively, have been processed into 0.070" (1.78 mm) filament stock for use in the FDM 1600 rapid prototyping system. The FDM 1600 liquifier subsystem has been modified to accommodate the reduced column strength of the STPE filament stock. Sample STPE parts have been fabricated with ABS material support structures.

1.0 Introduction

There are a number of applications for layered manufacturing with soft elastomeric materials, however few layered manufacturing systems offer this fabrication capability. The work reported herein arose from the U.S. Air Force need to fabricate custom fit aircrew oxygen masks (CFAOMs). These masks would need to have a stiff and strong member to provide a fixed and firm interface to hardware, and a soft member to provide a seal against the unique geometry of each person's face. One potential solution towards this end would therefore be to fabricate these soft members using existing FDM rapid prototyping systems loaded with 65-85 Shore A thermoplastic elastomer filament materials.

A theoretical feasibility study by the University of Texas at Austin [1] concluded that the weak column strength and high melt viscosity of STPE filament materials relative to other FDM filament materials would be the major obstacles to using STPEs with existing FDM ram extruder systems (Figure 1). The higher melt viscosity increases the force required to ram the filament through the liquifier, while the weaker column strength reduces the available ramming force provided by the filament. A number of recommendation were made to overcome these problems. First, it was recommended that sleeve be extended to prevent filament buckling between the drive wheels and the liquifier. Second, it was recommended that the drive wheels be modified to increase their friction with the filament, thereby maximizing the force transferred to the material in the liquifier. Finally, it was recommended that the filament be cooled to make it

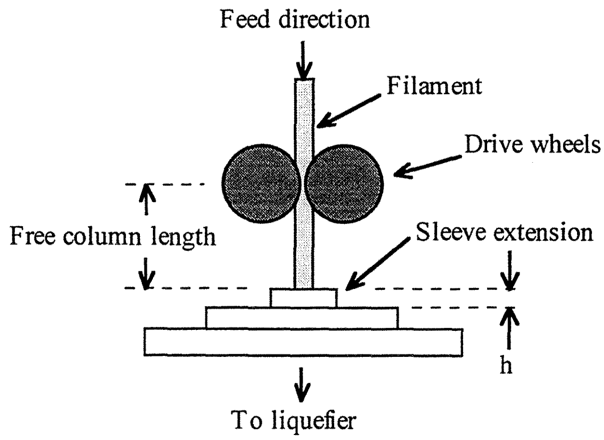


Figure 1 : Diagram of filament loading

stiffer, thereby both preventing it from buckling and enabling it to exert more force into the liquifier.

This paper describes the subsequent effort at Virginia Tech to implement these recommendations on an existing FDM 1600 rapid prototyping system. The following sections discuss the materials selection, the hardware modifications, and the fabrication results.

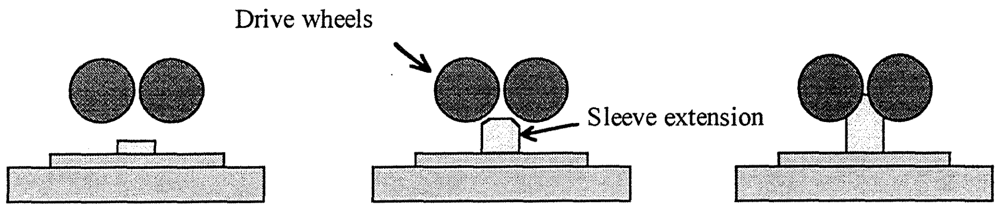
2.0 Materials Selection

The FDM 1600 ram extruder places a number of restrictions on candidate materials with respect to melt processibility and compressive strength. For instance, while most commercial thermoplastics are processed by mechanically inducing shear to help, or make, the thermoplastic flow, the FDM 1600 ram extruder generates minimal or no shear. Candidate materials must therefore be melt processible; that is, they must have the ability to flow with only the addition of heat. Furthermore, since unmelted filament is used as the ramming piston in the FDM 1600 liquifier, it is essential that candidate filament materials have enough compressive strength to push the molten thermoplastic through the liquefier. Specifically, sufficient compressive strength is required for the filament to retain its shape after being forced through the drive wheels so it can transfer the force provided by these wheels forward into the liquifier.

Two soft thermoplastic elastomers that satisfy these requirements and that can be processes by the FDM 1600 ram extruder, have been identified. These two STPEs, which have a respective hardness of approximately 78 and 72 Shore A, will be referred to in this paper as "STPE-1" and "STPE-2".

