Sample Pages

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Robust Process Development and Scientific Molding

Theory and Practice

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viscosity drops, resulting in a negative slope of the line. Therefore, the value of \( n \) is always less than 1 but greater than zero.

In polymer melts, as the shear rate is applied, the molecules start to align themselves in the direction of flow, moving away from their equilibrium intertwined states. Increasing shear rates stretch and align more and more molecules in the direction of flow. This alignment facilitates the easy movement of the flow layers past each other, thus reducing the resistance to flow or viscosity. At a certain point, all the molecules become aligned in the flow direction and increasing the shear rate further has little or no further effect on the viscosity.

For the sake of practical injection molding, we could consider the region of higher shear rates as a Newtonian region where the viscosities become consistent. Since the viscosities are a result of the fill speeds, the corresponding regions of fill speeds are now treated as the consistent region. Injection speed is synonymous to shear rate and an in-mold viscosity curve appears similar to the one shown in Fig. 3.8. Shear rate can be calculated as the reciprocal of the fill time, where fill time is the time the screw takes to travel from the set shot size to the holding phase transfer position of the screw on the molding machine. Simply put, it is the time for which the screw moves in the injection phase.

3.4 Effect of Temperature on Viscosity

In the solid state the molecules have very little thermal energy and therefore are almost immobile. Depending on the ambient temperature and the glass transition temperature \( (T_g) \) of the polymer, the polymer can be either brittle or soft and tough. The thermal regions are explained in Chapter 2. Below the \( T_g \), the plastic is very brittle and is said to be in the glassy state. Above the \( T_g \) the plastic is soft and is said to be in the rubbery or viscoelastic state. Above the melting temperature \( (T_m) \), for crystalline plastics, the plastic is in the melt form.

Figure 3.8 Effect of apparent shear rate (injection speed) on the viscosity of the polymer
In general, as the temperature is increased, the thermal energy reduces the weak intermolecular attraction that holds the molecules together, making them more mobile. Amorphous polymers continue to soften and crystalline polymers show a sharp melting point. Increase in temperature increases the mobility of the molecules, thereby reducing the viscosity of the polymer. Temperature and viscosity are inversely related. Figure 3.9 shows the effect of temperature on the viscosity of the melt. It is also clear that the effect of shear rate is higher than the effect of temperature.

In injection molding, it is common practice to increase the melt temperature to make the plastic flow easier. However, Fig. 3.9 demonstrates that increasing the injection speed will have a greater effect on part fill. This advantage is discussed in Chapter 7 and a procedure to generate the in-mold rheology curve is also discussed.

**3.5 Velocity and Shear Rate Profiles**

The velocity profile shows the relative velocities of the different layers in the polymer melt as it flows through a channel. The length of the arrows in the velocity profile represents the
velocity of each of the layers. The velocity at the wall is zero and therefore the shear rates are very low near the wall. The velocity increases towards the center of the channel, following a parabolic profile and it is highest at the center. As discussed earlier, shear rate is the difference in the velocities of the adjacent layers. In Fig. 3.10, the difference in the velocities in the first two layers near the wall is very high compared to two layers near the center of the channel. Therefore, the shear rate is higher near the wall, compared to the center of the chan-

![Velocity and shear rate profiles in polymer melts](image)

**Figure 3.10** Velocity and shear rate profiles in polymer melts

![Outputs from a finite element, finite difference flow analysis program providing information on the melt conditions through the cross-section of a cold runner. Y-axis is from the center line of the channel to the channel wall: (A) velocity; (B) shear rate; (C) melt temperature; (D) viscosity [1]](image)

**Figure 3.11** Outputs from a finite element, finite difference flow analysis program providing information on the melt conditions through the cross-section of a cold runner. Y-axis is from the center line of the channel to the channel wall: (A) velocity; (B) shear rate; (C) melt temperature; (D) viscosity [1]
3.6 Application to Injection Molding

The direct effect of the shear rate distribution discussed above is visually evident in injection molding, particularly in the filling pattern of multi-cavity molds. As the plastic begins to flow in the runner, the shear layers are formed as shown in Fig. 3.10. Since the melt flow is always laminar, these layers split and/or flow into the various flow channels in lamina. Each of these lamina has their own characteristic properties, such as shear rates and temperatures. The high shear lamina just below the wall of the flow channel create a low viscosity region changing the velocity of flow in some cavities and causing cavity-to-cavity flow imbalances. Some of the typical and common characteristics of such flows and their effect on the parts are described in the following.

