2.3 “Plastics Are Not Metals”

2.3.1 Color, Gloss, and Aesthetics

Now that we have covered the basics of polymeric materials, let us look at how they are different from metals. Most of the engineers and designers come from the metals world. Therefore, most of us make assumptions on the predicted performance of plastic properties based on our metals background.

I started with a discussion on color and appearance because this knowledge is extremely important in the case of plastics. Most plastic parts have dual functions—aesthetics and physical performance. This is due to the fact that very few of them need to be painted or otherwise decorated if designed and manufactured with due diligence.

On the other hand, even if we are designing the most aesthetically critical metal components such as exterior automotive parts, we mostly choose the metals and alloys based on the physical properties, weight, and cost. The aesthetics are left to the paint specialist, who will in most cases find a paint system (primer, paint, and application method) that will meet the cost, durability, and the cosmetic requirements. In other words, aesthetics and physical properties are quite independent of each other. A vast majority of metal parts meet their aesthetic and environmental requirements just by getting plated, getting chromate conversion coated, or being anodized.

Plastic parts not only need to meet the short term color and appearance requirements, they also need to be resistant to long term color shift and fading.

In Figure 2.30, the first set of pictures is of air conditioning ABS vents in my own house. Some of them turned from white to various shades of yellow to brown in a matter of months when exposed to the normal sunlight entering the house. The others retained the original white color.

Both covers for the TV are made of ABS. One remained the original white and the other turned yellow.

The middle picture is one of my neighbor's PVC mailbox, a few months after installation. In this case the plasticizer from the PVC completely evaporated, leaving the mailbox very dull and also brittle. (For those old enough, remember the cracks across the speaker grills in the PVC dashboards of the cars of the seventies and eighties?)

The bottom picture shows a very similar mailbox before exposure to the environment.

The long term properties of plastic resins are carefully modified by adding UV stabilizers and antioxidants by the resin suppliers. One just needs to choose the resin with the right protection.

Figure 2.30 Long term yellowing and fading of plastics

Figure 2.31 shows the yellowing and fading of various GE (now SABIC) plastics. Figure 2.32 and Figure 2.33 show that fading and color shift are very dependent on the colors even in the same resin and that care should be taken in the color selection. In the case of color retention, green is the worst and bright white and black are the best.

The same applies to gloss retention. Here the green performed the best but the white and black did not do too badly.

Notice that Delta b (dB in Figure 2.31) is used for the yellowness shift and Delta E (dE in Figure 2.32) for color. Going back to our previous discussion, an increase in the b value indicates that the color is more yellow. Delta E, obviously, indicates total color shift.

Do the same for a plastic cross section that is designed to take the stress of the force of a hanging 100 kg mass. You better not stand under the weight! The weight may drop on you within minutes, depending on the specific plastic and the environmental conditions. All plastics are viscoelastic and are subject to creep and stress relaxation. Under continuous stress their properties will change to the point of rupture.

2.3.3 Plastics and Chemical Resistance

Although both metals and plastics can degrade due to environmental exposure over time, the degradation of metals is a lot more predictable and controllable. The most common alloy and degrading phenomenon are steel and rusting. With the right paint or plating and with periodic maintenance, the rusting can be kept under control for centuries.

A great example of the longevity of metals is the iron pillar in front of the Qutub Minar in Delhi, India. Though the pillar was forged about 1600 years ago and moved to Delhi nearly 1000 years ago, it still stands fully intact and free of rust.

Figure 2.34 The iron pillar in front of the Qutub Minar in Delhi [12]

Also, the level of stress in the metal structures plays almost no role in how fast the metal will oxidize or be affected by common environmental chemicals such as acids, alkali, salt, or solvents. Even galvanic corrosion is very predictable and controllable by using the right pairs of metals in contact with each other.

Now let us step into the world of plastics.

Different plastics have different resistance to common solvents and chemical agents. Even moisture in the air can degrade plastics by breaking down the polymer chains. Plastics can also get oxidized and lose their mechanical properties.

Here is the key difference, though. Plastics under even a small amount of tensile stress are a lot more vulnerable to Environmental Stress Cracking (ESC) and chemical attack than those without it. Generally, amorphous plastics are more vulnerable than semicrystalline ones.

Let us look at the reason why.

