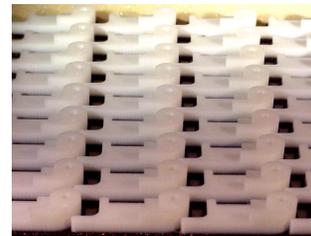


DIRECT RAPID MANUFACTURING WITH REAL PRODUCTION PLASTICS USING FUSED DEPOSITION MODELING (FDM)

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Manufacturing parts for end-use directly from a rapid prototyping system is an emerging process. This technique is already used for short-run production; individualized part manufacturing; and custom repair-part building. Rapid manufacturing is being fostered in part by advances in materials used by rapid prototyping systems. These advances include high-performance production plastics that offer high strength at high temperatures.

This paper will discuss recent material advances in fused deposition modeling that benefit rapid manufacturing. The materials discussed include polycarbonate and polyphenylsulfone and also water-soluble support material, which automates the support-removal process. This paper will also briefly address the material blend of ABS / PC, on the horizon for FDM.

Material Property Improvement

Among rapid prototyping and rapid manufacturing users, it is a widely expressed sentiment that no industry advances are more welcomed than material improvements. Specifically, users have said they want to model in more stable and durable plastics and ideally in their end-product's production material.

FDM-technology inventor, Stratasys, Inc., has taken a leading role in developing durable materials for rapid prototyping. It has expanded from ABS plastic in the 1990s, to polycarbonate (PC) in 2001, and polyphenylsulfone (PPSF) in 2003. Unlike materials used in some popular competitive processes, these three plastics are not "lookalikes" or epoxies but real production plastics, widely used in end-products.

Using any of these three materials for prototyping allows the designer to have a more durable part than is otherwise available, and it allows them to more-accurately predict how their end-products will perform.

With these materials, engineers can often design an end-product that uses less plastic, since they don't need the extra amount often used as overkill to "play-it-safe." Modeling with the end-product's material lets the designer use just the necessary amount of plastic to meet the exact performance standards desired. When manufacturing tens or hundreds of thousands of products, any extra plastic becomes a sizeable expense that cannot be eliminated.

Both polycarbonate and polyphenylsulfone are known for their high-performance characteristics. Some characteristics that are beneficial for rapid prototyping include:

Polycarbonate

- Very high tensile strength and flex strength (Twice as strong as ABS plastic)
- Hardness exceeds ABS
- High heat-distortion temperature
- Real engineering material used in end-products
- Tough enough to rapid manufacture usable parts
- Dimensional stability

Polyphenylsulfone

- Superior impact strength
- Very high tensile strength and flex strength
- V-Zero flammability rating
- Real engineering material used in end-products
- Tough enough to rapid manufacture usable parts
- Dimensional stability
- Resistance to chemicals, acids, and petroleum products
- Ability to sterilize for medical applications

Note: Material specification comparison chart follows later in this paper.

The availability of a rapid-prototyping platform that can build parts with these high-performance properties is an important milestone for the industry. It offers a benefit to any manufacturer who wants more durable, functional prototypes, and even greater benefit if the end

strength, like PC or one that could take high temperatures while maintaining its integrity like PPSF.

High-performance Platform: The FDM Titan

In the late 1990s Stratasys' material-development group set out to prove feasibility of a rapid-prototyping platform that could support high-performance materials. Once it did so, the company made the decision to invest \$10 million for development, which required four years. The goal was realized with the introduction of the FDM Titan, which builds with both PC and PPSF, besides the company's flagship material – ABS. The Titan enabled FDM to overcome its material limits, and it allows for virtually unlimited high-performance thermoplastic use in the future.

Other RP Processes Produce Less- Durable Parts

Although it has a deserved reputation for its fine surface-finish, the popular UV laser-curing RP technology uses resins that cannot offer the dimensional stability and strength of a real production plastic such as PC or PPSF. Recently introduced resins for the laser-based process have improved in material durability, but they are still less durable than PC and PPSF and pose real limitations to functional testing and dimensional stability.

In order to simulate an end-product, the laser-based process requires an additional step of RTV molding using urethanes, which, even then, are still

only an approximation of the end-product's properties. Most engineers will not take the risk of using these prototypes to simulate properties of their end product. If they decide not to take this risk, they must either machine prototype parts from a block of plastic or add thicker walls to the design to play it safe, which increases production cost.

