In-Process Measurement and Control

Edited by
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OTHER VOLUMES IN PREPARATION

Preface

Inspection, including dimensional inspection, has commonly been an activity performed after, rather than during, a manufacturing step or process. In many instances, several steps may have been performed before a part is measured. If the part is found to deviate from the manufacturing blueprint tolerances, it must either be rejected at a point where considerable value has been added or be reworked. In either case, the manufactured cost has been boosted.

In view of the Japanese threat to American manufacturing, as well as internal competitive pressures, the American industrial community is turning to means of reducing manufacturing costs while improving quality. In addition to more standard approaches, such as increased automation and the use of robots, other more subtle approaches that work hand in hand with automation are being implemented. One such approach is in-process measurement.

In-process measurement is significant in that it ultimately allows a manufacturer to achieve a goal of zero scrap, since deviations in the manufacturing process measured by sensors can be used in a corrective manner to control the process before tolerances are exceeded. Advances in sensor technology and digital computers and controllers are permitting a dramatic increase in the application of in-process measurement and control.

Initially, digital computers were used for industrial control in the continuous process industries (e.g., petrochemicals). Although critics once believed that computers could not be used cost effectively by batch industries, they were ultimately proved wrong, as evidenced by the computers, programmable controllers, numerical controllers, and robots in use by these industries today. In the same way that temperature, flow, and pressure sensors are used in conjunction with digital computers for closed-loop control by the continuous process industries, dimensional sensors can be utilized within an in-process control loop for batch manufacturing processes.

This text attempts to encompass in-process measurement and control holistically as opposed to dealing with the bits and pieces, since the real power behind the concept comes from closing the control loop around the machine tool. It discusses not only various types of sensors but also strategies for using the data derived from the sensors in a closed-loop feedback arrangement. Also presented are discussions concerning the improvement in quality and reduction in cost achievable by in-process measurement and control through the use of numerical and programmable controllers. The text centers on the use of dimensional sensors; however, a logical extension of the concept reveals how nondestructive evaluation sensors could be used in a similar fashion to ensure material integrity.

Some of the material in this text has been excerpted from technical papers, while some reflects manufacturers' information concerning devices usable in an in-process control loop. The initial chapter deals with the title subject, and subsequent chapters discuss specific sensors, both contacting and noncontacting types. Later chapters discuss how data from the sensors can be used to close the loop around the process, and the last chapter discusses how in-process measurement and control can improve quality while reducing manufacturing costs.

This text is directed toward manufacturing and industrial engineers, technologists, and managers who are attempting to increase the level of automation in their factories while seeking ways to reduce manufacturing- and quality-related costs without compromising product quality. The concept of in-process control is especially important for those moving toward fully automated factories, since the on-line measurement capability also provides the process monitoring function previously relegated to the human operator.

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I would also like to thank all the contributing authors who made this book possible. Nowadays, in our busy, highly competitive business environment, it seems that there is barely enough time to do your job, let alone perform some extracurricular activities. I appreciate the effort put forth by all contributors.

Lastly, I wish to expres~ thanks to my wife, Nancy, who assisted me in typing the manuscript.

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Concepts of In-Process Measurement and Control

STEPHAN D. MURPHY / Textron, Inc., Danville, Pennsylvania

When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter might be.

—**Lord Kelvin**

When William Thomson, Lord Kelvin, wrote these lines, he hardly suspected that the Japanese would one day surprise the American manufacturing community with low-cost, high-quality goods. He did, however, live during the beginning era of the industrial revolution, and, as the last line implies, these words can certainly apply to interchangeable manufacture. Measurement, particularly in-process measurement, is key for successful manufacturers. If manufacturers cannot measure their products' key features while the products are being made, they cannot begin to control their processes. This is fundamental to the implementation of in-process measurement and control and statistical process control (SPC).

The concept of in-process measurement and control has to do with measuring a process variable while that variable can still be influenced and applying a corrective feedback to the machine that affects the process so as to encompass the sources of error that normally occur during the process and thus eliminate error from the variable on the resultant workpiece. This text deals primarily with in-process measurement and control applied to batch machining operations, but the concept can be applied to other disciplines and is the basis for closed-loop control, whether it be a servomechanism loop, an engine speed governor, an analog amplifier feedback circuit, or a digital phase-locked loop.

