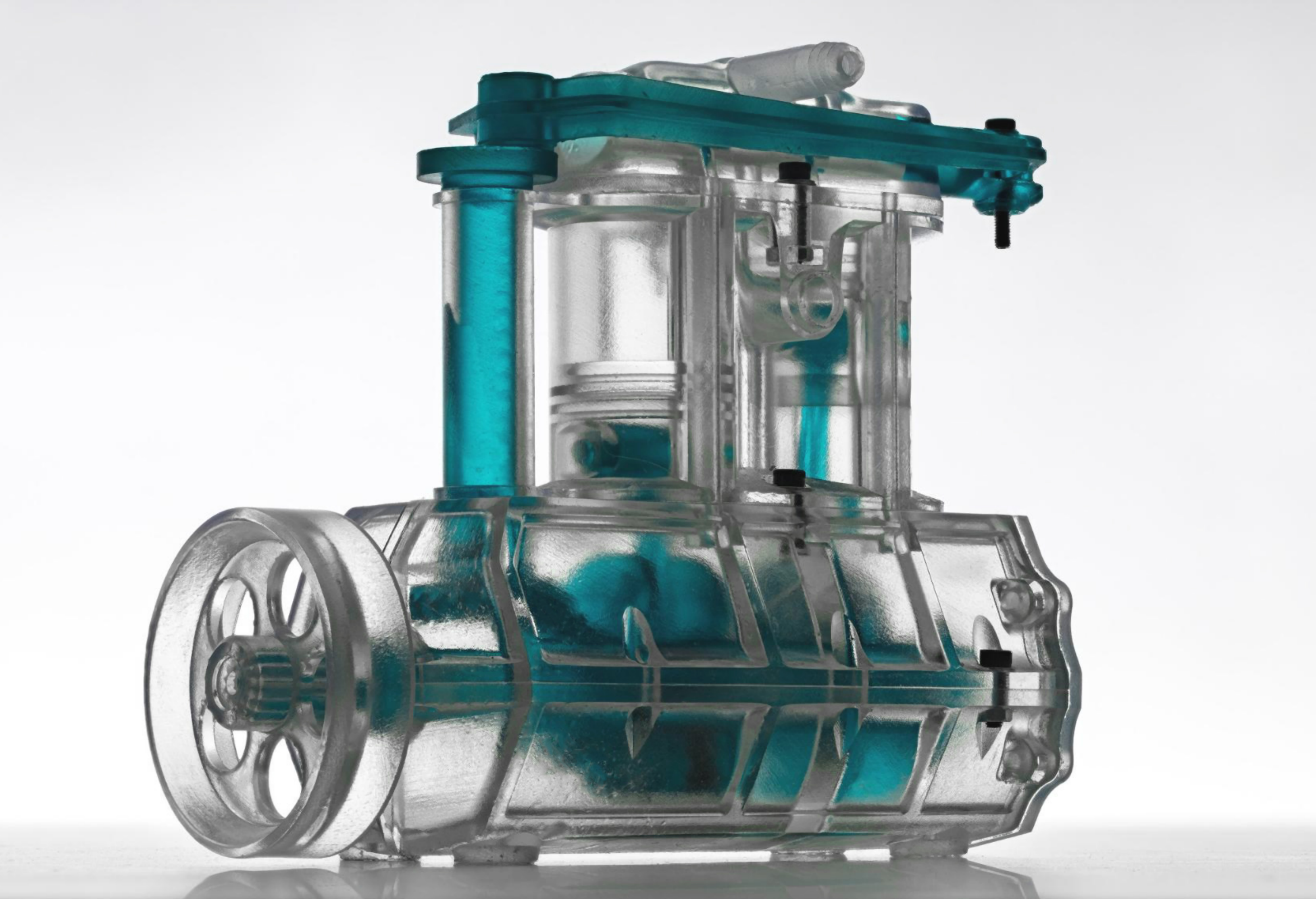

FORMLABS WHITE PAPER:

Engineering Fit: Optimizing Design for Functional 3D Printed Assemblies

Tolerance and fit are essential concepts that engineers use to optimize the functionality of mechanical assemblies and the cost of production. Formlabs extensively studies the accuracy of our materials and works to maximize repeatability between prints and across printers. The data and best practices in this white paper can help Form 2 users to design functional assemblies that work as intended, with the least amount of post-processing or trial-and-error.

