Control Engineering Practice 41 (2015) 164–175

Contents lists available at ScienceDirect

Control Engineering Practice

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

Modeling and control of a rotating turret winder used in roll-to-roll manufacturing

Aravind Seshadri, Prabhakar R. Pagilla*

School of Mechanical & Aerospace Engineering, Oklahoma State University, Stillwater, OK 74078, United States

A R T I C L E I N F O

Article history:
Received 30 July 2014
Accepted 18 April 2015
Available online 1 June 2015

Keywords:
Roll-to-roll manufacturing
Web handling
Winding
Rotating turret
Tension control
Flexible materials

A B S T R A C T

In this paper, winding issues in an industrial R2R printing press using a rotating turret winder are investigated by utilizing a new mathematical model and data are collected during production runs. Production data and simulation results from the developed model are analyzed to identify the causes for tension disturbances that affect winding quality. Model simulations are conducted by incorporating production data as inputs to the model to gather insights into the effect of dynamic behavior of the rotating turret winder on winding web tension. The developed model captures the various dynamic events associated with the roll change operation with a rotating turret winder. Measured data are provided to support the results of this work in improving winding tension regulation during the roll change operation. The new model together with the analysis and recommendations provides a good framework for the development of model-based tension control schemes that can further improve winding tension regulation performance, and thereby improves wound roll quality.

1. Introduction

In roll-to-roll (R2R) manufacturing, flexible materials (called webs) are transported over rollers through processing machinery where operations such as printing, coating, lamination, etc., are performed. A wide variety of products, such as paper, plastics, polymers, textiles, etc., are manufactured in R2R form via high speed automation because of minimal stoppage time of the machine due to continuous processing.

Winding is a critical operation in R2R manufacturing and affects the overall productivity and quality of the finished products (Roisum, 1990). Productivity is the ability of the winder (machine and operators) to keep up with the upstream processes to minimize line stoppage and maximize continuous operation. Productivity can be increased by increasing winder speeds, reducing roll change time, and improving the reliability of the roll change process. The quality of the wound roll directly affects the yield of the overall web line since defective rolls must be scrapped.

Much of the winding research has primarily considered the issue of wound roll quality and factors influencing it, by studying the stresses developed within the wound roll, with the aid of winding models (see Good & Wu, 1993; Good & Roisum, 2007; Hakiel, 1987; Kandadai, 2006; Roisum, 1990 and references therein) that consider steady-state winding operation. The quality of the wound roll is predicted based on (a) the type of winding method used, such as center winding, surface winding, turret winding, two drum winding or duplex winding, (b) the input parameters, such as winder torque, nip pressure on the winding roll, tension upstream of the winder, and web transport speed, and (c) web material properties (Good & Roisum, 2007; Kandadai, 2006; Roisum, 1990). These models, which are generally algebraic or empirical, are typically used to determine the required steady-state set-point profiles (based on roll diameter) for winder torque, rewind tension, winder speed, and nip pressure that would result in producing a quality wound roll.

It is often challenging to maintain the required set-points in dynamic conditions because of machine and process induced disturbances while transporting the webs. A primary reason for this is the roll change operation when a fully wound material roll is replaced with an empty core. When the winding operation is halted during roll change, the web continues to be transported through the process at constant speed and gets accumulated in a mechanical device with multiple spans called an accumulator (festoon) which contains a moving carriage with rollers (Kuhm, Knittel, & Bueno, 2012; Pagilla, Garimella, Dreinhoefer, & King, 2001). After the roll change operation is complete, the rewind is accelerated to empty the material stored in the accumulator to enable web accumulation for the next roll change operation. The time taken for the roll change operation determines the capacity of the accumulator and affects the magnitude of speed change experienced by the rewind. The use of a rotating turret winder,

* Corresponding author.
E-mail address: pagilla@okstate.edu (P.R. Pagilla).

http://dx.doi.org/10.1016/j.conengprac.2015.04.009
0967-0661/

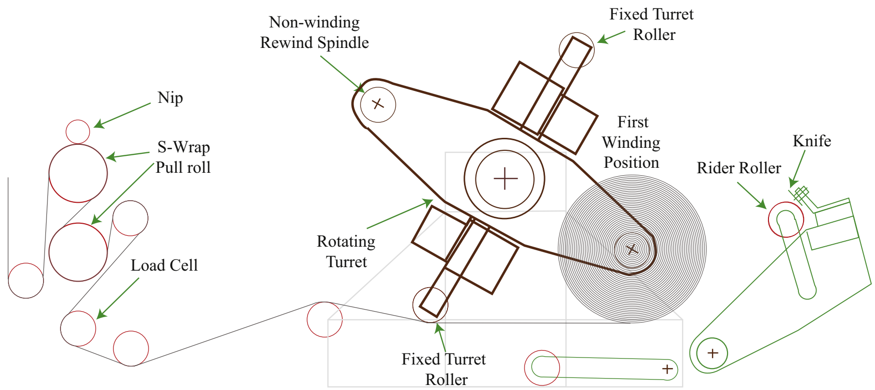

Fig. 1. Rotating turret winder – winding roll at the first position.

which consists of two driven spindles on a rotating turret, considerably reduces the time required for a roll change operation.