As discussed previously, most polymers have long chains mostly of hydrocarbon molecules. When the plastic is cooled down from a high temperature, the chains re-entangle themselves. In the process they leave some spaces between the chains, which are called the “free volume.” As a side note, because of the orderly structures of the crystalline areas in semicrystalline materials, the free volume is less and therefore they are more chemically resistant than their amorphous counterparts. Most oils and solvents are also hydrocarbons and have a natural affinity to the hydrocarbons in the polymer. If allowed to enter the free spaces, they can cause the chains to break. If the chains are packed tightly, the attacking agents have less opportunity to enter and cause the degradation [2].

Now let us look at the typical injection molded wall. See Figure 2.35.

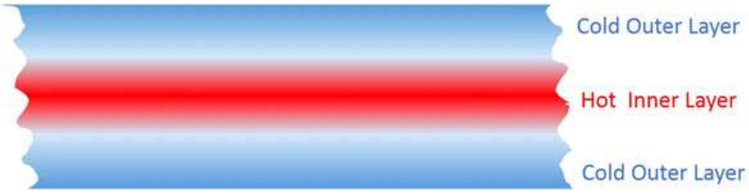

Figure 2.35 Cooling of injection molded wall

Plastic basically is a very poor conductor of heat. An injection molded part may be ejected out of a mold at upwards of 200 °C. As soon as it comes out, the outer layers are exposed to the ambient air and start to cool and shrink. The inside layers are insulated by the outside layers and stay hot for a much longer time.

The net result is that the outside layers are continuously pulled in by the inside layers and the inside layers are pulled out by the outside layers when the part has finally cooled down. This results in the stress pattern for the part shown in Figure 2.36.

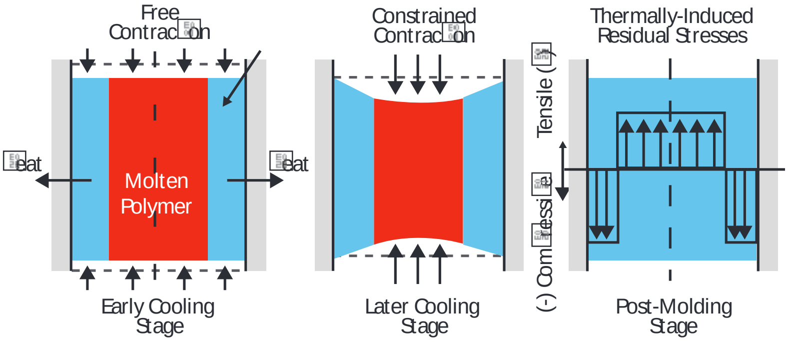

Figure 2.36 Stresses induced during cooling [6]

2.3.3.1 Physical Effect

To actually demonstrate the above stress pattern and the effect it has on its physical properties, the top surface of a 3 mm thick PC dog bone was machined about 0.5 mm deep. Care was taken to make sure the plastic stayed at room temperature during the machining, by circulating plenty of cold water at the interface of the cutting tool and the surface being machined. As soon as the piece was released from the holding fixture after machining, the dog bone curled upwards. The top layer of compressive stress was removed and tensile stress in the next layer pulled the two ends in. Whereas the original dog bone could be bent hundreds of times without a fracture, one bending cracked the part in the middle! See Figure 2.37.

As I will mention in Chapter 3, this is one reason I strongly advocate against using machined plastic parts for doing any kind of impact or physical testing during the development of a project.

Figure 2.37 Stress relief with machining

2.3.3.2 Chemical Resistance

Let us also look at what it does to the free spaces. In a compressive layer the free spaces are reduced and in the tensile layer the free spaces are increased. Therefore, as molded, any plastic part is naturally more resistant to ESC and chemical attack.

What happens when the part is made to bend (or "unbend" in the case of a warped part)?

Figure 2.38 shows the simulation of a dog bone being bent. As can be seen from these pictures, the compressive layer quickly turns into a tensile one.

The fact that the load carrying capacity of a plastic part is in a state of continuous stress may be secondary to the fact that it has now become more susceptible to chemical attack and ESC. Never mind strong chemicals, it can now be made to fail even with the humidity in the air.

In the training I conduct, I take a PC dog bone and flex it back and forth tens of times. I then smear it with acetone and leave it aside. I take another dog bone and bend it very slightly to induce a tensile stress on it. I put a small drop of acetone on it. It completely breaks apart into two pieces. See Figure 2.39. At the end of the session I look at the piece that I smeared with acetone and bend it back and forth. Practically no damage is done because the acetone evaporated before it could penetrate the surface with the compressive layer under it.

Please visit my website to view a video of the above. Here is the link: *www.vikpedia.org*.