May 2017

formlabs

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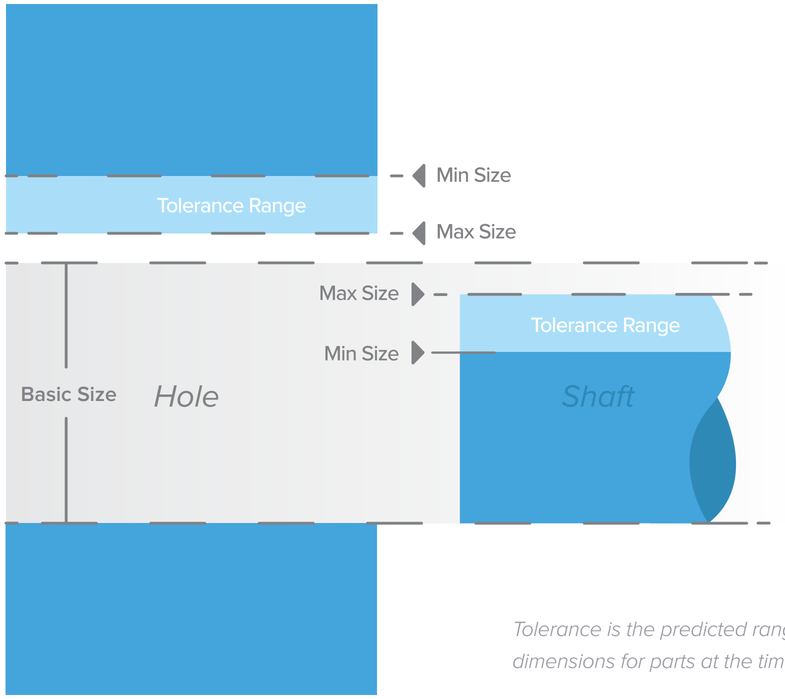
Value of Tolerances in 3D Printing

In traditional machining, tighter tolerances are exponentially related to increased cost. Tighter tolerances require additional and slower machining steps than wider tolerances. Machined parts are designed with the widest tolerances allowable for a given application.

Unlike machining, where parts are progressively refined to tighter tolerances, stereolithography (SLA) has a single automated production phase. Proper dimensional tolerancing lowers post-processing time and ease of assembly, and reduces the material cost of iteration. Improper tolerances for a particular material can also result in broken parts, especially for press-fit components in brittle materials.

