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Process adjustment with an asymmetric quality loss function

Jun Zhang[a,*], Wei Li[a], Kaibo Wang[b], Ran Jin[c]

[a] The State Key Lab of Fluid Power Transmission and Control, Zhejiang University, Hang Zhou 310027, China
[b] Department of Industrial Engineering, Tsinghua University, Beijing 100084, China
[c] Grado Department of Industrial and Systems Engineering, Virginia Tech., VA 24061, USA

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ABSTRACT

Controlling an engineering process usually focuses on maintaining the process output on-target with minimum variation. Conventionally, the quality loss incurred by the deviation from the nominal values is assumed symmetric. However, in some engineering processes, the penalties incurred by positive and negative deviations of the quality variables are different. In such cases, we need to redesign the controller so that the overall quality loss is minimized. In this work, motivated by a real ingot growing process, a new controller is proposed for an asymmetric quality loss function. Its performance and stability are studied via numerical simulation. The effectiveness of the method is also demonstrated in the real engineering process.

1. Introduction

Process adjustment is an important quality control method used in semiconductor manufacturing to maintain process output on-target with minimum variation. The control algorithm usually takes the output obtained at the previous step or time point, and derives the optimal set-point for the next step. In this way, the expected output of the next step is driven to a desired target value. The set-point contains another automatic control loop guided by engineering controllers. Such a framework is implemented to learn process dynamics and gradually move the process on target with reduced variation [1].

Process control has been widely used in the industry with repeated discrete production runs, due to its effectiveness in improving quality and yield, and reducing cost. Examples include chemical vapor deposition [2], plasma etching [3], chemical mechanical polishing [4–6], photolithography [7] and ploy silicon gate etching [8]. Card et al. [9] studied a plasma etch process for 8-in. silicon wafers by maintaining targeted values of post-etch metrology variables. Sachs et al. [10] combined the Statistical Process Control (SPC) and the feedback control. Bode et al. [11] developed a control scheme for overlay control based on linear models in semiconductor processes, and successfully implemented it in a commercial facility. All the existing work has reported the effectiveness of the controllers in reducing process variation and improving product quality.

To design such an adjustment algorithm, quality loss is the key performance index. Taguchi et al. [12] established a number of ways to measure quality loss in different scenarios. He proposed three functions for measuring quality for different quality characteristic: nominal-the-best, smaller-the-better or larger-the-better.

In the nominal-the-best case, the output has a clear target. Any deviation from the target incurs penalty, and the penalty is symmetric and increases quadratically with the amount of deviation. Let y be the process output and T the target value, the quality loss is then defined as follows:

$$L = k(y - T)^2 \tag{1}$$

Fig. 1(a) shows this quality loss function. For this type of processes, the output y should stay close to the target value such that the mean square deviation can be minimized. In practice, the nominal-the-best type of quality variables are widely used.

Taguchi et al. [12] also introduced smaller-the-better and larger-the-better loss functions for cases in which the quality characteristic is expected to be as small as possible, or as large as possible. Sharma et al. [13] studied the quality loss functions, and compare these three cases to devise a common methodology to represent these three loss functions. Their quality loss functions are shown in Fig. 1(b) and (c).

The different types of quality loss functions are widely seen in different manufacturing processes. For example, in a wafer preparation process (see Han and Wang [14] and Wang and Han [15] for more details), the thickness of the wafers after the lapping

* Corresponding author. Tel.: +86 137 58193796; fax: +86 575 82338128.
E-mail addresses: cjwcolin@zju.edu.cn, tlyoufa@126.com (J. Zhang).

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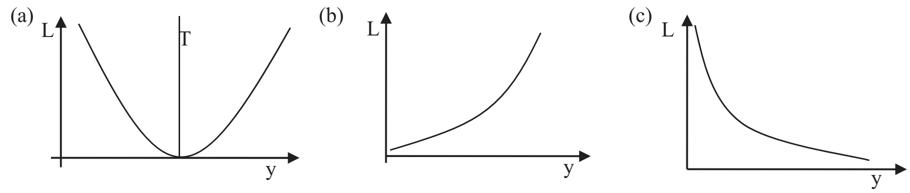

Fig. 1. Traditional quality loss functions: (a) nominal-the-best; (b) smaller-the-better; (c) larger-the-better.

operation has a target values; all wafers are expected to stay as close as possible to the target thickness value. On the other hand, the uniformity of the wafers, which is measured by the total thickness variation (TTV), is a smaller-the-better type of quality indicator; a smaller TTV value means better uniformity condition and is always the pursuit of the industry. In a footwear manufacturing process (see Jiang et al. [16] for more illustration), the inner sole, middle sole and outer sole are bounded together using a certain type of adhesive; the adhesive force between the different layers is a larger-the-better type of quality matric.

