

Liquid Silicone Rubber Injection Molding

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Abstract

Liquid Silicone Rubber Injection Molding has been steadily gaining a foothold in many markets due to its ability to produce intricate elastomeric components with relatively short cycle times. The automotive industry employs silicone's high degradation temperatures for engine sealing and medical markets rely on silicone for its biological inertness. Liquid Silicone Rubbers (LSRs) can be processed using slightly modified thermoplastic molding equipment, making them easy to integrate into existing business structures and facilities. In recent years, an increase in use has driven down the raw material cost of LSRs as to make them more competitive with historically less expensive thermoplastic elastomers, thus extending their use into new markets. An increase in specialized auxiliary equipment such as robotics and other demolding devices will further facilitate LSRs push to the mainstream of polymer manufacturing.

Introduction

Among elastomers, Liquid Silicone Rubber (LSR) has a relatively short history. Developed during the late 1970s [1], LSR two component systems have quickly increased in popularity over the past 3 decades due to their advantages over Gum Silicone Rubbers. Not only are faster cycle times and flashless molding possible, but all secondary equipment is contained near the molding press and there is no need to mill or process the material in any way prior to use. LSR is also popular due to its ability to compete with typical thermoplastic elastomers: similar production rates can be achieved and LSR utilize slightly modified thermoplastic molding equipment, allowing for minimal initial capital investment.



Figure 1: Various LSR Components

Material Description

The two part material delivery system employed by LSRs consists of an A component which contains a catalyst and a B component which contains the crosslinking constituent. The catalyst is a platinum curing agent which will cause crosslinking at room temperature, hence the necessity of separating the two parts before processing. Component A also contains an inhibitor which slows the crosslinking action below a certain temperature. Above this temperature, crosslinking occurs freely and quickly, leading to the improved cycle times over gum silicone rubbers.

Both LSR components are translucent to slightly opaque as delivered from the manufacturer. Material rheology can range from nearly-Newtonian for unfilled LSRs to non-Newtonian with fillers and other additives. Most LSR grades are filled to some degree and thus exhibit shear-thinning behavior. LSR consistencies differ depending on durometer, from thin gels to thick pastes which retain their shape at room temperature. Colorants are easily added to the process at a point just prior to static or dynamic mixing devices as the A and B parts are introduced. Liquids or thin pastes are the most common method for color introduction.

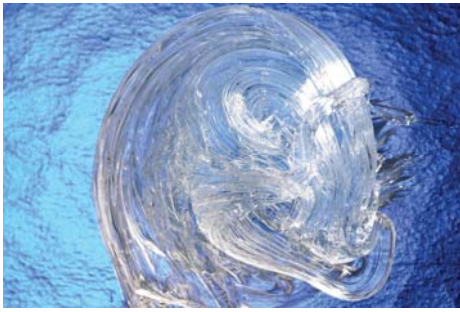


Figure 2: Typical LSR Consistency

Process Description

Two component systems are delivered from the manufacturer in 200kg (450lb) drums or 18kg (40lb) pails and are transferred to the molding machine via a pumping mechanism, typically pneumatic. A series of check valves on the pumping unit allow for positive material displacements regardless of pumping direction. A metering device such as a gear pump is used to ensure proper delivery of both the A and B component to the mixing head. The most common mixing ratio is 1:1; however, 10:1 is also used with the catalyst contained in the smaller ratio B component.

The A and B components combine in a mixing block where color can also be introduced. Mixing is typically achieved via a static mixing device such as a Kinex mixer where material streamlines are turned by 90° over several twisted tapes.

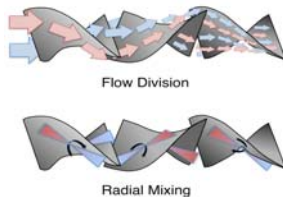


Figure 3: Kinex Static Mixer [15]

Prior to introduction to the injection unit, LSRs are often screened to remove any gels, contaminants, or prematurely cured material that can develop in the mixing device. Screen packs, consisting of several different mesh sizes, are retained in a steel housing with inlet and outlet ports. Typical max mesh is 200 (threads/in), with stepped increases (60/100/150/200) from the inlet direction.



