Maria del Pilar Noriega E.
Chris Rauwendaal

Troubleshooting the Extrusion Process

A Systematic Approach to Solving Plastic Extrusion Problems


3rd Edition

HANSER

Noriega / Rauwendaal

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Acknowledgments

From author **Chris Rauwendaal:**

I want to thank my family for their continuing support and patience when I work on these time-consuming projects. I would also like to thank the hundreds of companies I have worked with. Each troubleshooting problem is not only a challenge but also an opportunity to learn. After working in the extrusion industry for over 45 years I have had the good fortune to learn more than I ever expected. Also, I would like to thank the thousands of people that have attended my extrusion seminars. I have found that the best way to learn a subject well is to teach it – this is one of many enjoyable and rewarding aspects of teaching. In most seminars there is very good interaction. As a result, not only the attendees learn from the instructor but the instructor also learns from the attendees – truly a win-win situation.

I would like to acknowledge Verena Resonnek at the department of Kunststofftechnik Paderborn, University of Paderborn, Germany for providing information on the development of a controller capable of automatic optimization of extruder barrel temperatures.

Author **Maria del Pilar Noriega Escobar** thanks her husband, family, and best friends for their valuable support and patience during all these years of applied research, industrial applications, and innovation in polymer processing. She is grateful to Mr. Hans Udo Steinhäuser, President of the Plastics and Rubber Research Institute (ICIPC) and her Institute’s colleagues for their support during the preparation of this book.

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Preface

One of the greatest challenges in actual extrusion operations is efficient and rapid problem-solving. Extrusion problems often result in downtime and/or out-of-spec product, and this can be very costly. However, because of the nature of the extrusion process, it is often quite difficult to determine the cause of the problem and find the proper solution, particularly if it must be done quickly. Despite the industrial importance of extrusion troubleshooting, no book currently deals exclusively with this topic. This book is an attempt to rectify this situation.

Both authors have worked in extrusion for many years and have been involved in numerous troubleshooting projects. Although it is impossible to discuss all possible extrusion problems, it is possible to discuss the main categories and to develop a systematic and methodical approach to solving extrusion problems. In this book, the authors frequently use flow charts and fishbone charts to allow systematic troubleshooting.

The authors added a substantial amount of new material to this third edition, including:

- Chapter 1: new section on collection and interpretation of extrusion process data
- Chapter 2: data acquisition systems section substantially expanded and updated with cloud-based DAS and systems that can automatically detect machine problems; new sections on rotational rheometry and the smartphone
- Chapter 3: new sections covering how screw design can affect extruder performance and melt temperature variation; additionally, barrel temperature profiles for many polymers from LDPE to PEEK
- Chapter 4: ten new case studies
- Appendix 3: new section with information on barrel temperature optimization for PP and HDPE for a 2.5-inch (63.5 mm) extruder and a description of recent research on automatic optimization of extruder barrel temperatures conducted at the department of Kunststofftechnik Paderborn, University of Paderborn, Germany by Verena Resonnek

- Appendix 4 (new): process signal analysis using Fast Fourier Transform

The authors welcome feedback from readers, along with additional material on extrusion troubleshooting. This will allow more information to be incorporated into future editions of this book.

List of Acronyms

ABS	Acrylic-butadiene-styrene copolymer
BTP	Barrel temperature profile
DAS	Data acquisition system
DOE	Design of experiments
FPVC	Flexible polyvinylchloride
HDPE	High density polyethylene
L/D	Length to diameter ratio
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
OTE	One-at-a-time experiments
PC	Polycarbonate
PE	Polyethylene
PEEK	Polyether ether ketone
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate (acrylic)
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride
RPVC	Rigid polyvinylchloride
SPC	Statistical process control

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1

Requirements for Efficient Troubleshooting

Before acting on a specific extrusion problem, the troubleshooter should address certain issues. It is important to diagnose a developing extruder problem quickly and accurately to minimize downtime or off-quality product. Good instrumentation and a solid understanding of the extrusion process are important requirements for efficient troubleshooting. Instrumentation is very important in process control, but absolutely essential in troubleshooting. Without good instrumentation, troubleshooting is a guessing game at best, even when the troubleshooter fully understands the entire process. Thus, lack of instrumentation can prove very costly when it causes a particular problem to remain unsolved for even a limited length of time.

