Using Hypothesis Setting to Optimize the Troubleshooting Process for Single-Screw Plasticators

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Abstract

The goal of all troubleshooting operations is to restore the process to its original performance as quickly as possible. This paper describes a process that is based on developing hypotheses using verified data. Next, the hypotheses are tested using properly developed experiments. Once the root cause of the problem is identified, the best technical solution is implemented. Three case studies are presented.

Background

The goal of all troubleshooting operations is to restore the process to its original performance as quickly as possible. If the process is operational and producing a high level of off specification product, then the manufacturing costs can be very high. Restoring the line to its original performance quickly will reduce costs by eliminating some quality control operations and labor wasted in making product that is not fit for use, reduction in resin consumption, eliminating recycle due to off specification product, and decreasing energy consumption. Moreover if the line is inoperable due to the defect, the downtime of the line can be extremely costly, especially if the line is sold out. In this latter case, the goal would be to bring the line back to production operation as quickly as possible. Excellent overviews of the troubleshooting process for extrusion systems were provided by Gould [1] and Christie [2]. Procedures to troubleshoot processes in general were outlined by Mager [3] and Fogler and LeBlanc [4]. Troubleshooting a process can range from solving a very simple problem such as replacing a malfunctioning barrel heater to a very difficult flow problem that is very complicated to diagnose. Collecting the proper information on machine performance can minimize the time required to restore the machine to its original performance while reducing the cost of the troubleshooting process. The machine owner will provide details and information for the operation. Typically, the information will be a collection of facts, ideas on the root cause, and data that are not relevant to the problem. The troubleshooter must be able to listen to the information provided and then sort the important facts from the nonrelevant information. Often, several different solutions will be possible. The best solution will be based on a combination of the cost of lost production, the time and cost to implement, machine owner acceptance, and the risk associated with the modified process.

The first thing that a troubleshooter should do is talk to the plant personnel and the process operators about the defect. The operators in many cases witnessed the event that caused the problem or they can provide the recent history leading up to the failure. In some cases the operator may have inadvertently caused the problem. Interviewing the operator and having the operator assist in the diagnosis of the problem can speed up the troubleshooting process. After the interviews, the troubleshooter must verify the accuracy of the information. Verification of the information can be as simple as viewing computer fault information on a control panel to questioning events that are impossible to reproduce or verify. The information that is verified will become part of the basis for setting hypotheses on the root cause of the problem.

The troubleshooter should obtain the performance and modification history for the machine. This information is typically available from electronic data storage devices associated with the extruder, the machine owner, maintenance personnel, and the operators. A schematic for the screw is required for most troubleshooting operations. Most screw vendors will provide, as a courtesy, a diagram that shows the flow channels of the screw. If these diagrams are not provided during the original purchase, a diagram of the screw should be made by plant personnel prior to installation. Other required data include the rate, screw speed, motor current, barrel temperature settings, and discharge pressure and temperature. Additional sensor data are occasionally available on some machines including pressure measurements in the barrel, gear pump rate via its rotation rate, and sensors specific to a process. The screw speed and motor current values displayed on the control panel should be verified. For the screw speed, counting the rotations of the screw at the back of the gearbox for a time period must be performed to verify the speed displayed on the panel. Most displays show the screw speed within a 5% error, but for some processes the screw speed display has been in error by a factor of 2. Verifying the motor current is easily performed by an electrician using a simple current meter. As a general practice, all instruments and sensors should be verified for accuracy.

All mechanical and electrical components should be examined and verified that they are functioning properly. These components include the solenoid valves for water cooling systems, cooling water pumps, cooling fans, electrical heaters, thermocouples and other temperature sensors, pressure sensors, and gear pump operations.

Most extrusion processes measure the discharge temperature using a thermocouple sensor positioned in the transfer line downstream from the tip of the screw. The thermocouple is often positioned into the polymer stream about 1 cm past the inside wall of the transfer line. This equipment configuration is the best for most applications, but it can provide temperature measurements that are considerably different from the actual resin temperature [5]. The thermocouple measures the temperature at the sensor junction, and this junction is influenced by the temperature in its vicinity, including the temperature of the resin, the temperature of the sensor sheath, and the temperature of the transfer line. Since the thermal conductivity for a metal is typically 300 times higher than that for a polymer, thermal conduction is more influenced by the surrounding metal than the temperature of the resin in the transfer line. Thus, for a transfer line that is controlled at a temperature less than the bulk resin temperature, the thermocouple is going to report a temperature that is less than the bulk temperature of the resin. A better way to measure the discharge temperature is by placing a hand-held thermocouple in the resin discharging at the die opening. In order to mitigate conduction of energy away from the junction, the thermocouple sheath should be immersed in hot resin. If the transfer line is relatively short with no significant cooling or heating occurring in the line, then the measured value should be close to the actual discharge temperature from the extruder. For many systems where the polymer flow is always inside lines, hand-held measurements are not possible and the troubleshooter must rely solely on the temperature measurement through the transfer line. Hand-held temperature sensors that measure the infrared (IR) radiation level from the resin provide an excellent measure of relative temperatures, but because of the difficulty in measuring the emissivity of the polymer these devices are not as accurate as hand held thermocouple sensors.