3.6.1 Flow Imbalance in an 8-Cavity Mold

Consider an 8-cavity mold as shown in Fig. 3.12. As the plastic flows through the primary runner, the shear layers are developed.

If we disregard the frozen layer (in a cold runner mold), we can distinguish between two distinct layers. The outside layer is the high-shear layer and the inside layer is the low-shear layer. In the diagram, the high shear layer is the shaded area. Section A-A is the cross section of the primary runner and shows the two layers concentric to each other. Since the flow

![Figure 3.12 Split of different shear rate regions in an 8-cavity mold [2]](image-url)
through the mold is laminar, the variations in shear, temperature, and viscosity across the runner proceed into the secondary runner. The inner low-shear laminas hit the far wall of the secondary runner and the high-shear laminas on the outer perimeter continue to flow along the near wall of the branching secondary runner. The cross section shown in Section B-B illustrates this distribution of high- and low-sheared material in the branching secondary runner.

The laminar flow continues through the secondary runner, the tertiary runner, and then into the cavities. The result is that inside cavities (those close to the sprue) are filled first, as they are fed by the hotter, high-sheared, lower viscosity material developed earlier in the runner. This is shown in Figure 3.13. A visual proof of the high-shear lamina is shown in Figure 3.14. Here, a runner used in the molding of a PVC part clearly showed degradation caused by the high shear. The black streak on the inside is the high-shear lamina in the figure. Note that the burning/streaking of the material develops prior to the actual corner. We point this out in particular, because shear induced imbalances are sometime misrepresented as being caused by a sharp corner in a runner. Here, the evidence dispels this theory as the runner is not only radiused (no sharp corners) but the burning begins before the corner.
The cavity-to-cavity imbalance described above is called a rheological imbalance. The runner is said to be rheologically imbalanced despite the fact it is geometrically balanced. When the distance from the sprue to the gate is the same for each cavity, the mold is said to be geometrically balanced. This geometrical balance in a runner is still commonly incorrectly referenced as a “naturally balanced” runner.

### 3.6.2 Racetrack Effect in a Part with Constant Thickness

The part shown in Fig. 3.15 is made with a single-cavity mold, producing a 100 mm × 2 mm thick flat part with a constant wall thickness. The shear effect on viscosity can be seen in the flow pattern developed in this cavity. The high-sheared low-viscosity material developed in the perimeter of the runner splits and concentrates along the perimeter of the flat disc, causing the race tracking effect. Note that the photo in the right shows that the effect is significant enough to create a gas trap, opposite the gate, in this flat part.

![Figure 3.15](image)

**Figure 3.15** Racetrack effect causing a gas trap in a part with uniform thickness [3]

### 3.6.3 Stress Build-Up in Molded Parts

The part shown in Fig. 3.16 is made from a transparent material in a two-cavity mold. The parts are packed out and examined with a polarizing lens after molding. The build-up of stress can be seen on the inside of the parts. This is the area where the hotter laminas flow, causing differential cooling and therefore stress.

![Figure 3.16](image)

**Figure 3.16** Stress build-up observed under a polarizing lens [3]
3.6.4 **Warpage Difference Between Cavities**

Figure 3.17 shows parts molded in a 4-cavity mold. Because the location of the hot laminas in the cavities is different, two of the cavities are warped while the other cavities are perfectly flat.

![Warp in Cavities 2 & 3](image1) ![No Warp in Cavities 1 & 4](image2)

**Figure 3.17** Warpage differences between cavities from the same mold caused by a melt imbalance [3]

3.7 **Solving Flow Imbalances Using Melt Rotation Techniques**

The solution for balancing the flow and creating rheologically balanced molds was developed and patented by John Beaumont of Beaumont Technologies in Erie, Pennsylvania (please note that the use of this technology requires a licensing agreement from Beaumont Technologies Inc.) Beaumont’s varied methods of melt management, commonly known as Melt-Flipper® technology, can be used in applications that include the rheological balance of mold and part filling, control of intra-cavity filling, warpage, part property, and cosmetic manipulation. One of the more common applications is shown for an 8-cavity mold in Fig. 3.18 a. This is a conventional H-shaped runner with eight cavities. The cross sections of the flows are also shown. In the primary runner, the high shear and the low shear areas are concentric to each other. As the flow splits at the secondary runner, the high-sheared material stays on

![Before and after examples using the melt rotation technology](image3)

**Figure 3.18** Before and after examples using the melt rotation technology [3]
the inside. At the split at the tertiary runner, the high-shear material ends up in the inside cavities, causing these cavities to fill before the outside cavities. Inside and outside cavities exhibit different melt conditions. The result is that the parts formed in these two cavity groups will be different in size, weight, and properties.