Important prerequisites to an efficient problem solving process are:

- Good instrumentation
- Good understanding of the extrusion process
- Collection and analysis of historical data
- Team building
- Good information about the condition of the equipment
- Good information about the feed stock

1.1 Instrumentation

The extrusion process is, to a large extent, a black box process. It is not possible to visually observe what goes on inside the extruder. We can see material going into the extruder and material coming out of the extrusion die. However, what happens between the feed opening and the die exit cannot be seen in normal extruders because the process is obscured by the extruder barrel. Therefore, we are largely dependent on instrumentation to determine what happens inside the extruder. We can think of instrumentation as our “window to the process”. Because it is very difficult to determine what is happening inside the extruder without good instrumentation, successful problem solving requires good instrumentation.

It is not sufficient to have ample instrumentation on the extruder; it is also important to confirm that the sensors and readouts are working correctly. For instance, if a temperature zone along the extruder is showing an excessively low or high temperature, we should verify that the temperature reading is correct. The measuring instruments must be correctly calibrated, and we should establish that the instrument is capable of measuring the variation of interest. In statistical process control (SPC), specific procedures have been developed to determine the capability of the measuring instrument [1].

1.2 Understanding the Extrusion Process

A good understanding of the extrusion process is necessary to solve extrusion problems efficiently. It is recommended for the reader new to extrusion to take classes covering the material characteristics of plastics, typical features of extrusion machinery, instrumentation and operating controls, the inner workings of extruders, and screw and die design. Classes and continuing education short courses on extrusion are available from a variety of colleges and organizations. There are also a number of training programs available [2] as videos, interactive computer-based instruction, and web-based instruction.

In many extrusion operations, the primary mode of training is on-the-job training. However, on-the-job training is often the least effective and most expensive method of training. Extruders are expensive machines that must be operated correctly to produce good parts. If an extruder is not operated correctly, out-of-spec parts may be produced, or the extruder may be damaged. It is also important to realize that extruders are potentially dangerous devices. Serious accidents can occur when extruders are not operating properly. Therefore, it is imperative that people who operate extrusion equipment receive comprehensive safety training.

A short review of the extrusion process implies the understanding of the functional zones. The functional zones of a conventional single-screw extruder are shown in Figure 1.1:

- *feed hopper*, this zone is designed to operate under gravity flow and it feeds the granules or the particulate solids into the extruder,
- *solids conveying zone*, this zone is designed to transport and to slightly compress the granules or the particulate solids,

- *plasticating zone*, polymer melting takes place in this zone due to viscous dissipation and heat transfer by conduction from the extruder barrel,
- *melt conveying zone* (or *metering zone*), this zone is intended to transport the molten polymeric material and to achieve pressure buildup,
- *mixing zone*, this zone is designed to improve melt homogeneity by means of shear mixing elements, such as distributive, dispersive, or elongational mixers,
- *die forming*, the forming or shaping of the extrudate takes place in this zone for subsequent post-extrusion processes, such as calibration, cooling, winding or cutting, among others, and
- *venting*, this zone is only present in two-stage screw extruders or vented extruders and is used to remove any residual moisture or volatiles from the polymer melt.

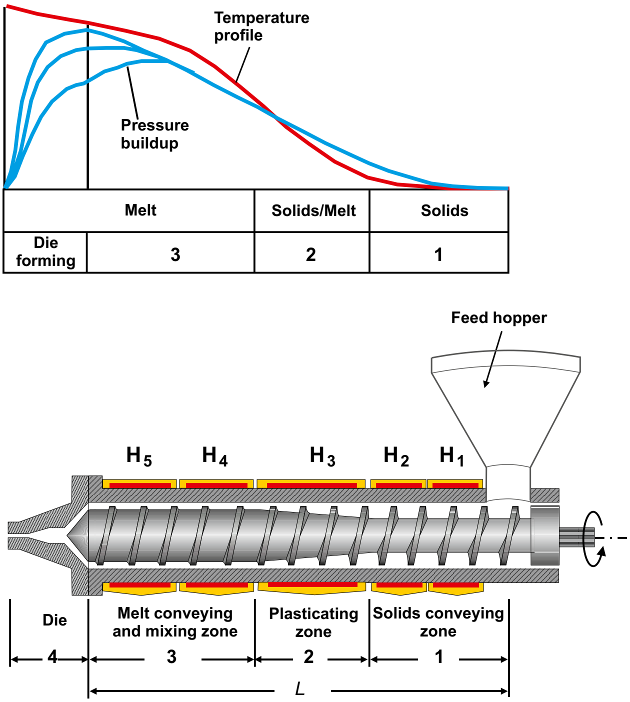

Figure 1.1 Functional zones in a single-screw extruder

■ 1.3 Collection and Analysis of Historical Data (Time Line)