Next, the troubleshooter should perform a basic series of calculations for the screw and process. These calculations include the rotational flow rate (or drag flow rate) and pressure flow rate [6]. These calculations will allow the troubleshooter to determine if the metering section of the screw is the rate limiting section of the process. The metering section of a flood-fed single-stage screw or the first-stage metering section of a multi-stage screw must control the rate for the process. If the metering section is not rate controlling, then the extruder will operate at reduced rates and has the potential to flow surge and cause resin degradation products to occur in the discharge [6,7]. For a multi-stage screw, if the first-stage metering section does not control the rate then flow of resin into a vent opening may occur. These calculations are simple and will guide the troubleshooter to develop appropriate hypotheses on the root cause of the process defect. Other calculations that should be performed are the compression rate and compression ratio. The calculation of the compression ratio for a screw with a constant lead length is as follows:

$$C = \frac{H}{h} \qquad (1)$$

where C is the compression ratio, H is the channel depth of the feed section, h is the depth of the metering channel. The compression rate for the transition section of the screw describes the rate that the channel depth changes as the resin is transported through the section. The compression rate is calculated as follows:

$$R = \frac{(H-h)\sin\theta_b}{ML} \qquad (2) \qquad \tan\theta_b = \frac{L}{\pi D_b} \qquad (3)$$

where R is the compression rate in the transition section, M is the number of turns in the transition section, θ_b is the helix angle at the barrel wall, L is the lead length, and Db is the inside diameter of the barrel. The compression rate and ratio should be within an acceptable range for the resin processed.

To aid in the calculations and the relevance of their application, the bulk density of the feedstock resin and the shear viscosity should be measured. The shear viscosity is needed for the pressure flow calculation while the bulk density is needed to assess the compression ratio and compression rate. For example, ground recycle streams when added to pellets cause the bulk density of the feedstock to decrease. If the bulk density of the feedstock is considerably less than just pellets, then the compression ratio and compression rate should be adjusted as follows:

$$C_f = \frac{\rho_{pellets}}{\rho_f} C_{pellets} \qquad (4)$$

$$R_f = \frac{\rho_{pellets}}{\rho_f} R_{pellets} \qquad (5)$$

where Cpellets and Rpellets are the compression ratio and compression rate used for a pellet feedstock, $\rho_{pellets}$ is the bulk density of the pellets at ambient conditions, ρ_f is the bulk density of the feedstock mixture at ambient conditions, and C_f and R_f are the compression ratio and compression rate that should be used for the lower density feedstock resin, respectively.

The specific energy inputted by the motor to the resin should be calculated and compared to similar processes. The power and specific energy inputted into the polymer from the extruder screw are estimated using Equations (6) and (7):

$$P = P_{max}\left(\frac{A}{A_{max}}\right)\left(\frac{N}{N_{max}}\right) \qquad (6)$$

$$E = \frac{(3600 \cdot J \cdot kg)}{(kW \cdot g \cdot h)} \frac{P}{Q} \qquad (7)$$

where P is the power that is dissipated in kW, P_{max} is the nameplate power (kW) for the motor, A is the motor current observed during the extrusion, A_{max} is the nameplate motor current at full load, N is the screw speed (rpm) during extrusion, and N_{max} is the maximum screw speed (rpm) that the extruder is capable of running (with full field voltage). After the power is computed, the specific energy inputted to the resin from the screw, E, in J/g is calculated using Equation (7) and the extrusion rate, Q, in kg/h.

Often troubleshooting guides are provided by equipment manufacturers for common problems. These guides are helpful for many of the simpler problems associated with the equipment. Some resin manufacturers are an excellent resource for troubleshooting processing problems that are specific to a resin. Subject matter experts or extrusion consultants are also resources for troubleshooting an extrusion process.