Beaumont’s patented melt rotations technologies use a variety of methods to manage the position of the high- and low-sheared laminates to achieve the desired balancing effects. In this 8-cavity example, the melt would be “flipped” or rotated, 90 degrees prior to entering the tertiary runner to the position shown in Figure 3.18b. This rotation is commonly created at the intersection of the primary and the secondary runner. When this melt exits the secondary runner, the high-shear area is now on the top rather than on the inside, as is shown in Fig 3.18a without the flip. When this reoriented material enters the split of the tertiary runner, the high- and low-sheared melt splits up evenly into the two branches and each of the cavities receives melt with equal amounts of high-shear and low-shear material. This creates a fill and rheological balance between all cavities in the mold.

In the above case, the melt was rotated at one location, the intersection of the primary and the secondary runner. In case of a 16-cavity mold, the concept can be extended and the melt will need to be rotated at two locations for balancing all sixteen cavities. In addition, by applying similar melt rotation techniques, some of the other problems in the parts can be solved. An excellent treatise on this subject with detailed explanation is provided in [1]. Some of the ‘before and after’ examples are shown in Fig. 3.18. Figure 3.18a shows the filling pattern resulting in a conventional geometrically balanced runner. Filling is not only unbalanced from cavity to cavity, but each side of the Flow #1 cavities (inside four cavities) is different. Figure 3.18b shows the filling pattern after melt rotation was applied. Note that a balanced filling results not only between cavities but also within cavities. Not only will all eight parts be almost similar, but the use of pressure transducers (or thermocouples) for controlling and monitoring the process can be significantly improved. Figure 3.18c shows the filling pattern resulting in a simple flat disk, where the high-sheared material from the runner is causing a race track effect around the perimeter. Figure 3.18d is the same disk, except the melt has been conditioned using Beaumont’s multi-axis rotation technology (MAX™ technology). Here, the majority of the high-sheared laminates have been repositioned to flow across the center region of the cavity.

Figure 3.19 shows the temperature distribution before and after the use of melt rotation technology. The photos of these parts were taken with an infrared camera immediately after molding. The left hand side part is the inside cavity fed by the high-sheared lamina. In the conventional

![Figure 3.19](image-url)

**Figure 3.19** Temperature distribution before and after using melt rotation technologies [3]
7 Scientific Processing and Scientific Molding

7.1 Introduction

Several parameters determine a successful molding process. There are various speeds, pressures, times, and temperatures to be considered. Scientific processing encompasses an understanding of the underlying scientific principles of each parameter and the application of these principles to achieve a robust process and consistency in part quality. Scientific processing covers the complete molding process, from the time the plastic enters the facility to when it leaves as a finished product. A robust process is one that can accept reasonable natural variations or a small purposeful change in an input but still delivers consistent output. The term consistency means molding parts with the least variation in the quality of the part. The quality of the part can mean its dimensions, appearance, part weight, or any other aspect that is important to the form, fit, or function of the part. The variation should be from special cause variations and not from any natural cause variations. Special cause variations are variations that are caused by an external factor. For example, if the chiller unit shuts down, the mold temperature will change causing a change in the quality of the part. Natural cause variations are inherent to the process. Their effect can be minimized but not eliminated. For example, if the plastic used to mold the parts has 30% of glass fiber mixed in it, in every molded shot the amount of glass will not be exactly 30%. It will be slightly more or less, for example, between 29.7 and 30.3%. This variation cannot be eliminated, but the mixing process can be improved and the variation can be reduced.

Robustness and consistency should not be confused with parts being molded within the required specifications. Parts can be out of specifications but the process can be robust and the quality can be consistent. The goal of scientific processing is to achieve a robust process at each stage of the molding process the pellet is subjected to.