There has been some existing work on controlling winding tension for a single center winder (Canuto & Musso, 2007; Lee & Shin, 2010), but there has been no published work related to modeling and control of winding tension in a turret winder, and the work in this paper is intended to fill the gap. First, we provide an analysis of a typical real-world problem encountered in an industrial R2R printing press with a rotating turret winder. A downstream coating and finishing web line that uses the finished wound roll from the printing press was experiencing issues due to unwind roll core separation which affected the productivity of the downstream process; these issues were attributed to the quality of wound roll created with the rotating turret winder in the previous R2R printing line. We utilize data collected during roll-change operations to analyze and provide causes for the winding issues; significant tension disturbances are observed during the roll change operation due to the turret rotation and winding roll speed changes which cause wound roll quality issues. A typical speed-based industrial tension control strategy used to simultaneously control web speed and tension is also discussed. Second, we develop a dynamic model for the rotating turret winder which accounts for the rotation of the turret and contact of the non-winding spindle with the web. Third, we provide a comparison of data from model simulations and production runs to validate the model and to highlight the tension control issues. Fourth, we provide data supporting improvement to tension control in the production machine as a result of this work. We also provide extensive remarks and recommendations on improving tension regulation in the winder.

The rest of the paper is organized as follows. An introduction to the basic operations of a rotating turret winder is given in Section 2. To understand the sources of winding issues, events that occur during the winding operation are sequenced and correlated with production run data in Section 3. The analysis of the production run data clearly highlights the poor tension regulation achieved during the roll change process. For the benefit of industrial practitioners, a typical control strategy employed in a rotating turret winder and the main drawbacks with the strategy are presented and discussed in Section 4. The problems with the existing control strategy are further highlighted with the aid of a new dynamic model for the rewind section developed in Section 5. Using the parameters from the actual operating conditions and data collected from production runs, model simulations of the rewind section using the developed model are conducted and data from these simulations are compared with actual measured data in Section 6. This comparison provides insights into the dynamics involved during the winding operation and the deficiencies of the existing control strategy. Some remarks and recommendations for machine and control design to improve winding performance are discussed in Section 7. Conclusions are provided in Section 8.

2. Rotating turret winder operation

The rotating turret winder consists of two rewind spindles on a turret as shown in Fig. 1. Winding of a new roll starts at this position and continues until the turret is rotated to the second rewinding position (see Fig. 2) where the rest of the roll is wound. When the roll is full in the second rewinding position, the web path is changed to start the winding of the new roll on the empty non-winding rewind spindle which now becomes the new rewind roll. While the new roll is wound on the core of the second rewind spindle, the fully wound roll from the first rewind spindle is replaced with an empty core in preparation for the next roll change. The web path from one rewind spindle to the other spindle is changed either by stopping both the rewind spindles or by using a flying splice. When both the rewind spindles are stopped, the rewind accumulator (which is not shown in the figures and is in the section upstream of the S-wrap pull rollers) accumulates web material from the process section which facilitates continuous process operation. Once a new rewind spindle starts winding the web, the accumulator is emptied to prepare for the next cycle of accumulation. Details on accumulators and their operation including their dynamics and control strategy may be found in Shelton (1999), Pagilla et al. (2001), Kuhm et al. (2012), and Pagilla, Singh, and Dwivedula (2004).

Two driven rollers (called as S-wrap rollers) that are used to regulate tension and transport velocity of the web entering the rewind section precede the rewind section. Web tension in the rewind section is regulated by controlling the speed of the rewind roll based on web tension measured by load cells mounted on an idle roller (more details on the control strategy is discussed in Section 4). Prior to the replacement of the wound roll in the second rewinding position, two rider rollers are pressed against the non-winding rewind spindle to provide enough friction to hold the web while an automatic knife mechanism cuts the web. The rider rollers also stay on for a brief duration of time after the splice to provide enough wrap and friction to maintain proper wound-on-tension as the web is wound onto the new roll. At the instant when the wound roll rotation is stopped, the S-wrap pull rollers are stopped and the rewind accumulator begins to accumulate the web from the process section.

3. Analysis of production data

During production runs, key process variables such as web tension, velocity and motor torques were measured. This data were analyzed by correlating various dynamic events and their effect on these process variables to understand the dynamics involved during the rewind roll change operation and turret rotation. Fig. 3 provides the evolution and correlation of rewind