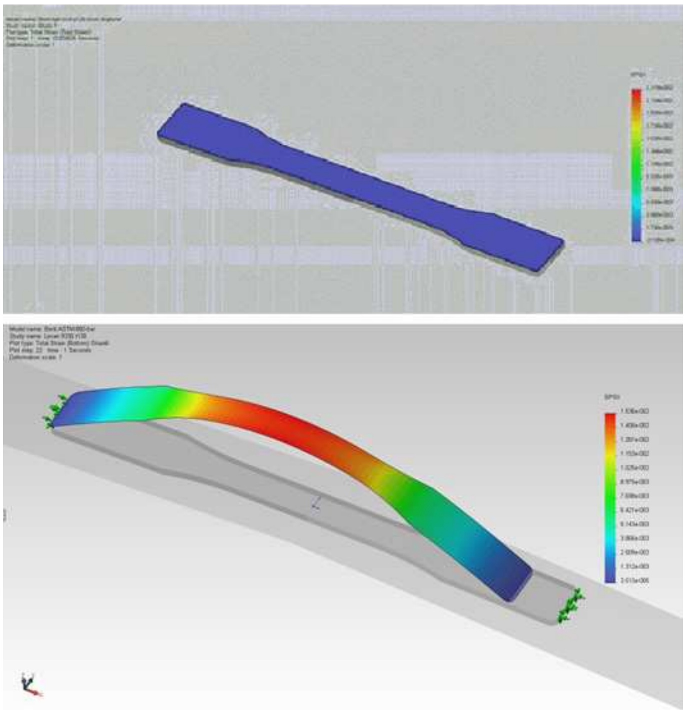

Figure 2.38 Stresses induced in bending [7]

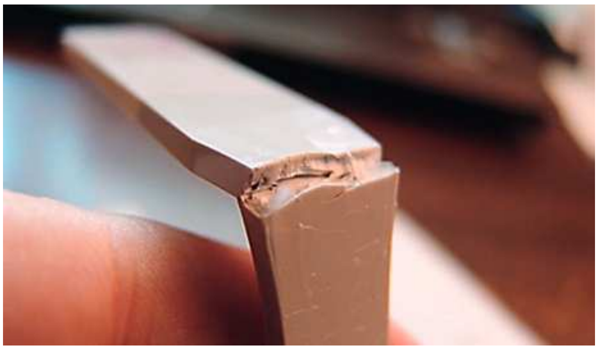

Figure 2.39 Bent dog bone—catastrophic failure with one drop of acetone [11]

2.3.4 Physical Properties—Plastics vs. Metals

Table 2.2 shows the salient differences between plastics and metals.

Published Properties

Since the actual properties are so dependent on the way testing is performed as well as the actual conditions of use (time, temperature, rate of loading, environmental conditions, molding conditions, physical design, tooling, etc.), the published plastic properties are more of a set of guidelines, as a starting point, and for comparing different plastics. As will be explained in Chapter 3, these properties have to be used with a lot of caution. In fact, most resin suppliers have disclaimers to this effect to make sure the users do not misunderstand the properties and apply them incorrectly. See Figure 2.40. This is a typical disclaimer most resin suppliers use.

Michael Sepe is an industry leader as a material analyst. Some of his thoughts on the data sheets are that they:

- Provide short-term mechanical properties at room temperature
- Provide values for yield stress and impact energy to break and tell us when catastrophic failure occurs but nothing regarding what works
- Do not provide a clear picture for the effects of time under load
- Are only an attempt to deal with the effects of elevated temperature—DTUL (Deflection Temperature Under Load) and Vicat softening (which can also be very misleading)

I encourage the readers to read some of his work to get more insights on what these properties are and provide.

Figure 3.38 Stress crazing in a clear polystyrene tumbler

Continued strain can lurk in different corners that the designer may not even be aware of. Here are some common examples.

3.3.2.1 Warpage

Figure 3.39 shows a polycarbonate part that came out warped from the tool. The part was “unwarped” in the process of being assembled with its mating part, thus introducing a continuous strain. In less than a few months cracks appeared in the part just from the sweat on the operators’ hands attacking the part under continuous strain.