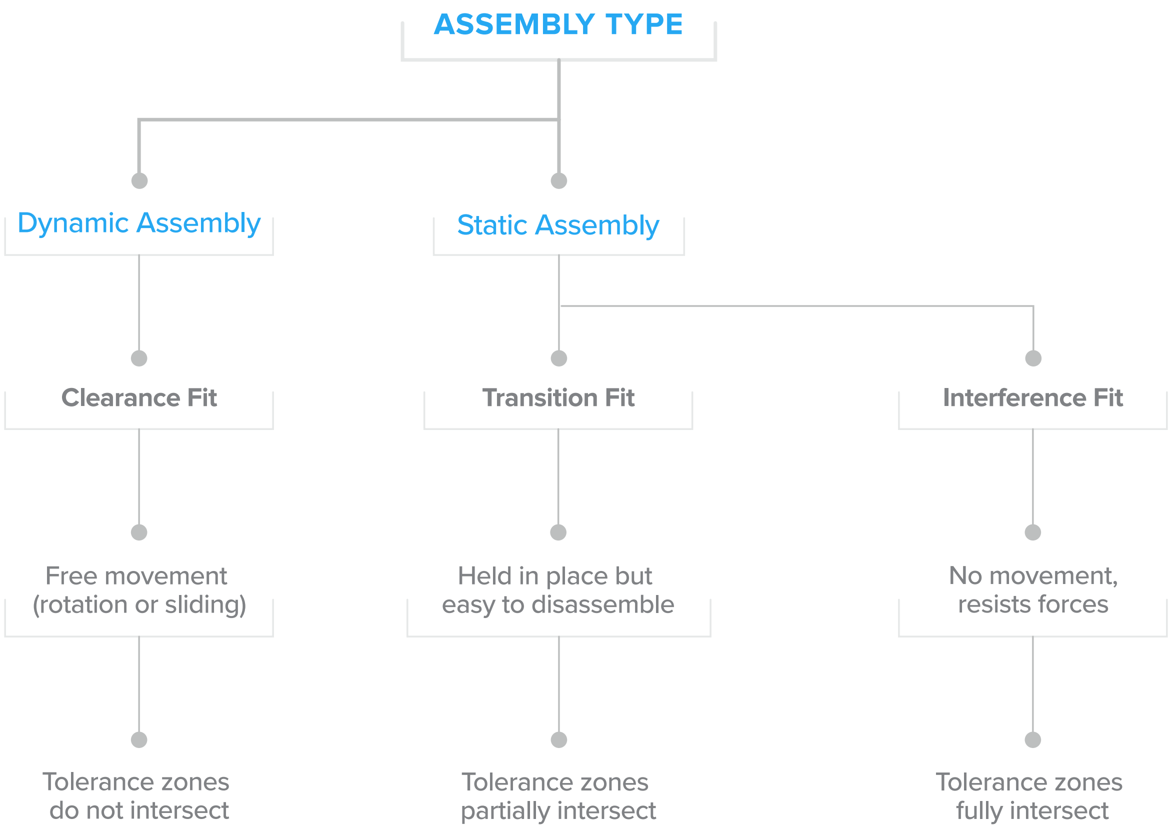
With larger assemblies, or when producing multiples of something, proper dimensional tolerancing quickly becomes worthwhile.



Tolerance is the predicted range of possible dimensions for parts at the time of manufacture.

Post-processing steps for printed assemblies include cleaning, sanding supports, and lubrication. Sanding an active surface is a reasonable method for achieving the correct fit if the part is a one-off, because less tolerancing work is required in the design phase. With larger assemblies, or when producing multiples of something, proper dimensional tolerancing quickly becomes worthwhile.

ACTIVE SURFACE Model region where two surfaces touch and either move against each other or have a static fit.



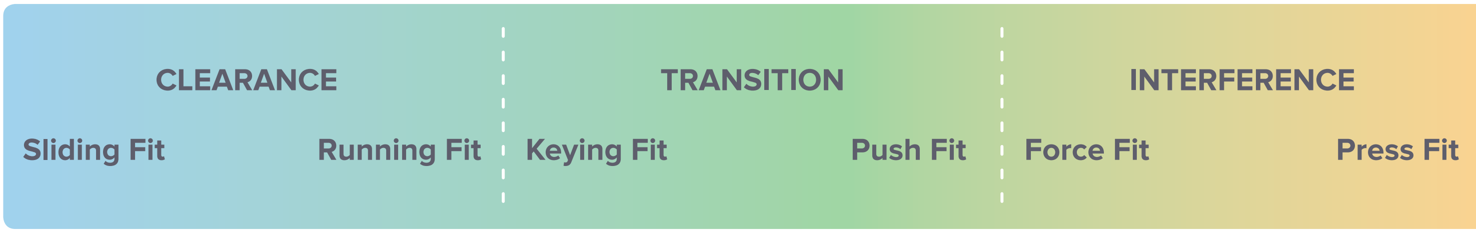
Fit Selection

The functional needs of the assembly will define how parts should fit together. Free movement of a component requires clearance, or space between the active surfaces. This is achieved by ensuring that the tolerance zones of the active surfaces do not overlap. If no motion between parts is needed, a transition fit will allow for easy assembly and disassembly. A transition fit has partially overlapping tolerance zones.