The term Scientific Molding was coined by a two pioneers in the field of injection molding, John Bozzelli and Rod Groleau. Their principles and procedures are widely used today and are industry standards. Scientific molding deals with the actual plastic that enters the mold during the molding operation at the molding machine. The term introduced here is Scientific Processing, which is defined as the complete activity the plastic is subjected to from the storage of the plastic as pellets to the shipping of the plastic as molded parts. Scientific processing is applying scientific principles to each of the steps involved in the conversion of the plastic to the final product, see Fig. 7.1. This chapter deals with the understanding and optimization of this complete process. The focus is on the understanding and the application of the theories to each of these steps and then optimizing them. Successful process development results in a process that is robust and one that molds parts with the required consistency.
7.1.1 Process Robustness

A process is considered robust when changes to the inputs have minimum effects on the quality of the part. The changes here can be intentional or may be due to natural variations. Naturally, intentional changes must be within reason. In general, a process becomes more robust as larger input changes can be introduced without adversely affecting the resulting output part quality. For example, after a certain injection speed is reached, the viscosity of the plastic remains constant. The viscosity curve is in a robust area and variations in injection speed have little effect on the viscosity and therefore the amount of fill into the mold. At low injection speeds, a slight change in the injection speed causes a large change in the viscosity, resulting in shot-to-shot fill inconsistency. Therefore, this is not a robust area of the process and should be avoided. In addition, it must be understood that natural variations can never be eliminated. Taking these conditions into consideration will help ensure building a robust and consistent process.

7.1.2 Process Consistency

A process is considered consistent when it meets the following two requirements.

- All variations in the outputs of the process are a result of only natural cause variation.
- The standard deviation of the variation is at a minimum value.

For example, the cushion value is an output of the injection, pack, and hold phases. If the cushion value shows minimum variation, and a distribution curve of the cushion value over time is normal, then the process is consistent. In this case, the process under consideration would include only the injection, pack, and hold phases.
A robust process will always produce parts of consistent quality because there is little variation in the output. It also goes without saying that for the quality to be consistent, the process must be robust. For injection molding, whenever there is an inconsistency in part quality, the robustness of the process is usually suspect because the process is reflected in the part quality. In general, based on how robust the process is and on the required tolerance limits, we consider four possible resulting production process scenarios, as shown in Fig 7.2, which shows a representation of a run chart for a particular dimension.

Figure 7.2a shows a process that is not robust because of dimensional changes in the part. The first four data points are closer to the upper specification limit, but the next data point drops down towards the lower specification limit. There are some parts being molded out of specifications. Figure 7.2b shows the same process, however with increased tolerances; this process is producing parts within specifications. In both these cases, a special cause variation seems to be contributing to the inconsistent part quality. An attempt must be made to eliminate this variation even though in the second case, the parts are within the required specifications. Figures 7.2c and 7.2d both represent a robust process, because the quality distribution is normal. In Fig. 7.2c, the tolerance limits are such that this process although robust, produces parts out of specifications. In Fig 7.2d, the tolerances are wider than in Fig. 7.2c and therefore the same process now produces acceptable parts. Clearly, the process in Fig 7.2d is the most desirable process. Setting of the tolerance limits is done by the product engineer. In some cases, the engineer does have the flexibility to open up the tolerances.
based on the form, fit and function of the part. If opening of the tolerances is not acceptable to the product engineer and if it is not possible with the current process setup to reduce the variation, alternative solutions such as selecting another plastic, changing the amount of filler, or using cavity pressure control must be considered. As mentioned earlier, an attempt must always be made to eliminate the special cause variation, even if the parts are within the required specifications. This makes part quality more predictable and the manufacturing process less vulnerable to molding defective parts. Another benefit of implementing the discipline of developing robust processes is a reduction in part inspection frequency and sample sizes. The goal of process development, using scientific principles and techniques, must be to establish a process that is consistent and well within the specification limits similar to the one shown in Fig 7.2d. Simply molding parts within the specification limits does not necessarily mean that the process is robust and stable.

There are ways to improve the robustness of a process, reduce variation and improve consistency. The aim of process development should be to develop a stable and robust process.

There are systematic steps that must be followed in order to achieve this goal. Unfortunately, these steps are often ignored because they are time consuming and can increase the number of mold trial iterations. Often overlooked is the amount of time, energy, and materials that are wasted and scrapped due to production of non-quality parts; the mold needs constant attention of a technician to adjust the process to produce the parts within specification;

Figure 7.2c,d Types of processes based on variation and tolerances
or decrease, depending on the dominant phenomenon. These phenomena and the resulting required pressures are described in the following.