As Schonberger has said (Ref. 1), one of the principles that the Japanese use to assure their high degree of quality is 100% inspection. In this way, the percentage of defective parts manufactured is measured in terms of parts per million instead of parts per hundred. There is a hitch to 100% inspection, however; simply stated, it is cost. Since the Japanese are in many cases the low-cost supplier, they have also addressed this issue. Schonberger states how devices called "bakayoke" are utilized to assure quality. These devices are the essence of in-process control, since they monitor the machine, measure the part, and warn the operator or supervisor of a malfunction or an imminent defective piece. As American manufacturers will learn, this approach of continuous in-process measurement coupled with tooling modification to permit fast changeovers will be the key to the implementation of just-in-time (JIT) procedures, which will allow the manufacturers to compete on par with the Far East.

Because of cost limitations associated with 100% inspection, the manufacturer must turn to a technological solution. A wide array of sensors are available which can be implemented to make dimensional measurements while the product is being made. In addition to these sensors, tremendous advances in the power of minicomputers, microcomputers, and computerized machine tool controllers have been achieved, along with an even more dramatic reduction in cost. These sensors, coupled with computerized control running appropriate software, can be utilized in a feedback arrangement to maintain the process within the allowable tolerance band. Consequently, extremely low defect rates can be achieved. Heretofore, the lack of sensors, the high cost of computers and associated controls, and the high cost of manual inspection precluded the use of in-process measurement

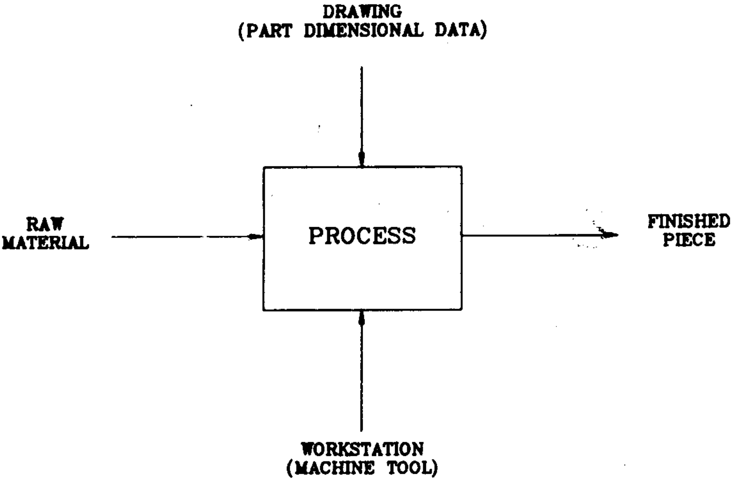

FIGURE 1.1 Basic metalworking process.

approaches. In addition, the in-process control solution involves a multidisciplinary approach requiring electronic engineers, computer scientists, control engineers, machinists, and computer numerical control (CNC) programmers. Many manufacturing shops do not have this type of talent under one roof. However, changes in American manufacturing are allowing many of the in-process measurement goals to be attained.

Figure 1.1 shows an IDEF (ICAM definition, where "ICAM" is integrated computer-aided manufacturing) model which represents the basic process and the basis for in-process control. In order to produce a part, raw material is required, a resource such as a machine tool is needed to effect the process, and something to describe quantitatively the amount of material to be removed—the part drawing or data from the drawing—is required. Normally, the engineering function of the manufacturing facility assures that the tooling design is done in such a way as to minimize changeover time for a new part and minimize operating loading variability. In some cases there may be an engineering trade-off between speed of changeover and the amount of variability in loading.