An interference fit provides a rigid, strong connection, but requires much more force applied in assembly.

Note: Interference fit has fully overlapping tolerance zones and requires the use of a resin with greater elongation such as Durable, Tough, Flexible, or Standard.

Small amounts of deviation in manufacturing means that engineering fit is a continuum rather than three completely separate stages. Larger clearance fits trade precision for freedom of movement. Tighter transition fits are stronger, but cause more wear on the connection. An interference fit that requires more force to join will be more challenging to disassemble.



Fit is a spectrum that can be divided into three categories, which help dial in fit based on the needs of your assembly. Color coding in this spectrum is applied to the graphs below.

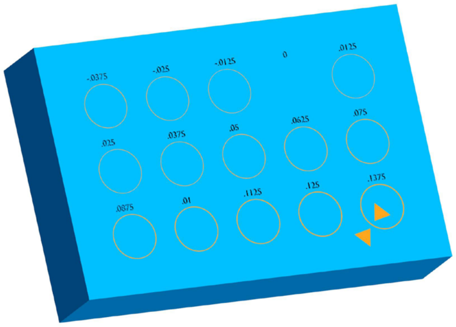
Fit can be divided into three categories—clearance, transition, and interference—and each category is defined by two types of fit.

CLEARANCE A sliding fit will have some lateral play, while a running fit will have almost no play. A running fit has slightly more friction, but more accurate motion.

TRANSITION With a keying fit, a component will accurately insert into or around another part, with only a light force needed to install and remove it. A push fit will require more force to join and remove the parts, but it will still be possible by hand.

INTERFERENCE A force fit requires substantial force, likely with additional hand tools like a hammer to install, and is not intended to be removed. A press fit will need much more force applied by a tool such as an arbor press to install.

PLAY The amount of space for movement in an unintended direction within a mechanism.



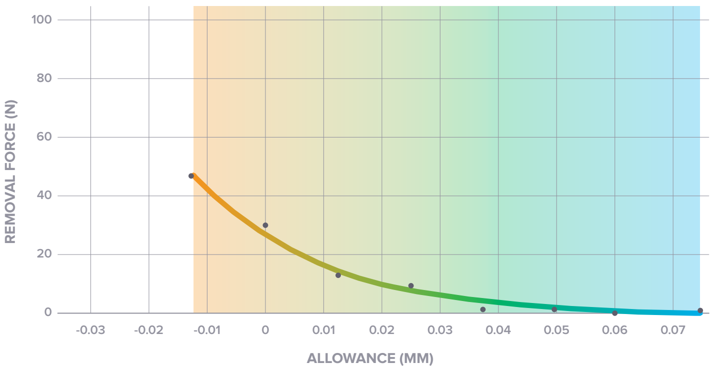
Measuring and Applying Tolerance

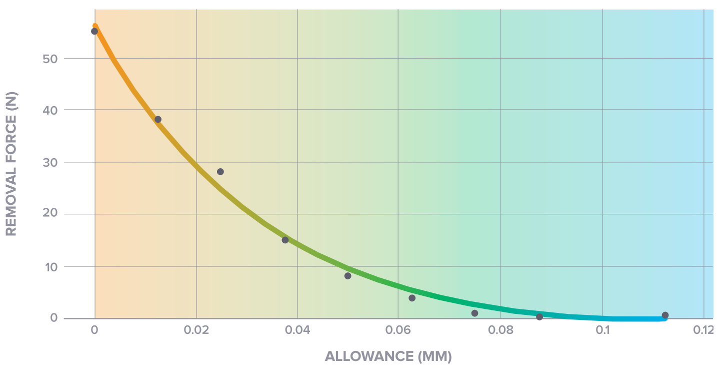
Formlabs examined a variety of common geometries to find the real-life tolerance needs of each kind of fit. The two SLA materials tested were Tough and Durable Resin, which were designed to be used to print functional product prototypes that undergo mechanical and tribological (friction) stress. The following examples demonstrate why it is beneficial to apply the correct material to each application. Fit conditions in each graph are color coded: blue is a clearance fit, green is a transition fit, and orange is an interference fit.