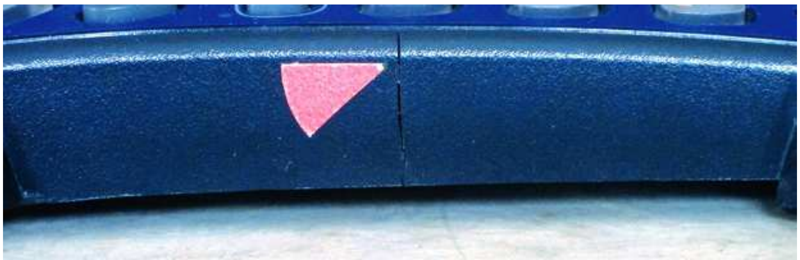

Figure 3.39 Cracks in part “unwarped” when assembled [8]

3.3.2.2 Plastic Screws

There are basically two types of screws used in fastening plastics without the use of threaded metal inserts. They are thread forming and thread cutting. See Figure 3.40: the one on the left is thread forming and the one on the right thread cutting.

The thread forming screw basically forces its way into the plastic boss and distorts the plastic, introducing a continuous hoop strain. The thread cutting screw, on the other hand, has a drill-like cutting edge that cuts its path into the plastic, minimizing continuous strain on the boss.

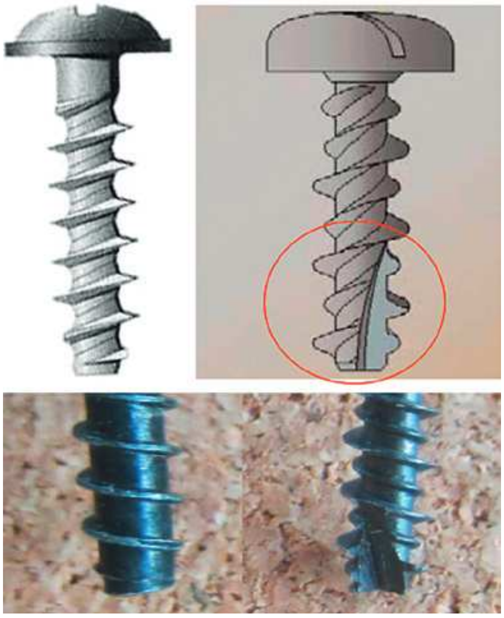

Figure 3.40 Thread forming and cutting screws

Figure 3.41 shows the catastrophic failure of a boss in a PC/ABS part fastened with a thread forming screw. This happened in a matter of weeks after the product was shipped. Changing to a thread cutting screw completely eliminated the problem.

Figure 3.41 Catastrophic failure of PC/ABS part with thread forming screw

3.3.2.3 Force Fit Assemblies

Unlike in metal parts, force fitting a peg into a hole will cause failures. Figure 3.42 shows a portable phone with one cover fastened to the other by force fitting a hole over a stud. In no time at all cracks developed around the hole. I sent the phone back to be replaced by another phone with no cracks. Within a few months cracks developed on the new phone too.

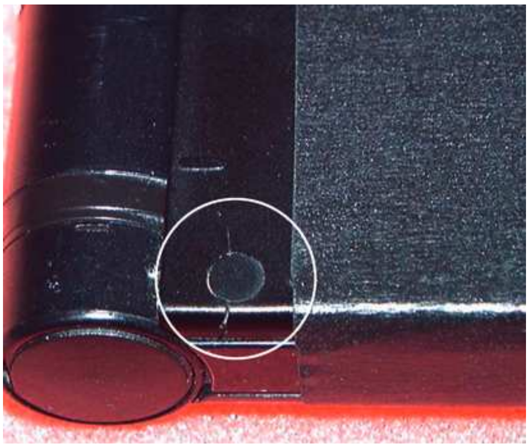

Figure 3.42 Strain crack with force-fitted stud

Flat head screws work wonderfully well for metals and wood.

One may design a conical opening for the flat head in a plastic part. However, the seating torque required to prevent the screw from coming loose introduces a continuous hoop strain in the opening. Figure 3.43 and Figure 3.44 show the failures in low and high modulus materials respectively. The part in Figure 3.43 is made out of high density polyethylene with an elasticity modulus of approximately 400-1,000 MPa. The failure is thus in the ductile mode[4] and shows the white stress marks around the hole. Figure 3.44 shows the failure in an acrylic sheet. This is a much stiffer material and the elasticity modulus is approximately 2,800 MPa. This leads to a catastrophic brittle[4] failure.

---

[4] See discussion on brittle and ductile failure starting in the reference chapter (Chapter 9).

