Journal of Process Control 40 (2016) 1–12

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Average dwell time-based optimal iterative learning control for multi-phase batch processes

Limin Wang [a,c], Xiao He [a], Donghua Zhou [b,a,*]

[a] Department of Automation, Tsinghua University, Beijing 100084, China
[b] College of Electrical Engineering and Automation, Shandong Univ. of Science and Technology, Qingdao 266590, China
[c] College of Sciences, Liaoning Shihua University, Fushun 113001, China

ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form 8 January 2016
Accepted 18 January 2016
Available online 11 February 2016

Keywords:
Multi-phase batch process
Different-dimensional subsystems
Iterative learning control
Average dwell time method
Exponential stability

ABSTRACT

Multi-phase batch process plays an important role in modern industry, especially for processes with different dimensional phases. As the different phases may interact with each others deeply, when and how to perform the transfer between adjacent phases highly affect the control performance and product quality. Meanwhile, the running time in different phases influence the production efficiency. Therefore it is of crucial importance to study the control of multi-phase batch processes with time constraints. Take the injection molding process as an example, a multi-phase batch process can be regarded as a switched system with different-dimensional subsystems in each batch. In this paper, the multi-phase batch process is converted to an equivalent two-dimensional (2D) switched system and the repetitive and 2D nature of batch processes is explored. Within the framework of 2D system theory, both the exponential stability and the shortest running time are considered. Meanwhile, a compound 2D controller with optimal performance is designed. The contributions of this paper are as follows: (1) the batch process studied is with different dimensions in each phase. (2) using the average dwell time method, a sufficient condition ensuring the exponential stability is obtained, meanwhile, the minimum running time of each subsystem, i.e., the running time of each phase can be calculated. Finally, the proposed method is illustrated with an injection molding process to show the effectiveness.

1. Introduction

With the characteristics of small scale, multi species, high added value, the batch process is commonly encountered in modern systems in the area of fine chemical, biological pharmaceuticals, pharmaceutical production and other fields [1]. As a major plastic processing technique to convert thermoplastics into variety of plastic products, injection molding is a typical batch process. As is shown in Fig. 1, it operates sequentially in the fixed phases of mold close, filling, packing-holding, cooling and mold open. Among those phases, filling and packing-holding are two important phases which determine the product qualities such as weight and dimension [2]. The injection velocity in the filling phase and the nozzle pressure in the packing-holding phase are the main control parameters, which need to be adjusted to track the given profile respectively. The transition from filling phase to packing-holding phase has a direct effect on the control performance and product quality [3].

Fig. 2 illustrates the melt flow pattern in a simple rectangular mold [4]. The melt is injected through the valve and fills the mold cavity from the left to the right. The contours indicate successive flow front positions at different filling times in the spreading plane. It is a critical time instant when the cavity is filled up with melt. For simplicity, we call this time instant “filled-time”. The process dynamics has a significant difference before and after the filled-time. Before the filled-time, the cavity pressure increases gradually, while it rises rapidly after the filled-time. Taking this situation into consideration, we use two separate control algorithms in practice, one is for the filling phase and the other is for the packing-holding phase. In the filling phase, the injection velocity needs to be controlled to achieve a uniform mold filling, and in the packing-holding phase, the nozzle pressure needs to be maintained to compensate for the material shrinkage.

* Corresponding author at: College of Electrical Engineering and Automation, Shandong Univ. of Science and Technology, Qingdao 266590, China.
E-mail address: zdh@mail.tsinghua.edu.cn (D. Zhou).