HOLE AND SHAFT

A hole and shaft will usually require a clearance condition, which may range from a sliding fit to a running fit depending on needed accuracy. A running fit will require sufficient lubrication for free movement. The hole and shaft print is a useful general test of fit conditions for both Durable and Tough Resins.

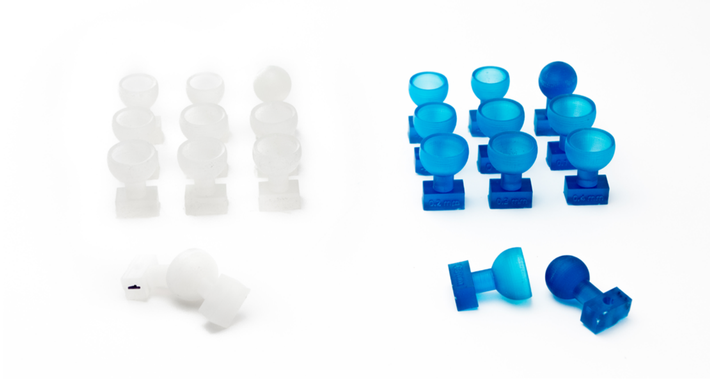
Download Hole & Shaft Test Model →





Tough Results: 0.05 mm or greater of allowance resulted in a clearance fit between the hole and shaft. Between 0.0 mm and 0.0375 mm resulted in a transition fit—the shaft could be inserted with a normal amount of hand pressure. Below 0.0 mm (an interference fit), the shaft becomes much harder to insert, and quickly exceeded the 55 N limit of the force meter. The shaft was able to be inserted with an arbor press at -0.0375 mm, but could not be removed.

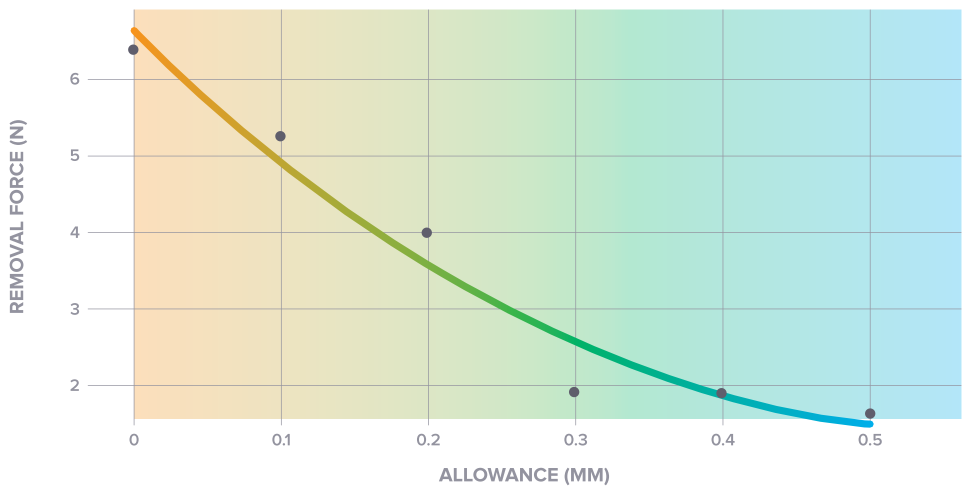
Durable Results: In this test, the Durable part transitioned from a transition fit to a freely insertable clearance fit at 0.0625 mm of allowance. At 0.0125 mm of allowance and below the parts had an interference fit and were difficult to remove. However, the parts could still be joined even at a negative clearance of -0.0375 mm. This is due to the high elongation of Durable Resin.