PC and PPSF parts produced with FDM are dimensionally stable. They will not shrink, warp, or absorb moisture, which has been a traditional problem with models produced on the laser-based process. Other competitive processes, such as sintering and inkjet printing, also result in prototypes that are less durable than those made via FDM.

Polycarbonate: Strong, Versatile, and Widely Used

Due to its high impact strength, tensile strength, and compressive strength, polycarbonate and blends of it are used in myriad products from toys to medical-equipment cabinetry. Toys need to take abuse in normal use, and medical-equipment cabinetry must be strong due to the serious nature of its purpose as life support and monitoring equipment.

Polycarbonate is the material from which bullet-proof "glass" is made. In today's auto industry, a large part of car interiors are built from the material. Hubcaps, too, are often made of a chrome-plated PC or PC/ABS blend, due to the high level

of stress exerted on them at highway speeds.

Other PC applications include cell phones, business equipment, computer products, and a wide variety of consumer products, such as appliances.

Rapid Manufacturing a Custom Repair Part

During its initial trial of the FDM Titan high-performance platform, a beta customer used the machine in a way it hadn't anticipated: rapid manufacturing a replacement part from polycarbonate. A table-top sander used in a finishing step on the production line failed because one of its aluminum pulleys cracked, idling production.

Because it would take three days to order in a replacement pulley, the company's fabrication manager had a new one drawn in CAD and then created in polycarbonate on the FDM Titan. It took less than four hours to have the polycarbonate part in his hand. He was able to bolt in the pulley and resume production immediately. The company left the polycarbonate replacement in one month before installing a new aluminum one.

PPSF: A Super-material

As noted, PPSF has an excellent impact-strength rating besides being flame retardant. It also remains strong at very high temperatures. Its heat-deflection temperature is rated at 214° C at 66 psi, and 207° C at

264 psi (417° F and 405° F respectively) [ASTM test D-648]. This enables makers of products with thermal requirements to subject prototypes to much more realistic test conditions than they could previously.

PPSF has other notable characteristics. In the event of the material being exposed to a heat source hot enough to melt it, such as an uncontrolled fire, PPSF passes the 1990 FAA regulation, which requires low heat release, low smoke generation, and low toxic gas emissions. This is a big benefit in modeling for aerospace applications because many of the industry's end-products must meet this requirement.

Two other important properties of PPSF are its ability to be sterilized in an autoclave and its resistance to chemicals, acids, and petroleum products. Ability to sterilize is of major importance to medical-device manufacturers, and resistance to caustic agents is important to the auto-motive industry, which builds models for under-the-hood applications.

PPSF Application Examples

Stratasys first introduced PPSF for the FDM process at the annual Rapid Prototyping & Manufacturing Show in April, 2002. It demonstrated the material in its show-floor booth by brewing coffee into a PPSF carafe and by baking cookies in a toaster oven with a PPSF oven rack. It also displayed and operated a gas-powered leaf blower, which had a PPSF gas tank.

Property	Test	ABS	PC	PPSF	DuraForm (SLS)	SL7510 (SLA)
Tensile Modulus (psi)	D638	360,000	350,000	340,000	323,000	330,000
Tensile Strength (psi)	D638	5,000	9,211	10,100	6,380	7,340
Flex Modulus (psi)	D790	380,000	321,700	350,000	186,325	271,000
Flex Strength (psi)	D790	9,500	14,370	13,200	N/A	8,900
Impact Strength (ft.lb/in)	D256	2	13.7	13	4	0.5
Heat Distortion (Temp)	D648	93° C 200° F	125° C 257° F	207° C 405° F	125° C 257° F	68° C 154° F
Flammability	UL94		V-2 1.1mm	V-0 3.2mm		