Figure 3.43 White stress cracking marks with flat head screw in a polyethylene part

Figure 3.44 Catastrophic failure with use of flat head screw in acrylic sheet

3.3.2.4 Tolerance Stack Up Issues

This kind of failure is very common and occurs due to continuous strain attributable to tolerance stack up issues. Figure 3.45 shows the tolerance analysis of the top and bottom covers of a power supply made out of polycarbonate. When assembled, surface A should rest against surface B and surface C against D. Under the theoretical nominal conditions all of them come together when assembled. However, in the worst case A and B have a gap of 0.030. This does not even take into account additional possible gaps due to part warpage.

The continuous strain, therefore, is approximately 0.030/0.500 = 6 % because of the strain being borne solely by the 0.500 length above the four gussets on the long boss. Also to be noted is the fact that these components can easily be subjected to a continuous temperature over 60 °C in use.

Figure 3.46 shows the actual failure of the long boss under these conditions.

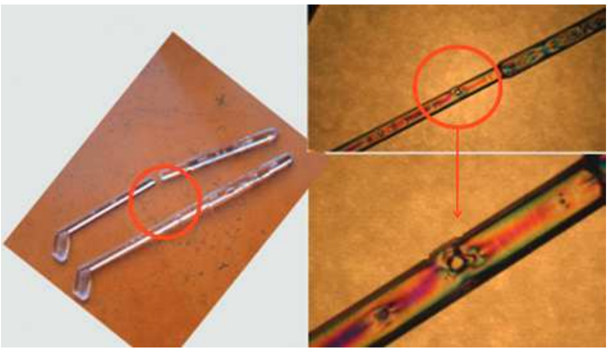

Figure 3.61 Gate location on polystyrene drink stirrer along with the birefringence image

With the above discussion in mind, the gate location should be based both on balanced flow and functional requirements of the part. It is therefore reasonable that the designer be involved in deciding the location of the gate and that this is not just left to the flow simulation or tooling personnel.

3.3.7 Orientation

Figure 3.62 (top) shows the crack pattern when a polystyrene cold cup is crushed. You can clearly see the very straight and parallel lines that the cracks result in. This is because of the orientation of the polymer chains.

In normal processing, with the molds being heated to the optimum temperature, the polymer chains are allowed to go back to their normal random state before ejection. However, in the case of the cup, to reduce the cost, the cycle time is extremely low. To help reduce the cycle time, the mold is run very cold. The material freezes almost instantaneously upon injection and the chains do not have the required temperature or time to go back to the random entanglement state. As pointed out in Chapter 2, the chains are lined up so the chemical bond is only in the direction of the flow. In the cross direction there are only the weak secondary bonds. Thus, on impact the cracks develop across the secondary bonds. In Figure 3.62 (bottom) there is the same cup, in which water was boiled for a few seconds in a microwave oven. The chains have now reoriented themselves into their natural position and the cup itself is much tougher.

Polystyrene is an amorphous material. In the case of a semicrystalline material, running the mold at the optimum temperature is even more critical. If the mold is run cold, the crystalline areas are not allowed to develop during the molding cycle. The part is therefore very weak and will distort over time as the crystalline areas develop.

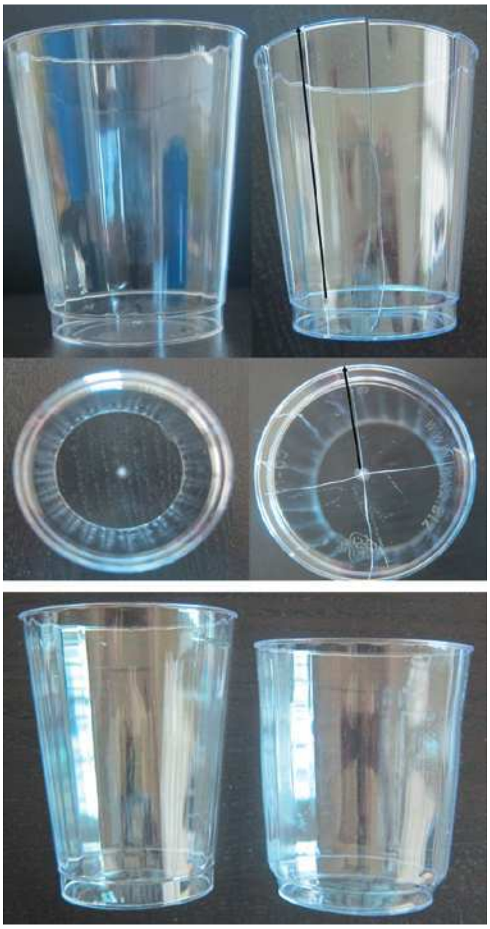

Figure 3.62 Orientation in common polystyrene cup

If life gives you lemons, make lemonade.