These quality loss functions, especially the nominal-the-best type function, are widely used in process adjustment. Most existing literature developed the algorithm by minimizing the expected mean sum of squared error, which is consistent with the nominal-the-best loss function, see, e.g. Wang and Tsung [17], Wang and Tsung [1], Lin and Wang [18], and Lin and Wang [19]. Many run-to-run (R2R) controllers have been introduced to reduce the impact of drift, shift and noise disturbance. These include the exponentially weighted moving average (EWMA) controller [20,10], PID controller [21], age-based double EWMA controller [4], and self-tuning controller [22]. However, the traditional definition of quality loss cannot satisfy the real engineering requirement in some manufacturing processes. For example, in silicon ingot growth, the ingot diameter is a “smaller-the-better but no-less-than” type of quality variable. That is, the diameter has a design target. The true diameter is expected to stay as close as possible to the target value, but not smaller than the target. More engineering background of this process will be introduced in the next section.

Harris [23] studied the control of a process with asymmetric loss functions. However, the loss functions the author considered, including two quadric functions, two constant functions and two linear functions, are inapplicable to the real process that we encountered. Similarly, the work done by Colosimo et al. [24] cannot be applied to our process, since the quality loss in our process is penalized differently. Therefore, the objective of this paper is to propose a new quality loss function that better suits certain engineering needs. Based on the new loss function, the optimal run-to-run (R2R) control action is also developed; and its performance is studied via simulation.

The rest of this paper is organized as follows. In Section 2, the quality loss function derived from a real engineering process is introduced. The optimal control action is derived in Section 3. In Sections 4 and 5, we study its control performance and stability. Finally, Section 6 concludes this work with suggestions for future research.

2. Quality loss for the smaller-the-better but no-less-than (SBN) variables

In this work, we use the silicon ingot growing process as an example for illustration. The silicon ingot growing process is the first step to transform polysilicon to single silicon in semiconductor manufacturing. Single crystal growth is mainly achieved by two methods, Czochralski (CZ) and float zone (FZ). Between these two methods, the CZ process is more commonly used to produce high-quality single crystal ingots [25]. Fig. 2 shows a schematic diagram of a crystal growing furnace based on the CZ process.

A typical crystal growing furnace usually consists of the pulling thread, which holds a thin seed crystal bar, the crucible, which holds raw crystal material, and a heating system, which is used to melt the raw material and create an ideal heat field for the growth of single crystal. The CZ growing process has three major phases, namely (1) seeding and necking, (2) body growth, and (3) termination. Among these steps, the body growth is the main step and lasts the longest period of time (usually 40–50 h in our example). In this step, the main body of the ingot is growing, and diameter control is one of the most critical tasks. When growing the ingot, there is usually a desired diameter value; the ingot is expected to be smooth and consistent in diameter throughout its body growth stage (see a sample ingot in Fig. 3). The diameter is monitored and measured by a CCD camera. A feedback-control system is therefore needed to maintain the diameter on target.

In most cases, it is difficult to keep the ingot diameter exactly on target due to process variation and a lot of unobservable noises (see Fig. 4 for the plot of the diameter of one sample ingot). The diameter is affected by a number of factors. It is directly affected by the pulling speed. When the pulling speed increases, the diameter decreases, or vice versa. Besides, the pulling speed, temperature, power of heater and many other factors need to be coordinated to achieve a target diameter. Due to the large number of factors, a large variation of diameters is commonly encountered in real production. In this paper, we focus on how to set and adjust the direct factor, the pulling speed online. Once the set-point of the pulling speed is known, the realization of the speed and the coordination among other variables will be achieved by a built-in automatic control system.

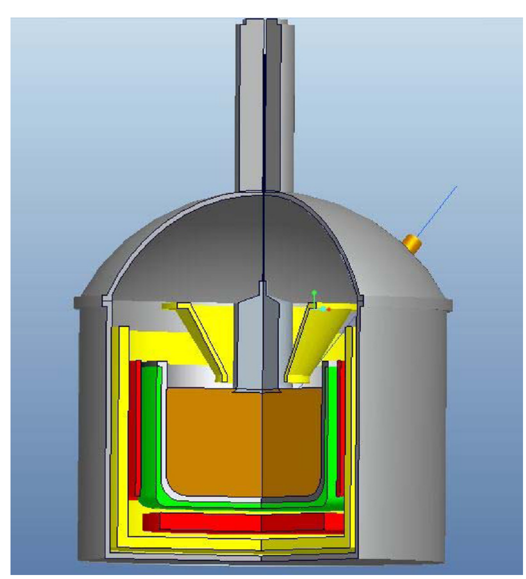

Fig. 2. A schematic diagram of a crystal growing furnace.