Properties for various materials used in rapid prototyping

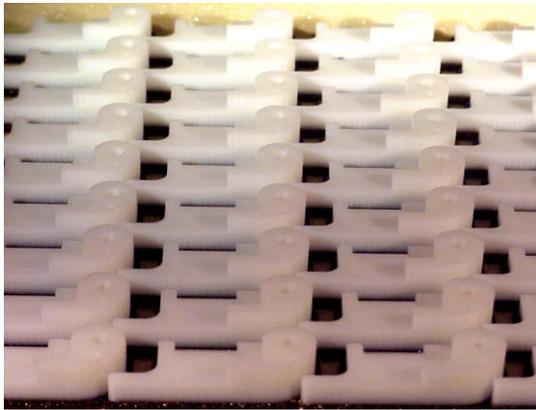
The coffee maker and toaster oven operated eight-hour days during the 3-day trade show. Throughout the show, the coffee carafe maintained temperatures of 82° C to 100° C, (180° F to 212° F) while the coffee maker's warmer plate operated at 100° C (212° F). The toaster oven operated at 177° C (350° F). Both of the appliances functioned properly without any melting or damage to the PPSF.



Working model of coffee-maker carafe made of PPSF

Rapid Manufacturing for Short-Run Production

While not as strong as PC or PPSF – ABS – the Titan’s other material, is a production plastic that can be used in short-run production. Bell & Howell Company, Lincolnwood, ILL, uses an FDM rapid prototyping system for limited production runs of an ABS plastic part used in its high-speed production scanners.



Bell & Howell Company rapid manufactures short production runs of a part (a “flag hold-down”) in batches of 50 using the FDM process.

Bell & Howell engineers found that the quality of a component called the *flag hold-down* built on the FDM system was better than needed to perform its job, so they decided to manufacture the units using FDM, rather than order them from a molding company.

On average, Bell & Howell produces 160 flag hold-downs each month, and in total it has made close to a few thousand units. They are manufactured in batches of 50 and installed directly on the end product.

“It’s advantageous to have the capability [to rapid manufacture parts],” says electro-mechanical technician Michael Jones. “If a supply company failed to deliver a plastic part for some reason, we could prevent a production stoppage by building the parts on the FDM machine. Another advantage is if we planned to change a component design after a relatively short time, it might be more cost effective to build our own parts rather than pay a molding company for tooling and production.”

Water-Soluble Support Material Automates Removal

After a model is created with the FDM process, it requires no post-processing steps — only support removal. In 1999, Stratasys automated this support-removal step, and in 2002 extended it to the Titan high-performance platform. The automated support-removal process uses a water-soluble material system marketed as *WaterWorks*. To remove supports, a user places the model in a water-based solution, which dissolves the support material, leaving the model clean. This is especially important for models with complex geometry or difficult-to-reach internal areas.

Not only does this method streamline the process, but it allows users to orient the model for optimal outcomes of strength and appearance without having to consider how the supports will be removed. Although *WaterWorks* is currently available on the Titan only for ABS, plans call for its use with PC and other high-performance materials in the future.



Skil-Bosch uses soluble support material to streamline support removal of prototypes such as this saw.

Skil-Bosch Power Tool Co., Chicago, manufactures hand-held power tools for the consumer market. Model shop supervisor Mike LeFever says using the WaterWorks system has significantly sped up modeling operations for the company. In the past, removing support structure would take “two to three hours. And that’s not factoring in the number of models you would ruin when you accidentally broke off a desired feature. With a traditional support system, no matter who makes the rapid prototyping machine, you have to be very aware of how you orient the model [for support-removal considerations] because the orientation affects strength and appearance. You would always sacrifice [strength or appearance for support-removal considerations].”

“[[If] a screw boss is the major feature of a model, the way to rapid prototype this piece without using supports is to position the hole face up. Even though there is bonding between layers, the screw boss is not as strong as if you would build it on its side. However, [if

the model is built] on its side, you have to think about supports and how to remove them without breaking the part. With WaterWorks, you can maximize the orientation for strength.”

Now that supports are not an issue for the company, LeFever says, they can experiment with build-orientation and they can position the model with the best physical appearance or strength as the project calls for, significantly improving modeling for Skil-Bosch.

On the Horizon: ABS/PC Blend

Many of today’s products are constructed of a blend of polycarbonate and ABS, and there is a need for it in the RP process as well. The ABS/PC blend is currently under development and is planned for future use with the FDM Titan.

The ABS/PC blend isn’t the last of the materials for the Titan, however. Because the Titan’s platform was designed to accommodate future high-performance materials, plans are set to continue developing them. These materials will take time to develop and will be released only gradually as the market dictates.

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