Figure 4: Various Screen Packs [8]

Pressure regulation is often required before the mixed material enters the injection unit. This device allows for a restriction in the fluid path that can increase pressure, which allows for proper shot dosing. Pressure regulators are adjustable, but typically kept in the 0.7-3.5 MPa (100-500 psi) range to prevent over-compression of the metered shot.

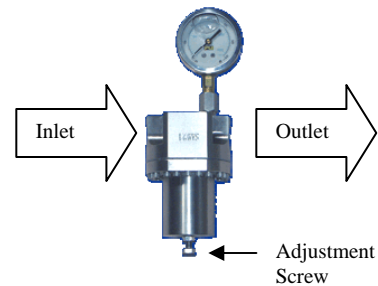


Figure 5: Typical Pressure Regulator [8]

Post-regulator, material enters the feed throat of the injection molding machine. Shot dosing for most LSR systems is no different than for typical thermoplastic processing. There is no melting requirement during metering, so compression ratios in the screw are kept low. As such, nearly continuous flight depths and root diameters are common. Also, in order to prevent premature crosslinking, or curing, during dosing and injection, the injection unit barrel is water cooled. This limits the effect of viscous heating that occurs between the LSR, screw, and barrel.

The screw tip for an LSR system must have a positive shutoff, or non-return valve, which is both consistent and precise. Ring type non-return valves are typical for thermoplastic molding, but do not have the tight clearances required to prevent material backflow during injection of lower viscosity materials. A better option for LSRs is the ball-check valve which has either a spring-loaded or floating ball that is in the closed position during injection, but open during shot dosing.

Similar in function to the screw tip, a shutoff nozzle is necessary prior to introducing material into the mold and prevents material backflow during part curing. The most common type is the pneumatically driven needle valve. Within the nozzle material is diverted around the piston that drives the shutoff needle, and reintroduced to the flow path near the nozzle tip. Like the barrel, nozzles are water cooled to prevent premature crosslinking during injection and dosing. The cooling channels are arranged so that they avoid the fluid path and cool nearer the nozzle tip, where LSR curing is most likely to occur.

This curing near the nozzle tip is due to the nozzle resting against a hot mold. LSR molds are typically heated 160-200°C (320-400°F). The crosslinking action which occurs in the hot mold causes the LSR to expand slightly during curing. This expansion makes it unnecessary to retain a shot cushion which is a necessity with thermoplastic injection molding.

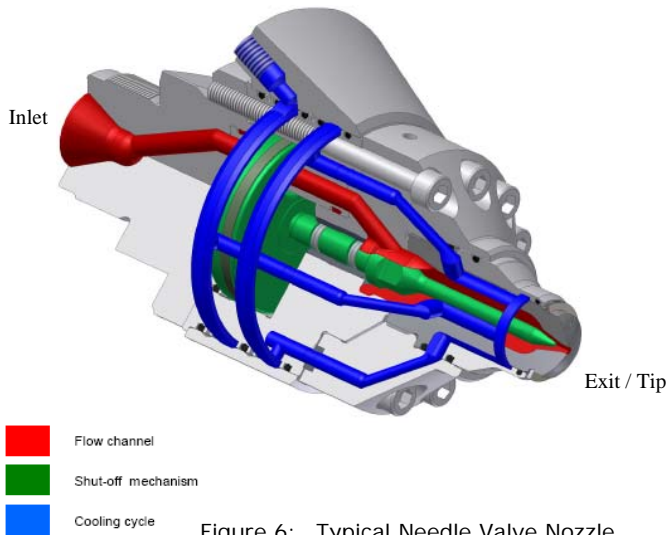


Figure 6: Typical Needle Valve Nozzle

[10]

Upon entering the mold, a thin skin of cured silicone is formed against the mold walls. This cured skin formation is analogous to the skin formed during thermoplastic molding where the skin acts as an insulator between the hot material and cool mold walls. With LSR, however, the skin insulates the cool material from the hot mold walls until the cavities can be completely filled. Once mold filling is complete, packing pressure is kept on

the material until the gates cure, again a process which is similar to gate freeze for thermoplastics.