To understand why a process is not behaving correctly, we must compare the current process conditions with previous conditions when the problem did not exist. This is known as constructing a time line. The data to be collected include not only process information from the extruder, such as temperatures, pressures, motor load, line speeds, barrel dimensions, screw dimensions, and such, but also information about the material as well as any other variables that can affect the process. Changes in the process can occur not only as a result of deviations in machine parameters, but also as a result of material variations. For instance, a change in the stabilizer level of the plastic can cause degradation problems in the absence of changes in the machine conditions and settings (Section 1.6).

The time line is constructed on the basis of the fact that the process was running well for a certain period of time. Therefore, there must be an identifiable change or changes that precipitated the process upset. The task is to identify these changes and correct them, and thus get the process back under control. The time line creation process starts during a period of process stability and ends some time after the problems in the process were noticed. All events even remotely connected to the process are listed on the time line. Once the time line is complete, it becomes a helpful tool for identifying the event that precipitated the problem.

It should be noted that not all events result in an immediate problem. In some cases there can be a considerable incubation time before the effects of a change become noticeable. This, of course, complicates the troubleshooting process; it is important to keep this in mind and not jump to conclusions. The author (CR) experienced a case when a disastrous wear problem was the result of an event that took place four months earlier. The wear remained insignificant until approximately four months after a new feed housing was installed. However, once rapid wear commenced, a screw was destroyed within 48 hours.

Figure 1.2 shows an example of a time line leading up to a gel problem. In constructing the time line, the troubleshooter should be sure to list all events that could potentially affect the process. Events such as a power outage, the installation of a new or refurbished extruder screw, or a new resin lot should obviously be included. Some events (such as construction in the area, changes in material handling, maintenance on the plant water system, operator training, or power surges) are less obvious but may still affect the process.