3.0 Hardware Modifications

In order for material to be extruded by the FDM 1600, the force that is generated by the motors must be transferred to the filament via the wheels and then into the liquifier (Figure 1). This transfer of force can be inhibited by a number of factors. First, the motors must generate



(a) Original sleeve (b) First sleeve redesign (c) Final sleeve redesign; contoured to the wheels

Figure 2 : Sleeve modifications

sufficient force. Next, the wheels must have enough friction with the filament to transfer the force from the wheels to the filament. At the same time, the filament must be strong enough to avoid shearing due to the friction from the wheels. Finally, the filament must not buckle between the drive wheels and the entrance to the liquifier. That is, the force transferred from the drive wheels to the filament should be efficiently transferred into the center of the liquifier in the direction of the melt flow, with minimal loss to filament buckling and compression.

The following sections will discuss the hardware modifications that were made to the existing FDM 1600 ram extruder system to facilitate this efficient transfer of force. They include extending the liquifier sleeve, increasing the friction between the drive wheels and the filament, and the use of air cooling to prevent softening the filament.

3.1 Sleeve Extension

One of the main challanges to extruding a soft filament through the FDM 1600 ram extruder system is its low column strength. The driving force supplied by the motors is greater than these soft materials can support. Consequently, these soft filaments buckle across the free column length in the FDM 1600 system; that is, between the drive wheels and the filament sleeve extension shown in Figure 1.

Since the maximum force that can be transferred by a filament without bucking is inversely proportional to the square of the free column length, an obvious solution to this buckling problem is to reduce the free column length by extending the sleeve up towards the drive wheels (Figure 2). In our first redesign iteration, the sleeve extension height was increased from 0.050" (1.27 mm) to 0.237" (6.02 mm), illustrated in Figures 2(a) and 2(b), respectively. This modification prevented the soft filaments from buckling. However, now the filament material squeezed out through the small triangle formed by the two drive wheels and the flat tipped sleeve. To prevent this leakage, the sleeve was extended further upwards and was contoured to the drive wheels as shown in Figure 2(c), for a maximum sleeve extension height of 0.350" (8.89 mm). This effectively closed the entire gap between the drive wheels and the sleeve extension, leaving only an approximately 0.030" (0.76 mm) gap between the wheels and the curved sides of the sleeve, in addition to the small space provided by the narrow filament guiding

Table 1 : Candidate drive wheel descriptions

Wheel Type	Description
Hard	A pair of hard epoxy wheels, typically used with the ABS filaments
Soft	A pair soft rubbery wheels, also available on the FDM1600
Coarse Gear	Two gears : 32 Pitch, 3/16" Face, 1/4" Bore, 15 teeth, Pitch Dia. = 0.469", Outer Dia = 0.531"
Fine Gear	Two gears : 72 Pitch, 3/16" Face, 1/4" Bore, 36 Teeth, Pitch Dia. = 0.500", Outer Dia. = 0.528"
Sandpaper	One 'soft' wheel and one wheel covered with a coarse grit sandpaper

groove which is carved into the drive wheels. Indeed, this latter redesign has proved itself sufficient for FDM fabrication with our two target STPEs.

3.2 Drive Wheels

The force required to extrude the filament through the liquifier is supplied by two counter-rotating drive wheels as shown in Figure 1. The drive wheels are circumferentially grooved to fit around the filament diameter, in order to properly guide the filament towards the liquifier. The filament is fed through the wheels which contact the filament on both sides. All of the driving force is transferred by the frictional force along the filament as it comes into contact with the wheels. The driving force transferred to the filament is dependent on the coefficient of friction between the wheels and the filament, and on the normal force exerted by the wheels on the filament. It is important that the wheels are positioned close enough together to provide sufficient normal force on the filament, and that a suitable drive wheel surface is selected to maximize the coefficient of friction between the wheels and the filament.