A cure time follows injection and packing, and is highly dependant on part geometry: longer time for thicker parts and shorter for thinner parts. Unlike thermoplastics, relatively thick part geometries may be utilized with LSRs due to the crosslinking action. During the cure portion of the cycle, shot metering is also taking place. And the dosing time can be adjusted to match cure time by optimizing the screw speed and back pressure.

Post-curing, the mold opens, allowing for shot demolding and continuation to the next shot. Demolding is particularly challenging due to the LSRs relatively low viscosity. Ejector pin clearances may flash, so demolding is often accomplished with other means such as brushes or ejector plates.

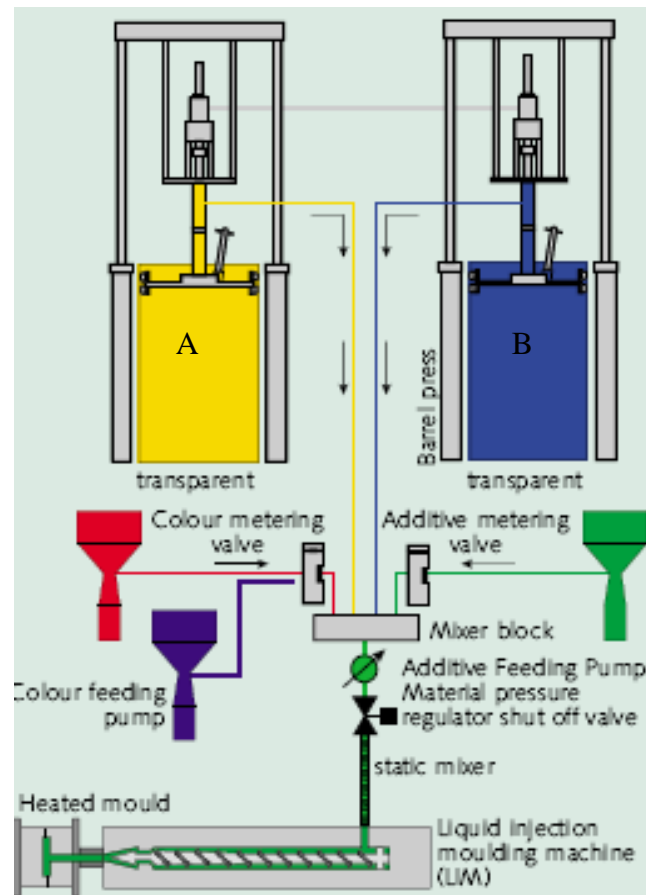


Figure 7: Schematic LSR Dosing System [7]

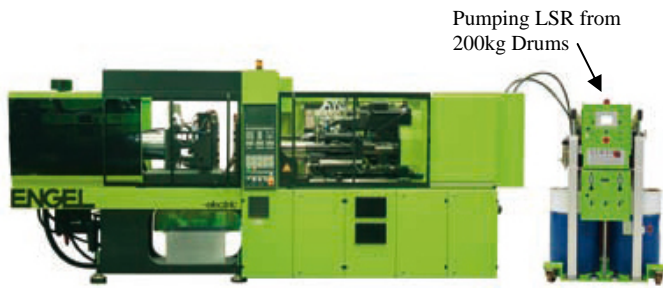


Figure 8: Common Horizontal LSR Molding Equipment [9]

Process History and Development

High-molecular-weight silicone gums were introduced commercially during the 1940s. Pre-existing rubber processing equipment was utilized to mill, mix, and mold these materials. The 1950s saw the introduction of Room Temperature Vulcanizing (RTV) rubbers which came in the form of two component liquids or pastes. When mixed, RTVs vulcanize (cure) at room temperature over extended periods of time [4].

LSRs are the result of these early RTV silicones. Formulations which could be cured more rapidly under higher temperature were developed during the late 1970s. As was previously done with rubber processing equipment, plastics processing equipment was soon co-opted for manufacturing LSR products. Injection molding machine barrels were water cooled, rather than heated, and shutoff nozzles were added to prevent material backflow during curing. This is the basic production setup for LSRs used today.