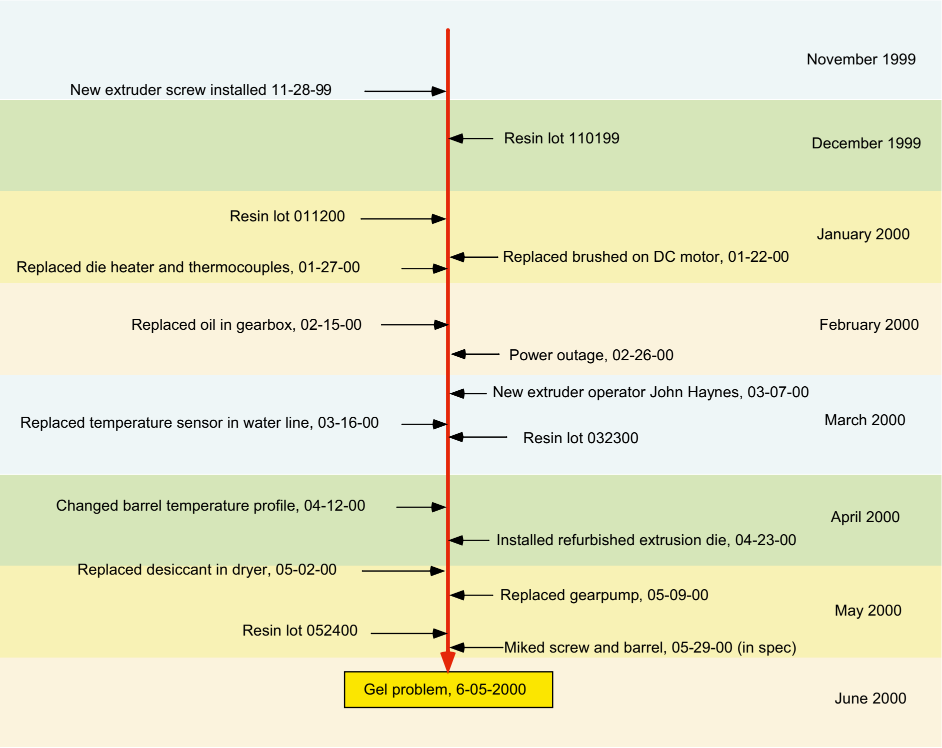

Figure 1.2 Example of a time line leading up to a gel problem

■ 1.4 Team Building

If the scope of a problem is small, a single individual can perform the problem-solving process, and there is no need to organize a team. In many cases, however, problems involve several different departments and functions and require a wide range of skills for solution. In such cases, a team effort is needed. Extrusion problems often require input from materials quality control (QC), purchasing, maintenance, engineering, and possibly from other departments.

1.5 Condition of the Equipment

When a problem develops on an extruder, it is important to have good information on the condition of the equipment. Extruders should be well maintained, and good maintenance records should be available to assess the condition of the various components of the machine. Maintenance recommendations from the extruder manufacturer should be followed to ensure good performance.

Extruder screws and barrels will wear over time. The wear rate depends on many factors. Extruder screws can last for several years or only several weeks. It is important to measure the internal diameter (ID) of the barrel and the outer diameter (OD) of the screw on a regular basis, at least once a year, so that the life of the screw and barrel can be predicted. This allows the screw and the barrel to be replaced at predetermined intervals preventing unpleasant surprises.

1.6 Information about the Feed Stock

The performance of an extruder is determined as much by the characteristics of the feed stock as by the characteristics of the machine. Feed stock properties that affect the extrusion process include bulk flow properties, melt flow properties, and thermal properties. Important bulk flow properties are the bulk density, compressibility, particle size, particle shape, external and internal coefficients of friction, and agglomeration tendency. Important melt flow properties are the shear and elongational viscosities as a function of strain rate and temperature. The commonly used melt indexer provides only limited information on the melt viscosity. Important thermal properties include the specific heat, the glass transition temperature, the crystalline melting point, the latent heat of fusion, the thermal conductivity, the density, the degradation temperature, and the induction time as a function of temperature.

In general, polymer material data is dependent on temperature and pressure. In other cases they are also dependent on surface roughness, sliding velocity, granulometry, shear rate, strain rate, and time. It is important to point out that thermal material data of polymers differ strongly depending on whether the polymer is an amorphous or a semi-crystalline material.

A change in the material can cause a problem in extrusion when it affects one or more polymer properties that determine the extrusion behavior of the material. If a material problem is suspected, the troubleshooter should first examine the QC records on incoming material to look for any record of a change in feed stock properties. Unfortunately, often, the only QC test on incoming material is a melt index (MI) test. This test detects only a very limited number of material-related extrusion problems. Thus, in many cases, more extensive material testing than the regular QC testing may be required.

There are a number of problems associated with making measurements on the critical properties of the feed stock. Approximately ten properties should be measured, and some of the measurements are fairly time-consuming. Thus, when a quick solution is required, it may take too much time to fully characterize the extrusion properties of a material. Another problem is that some important properties are difficult to measure with a high degree of accuracy and reproducibility. The most notable property in this category is the external coefficient of friction. Instruments to measure all the pertinent properties may not be readily available. Not all companies can afford to maintain a fully instrumented laboratory. Finally, even after a material is fully characterized, and no significant changes in properties have been found, there is no guarantee that the extrusion problem is not material-related. Because most tests are done on samples of about 0.01 kg or less, and most extruders run at a throughput of several hundred to several thousand kg/h, there is a considerable chance that the test sample may not have been representative of the entire feed stock.

A practical test for a material-related extrusion problem is to extrude some material from a previous batch to see if the problem will disappear. If this is indeed the case, it strongly indicates that the problem is material-related. For this reason, it is helpful to retain some material from older batches; this also provides a reference for more detailed measurements. If the problem is material-related, there are two possible solutions. The easiest solution is to change the material back to the way it was before the problem developed. However, this may not always be possible. Thus, if the material-related change is permanent, then the extrusion process will have to be adjusted to accommodate the material change. At this point, the nature of the problem may change from an upset to a development problem. The chance of solving the problem will depend on the nature and the magnitude of change in the material.