- As the melt hits the mold, it starts to cool, resulting in an increase in the viscosity of the plastic. This will result in an increase in the required pressure.
- The flow channels in the mold typically call for progressively smaller cross-sectional areas towards the end of the flow. Smaller cross sections result in higher required pressures. However, if the cross sections are generous, the resulting pressure may not change.
- When the plastic first enters the mold, the layer of plastic next to the wall forms a frozen layer and the hot melt that is entering the mold now flows in between these frozen layers. This is also called fountain flow. This frozen layer gets thicker and thicker during the filling phase, again increasing the required pressure to move the screw at the set injection speed. With thick parts or generous flow channels this effect is not significant because the filling may be completed before the frozen layer is sufficiently built up.
- Because plastics exhibit non-Newtonian behavior, with increasing injection speeds the viscosity drops and the pressure required to move the screw will reduce.

### 7.6.2 Step 2: Determining the Cavity Balance – Cavity Balance Study

A specific volume versus temperature graph was discussed in Chapter 2. The graph is shown in Fig. 7.21 with the areas that correspond to the different phases of the injection molding cycle. The injection phase corresponds to the plastic being in the melt phase and as the melt starts to cool, the pack and hold phase come into effect. When the pack and hold is done, the plastic is cooled down below the ejection temperature where it can be safely ejected out of the mold.

Shrinkage is directly related to specific volume. As the pressure increases, the specific volume decreases. The packing pressure therefore affects the shrinkage of the part. The higher the packing pressure, the higher is the pressure of the plastic inside the cavity and the lower is the shrinkage. Therefore, to control the dimensions of a part, the packing pressure or cavity pressure must be controlled. Incidentally, this is the principle behind the use of cavity pressure sensing technologies that will be described in Chapter 12.

Figure 7.22 shows the effect of cavity pressure on the length of a tensile bar. The tolerances are also shown on the graph. As the cavity pressure increases, the length of the tensile bar increases.
Now let us consider a two-cavity tensile bar mold. To mold tensile bars of equal length, the plastic pressure in each of these cavities must be identical. When the cavity fill is identical, the pack and the hold phases that follow will have the same effect and produce identical cavity pressures. If one cavity happens to fill less than the other, then at process switch-over from pack to hold, the cavity that fills first will get pressurized more, leading to higher cavity pressure and therefore a larger dimension. This will result in cavity-to-cavity dimensional variation. One cavity may replicate the first tensile bar dimension in the figure and the other may replicate the last one. When one is within specifications, the other may be out of speci-
fications. In addition, when the process windows are small, the cavity that fills first may end up with flash, even when the other cavity is still unfilled (short).

Figure 7.23 shows parts from a two-cavity mold, where one part is short while the other exhibits flash. To avoid these issues, the flow of the melt into each of the cavities must be identical. Determination of cavity balance is therefore an important step during process development.

There are several reasons for flow imbalances:

- **Flow channel variations**: If the runners and the gates are not identical, there is more restriction to flow in one cavity than in the other. This will lead to a fill imbalance.

- **Venting variations**: Vents are added to the mold in order to provide a pathway for air in the cavity to escape as it is being displaced by the plastic melt that is entering the cavity. Therefore, the vents must be capable of allowing air to escape from the cavity at a rate equal to the flow rate of the plastic into the cavity. Consider a worst case situation, where one cavity does not have any vents. In this case, the plastic would not be able to enter the cavity as fast as it could in the other cavity. There would be some amount of cavity fill due to natural venting, but it would be not nearly as effective as in the other cavity with the deliberate addition of vents. Therefore, if the size of the vents and the position of the vents are not identical, this will affect the fill pattern leading to dimensional variations in the parts.

- **Cooling variations**: The mold temperature can significantly affect the flow of the plastic, especially with crystalline materials and parts with long flow lengths. Generally, higher mold temperatures result in higher flow rates of the plastic. Mold temperature will also affect the amount of shrinkage. Therefore, if the cooling is not identical in all cavities, the plastic will flow and shrink differently in each cavity, causing dimensional variations. A similar effect is seen when a water line is plugged or not connected correctly, causing one section of the mold to run hotter than another section where coolant is flowing properly.

- **Rheological flow variations**: This topic was discussed in detail in Chapter 3. Consider the following example: in an 8-cavity mold with an H-shaped runner, the four inside cavities

![Figure 7.23](image_url) **Figure 7.23** Two-cavity mold with one cavity short and the second with flash molded in the same shot
X-axis: Cooling Time. Below 20 seconds, thicker areas of the parts appeared soft when ejected and there was evidence of warp. Therefore, this was taken as the low limit for the cooling time. Above 30 seconds, the cycle time became prohibitively long and therefore this was defined as the upper limit for the cooling time.

