Journal of Manufacturing Processes
Vol. 2/No. 2
2000

Process Planning for On-Line Consolidation in Tape Winding of Noncircular Thermoplastic Composites

M. Atif Yardimci, Advanced Engineering Design Center, CRTS, Baxter International, Round Lake, Illinois, USA.
E-mail: atif_yardimci@baxter.com
Christoph M. Pistor, Center for Advanced Rapid Tooling, Ecole Polytechnique Fédéral de Lausanne, Lausanne, Switzerland. *E-mail*: Christoph.Pistor@epfl.ch
Selçuk I. Güçeri, College of Engineering, Drexel University, Philadelphia, PA, USA.
E-mail: Selcuk.Guceri@drexel.edu

Abstract

On-line consolidation of thermoplastic composites proved feasible to fabricate high-quality precision parts using pre-impregnated tapes as the building material and lasers as the heat source (laser-assisted tape winding [LATW]). The narrow LATW operation windows for thermoplastic matrix materials of engineering interest necessitate careful process planning. Noncircular cross-section parts pose additional challenges. In this work, a general planning methodology was developed and implemented into process planning software to produce structurally sound thermoplastic composite parts with LATW. The methodology includes geometry definition, mandrel trajectory, winding speed prediction, and calculation of required laser power. Thin and thick-walled test cases were studied. Parametric studies assessed the variation of required laser power distribution vs. process parameters (mandrel rotation speed, winding speed, and part geometry). The software also assessed manufacturability with the positive, definite winding speed constraint. It was determined that the winding speed may become negative when producing high-aspect ratio (>2.0) elliptical rings on the current prototype configuration, resulting in unwinding and/or tape buckling.

Keywords: *On-Line Consolidation, Composites, Thermoplastic, Tape Winding, Planning*

Nomenclature

a	Coefficients of cubic spline for x-coordinate
b	Coefficients of cubic spline for y-coordinate
h	Cubic spline to time mapping description of motion
LP	Laser power
M	Number of curve segments
N	Number of points for segment
n	Number of points on the curve
P	Coordinate variable
P'	Derivatives of coordinate variables with respect to parameter
p	Coordinates of mandrel centerpoint in mandrel reference frame
q	Coordinates of mandrel centerpoint in nip-point reference frame
s	Cubic spline parameter
t	Time
x, y	Cartesian coordinates
V	Mandrel velocity induced by linear stage
W	Winding speed

Superscripts

-1	Inverse mapping
j	Segment index

Subscripts

0,1,2,3	Coefficient indices for cubic splines
i	Index for points inside curve segments
k	Value at the beginning of curve segment
$k+1$	Value at the end of curve segment
o	Instantaneous
t	Tangential component
x, y	Components/Coordinates in respective Cartesian directions

Special Characters

l_c	Chord length for each segment
$\vec{k}$	Unit vector in z-direction
$\vec{n}$	Unit normal vector of mandrel in x-y plane
$\vec{r}$	Position from centerpoint to points on the curve
$\vec{t}$	Unit tangent vector of mandrel in x-y plane
Ω	Angular mandrel speed
Γ	Perimeter of exterior layer
ς	Integration variable
τ	Unnormalized curve tangent vector

Introduction

Laser-assisted tape winding of thermoplastic composite parts[1] and ceramic green bodies[2] involves the continuous consolidation of a pre-impregnated tape using a focused heat source, as shown in *Figure 1*. The process produces cylindrical parts when the tape is wound onto a mandrel and continuously fused to the layer that has been laid down previously. The laser beam is focused to consolidation or nip point, where tape is wound onto the substrate. Mandrel geometry defines the shape of the inner perimeter of the component, whereas the outer perimeter is defined by both the number of layers wound and the inner perimeter. The winding operation is a special case of the lamination process. Characteristics of lamination onto a curved surface and its properties are discussed in detail in the part configuration section. Though the winding of 3D structures, such as helices and springs, has been demonstrated before, the current study will focus on the winding of cylindrical objects, for example, rings with general cross sections.

On-line (in-situ) consolidation of thermoplastic materials offers several advantages over traditional winding of thermoset matrix composites. In a filament winding process, the winding tension is cumulative, which can lead to fiber microbuckling in lower layers. Furthermore, fiber movement due to stress relaxation during the cure of thermoset matrix is also probable. In a LATW process, melting/consolidation/solidification is confined to a small region around the contact point, therefore, winding takes place over an already solidified substrate. This locks in the microstructure and eliminates microbuckling because fibers are no longer subjected to the effects of cumulative winding stresses. The absence of cumulative stresses in fibers and presence of rapid cooling rates enable fabrication of composite parts with diminishing residual stresses and, hence, lead to better part integrity and dimensional stability. On-line consolidation in filament winding was later adapted for thermosetting composites using infrared and electron beam energy as the heat source to capture some of the advantages of the LATW process.[3,4]

In an on-line LATW process, the part quality depends primarily on the proper adjustment of the winding speed and laser power. Quasi steady-state thermal models, coupled with nonisothermal bonding and crystallinity evolution models, have been employed to develop processing windows and laser power bounds for acceptable part quality.[1,5,7] Process and material behavior models have been calibrated and validated experimentally.[1,6-11] Experimental studies have also been performed to determine the influence of geometric parameters, such as angular and transverse offset of the laser beam on the mechanical properties,[12] thermal properties, and crystallinity [13] of the processed parts.

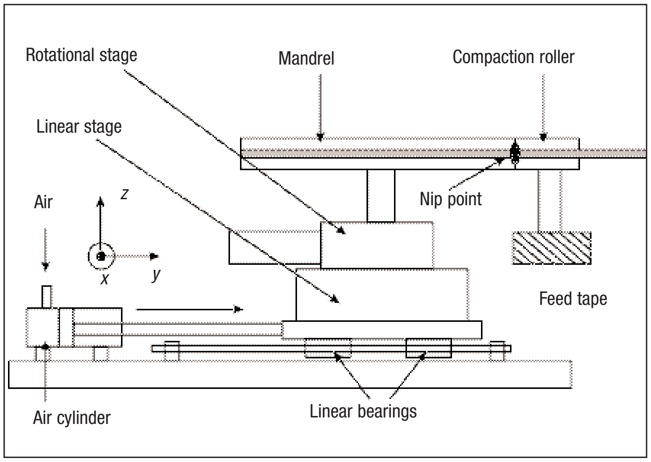

Figure 1
Laser-Assisted Tape Winding Setup

The current LATW prototype machine includes three major components: a 80W $C0_2$ laser, a two-axis (one rotation, one translation) motion-control stage with controller, and a computer with an integrated data acquisition board. The motion control commands for rotational and translational stages are downloaded from the computer to the controller run-time memory and executed sequentially. The controller/computer interface was constructed in the LabVIEW software environment with special toolboxes and serial communications functions. The existing software environment has also been extended to include an on-the-fly laser power control utility for parts, which require varying laser power distribution during fabrication as for noncircular components.[14]

One of the most important design features of the current LATW configuration is the stationary point of consolidation. In contrast to common filament and tape-winding machines where the tape-laying head and, hence, the nip point moves during the winding operation, in the current configuration the mandrel rotates while maintaining a fixed location for laser impact. The mandrel slides on a set of linear bearings and is constrained by an air cylinder that applies the compaction pressure while the thickness grows layer by layer. For winding noncircular cylindrical objects, it then becomes necessary to control the planar move-