The fact that chains get oriented under certain processing conditions can be taken advantage of. The common polypropylene bags are oriented such that chains run in the direction of the handle. Thus, it takes very little effort to tear the bag at the right angle to the handle direction and it is extremely difficult to do so in the long direction of the handle. Figure 3.63 illustrates this.

Living hinges are another common example of taking advantage of orientation and the resultant superior properties in the length direction of the chains. Figure 3.64 shows a simplified illustration of a living hinge. The material is made to flow from one thick section to the other through the thin one. Ideally, the thin section is cooled rapidly by putting cooling lines directly above and below it. This freezes the chains across the thin section, giving it an enormous fatigue life. More information on designing living hinges in the reference chapter (Chapter 9).

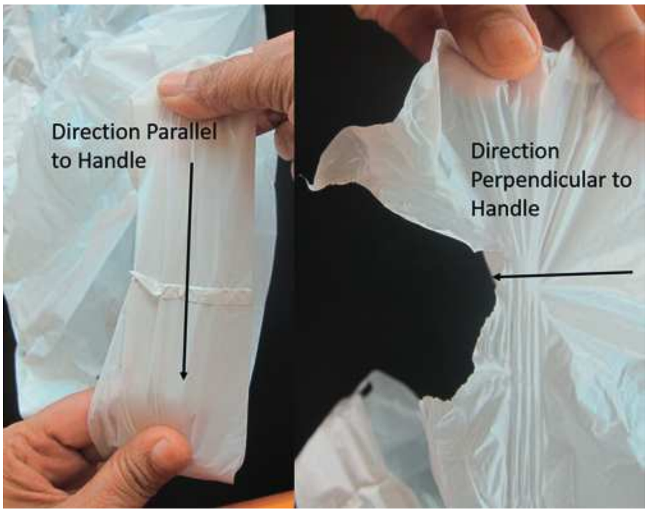

Figure 3.63 Orientation effect in common polypropylene shopping bags

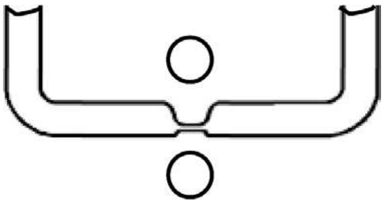

Figure 3.64 Simplified living hinge illustration

Figure 3.65 shows a common a dental floss container with a very efficient living hinge.

Figure 3.65 Common dental floss container with living hinge

3.3.8 Wear of Plastics

Care has to be taken when designing plastic members that slide against each other during use.

When two plastics rub against each other, the materials from the surface are gradually removed due to adhesion or abrasion. Adhesive wear takes place when very small pieces of the materials are removed by the rubbing surface. This results in a fine dust. When a harder surface digs up a softer surface, abrasion takes place and this results in grooves or scratches on the surface.

The button in Figure 3.66 was made of PC and was supposed to rub against the mating surface also made of PC. Most amorphous materials have a very high surface energy and therefore good adhesion. Just a few hundred cycles caused the button to get sticky due to adhesive wear. The button was changed to acetal and the combination worked as desired.

Figure 3.66 Trigger button failure: the circled area shows vertical wear scratches on the button

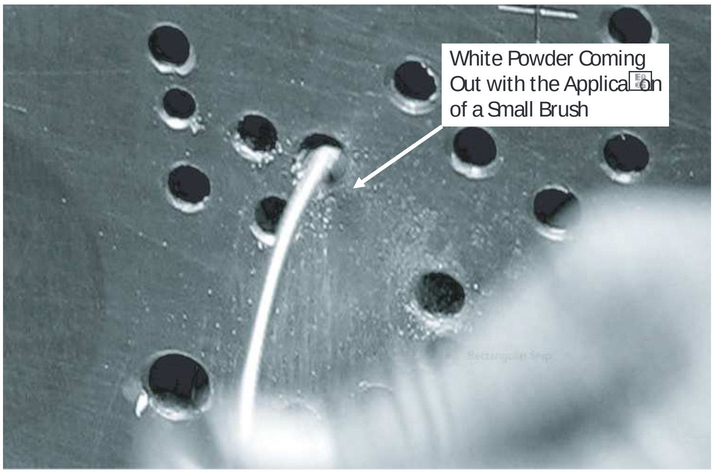

Figure 5.23 Clogged ejector holes due to juicing

The appearance and strength of the knit line depend on the following:

5.5.3.1 Venting

When flow fronts come together, they generally trap air and gas between them. This trapped air and gas can affect the appearance in the following ways (see Figure 5.24):