Y-axis: Holding Pressure. Below 30 bar, the parts had sinks and above 55 bar the parts flashed. Therefore these values were taken as the lower and upper processing limits for the part. Within these limits the molded parts were acceptable aesthetically. They were free of all sink or flash. The DOE was performed using limits and a contour plot was plotted. This plot is shown in Fig. 9.2. The LSL, USL and the nominal values are also shown.

Table 9.1 Quality Requirements

<table>
<thead>
<tr>
<th></th>
<th>Length</th>
<th>Diameter</th>
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</thead>
<tbody>
<tr>
<td>Nominal</td>
<td>144.65</td>
<td>6.18</td>
</tr>
<tr>
<td>+ Tolerance</td>
<td>0.13</td>
<td>0.09</td>
</tr>
<tr>
<td>− Tolerance</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Upper Specification Limits (USL)</td>
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</tr>
<tr>
<td>Lower Specification Limits (LSL)</td>
<td>144.52</td>
<td>6.05</td>
</tr>
</tbody>
</table>
9.2 The Dimensional Process Window (DPW)

The green shaded area in Figure 9.3 defines the process window in which dimensionally acceptable parts are molded. In this example, pressures above 800 psi will cause flash in the parts and below the red LSL line the parts will be out of specification. The window that is now a subset of the aesthetic process window is called the “Dimensional Process Window”. In the case described, the window is not a uniform quadrilateral and the molding parameters must be selected inside this area.

9.3 The Control Process Window (CPW)

We shall now expand on the concept of dimensional process windows. If the dimension under consideration is a dimension that needs to be statistically capable, then based on the calculated control limits, a Control Process Window can be defined. The control limits are calculated on the standard deviation of the measured dimension. With the capable process, these limits are always within the USL and LSL and therefore the CPW is always within the DPW. The CPW is a subset of the the DPW. Once the molding process is started, the process capability can be calculated and the control limits can be established. Based on the statistical process capability, the Lower Control Limit (LCL) and the Upper Control Limit (UCL) were
calculated and are shown in Figure 9.4. These contours can now be plotted on the contour plot and the CPW can be determined. This new window, in which the parts are not only acceptable but also under statistical quality control, is called the Control Process Window (CPW). In Fig. 9.4 the yellow shaded area is the CPW.

With the explanations given in the preceding paragraphs a more precise definition of the terms are given below.

- **Aesthetic Process Window (APW):** The limits between which an aesthetically or cosmetically acceptable part can be molded. Dimensions are of no concern.
- **Dimensional Process Window (DPW):** The limits between which a dimensionally acceptable part can be molded.
- **Control Process Window (CPW):** When the statistical control limits are applied to the dimensions given by the dimensional process window, the resulting window of operation is called the control process window.

During the process of initial mold sampling the APW should be as wide as possible. The parts that are molded should be aesthetically acceptable over a wide range of processing parameters. Once a wide APW has been determined, we can use the low limits and the high limits to set the high and low levels required for each DOE factor. The higher the difference between the high and the low limit, the higher will be the magnitude of change on the quality of the part. The results of the DOE can then be analyzed and the DPW can be determined. The wider the DPW, the more robust the process will be. If the DPW is skewed towards the corners or the sides of the APW, an effort must be made to make steel changes in the mold

![Figure 9.3 Dimensional process window for the 144.65 mm dimension in Table 9.1](image-url)
cavity to bring the nominal of the dimensions to the center of the APW in order to make the process robust. In an ideal situation, the DPW should be as big as the APW and both should be as wide as possible. The DPW will also give the product designer a chance to review the robustness of the dimension under consideration. Setting the tolerances to practical limits is often a battle between the product designer and the processor and the DPW is a good tool to facilitate such discussions.

The CPW is a subset of the DPW and the DPW is in turn a subset of the APW. Naturally, a wide APW favors the possibility of a wide DPW and CPW, provided the nominal of the dimension is centered in the APW. This data can be reviewed with the tooling engineer to support justifying a mold steel adjustment to center the part dimension within the specification limits which will provide a wider DPW.

### 9.4 Multiple Dimensions

The above discussion covered a single dimension under consideration; however, almost all parts have multiple dimensions. With multiple dimensions involved, the contour plots become exceedingly complex. The contours for the nominal and specification limits of each dimension will rarely overlap and it would be even more unusual for the slopes of the contours of each dimension to be identical to each other. The effective process window will therefore be the intersection of the two individual process windows. Figure 9.5 shows the

**Figure 9.4** Control process window for the 144.65 mm dimension in Table 9.1