Spare parts for common components such as heaters for barrels, transfer lines, and dies, thermocouples, pressure transducers, drive belts, and fuses should be kept in stock. Since the goal is to maintain the line operational at all times, keeping these low cost but necessary components in stock can reduce the amount of downtime due to simple failures. For operations where the resin is abrasive or corrosive, a spare screw should be kept in stock. As the screw wears in the extruder and the performance decreases beyond an economic limit, then the screw should be replaced with the spare screw and the worn screw should be sent to a screw manufacturer for refurbishment.

Hypothesis Setting and Problem Solving

With the plant interview information, verification of the data, and the completion of the simple calculations, an experienced troubleshooter will develop a set of hypotheses for the root cause of the defect. After the hypotheses are established a series of experiments need to be developed that accept or reject the hypotheses. Once a hypothesis is accepted via experimentation, then the next step is to develop a technical solution to remove the defect. Often more than one technical solution is possible. The best technical solution will depend on the cost and time to implement the solution, machine owner acceptance, and the risk associated with the modified process. An accepted hypothesis must drive the technical solution. If a hypothesis is not accepted prior to developing a technical solution, then the troubleshooter may be working on the wrong problem and the defect may not be eliminated from the process.

A hypothesis is a proposed explanation for an observation. The hypothesis should be stated such that it is clear and testable. For each hypothesis, an alternative hypothesis should be stated that is accepted should the original hypothesis be proven false. Developing alternative hypotheses allows the troubleshooter to quickly arrive at the defect while moving through a complicated decision making process. The alternative hypothesis provides a logical branch that directs the troubleshooter to the root cause. Each troubleshooting process should be developed with a set of alternative hypotheses, design of experiments that exclude one or more of the hypotheses, and then performing the experiments such that definitive results occur [8]. At the conclusion of this process, a new set of alternative hypotheses may be required to continue the decision making process.

As an example of an alternative hypothesis, a simple case study is presented here. For this case, an extruder is discharging degradation products into the product stream. The hypothesis and alternative hypothesis statement is "the metering section of the screw is not operating full and not under pressure, creating regions where resin can degrade, or the process is operating with the metering section full and under pressure and the degradation products are coming in with the resin or generated in some other section of the process." This combination of hypothesis is referred to here as the alternative hypothesis since it allows for a decision to be made about where the root cause occurs. Once an experiment is developed to test the hypothesis, the troubleshooter can then focus the next hypothesis and experiments looking at only one side of the decision branch. Developing acceptable hypotheses depends on validated information, a fundamental knowledge of the process, and knowledge of the properties of the resin.

Some of the most common root causes along with the defects that they create are provided in Table 1. As shown in this table, several defects can occur from the same root cause, and a particular defect can be produced by several root causes.

Once the root cause has been properly identified as the source of the defect, a technical solution must be devised that eliminates the root cause from the process. As previously discussed, often more than one solution exists. The best solution will depend on many factors including the economic conditions for the plant and product line, the cost the defect is creating at the plant, the cost and time for implementing the technical solutions, and the risk associated with each solution. Plant personnel will ultimately decide on the best technical solution for their plant.

Three case studies are presented next that demonstrate the approach to troubleshooting problems. The first two cases were developed with poor hypotheses while the last case study had a problem that was solved quickly using strong hypotheses and a strong experimental plan for verification.

Case Study for the Design of a New Resin

A new general purpose polystyrene (GPPS) resin was trialed at a customer's injection molding plant as an improvement over an incumbent resin manufactured by a competitor. The new resin performed well in the process except that it created parts with a 5% rejection rate due to a splay defect. A photograph of a part with splay is shown in Figure 1. The competitive resin was reported to run well but with a lower defect rate. The plant manager asked that the new resin be redesigned such that it had a defect rate comparable to the competitive resin. Here the hypothesis was that the new resin had a poor performance relative to the incumbent resin, and the technical problem to be solved was that the new resin needed to be modified such that it performed as well as the incumbent resin. As will be shown later, this technical problem was the wrong problem to be solved.

Performance information for the incumbent resin was missing from the early parts of the decision making process. The decision that the technical problem was the performance of the new resin was based on anecdotal information from plant personnel on the performance of the incumbent resin. That is, the plant personnel believed that the reject level for parts made from the incumbent resin was less than 5%. A statistical analysis of the part defect rates was not performed. This lack of information early in the process allowed the plant manager to pose a poor technical solution without understanding the root cause for the defect. A statistical analysis of the defect rate indicated that the incumbent resin had a defect rate that was statistically equivalent to the new resin.