Great advancements in pumping LSRs have been made in the past two decades. Early pumping equipment relied solely on direct pneumatic driving to transfer material, and off ratio mixes were common. More recent developments use closed-loop controls to ensure proper the proper ratio of the A and B components. Material transfer rates are measured directly by flow metering devices and fed back to the control unit to either increase or decrease pumping speeds.

Process Economics

From a cost perspective, LSRs are competitive with traditional silicone gum rubbers with prices on the order of €7.00-€14.00/kg (\$5.00-\$10.00/lb). This is simply a baseline value: specialty materials and implantable medical silicones can be considerably more expensive, on the order of €140.00/kg (\$100.00/lb). Substantial savings can be generated, however, when comparing the processes. LSR has a vastly shortened rate of cure compared with traditional silicones, allowing for much faster cycle times. LSR cycles are also competitive with thermoplastic elastomers, making their higher material cost less of an obstacle.

Advantages / Disadvantages

Advantages vs. Silicone Gum Rubber

Faster Cycle – Common LSR cycle times are 30-60 seconds, where cycles for millable injection molding, compression, or transfer molding are often several minutes.

Complex Geometries – LSR's low viscosity at injection allows for flow into thinner, more complex geometries than gum rubbers. Solid silicone rubbers can encounter flow and gassing issues with such geometries.

Automation – Silicone gum rubber molding is quite labor intensive. Transfer and compression molding require preformed silicone gum and these processes are traditionally manually demolded. LSR allows for automation of both the shot dosing and part demolding.

Improved safety – LSR machine operators, with the proper automation, must rarely enter the molding area; parts can be transported out of the injection molding machine via robot, chute, or conveyor. This allows for fewer chances of burns from the hot mold or other safety issues.

Material Preparation – Gum rubbers require milling, a process of mixing the base rubber with a catalyst, and breaking down

intermolecular bonds, prior to use. This process is not only labor intensive, but adds chances for contamination and improper portioning. LSRs require no material preparation and are introduced to the molding machine as delivered from the manufacturer.

Advantages vs. Thermoplastic Elastomers

Heat Resistance – Silicones have an operating temperature well above the melting temperature of most thermoplastics making them suitable for high temperature applications.

Low Viscosity – LSRs have relatively low viscosities when compared with thermoplastics. Typical viscosities at injection for thermoplastics are on the order of 5,000-10,000 Pa-s, while LSR viscosities are on the order of 500-1,000 Pa-s (at shear rates around 10 s^{-1} , see Figure 9), allowing for much lower injection pressures during filling.

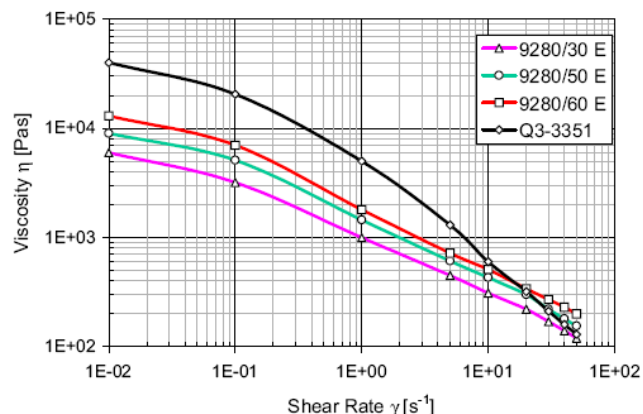


Figure 9: Typical LSR Viscosity Curve [2]

High Strength – The crosslinking of silicone molecules gives LSR products higher tear strength than thermoplastic elastomers. This allows for molded in undercuts that do not damage parts upon ejection, without the need for actuating mold cores.

Biological Inertness – LSRs can be formulated to comply with FDA biocompatibility guidelines. They are odorless and tasteless, do not support bacteria growth, and will not stain or corrode other materials. Most importantly, silicone rubbers exhibit

superior compatibility with human tissue and body fluids [13].

Disadvantages vs. Thermoplastic Elastomers

Premature Curing – Once the two components of the LSR system are mixed, they will cure over time. If cooling to the injection unit or cold runner (see Figure 13) is blocked or stopped, material crosslinking may occur to the point where no material will flow. When this condition arises, all components must be disassembled and cleaned, which is costly in terms of both production time and labor.