- Not allowing the fronts to meld, thus leaving a microscopic void
- Burning the flow front due to dieseling (see Chapter 3, Figure 3.33)

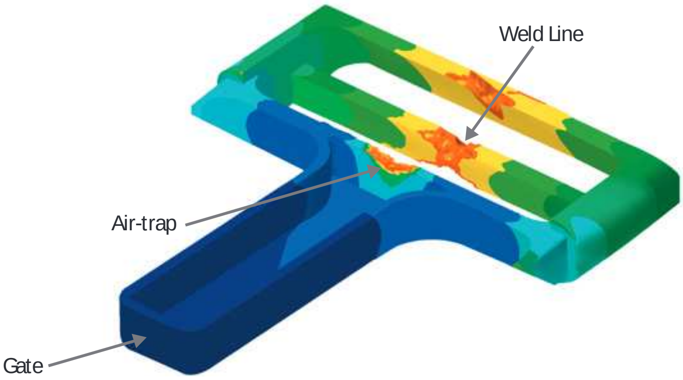

Figure 5.24 Knit line appearance due to trapped gases [5]

5.5.3.2 Melt Temperature

Higher melt temperatures intuitively should make the knit lines stronger, since the flow fronts meet at a higher temperature and therefore cause better fusion between them. However, they can also result in a higher amount of volatiles, due to the degradation of the low molecular additives and the polymer itself. These volatiles and degradation products travel faster than the polymer and therefore come in the way of an optimum fusion of the fronts. Therefore, the effect of a higher melt temperature on the weld quality depends on the specific combination of material, part, and tool design.

5.5.3.3 Injection Speed

Higher injection speeds go hand in hand with a higher melt temperature because of the increased shear. Therefore, the previous discussion also applies to injection speeds.

Additionally, on the negative side, the volatiles do not have the time to be completely vented and may get trapped between the fronts from the opposite sides, causing the weld to be weaker.

5.5.3.4 Packing Pressure

Higher packing pressures generally result in better knit lines, due to the better fusion of the flow fronts and the expelling and/or compression of the volatiles. They also help the melt flow into the nooks and crannies of the mold surface instead of just skimming it. See Figure 5.25.

5.5.3.5 Mold Temperature

The mold temperature has the most effect on the quality of the appearance and, consequentially, the strength of the knit lines. This is primarily due to two reasons:

1. The melt is kept hotter, without the degradation associated with the melt temperature and injection speed
2. The melt reproduces the surface of the mold instead of skimming along it; Figure 5.25 shows the difference in the surface with low and high pressures and melt temperatures

[redacted] [redacted]

Figure 5.25 The left view shows a part with lower mold temperature and pressure; the right view shows the same part with higher mold temperature and pressure

5.5.3.6 Mold Surface

Textured surfaces generally hide the knit line and shiny surfaces do the opposite. Therefore, where possible, the inclusion of even a light texture improves the appearance.

5.5.3.7 Material

Finally, the material itself can add to or take away from the strength and appearance of the lines. As an example, flame retardant materials may have more volatiles that prevent fusion of the flow fronts than their non-flame retardant counterparts.

Within the same family, glossier plastics may show the knit line more than their less glossy counterparts. As an example, a straight PC may show the knit line more than a PC/ABS, which is somewhat less glossy.

5.5.3.8 Putting It All Together through a DOE

Below is a case study to validate some of the preceding discussion on the appearance of a knit line.

Figure 5.26 shows the knit lines in a PC/ABS part before and after adjusting the molding parameters. The part in question had visually unacceptable knit lines, as can be seen from the photographs.

This study is also an example on how a simple DOE (Design of Experiments—see details of the methodology in Chapter 8) can quickly and efficiently get to the best solution. Without a DOE, it might have taken days or even weeks of changing parameters one at time to come up with a solution. Even then, the solution might have not been the optimum one.

The factors considered were: mold temperature, melt temperature, and injection speed, per the preceding discussion. The mold did have adequate venting through vented ejector pins in the back.

One of the requirements of a DOE is that the effect of the study be a numerical value and not an attribute such as “good” and “bad.” The task, therefore, was to convert a visual defect or lack thereof to a numerical value. In order to do this, a team of engineers and QC personnel was asked to rate the appearance of each study from 0 to 5, zero being totally unacceptable and five being totally acceptable.