BALL AND SOCKET

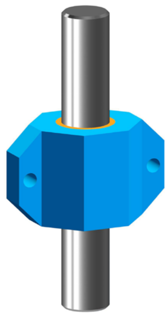
A clearance condition should exist to allow the ball to rotate freely in the socket. However, there is a large interference between the radius of the ball and the socket opening. The socket opening needs to deform enough to be inserted, but not come out in normal use.

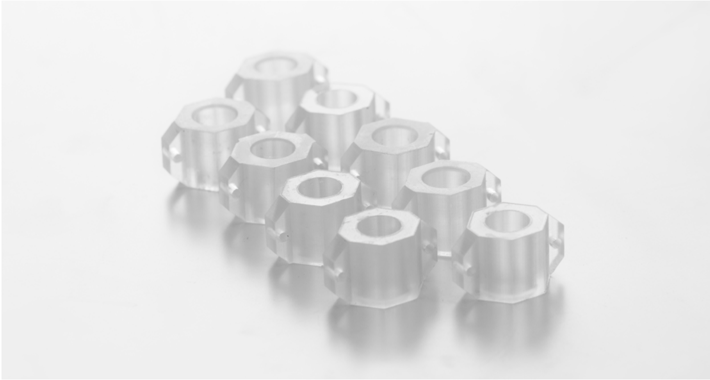
Download Ball & Socket Test Model



Durable Results: In this test there was an inflection point between 0.2 mm and 0.3 mm of allowance where the ball and socket becomes easier to separate. Between 0.0 mm and 0.2 mm, the ball moves smoothly in the socket but stays in position. The interference fit in this range would be ideal for articulated figurines, which need to keep their orientation. Above 0.3 mm, the ball is slightly loose and moves freely in the socket. Below 0.0 mm, the ball could not be inserted at all.

Tough Results: The ball and socket model was also printed in Tough Resin, but could not be inserted by hand because of the high friction and high strength of the material. Durable is better suited for a ball and socket geometry due to its wear resistance.

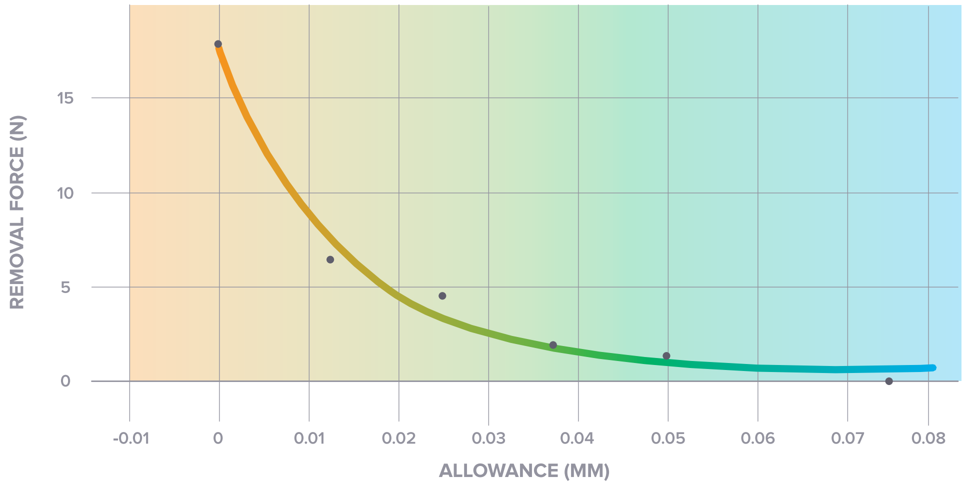




ROD AND BUSHING

A bushing is a type of plain bearing designed for smooth, free movement along a rod. There should be a clearance fit between the rod and the bushing. Depending on the application, the clearance may be larger or smaller.