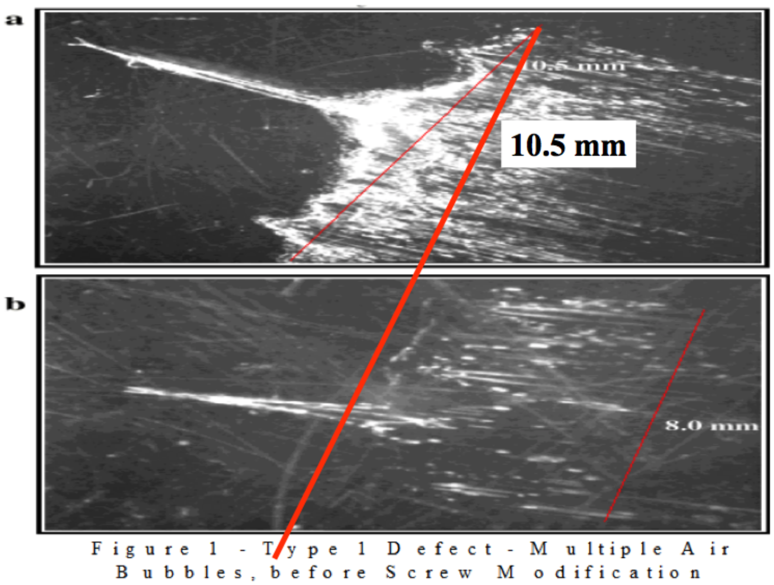

Figure 1. Microphotograph of the splay defect in a clear GPPS injection molded part. The flow direction was from the upper left to the lower right.

The primary and alternative hypotheses here are that the injection molding machine process was creating the defects in the parts, or the resin design was creating the defects. The statistical analysis on the part defects molded using the new and incumbent resins showed that the resins were not the root cause for the defects. A small set of exploratory experiments on the injection molding machine allowed the development and acceptance of the hypothesis that the screw design used in the plasticator was not effective at melting the resin at high rates and expelling entrained air out through the hopper. The new technical problem to be solved was to increase the melting capacity of the process and eliminate the entrainment of air via process changes and screw modifications. The technical details and the modifications that were made to the screw were presented earlier [9]. When the modifications to the screw were finished, the splay defects were eliminated and the capacity of the plant was increased by about 14%.

This example clearly shows that developing and accepting a hypothesis based on accurate and complete information is necessary for setting an acceptable technical solution. If the plant manager could have persuaded the resin manufacturer to develop a new resin that was similar to the incumbent resin, then the defect would still be there, the cost of the troubleshooting process would have been extremely high, the supplier would have incurred unnecessary development costs, and a high level of defective parts would still have occurred because the root cause would not have been removed.

Case Study for a Surface Blemish

A surface blemish on a specialty sheet product was severely limiting the rate of the process. The blemish appeared as a small (2 mm diameter) hemispherical pit or crater in the surface. The level of surface defects could be minimized but not totally eliminated by reducing the rate of the process by 50%. A series of exploratory experiments were performed and the defects could be eliminated by decreasing the temperature of the last 6 barrel zones. The first 2 barrel zones were not adjusted so as to not change the solids conveying behavior of the resin. When large temperature changes (decreases in set point temperatures of up to 50^{o}C) were made to these zones, the extrudate temperature was decreased by about 15^{o}C and the defects were totally eliminated. The hypothesis developed was that when the extrudate temperature exceeded a specified value then surface defects occurred. The technical solution was to develop a process that discharged the resin at less than the specified temperature and at high rate. The reason why the defects occurred at higher discharge temperatures, however, was unknown.

The resin was analyzed for moisture and other volatiles that might cause a gas to be evolved at higher temperatures. All analyses, however, did not indicate that a gas was evolving or that the material was degrading. These data are conflicting with the stated hypothesis. The technical solution for this path was to design a screw with a very deep metering section such that the extrudate is discharged at as low a temperature as possible. Since the material will discharge at increasing temperatures with increasing screw speeds, the maximum rate will be bounded when the extrudate exceeds the maximum specified temperature.

In this case, the experiment developed to test the hypothesis that high discharge temperatures create the surface defects was flawed. The screw had a very low compression ratio and compression rate. A better hypothesis is that when the barrel zone temperatures are decreased over the melting section, the temperature and bulk density of the solid bed are decreased, allowing entrained air to egress out through the hopper. To test this new hypothesis, the barrel zone temperatures over the melting and metering sections were selectively changed such that the melting zones were kept low while the metering zones were increased. For these tests, the defects in the sheet only appeared when the melting zone barrel temperatures were high. The discharge temperature was not a factor in controlling the defects. The new technical solution was to design a screw with a high compression rate and compression ratio such that entrained air can be forced backward and out through the hopper.