Once the part is loaded, the process can begin. If the parts are measured after the process, it can easily be seen that the dimensions will vary according to some statistical variation. This variation occurs because the process on the shop floor is not ideal. In addition to the variability in loading the part just mentioned, there is variance in the process due to deflection of the part, the cutter, the fixture, and the machine tool itself. In addition to the deflective variability, the different thermal coefficients of these members result in dimensional changes. There is wear of the cutting edge, and the material being cut may work-harden. Other problems may occur during the process, such as a catastrophic failure of the cutting tool or breakdown of a component in the machine tool. Moreover, many of the process parameters are interdependent and will change according to the spindle speeds, axes feed rates, amount of cutter engaged, type of material being cut, and depth of the cut. The result of all sources of variation may be a defective dimension and, ultimately, a defective part. For any particular process, the tighter the manufacturing tolerance, the more frequently dimensions will deviate, and any dimension that is not monitored and controlled can and will deviate. In many instances in manufacturing, the sources of variance are multiple and their interactions complex, to the extent that it is not practical to establish a deterministic process model for every operation that could encompass all sources of variability.

Therefore, it may be desirable to monitor and measure the dimension under question, in effect monitoring the performance of the machine while it is affecting this dimension. The measurement of the actual dimension can then be compared with the size mandated by the part blueprint and, finally, the machine can be adjusted accordingly to bring the dimension into the proper range.

Figure 1.2 expands on Figure 1.1 to illustrate this concept. As shown in the figure, the machine tool is fitted with a measurement sensor suited to the process and the type of dimension under measurement. This sensor provides a continuous measurement that can be in the form of an analog signal or a digital data word, which is compared with the required dimension derived from the part blueprint. The result of the comparison is a compensatory signal which is applied to the machine control so as to restore the dimension within its allowable range on either the part being machined or subsequent parts. The concept is directly analogous to a setpoint temperature controller used in a continuous process application where the setpoint is the desired or nominal temperature, the thermocouple is the measurement

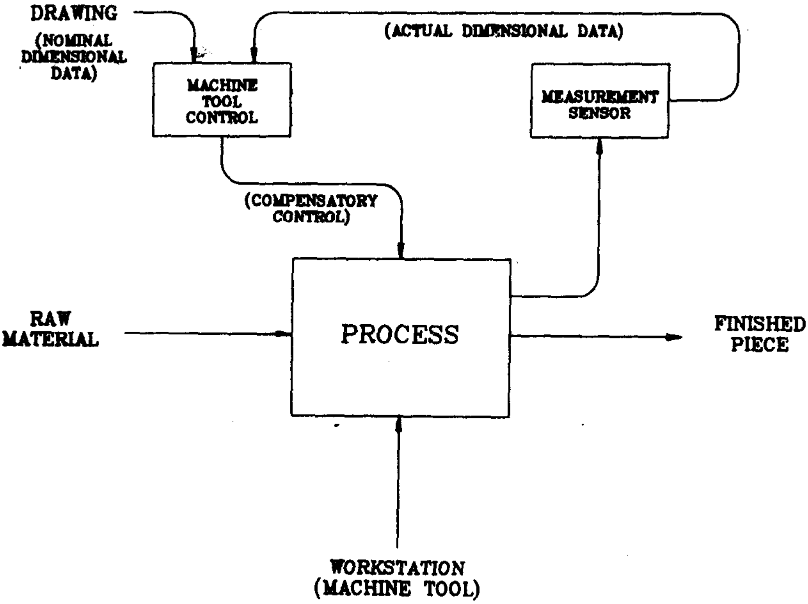

FIGURE 1.2 Concept of in-process measurement and control.

sensor, and the process is an oven. The thermocouple measures the temperature, which is compared with the setpoint. An error signal is determined, and the rate at which power is applied to the oven is controlled accordingly to keep the temperature within a desired band. In the case of the machine tool, the setpoint is the nominal blueprint dimension, which is being monitored by a measurement sensor. The difference between the two, the error, is fed to the machine control, which activates the machine's actuators to restore the dimension within range. Since many of today's machines have computer numerical controls and the requisite servomotor axis drives, the task of implementing in-process control becomes one of selecting the appropriate measurement sensor and interfacing it to the machine tool control with suitable hardware and software.

As will be discussed in later chapters, different types of measurement sensors have different requirements for processing