Download Rod & Bushing Test Model →



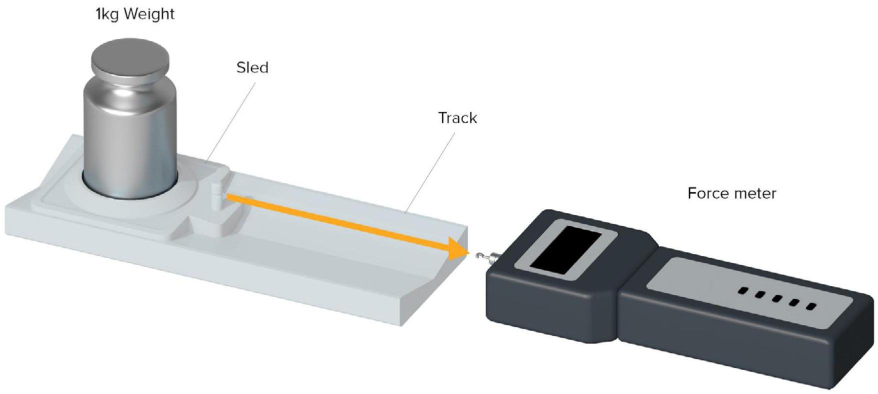
Durable Results: Bushings printed in Durable Resin had smooth and low-friction movement over the polished steel guide rod. With a designed allowance of 0.025 mm, the bushing showed a smooth running clearance fit with no play. At and above 0.025 mm, the bushing did not grip the rod at all, allowing it to slide freely. Between 0.0 mm and 0.025 mm, the bushing required a light force to push it over the rod. Below 0.0 mm of clearance an interference fit was observed that required significant force to slide the bushing over the rod, although the rod was insertable due to the compliance of the material. In this range the part isn't functional as a bearing.

Correctly lubricated, Durable Resin is a good choice for quickly prototyping custom bushings, gear systems, and smooth polypropylene-like products with moving parts. For kinetic assemblies that need to last for many motion cycles without wear, it is best to to use off-the-shelf Delrin bushings embedded in Tough Resin parts.

Note: Tough Resin is best suited for creating strong structural components that do not need to experience long term friction.

Friction

The amount of friction force between two components is the product of the force on the mating surface (directly related to fit), and a constant (the coefficient of friction), which is specific to each material. Coefficient of friction is useful for predicting how much resistance your parts will have to movement and wear, and how you can expect Formlabs resins to perform relative to other common materials.



Formlabs tested coefficient of friction using a weighted sled, a track, and a force meter.

Below are the unlubricated coefficients of friction between the following pairs of materials printed with 100 micron settings:

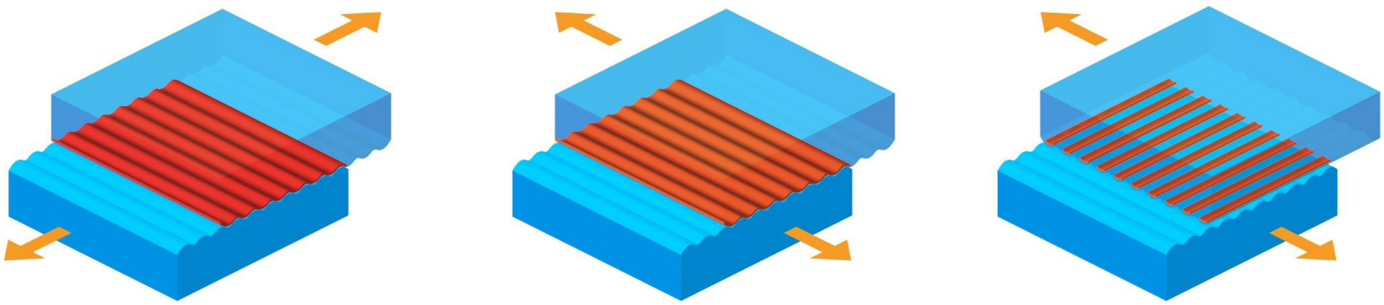
	Coefficient of Static Friction (μ_s)	Coefficient of Kinetic Friction (μ_k)
Durable | Durable	0.32	0.14
Tough | Tough	0.77	0.2
Durable | Tough	0.57	0.16

Parts were measured without any post-process smoothing or sanding. Durable Resin has the lowest sliding friction of Formlabs resins due to its high inherent lubricity. By contrast, Tough Resin has a higher sliding friction and markedly higher static friction which caused stick-slip behavior in our tests. Durable Resin's lower coefficient of friction makes it best suited for moving components which interact in kinetic assemblies.