Difficult to Recycle – The chemical bonds formed during crosslinking of LSRs cannot be broken by thermodynamic means. They must go through several chemical processes which break the bonds to their constituent components, but can never be taken back to their A and B states. Thermoplastic elastomers, on the other hand, may be reground and directly reintroduced to the raw material stream.

Demolding – Lightly textured mold finishes are often employed with LSR tooling to improve transparency. Silicones have a tendency to stick to mold steel, especially more polished surfaces, so demolding is can be problematic. Rather than traditional ejector pins or robotic removal, LSR molding may include the use of ejector plates or brushes to remove molded parts and prepare the mold surface for the next shot.

Material Conveyance –

Thermoplastics are typically gravity fed into the injection barrel in their pellet or powder forms. LSRs, on the other hand, require pumping and mixing under pressure, which requires far more regular maintenance than a simple gravity feed system. LSR pumping also adds an additional element to injection molding troubleshooting, in that dosing issues and part performance issues may be related to pumping efficiency or proper mixing of the A and B components.

Application Areas

Medical – Due to their biocompatibility, stability over a wide range of temperatures, and mechanical resilience liquid silicone rubbers have a variety of advantages over other elastomeric materials for medical and healthcare applications:

Needleless Injection Sites – self-sealing valves

Infusion Pumps and Tips – cataract eye surgeries

Caps and Stoppers – vials and other containers

Membrane Pumps – fluid dosage

Ultrasonic Blades – vibration damping

Metal Overmolding – autoclave sterilization

Skin Contact Products – hypoallergenic

Implantable Products – biocompatibility

Multitude of Additional Uses



Figure 10: Examples of a various LSR sealing and pumping components used in medical applications

Automotive – The self sealing nature of LSR products, along with their high temperature stability and electrical insulating properties make them very well suited for various automotive applications:

Spark Plug Boots – electrical insulation

Wiring Harnesses – insulation, wire gripping

Bellows – flexible hose / wire coverings

Gaskets & O-rings – high temp. engine usage

Mounts – vibration / noise damping

Interior Components – soft touch items

Various other items

Industrial – Like automotive, typical industrial applications rely on LSR products for sealing, flow control, temperature stability, and electrical insulation:

Gaskets & O-rings – sealing applications

Check Valves – flow control and sealing

Food Handling – mixing and heat resistance

Membranes – pressure regulation

Various Outdoor Applications – silicone can withstand great variability in environmental conditions

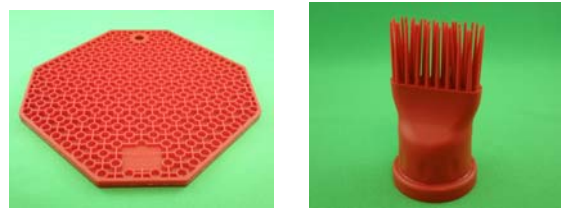


Figure 11: Examples a kitchen trivet (left) and a squeeze bottle basting brush (right)

Design Considerations

The first step in design is typically material choice; like thermoplastics, the particular grade and manufacturer of LSR have a great impact on final part design. Often for silicones, part durometer is the dominant consideration and can range from 20 – 80 shore A. Once a material is chosen for final product performance, many other decisions must be made regarding part shape, gating, material usage, and most importantly cost. The best method for determining these is to ask a series of questions:

How will the product be molded? –

Part geometries can have a great deal of impact depending upon the type of molding used. Some work well with automation typical for horizontal LSR molding, while others work better for the manual operation of vertical machine molding. Also, the complexity of the geometry plays a role in governing the size of the mold and thus the size of the molding machine.

How will the part be demolded? –

Design for ease of demolding is just as

important as design for molding. Silicone has a high green tear strength: meaning that very large undercuts may be designed into a product and the parts can be stretched over them during demolding without permanent deformation. This, however, does not mean that any geometry may be easily removed from the mold. Silicone's tendency to adhere to the mold steel after molding coupled with its natural tackiness can make it quite difficult to remove thick walled highly undercut parts. Undercuts and wall thicknesses should be carefully chosen during the design phase.