The recommended melt temperature for the material was 520-540 °F, so these values were chosen as the low and high, respectively. Similarly, the mold temperatures were 175 °F and 200 °F, respectively. The injection speed values were determined from a viscosity study that will be described in the following pages, in the scientific molding section.

Looking at the DOE analysis graphs in Table 5.3, it clearly shows that the mold temperature had the greatest effect on the appearance. Notice also that the increase in injection time improved the appearance! This is contrary to intuition. Ask any molder and he/she will say that increasing the injection time will degrade the quality of the knit line, as the material fronts will be cooler when they meet. This shows the value of letting the data drive our decision against the opinions of so-called experts.

One final point. Looking at Table 5.3, the best knit line would have been at the highest mold, melt, and injection time. However, keeping these extreme settings would have reduced the “processing window,” resulting in a relatively unstable process and reducing the process capability or Cpk. There will be more discussion on the processing window later in this chapter. The charts in Figure 5.27 show the above graphically.

The final settings were 530 °F, 190 °F, and 3.5 seconds for melt temperature, mold temperature, and injection time, respectively, for an appearance index of >3, which was visually acceptable as the best compromise.

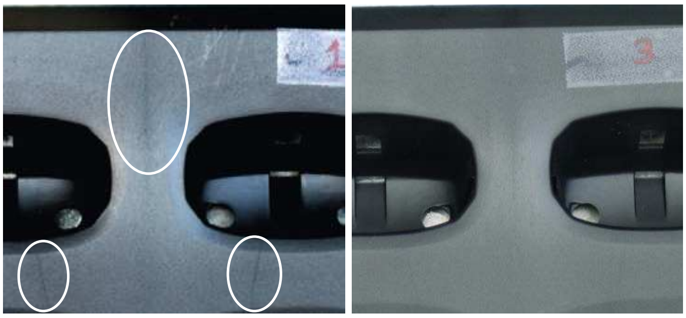

Figure 5.26 Before and after appearance of knit lines

One of the common methods to reduce the gate blush is by what is known as velocity profiling. The injection velocity is reduced in the first small fraction of the total injection phase to help reduce the shear during the wall formation in the gate area, to improve the thickness of the gate layer. Once this stable area is formed, it is less likely to erode during the rest of the injection phase.

5.5.9 Flow Marks, Gloss, and Texture Variation

There are multiple reasons for flow marks. Some of these are:

- Local burning or degradation of the plastic due to high shear
- Pigment or other additives separation from the resin or degradation due to poor compatibility of the pigment or additives or overheating. See Figure 5.40.

Figure 5.40 Flow marks due to poor compatibility of the pigment

- Inadequate homogenization of the material because of a large shot size relative to the barrel
- Degradation of the material because of a small shot size relative to the barrel
- Too much or too little back pressure
- Contaminants in the material including incompatible resins (such as nylon in PC)
- Glass fibers on the surface in glass-filled resins
- Splay due to excessive moisture or too long a residence time; see Figure 5.41

Figure 5.41 Splay due to moisture in the resin [9]

- Trapped air or gases
- Incomplete melding of the flow fronts
- Hesitation
- Sudden change in direction of flow
- Sudden change in the thickness
- Ribs being too thick
- Sharp internal corners
- Non-uniform packing resulting in shiny and matt areas near each other
- Non-uniform heating or cooling of the mold including hot spots; see Figure 5.42
- Non-uniform heating and/or packing causing the texture to appear more or less matt; see Figure 5.42


[redacted] [redacted]

Figure 5.42 Noticeable change in the reproduction and matt level in the textures with the change of mold temperature and/or pack pressure

- Non-uniform texture or polishing of the mold walls
- Too high or too low graphics interrupting the flow of the material. See Figure 5.43 top. One way to minimize the knit line appearance is to provide venting for the trapped air and gases to escape. In the middle of a part (as opposed to the edges, where conventional venting can be employed), this can be achieved by inserting a laminated section of steel right under the graphics with controlled venting gaps between them. See the bottom image in Figure 5.43.

Figure 5.43 Deep graphics causing interruption of flow

Because of the fact that flow marks are caused by multiple reasons, there is not one standard method to eliminate or reduce them. Instead, a careful and logical cause and effect study should be conducted with tools like a fishbone diagram, as will be explained in Chapter 8.

5.5.10 Record Grooving

Record grooving are concentric grooves that look like the old fashioned vinyl records—hence the name. These occur as the flow front hesitates, builds up pressure again, flows, and hesitates again. This is the result of a less than adequate pressure at the flow front and of inadequate velocity and/or stock temperature. Adjusting

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