A new screw was designed with a higher compression rate and compression ratio. The new screw was installed and the defects were totally eliminated. This case study shows a poorly developed experiment that incorrectly validated a poor hypothesis. If the second experiment would have been performed first, the original hypothesis of high discharge temperatures create surface defects would have been invalidated. Clearly, the experimental plan must be such that they definitively validate or invalidate the hypothesis.

Case Study for a Profile Extrusion Process

A customer wanted to switch to a resin with a higher modulus such that a large profile part could be made with additional strength. The initial production trial was performed and limited data were collected. The information that came out of this trial was that the part profile could not be maintained in specification, the discharge temperature was higher than normal, and the motor was operating at the maximum current load. Since the trial did not last long, rate data were not collected. The new resin was more viscous than the original resin. Based on these very limited data, a second trial was developed based on two hypotheses. The first hypothesis was that the higher modulus of the new resin created a blockage at the entry to a barrier melting section of the screw. The blockage would cause the motor current to increase dramatically and cause the specific rate for the extruder to decrease. This type of screw defect was presented previously [10]. The alternative hypothesis is that a blockage did not occur and some other section of the process other than the barrier section was the root cause.

Preliminary work was performed prior to the trial and included the measurement of the viscosities of both resins around the discharge temperatures and the calculation of the specific rotational flow rate for the metering channel geometry. The specific rotational flow rate for the resins were calculated at 11.3 kg/(h rpm). At the start of the trial, the extruder and line were processing the original resin at a specific rate of 11.0 kg/(h rpm), a value that is consistent with the specific rotational rate. The part profile was acceptable. Next the new resin with the higher modulus was added to the line. Within 30 minutes the part profile dimensions were out of specification and the motor was operating at near the maximum current limit. If the first hypothesis is correct that a blockage is occurring at the entry to the barrier melting section, then the specific rate should be significantly less than the calculated rotational rate of 11.3 kg/(h rpm). In this case, the specific rate was measured at 11.1 kg/(h rpm), and thus the first hypothesis that the barrier section was causing a blockage was not valid. A second hypothesis was developed that the higher viscosity of the new resin caused too much energy to be dissipated, increasing the motor load and the discharge temperature such that an acceptable part profile could not be produced. To test this hypothesis, the metering zone barrel temperatures were slowly decreased in 10^{o}C increments [11] until the cooling ability of the zones were at the maximum capability. In order to maintain the motor torque at an acceptable level, the temperature of the zones in the solids conveying section were increased slightly. The extruder was allowed to come to a steady-state operation. Within 45 minutes the part profile was on specification and the extruder was operating at a specific rate of 11.0 kg/(h rpm) and discharging at a temperature that was about 15^{o}C less than that at the start of the trial. The data indicates that the second hypothesis is valid. The technical solution for this case was to design a process that discharges the new high-modulus resin at a lower discharge temperature. In this case, plant personnel opted for a new screw design with a deeper metering section to decrease the energy dissipation level and decrease the extrudate temperature.

This case study was developed with an alternative hypothesis and then a second hypothesis, and the experiments were designed properly to determine quickly the root cause of the defect in the part profile. If the hypotheses and experiments had not been developed properly, the time required to troubleshoot the problem would have increased or the project may have failed.

Conclusions

The time required to troubleshoot an extrusion process or the plasticator on an injection molding machine can be decreased by verifying operational data, performing simple calculations, and developing strong hypotheses. Next, the troubleshooter must develop experiments that either validate or invalidate the hypotheses. Once the root cause is determined, the best technical solution will depend on many factors including cost of lost production, the time and cost to implement, machine owner acceptance, and the risk associated with the modified process.

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Root Cause	Potential Defects
Blockage at the entry of a barrier section [10].	Low specific rates, high discharge temperatures, resin degradation.
Small flight radii [12].	Resin degradation.
Splay and air entrapment.	Low compression rate and low compression ratio.
Improper solids conveying temperatures for the barrel [7].	Flow surging, and low specific rates.
High screw temperatures [7].	Flow surging and low specific rates.
Process exceeded the melting capacity of the screw.	Solid polymer fragments in the extrudate.
Improperly designed vent diverter.	Flow of resin out the vent opening.
Improper pump ratio for a two-stage screw.	Flow of resin out the vent opening.

Table 1. Common root causes and potential defects.

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