How will the material be fed to the cavities? – The use of a traditional runner system to feed material through the gate yields a great deal of wasted material which cannot be reused. A cold runner system, on the other hand, allows for direct gating with no material wasted. These systems consist of water cooled nozzles within the mold which feed material to each cavity, allowing for direct gating and no curing of the material within the cold nozzles. This system is analogous to a hot runner system for thermoplastics molding.



Figure 13: Typical cold runner system for LSR molding [15]

What type of gate should be used?

– Once the decision has been made regarding the type of runner system, gates may be chosen. For a cold runner system, pin, submarine, or other automatic degating design are often used. Standard runner systems may also utilize the aforementioned gate styles along with edge, fan, ring, or other gate types. Although these are the most common

methods, nearly any gating style may be used with LSR as with thermoplastics.

What is the best gate location? – As with thermoplastics injection molding, cavity filling should be achieved from the thickest areas of the part. If part of an assembly, gate location should not interfere with assembly or action of the final product.

Tooling Considerations

Product design and tooling design go hand in hand with LSR molding. Tool designers must take into account not only customer requirements of dimension and cavity geometry, but also how to reconcile those requirements with the limited space within an injection molding tool. These are some questions asked by mold designers and toolmakers:

What is the linear shrinkage of the LSR? – As with thermoplastics there is an overall shrinkage of molded LSR products after cooling. In general the linear shrinkage is 2-3%, but varying geometries change this value. Additionally, shrinkage is drastically affected by processes such as overmolding, where inserts do not shrink and the curing silicone shrinks less than expected. For cases where shrinkage is unknown or uncertain for a particular geometry, prototype tooling is often used to simulate full production.

Items		products		Highly transparent		
		Liquid A	Liquid B	KE1935 (A-B)	KE1987 (A-B)	KE1988 (A-B)
Before curing	Appearance	Liquid A	Transparent	Transparent	Translucent	Translucent
		Liquid B	Transparent	Transparent	Translucent	Translucent
	Viscosity*1	Liquid A	Pa*s	80	700	600
		Liquid B	Pa*s	45	700	450
After curing 2)	Appearance		Transparent	Transparent	Transparent	
	Specific gravity at 23°C(73.4°F)		1.03	1.15	1.15	
	Hardness, Durometer type A		55	55	62	
	Tensile strength	MPa	5.9	8.3	7.8	
	Elongation at break	%	350	430	250	
	Tear strength, crescent type	kN/m	8.0	35	35	
	Compression set	%	30	50	49	
	Linear shrinkage	%	3.2	2.1	2.2	
	Volume resistivity	TΩ·m	10	100	100	

Table 1: Typical Material Data [3]

How should the mold be heated? –

Consistent heating of LSR molds is crucial to producing parts of proper geometry both throughout a single run and between runs. Options for heating methods include resistance or induction. Both styles may be placed inside the plates of the mold or inside a universal base which heats the entire mold from the outside only. More precise control is given by placing heaters directly in the mold plates, so that the thermocouples tied to the PID controller can more effectively change the heater on/off timing. Choice of heating type depends largely on budget and geometric considerations, since heating the mold directly increases costs and heaters must be placed so that they avoid mold cavities, cores, and slide actions.

How much venting is required? –

Venting is very important for proper LSR molding. LSR's low viscosity results in very high injection speeds which tend to cause dieseling, or scorching, at the end of fill. This low viscosity also causes LSR to flash more readily than thermoplastics so the vents must not be cut as deep: near 0.005 mm (0.0002 in) for LSR compared to 0.025 mm (0.001 in) for thermoplastics. In addition to typical venting, vacuum evacuation is also common for LSRs as the trapped air can be more quickly taken from the cavity, reducing the chances of gas trapping.

What surface finish is best for proper demolding? – Surface finish is often dictated by customer requirements or product design. However, when finishes may be chosen, non-polished finishes are preferred – SPI mold finish of B1 or less. Finishes A1-A3 are highly polished and LSR tends to adhere to the mold surface, making demolding difficult.

