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Journal of Process Control 18 (2008) 543–557
JOURNAL OF PROCESS CONTROL
www.elsevier.com/locate/jprocont

Iterative learning model predictive control for multi-phase batch processes

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Received 4 July 2007; received in revised form 16 October 2007; accepted 24 October 2007

Abstract

Multi-phase batch process is common in industry, such as injection molding process, fermentation and sequencing batch reactor; however, it is still an open problem to control and analyze this kind of processes. Motivated by injection molding processes, the multi-phase batch process in each cycle is formulated as a switched system with internally forced switching instant. Controlling multi-phase batch processes can be decomposed into two subtasks: detecting the dynamics-switching-time; designing the control law for each phase with considering switching effect. In this paper, it is assumed that the dynamics-switching-time can be obtained in real-time and only the second subtask is studied. To exploit the repetitive nature of batch processes, iterative learning control scheme is used in batch direction. To deal with constraints, updating law is designed by using model predictive control scheme. An online iterative learning model predictive control (ILMPC) law is first proposed with a quadratic programming problem to be solved online. To reduce computation burden, an offline ILMPC is also proposed and compared. Applications on injection molding processes show that the proposed algorithms can control multi-phase batch processes well.

Keywords: Multi-phase batch process; Iterative learning control; Model predictive control; Constraint; Quadratic programming

1. Introduction

As a preferred choice for manufacturing of high-value products, batch processes play an important role in industries, such as specialty chemicals, pharmaceutical products and polymers [1]. Injection molding, a major plastic processing technique for converting thermoplastics into a variety of plastic products, is a typical batch process. As illustrated in Fig. 1, injection molding typically operates sequentially in phases, among which, filling and packing-holding are the most important phases in determining qualities such as weight and dimension [2]. For this process, injection velocity in the filling phase and nozzle pressure in the packing-holding phase need to be controlled to track their given profile, respectively. The transition from filling to packing-holding in each cycle, referred to as the V/P transfer, has a significant effect on the control performance and product quality. When and how to perform the V/P transfer, is an important issue in successful molding [3].

The melt flow pattern in a simple rectangular mold is illustrated in Fig. 2. Melt is injected through the gate and fills the mold cavity as shown from the left to the right. The contours indicate successive flow front positions at different filling times in the spreading plane. The time when the cavity is filled is a critical point. For convenience, this time is named *filled-time*. Before and after the filled-time, the process dynamics has a significant variation: the cavity pressure increases gradually before the filled-time; while the pressure rises rapidly after the filled-time. To deal with this dynamics variation, two separate control algorithms, one for filling and another for packing-holding, were widely used in practice. In the filling phase, the injection velocity

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doi:10.1016/j.jprocont.2007.10.014

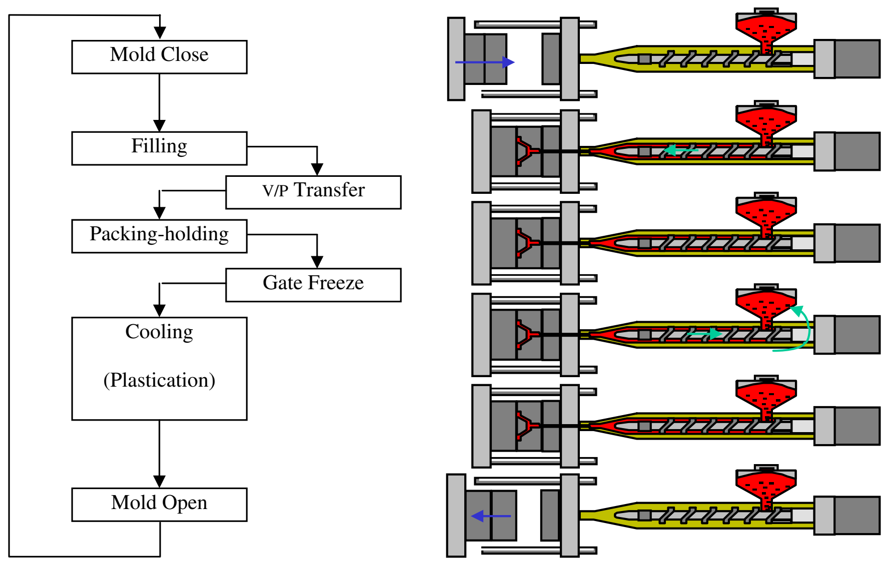

Fig. 1. Illustration of an injection molding cycle.

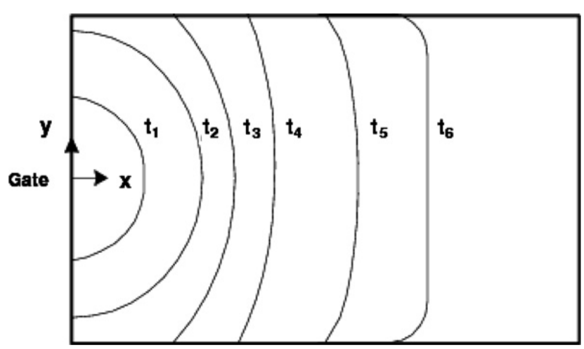

Fig. 2. Melt flow in a single-gate rectangular mold.

needs to be controlled to achieve a uniform mold filling, while in the packing-holding phase, the nozzle pressure needs to be maintained to compensate for the material shrinkage.

This phenomenon, in fact, is common in industrial processes, for instance fermentation [4] and sequencing batch reactor [5]. Hence, controller design study for this class of processes theoretically and systematically is important and interesting. This class of processes has the following character: *the batch process is multi-dynamics in each batch with same actuator*.

Most discrete-time batch processes are carried out in a sequence of discrete steps. In [6], two definitions were introduced: "Steps occurring in a single processing unit as succession of events caused by operational or phenomenological (chemical reactions, microbial activities, etc.) regimes are called phases. Steps occurring in different processing units and performing different unit operations are called stages." Hence, the difference between "multi-stage batch process" and "multi-phase batch process" is clear: the multi-stage batch process is multi-unit, while the multi-phase batch process is single-unit.

As pointed in [7], a batch process control system can be refined into four levels: planning, scheduling, supervision and coordination, and local control. There are many literatures on multi-stage processes, and most of them are about planning [8], scheduling [9] and supervision and coordination [10]. In all these works, the local control is assumed to be given. Since there are multi-actuators in multi-stage processes, the local controls can be designed separately as done in the conventional situation; designing local control is not the emphasis and nodus for multi-stage batch processes.

The situation for multi-phase batch processes is different. Since there is only one unit, there is limited planning, scheduling or supervision problem. While designing local control law to deal with multi-dynamics and achieve multi-objective by using single-actuator is difficult. To the best knowledge of the authors, there is little reported works on this problem. In our previous paper [11], this class of processes in each batch is formulated as a switched system with internally forced switching instants, and challenges within this framework are also discussed. In this paper, the formulation introduced in [11] will be used and some solutions will be proposed.

To exploit the repetitive nature of batch processes, iterative learning control (ILC) has been used widely [12,13]. Since the dynamics in each phase is repetitive to certain degree from batch-to-batch, ILC may be a good choice as the base-line controller. In each phase, as done in [13,14], the batch process under ILC is modeled as a 2-dimensional Fornasini–Marchesini (2D-FM) system and the designing of an ILC for a batch process is transformed into a robust stabilization problem of the 2D system. If ILC laws in different phase are updated separately ignoring the phase transition, there would be significant jump and oscillation in the control signal around the switching step. On the other hand, constraints exist on the actuator's slew