Sliding components such as rails, pistons, and rods have lower friction if the contact surface area of the two mating surfaces is reduced. This is achieved by orienting objects in PreForm so that the layer "grain" pattern is perpendicular between the parts. If the grain is parallel the layer grooves will mesh, creating more surface area and higher static and kinetic friction.

Formlabs tested static and kinetic coefficient of friction between Durable components with parallel and perpendicular grain patterns by orienting the the sled 90° in Preform.

A micro-scale diagram of friction between surface orientations.



Most static and kinetic friction | *High static and moderate kinetic friction* | *Least static and kinetic friction*

In both the static and kinetic tests, the perpendicular orientation had lower frictional coefficients. The coefficient of static friction is impacted more significantly by grain orientation: in our tests, friction between perpendicular grain surfaces was 43 percent lower than parallel grain surfaces. Kinetic friction was 11 percent lower between perpendicular grain surfaces.

Friction between parts decreases over time as the surfaces experience wear. This is often beneficial to kinetic assemblies, and sanding and polishing is a deliberate example of wear. However, excessive wear tends to increase clearances between parts. Lubrication is the best way to reduce long term wear.

Note: Durable Resin is designed to be the most wear-resistant Formlabs material, and is most suitable for for gears, bushings, and kinetic assemblies.

In some cases—such as rollers, wheels, and robotic grippers—more friction is beneficial. For these applications, Flexible Resin has a higher coefficient of friction and lower lubricity.

Lubrication

Lubricants are essential to keeping components running smoothly in kinetic assemblies. Mineral oil is an inexpensive and commonly available lubricant commonly used with SLA prints. Silicone oil based lubricants, such as Super Lube®, also work well, and last longer without becoming sticky.

Air-powered, functional scale model of a flat two-cylinder internal combustion engine printed in Durable and Tough Resin and lubricated with mineral oil.

Bonded Components

In order to bond printed components with adhesives, a narrow clearance fit is desired. Cyanoacrylate (Super Glue) will fill thin gaps due to its low viscosity. A syringe of resin cured by hand with a UV or blue-violet (405 nm) laser pen (and UV safety goggles) can be used to weld parts together in butt joints.

Machining Printed Parts

The most common post-processing steps for printed assemblies are sanding, polishing, and lubricating. Occasionally it can be useful to machine a plastic part after printing, for example, if the tolerances of a feature need to be tighter than 0.025 mm, or to alter a feature after printing. Adding holes with a drill press or threads with a tap can be faster and more efficient than re-printing if the tools are available and the design has changed in the middle of a print.

Tough and Durable Resin withstand machining the best of Formlabs range of materials due to their high strength and elongation. Other Formlabs Resins can also be machined, though they require more conservative techniques and faster tool speeds.

Which machining operations work best with SLA resins?

High Temp	Sanding High-speed fly cutting High-speed, small-diameter boring and reaming
Tough, Durable, Standard	Sanding Face and peripheral milling Drilling Boring Reaming Tapping
Flexible	Sanding Drilling Cutting

Conclusion

Specifying fit based on material properties and mechanical function is a necessary practice in product engineering. The fit ranges shown for common geometries can be broadly applied to many designs to achieve functional prototypes with fewer iterations. For even more accuracy and an intuitive understanding of how parts will fit together, print the test models in a wider variety of materials and see how they perform.

Beyond fit, choosing the right material is essential for creating working prints. Formlabs materials vary significantly in tensile strength, elongation, and wear resistance. Some basic geometries such as the rod and bushing will work significantly better in Durable Resin due to the high wear resistance and low friction of the material. Structural components under load would be most successful in Tough Resin, which has high tensile strength and a flexural modulus similar to ABS plastic.

Download our Full Materials Data Sheet →