What items may be improved to ease maintenance in the future? – Properly maintained molds are crucial to LSR molding. Tight tolerances are necessary to prevent flashing and dimensional issues. Wear items such as bushings and side locks which are used for alignment should be easy to change and placed on a regular PM schedule. Cavities and cores should be easy to access for regular cleaning. If the mold has a cold runner, it

should be designed so that disassembly and assembly are as simple as possible. Often, cold runner nozzle tips and shutoff needles need to be cleaned of cured material, and ease of access is of great importance to limiting downtime.

Process Considerations

Though similar to thermoplastic injection molding in many ways, LSR molding processing can be quite different.

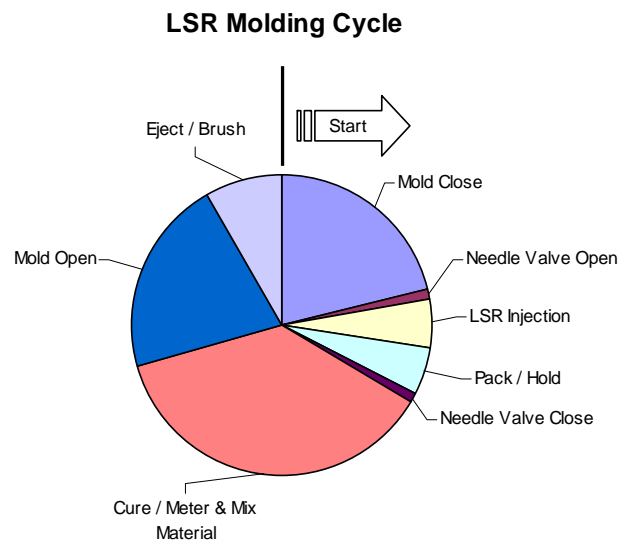


Figure 14: LSR Molding Cycle Breakdown

Molding Parameters

Rather than plastication during cooling, LSRs need only be conveyed through the screw flights for the next shot. As such, back pressures and screw speeds are kept low; only fast enough to complete dosing before the cure portion of the cycle is complete.

Shot size is determined by the rule of thumb that 99% of the cavity should be filled. The final filling will be done by expansion of the material during curing, so no cushion is needed. It is important not to fill the cavity completely as this is a main culprit for flashing [2].

Injection speeds should be set to optimize pressure during filling. Again, due to its low viscosity, LSR flashes easily and must be molded under as low a pressure as possible. Packing pressures are generally low

due to expansion during cure. Time for complete cure depend greatly on part thickness.

Mold temperatures should be set according to the suggested range of the material supplier. Hotter molds will cure faster, so shorter cycles can be achieved. However, material flow during injection is easily affected by mold temperature, so it must not be so high that the material cannot flow effectively into the cavity. Part shrinkage is also dependant upon mold temperature and should be considered during R&D for new products.

Mold Preparation

LSR tools must be carefully prepared before production. Isopropyl alcohol or other solvents are used to remove residues left from the previous molding run or during a run if the production cycle is quite long. Often, molds must be cleaned as frequently as once per week. After cleaning, mold release agents are applied to the cavities and runners, and are allowed to dry before the mold is placed into the injection molding machine.

Material Changes

LSR materials require constant pressure during pumping and thus material containers may not be changed while the pumping unit is operating. This means that the injection molding machine must be stopped in order to remove the empty container and replace with new material. The best method by which this situation may be avoided is via a second pumping unit which may be switched by valve in order to continually operate the molding machine. These units are quite expensive, however, so substantial capital investment is required to ensure continual operation.

Potential Innovations

Two Shot Molding – Typically, LSR overmolding requires the use of a priming agent to prepare the component surface for the liquid silicone. Recent advancements in self-bonding LSRs have lessened the necessity of priming, as they are designed to bond directly to a variety of materials. This advancement has also opened the door to

potential innovations such as two shot molding, where thermoplastics and LSRs are processed on the single machine, with a single mold. This process allows for not only lowered manufacturing costs, but also increased design freedom by molding the two components together.

Improved Cold Runner Technology

– Cold runner technologies are currently in a state of newfound importance. For the past few decades, each LSR manufacturer had developed proprietary cold runner shutoff nozzles and cooling technologies. Recently, several manufacturers have introduced off-the-shelf cold runner systems akin to the hot runner systems available for thermoplastic molding. Standardization may lead to improved systems which operate even more efficiently than those currently available.

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