http://dx.doi.org/10.1016/j.jprocont.2016.01.006

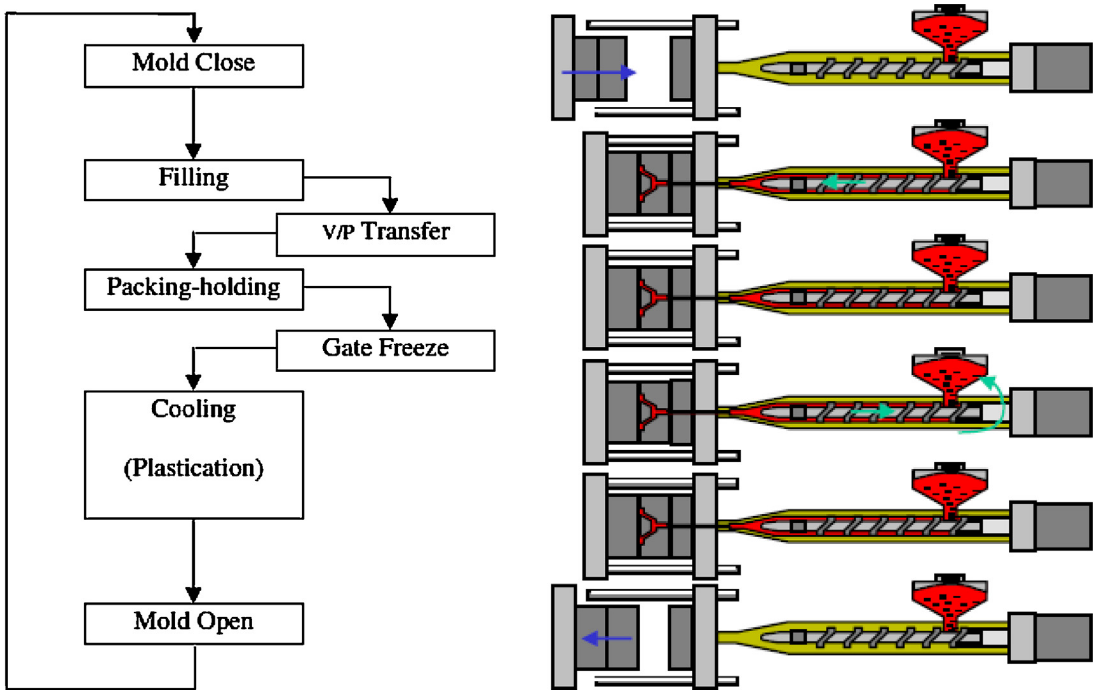

Fig. 1. Illustration of an injection molding cycle.

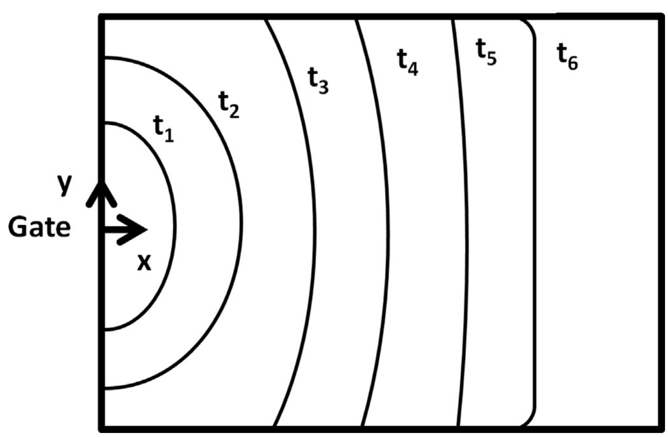

Fig. 2. Melt flow in a single-gate rectangular mold [4].

From the above discussion on the injection molding process, it can be inferred that a batch process is essentially a multi-phase industrial process and the study on the adjacent phase switching of multi-phase batch process is of great significance in engineering practice. Coming very naturally, as an important factor affecting the producing efficiency, the running time attracted much research attention. However, in the existing literature, batch process is not treated as a multi-phase process and the running time of the phases is rarely taken into consideration, most of which only focused on the switching design of adjacent phases [4–7]. In practice, the running time of batch process phases is always chosen according to practical experience while the running time of batches is also determined in the similar way. The shortcoming of this treatment is that the running time of phases is a little long in a certain degree, which will eventually make the batch run with a longer time. For the whole producing process, the running time will be much longer, which will definitely reduce the producing efficiency and increase the production costs. To the best of the authors' knowledge, there is a lack of research focusing on the running time of phases for multi-phase batch process, and this results in the main motivation of the present study.

Each phase of multi-phase batch process is repeated in a certain degree from batch to batch, which is regarded as the repetitive nature. Exploiting the repetitive nature, we can utilize iterative learning control (ILC) method. Batch processes can be regarded as a special 2D system since the process runs along both the time direction in batch and the cycle direction between batches. If the batch process can be analyzed from the 2D system viewpoint, the batch process properties can be separately investigated along the time and cycle directions, which can help us to interpret the actions of feedback controller and iterative learning controller. To design 2D controller for the processes allows all controllers to be designed in an integral fashion, which makes them work together harmoniously. 2D control determines that the dynamics change along the time and cycle directions [8–16]. ILC associated with the feedback control scheme has been discussed for batch processes with state delay and time-varying uncertainties [17–21]. The authors [22,23] also proposed an iterative learning fault-tolerant control strategy for batch processes with actuator/sensor faults. Iterative learning fault-tolerant control for batch processes with time delay has also been studied based on the delay-range-dependent method [24,25].