1.7 Problem-Solving Techniques

When analyzing complex extrusion problems that appear to have many interconnected causes it is important to use a so-called *cause-effect* diagram. There are several possibilities to represent *cause-effect* diagrams, including fishbone diagrams or Ishikawa diagrams, problem tree diagrams, problem checklists, mind maps, concept maps, among others.

The fishbone was introduced by the Japanese professor Kaoru Ishikawa in 1943. The diagram is drawn with an arrow that will serve as the backbone from which further possible causes (bones) will be categorized and related. Occasionally, the detailed causes may come from other origins. The diagram allows the identification of potential causes for the problem and it helps to determine which ones are most likely resolve the problem.

A problem tree diagram is a way of visualizing the *cause-effect* relationships with regard to a specific technical problem. In such a representation the causes are shown at lower levels and the effects at upper levels. The problem tree diagram facilitates the organization of problems into a logical sequence which will lead to logical conclusions and the identification of technically cost-effective solutions.

The checklist is a very common tool and easy to apply to systems, projects, and problems. It is a list of activities to be noted, checked, or remembered. The objective is to ensure that a long list of tasks is not forgotten. In the plastics industry, checklists are used to check process compliance, to prevent failures or errors, to assure product quality, and to solve technical problems.

Mind mapping is also a useful technique for troubleshooting. This tool was developed by Tony Buzan in the 1970s. A mind map uses pictures and/or word phrases to organize and develop thoughts in a non-linear manner. The elements of a mind map are arranged intuitively according to the importance of the idea or task. The map allows establishment of connections that are not obvious. It helps to “observe” a problem and its solution.

A concept map is a diagram that allows visualizing of relationships among concepts. It is also a graphical tool and is normally used to represent knowledge. Concepts are represented as boxes and are connected with labeled arrows in a hierarchical structure. The relationship between concepts can be done with linking phrases. Figure 1.3 shows a concept map visualizing a whitening problem in a plastic product.

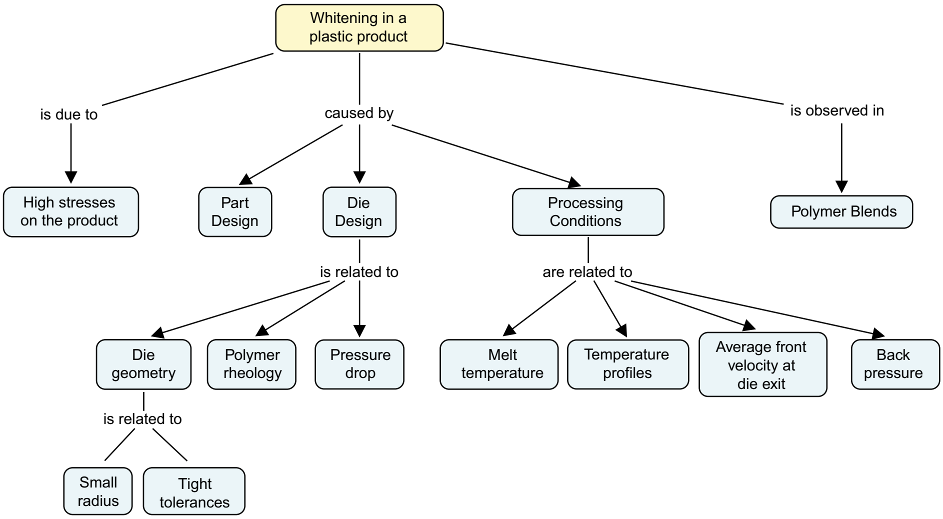

Figure 1.3 Example of a concept map visualizing a whitening problem

1.8 Collection and Interpretation of Extrusion Process Data

1.8.1 Introduction

Many modern extrusion lines are equipped with data acquisition systems (DAS). These systems can present extruder operators and process engineers with a large amount of data. There are several critical issues in the proper use of a DAS:

- Are the correct process variables measured and monitored?
- Are these process variables measured correctly?
- Is the data collection rate appropriate?
- Is the operating personnel capable of proper interpretation of the data?

These issues will be addressed in this section.

1.8.2 Vital Signs of the Extrusion Process

The three most important extrusion process variables are melt pressure (P), melt temperature (T), and motor load (I). These three process variables are the vital signs of the extruder. When the extruder is not functioning correctly, one or two or all three of these variables will show abnormal behavior. It is no coincidence that these three process variables are similar to the vital signs of the human body: blood pressure, body temperature, and pulse. The human body functions because the heart pumps blood through our vascular system. Blood pressure and pulse are measures of how well our blood is being pumped. In extrusion P, T, and I are measures of the pumping efficiency of the extruder.