A number of different drive wheels surfaces (Table 1) were tested experimentally with several different STPE filament materials. For this a special purpose test apparatus was built that measured the force exerted by the filament on the liquifier, as the filament is driven forward by the FDM drive motors and wheels. The apparatus consists of a 10 lbs maximum load cell, a bridge amplifier, a voltage meter, and a test rig holding the FDM drive motors and wheels and the load cell (Figure 3). The entire system is rated to 13.3 lbs (52.2 N) of force with better than 0.001 lbs (0.044 N) accuracy, though only 0.05 lbs (0.22 N) accuracy is required. The base plate and motor block assembly were mounted such that the SM-10 Interface load cell could be located at the point equivalent to just inside the liquifier. Its precise location could be adjusted with a bolt mounted in the load cell arm, and which would be raised until it almost touched the exit hole

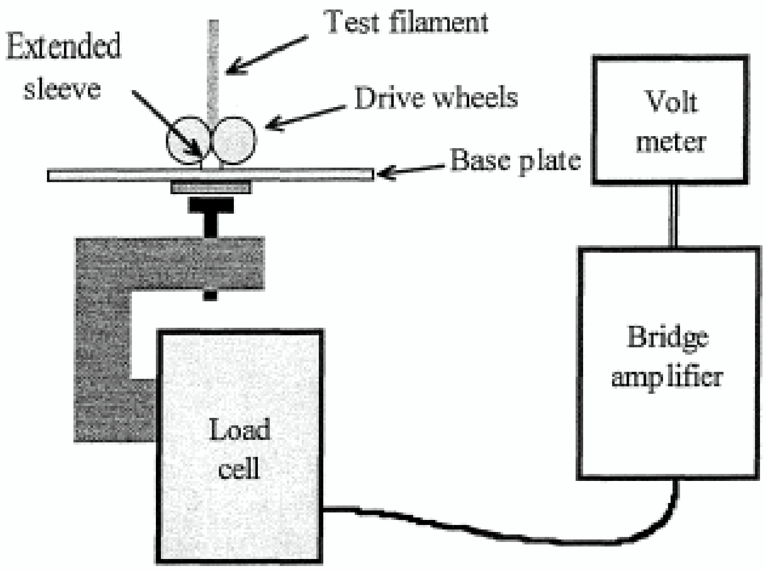


Figure 3 : Force test apparatus

that would mate with the entry hole of the liquifier. This setup would allow the filament to fed through the wheels and the sleeve, and dead end onto the load cell in place of the liquifier. The load cell was then attached to a Gould Brush bridge amplifier. The output from the load cell was calibrated to 0.001 lbs (0.044 N) accuracy, using the bridge amplifier and a set of 1 and 2 lbs (0.4536 and 0.9072 kg) weights. The output from the bridge amplifier was read using a Sperry DM-2A voltmeter.

Each of the five wheel types were tested on the force test apparatus with six different filaments (Table 2). Five measurements were taken for each wheel/filament combination. The forces recorded were the maximum axial forces measured by the load cell. These forces represent an upper limit on the available force for extrusion through the liquifier.

The results listed in Table 2 confirm that decreasing material hardness reduces the force exerted into the liquifier. It also shows that for these particular drive wheel surfaces, the rubber wheels produced in general the greatest amount of driving force for the soft filament materials.

3.3 Cooling

It had been suggested [1] that the filament be cooled using a thermoelectric cooler (TEC) to significantly increase the filament column strength, thereby both preventing filament buckling and increasing the force exerted by the filament into the liquifier. However, for most STPEs, a TEC system would be insufficient since their T_g's are in the proximity of, or below, what can be achieved with liquid nitrogen -77°C (-107 °F). Cooling a STPE filament to above T_g will only marginally increase its column strength. We verified this by bathing a STPE filament in liquid nitrogen; it displayed only a slight increase in stiffness compared to that at room temperature.

Table 2 : Force measurements for wheels and filaments
Values given as : Average maximum force in pound (standard deviation in pounds)

Wheel Type	**Santoprene** 80 Shore A	**Sarlink** 69 Shore A	**Multibase** 57 Shore A	**"STPE-1"** 78 Shore A	**"STPE-2"** 72 Shore A	**ABS**
Epoxy Wheels	1.32 (0.356)	1.04 (0.055)	0.52 (0.045)	1.84 (0.297)	0.98 (0.045)	12.92 (0.531)
Rubber Wheels	1.64 (0.055)	1.1 (0.071)	0.46 (0.055)	2.08 (0.303)	1.22 (0.130)	2.35 (0.147)
Fine Gears	1.04 (0.055)	1.04 (0.055)	0.44 (0.055)	1.2 (0.200)	1.22 (0.259)	TL
Coarse Gears	1.3 (0.071)	1 (0.071)	0.38 (0.045)	1.64 (0.114)	1.1 (0.000)	TL
Sandpaper Wheel	1.34 (0.055)	0.94 (0.055)	0.42 (0.045)	1.66 (0.055)	0.94 (0.089)	13.22 (0.179)

Note: TL -- Torque Limit. In these two cases the ABS filament was crushed between the two gears until the motors were stopped by the torque limit function of the FDM 1600. A larger gap between the gears would be required in order to use them for the ABS filaments.