One of the most important process measurements is the specific energy consumption (SEC). This is the motor power divided by the throughput. In the U. S. the SEC is typically expressed in units of hp · h/lb – more commonly, the SEC is expressed in kW · h/kg. The SEC is a measure of the amount of energy from the motor introduced into the polymer. As a result, the SEC is closely related to the increase in stock temperature in the extrusion process. Higher levels of SEC lead to higher melt temperatures.

The minimum SEC needed to extrude a polymer is determined by the thermal properties. It is the specific heat multiplied by the temperature rise in the extrusion process – this is the increase in enthalpy. For semi-crystalline polymers the minimum SEC value is about 0.10 hp · h/lb or about 0.16 kW · h/kg. It is good practice to monitor the SEC because it is a good measure of the energy efficiency of the extrusion process. If the SEC in a single-screw extrusion process is above 0.2 hp · h/lb (0.32 kW · h/kg), this indicates poor energy efficiency. This will likely result in high melt temperatures.

1.8.2.1 Melt Pressure

The most important process variable is melt pressure. Die inlet pressure is a direct measure of the flow rate through the die. Variation of die inlet pressure causes variation in flow rate; this, in turn, will cause dimensional variation of the extruded product, see Figure 1.4. A graphical display of die inlet pressure versus time provides a clear picture of the process stability – or lack thereof. A simple display of pressure (analog or digital) is much less useful.

When the extruder operator looks at a digital pressure readout with numbers typically changing ten times per second or more, it is impossible to get a clear picture of the pattern. The human mind has very limited ability to analyze large numbers of numerical data. On the other hand, when the operator can look at a graph of pressure versus time, the trend of the pressure pattern becomes immediately obvious. The human mind has remarkable ability to interpret graphical information. For this reason, trend plots are a very important element of a good DAS.

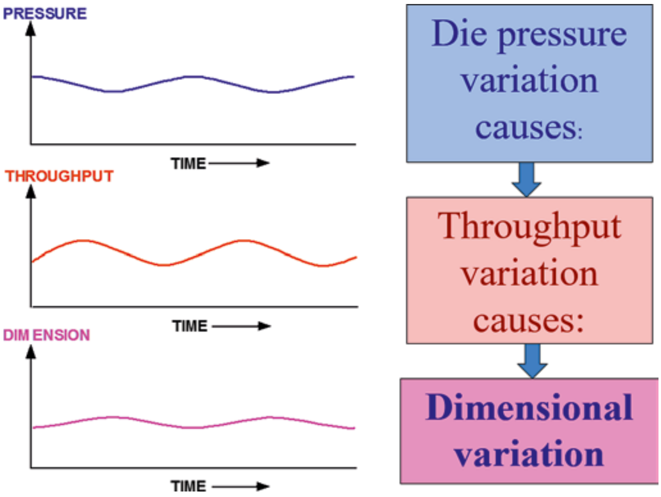

Figure 1.4 Effect of die inlet pressure variation on dimensional variation of extrudate

Pressure is measured with a pressure transducer. These pressure transducers have a thin diaphragm that is in contact with the molten plastic, see Figure 1.5.

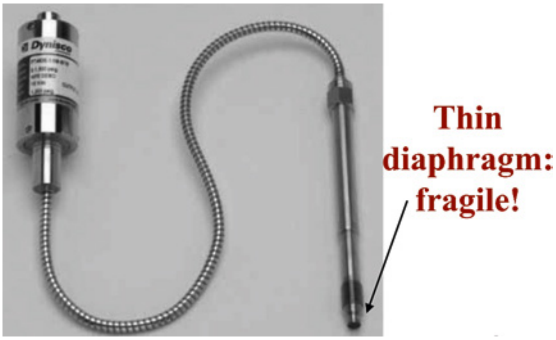

Figure 1.5 Typical pressure transducer

Increasing melt pressure will deflect this diaphragm and this deflection is a measure of the amount of pressure acting on the diaphragm. There are several different types of pressure transducers. Table 1.1 lists several types with a comparison in terms of robustness, maximum temperature, dynamic response, and error.