Limited cooling, however, does help the filament maintain its room temperature column strength as it approaches the liquifier. For instance, "STPE-2" has a softening point of 41 °C (106 °F) while the liquifier has a processing temperature of 230 °C (446 °F). As the filament approaches the liquifier, it heats up and quickly becomes too soft to act as a ram piston. The solution to this problem is to use the air conditioner attached to the standard FDM 1600. With it we have been able to cool the area around the motor blocks and drive wheels sufficiently to keep the filament from loosing its column strength as it approaches the extruder inlet.

4.0 FDM with Soft Elastomers

The FDM 1600 ram extruder system requires only a few minor modifications for it to fabricate with filament stock made from our two target STPEs. These modifications include extending the sleeve, contoured around the drive wheels; utilizing rubber drive wheels; and, in the case of "STPE-1", widening the die diameter to a 0.037" (0.94 mm).

The low force exerted by the "STPE-1" filament into the liquifier and the relative high viscosity of its elastomers necessitated widening of the die. The standard 0.025" (0.64 mm) die provided too much resistance. However, widening this die to 0.037" (0.94 mm) reduced the pressure drop sufficiently to enable extrusion. It is estimated that the minimum die diameter for "STPE-1" and the current wheel-sleeve-material combination is in the range of 0.032" to 0.035" (0.81 mm to 0.89 mm). This is still relatively wide compared to other FDM materials and would inhibit fabrication of smooth, non-horizontal surfaces and delicate part features. "STPE-1" is therefore ill suited for use in small-volume FDM systems. On the other hand, it might be acceptable for use in large-volume systems; in these systems, its limited deposition resolution might be of less consequence, and thus it be considered adequate.

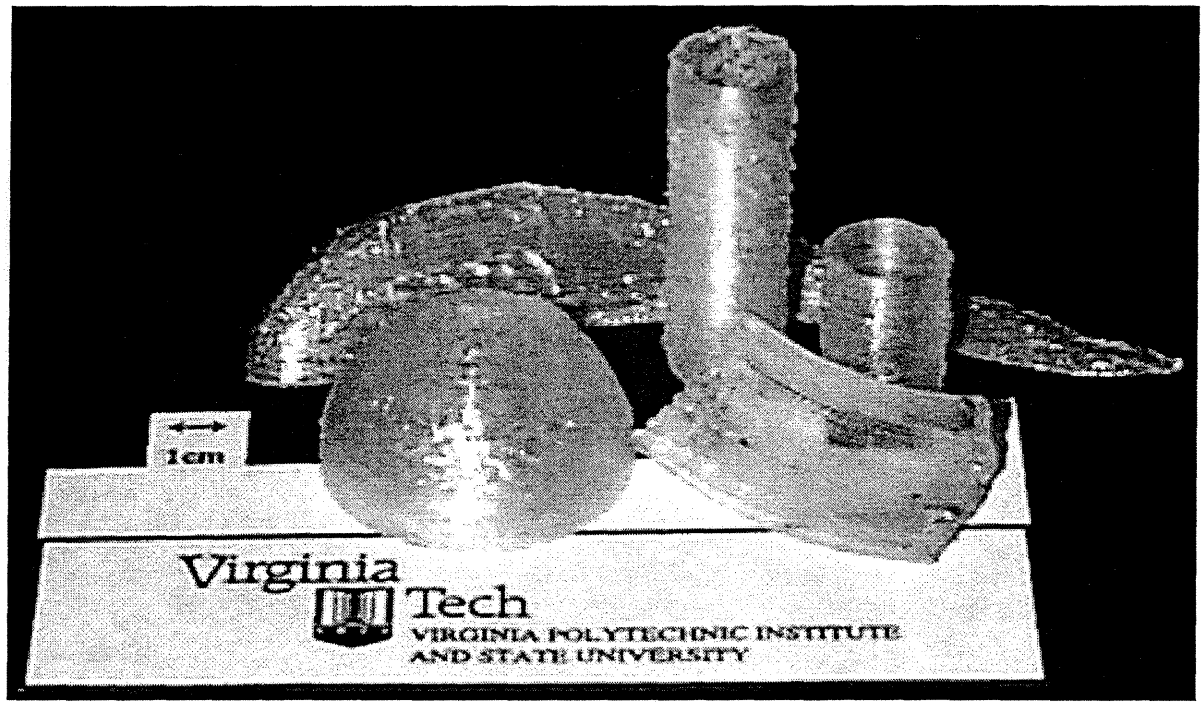


Figure 4 : Very first batch of sample parts fabricated with "STPE-2" on a modified FDM 1600 rapid prototyping system (0.010" layers, 0.030" roads, 0.037" die, 0.8"/sec head-speed) (0.25 mm layers, 0.76 mm roads, 0.94 mm die, 20 mm/sec head-speed)

Extrusion with the "STPE-2" filaments was actually less problematic, even though it is softer than "STPE-1" and has an order of magnitude lower melt flow index. For "STPE-2", the filaments extruded through the standard 0.012" (0.31 mm) die This enabled fabrication with 0.010" (0.25 mm) layer thicknesses, 0.012" (0.30 mm) road widths, and 0.8"/sec (20 mm/sec) head motion in the XY-plane. These are values are comparable to those of the ABS modeling material that is available for the FDM 1600.

The relatively high processing-temperature of "STPE-2", about 230 °C (446 °F), made it temperature-compatible with the standard FDM ABS support material. These two materials also bond reasonably well together, which enables the use of this ABS material for fabricating support structures. Several sample parts have been fabricated with this material combination, using both the 0.037" (0.94 mm) die (Figure 4) and the 0.012" (0.30 mm) die (Figure 5). The removal of these support structures appeared to be quicker, cleaner and easier than for those of other FDM build materials, in part because the elastomeric model material can flex while being peeled off the stiffer ABS plastic support structures.

The "STPE-1" model material did not bond well to the standard FDM ABS support material. Therefore, until a better support material is formulated, it will not be possible to fabricate parts with "STPE-1" that require secondary material support structures.

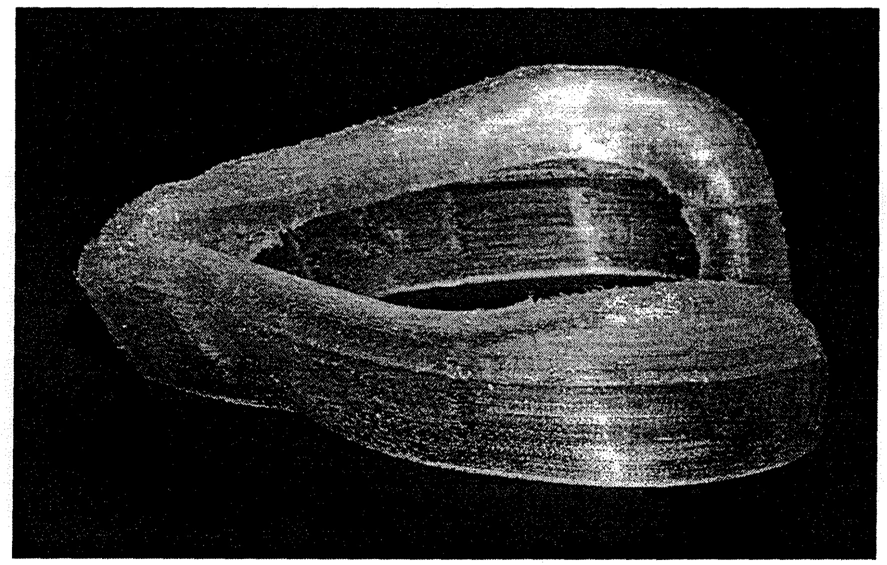


Figure 5 : The seal of custom fit aircrew oxygen mask, fabricated directly with FDM 1600 using "STPE-2"

5.0 Conclusions

The FDM 1600 rapid prototyping system has sucessfully been modified to facilitate direct fabrication of soft thermoplastic elastomer parts. The materials have hardnesses of approximately 72 and 78 Shore A, respectively. The hardware modifications that were necessary include (1) extending the liquifier sleeve up to and around the drive wheels; (2) using rubber coated drive wheels; and (3) widening the standard die to 0.037" (0.94 mm) in the case of the "STPE-1" material. "STPE-2" was the easier of the two materials to work with. Several sample parts were fabricated, using the standard FDM ABS support material for support structures. The support structures were quicker, cleaner and easier to remove than those for other FDM build materials.

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References

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