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Original Article

Control and Monitoring of the RTM Composite Manufacturing Process Using a Software Sensor

Amal El Amaoui[1], Mohamed Hattabi[1,2]

[1]*ECPI, Laboratory of High Energy Physics and Condensed Matter, Faculty of Science, Hassan II University, Casablanca, Morocco.*
[2]*Department of Mechanical Engineering, ENSEM, Hassan II University, Casablanca, Morocco.*

[1]*Corresponding Author : amal.elamaoui-etu@etu.univh2c.ma*

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Abstract *- Lightweight materials are widely used in aerospace, automotive and other industries. Because of the high specific stiffness and strength drives the attention to composite materials and manufacturing processes. Among the Resin Transfer Molding process is a range from the Liquid Composite Molding family, which has the capability of manufacturing polymer composites with maximum mechanical performance. Defects in parts produced by the resin transfer molding (RTM) process are often attributable to the formation of voids which degenerate the mechanical properties of the manufacturing part. However, it is essential to observe the mold-filling stage of the process from process inputs to achieve the quality of parts. This paper proposes a Software Sensor observer to determine the observability and estimate the RTM process state variables. The system observability is analyzed, and then a high gain observer is designed using a Lyapunov theory. Finally, the proposed observation scheme is verified through a simulation case.*

Keywords *- Composites materials, Manufacturing process, Resin transfer molding, Observability analysis, Observer design.*

1. Introduction

Lightweight components in industrial applications are mostly made of polymer matrix composites. Composites, the wonder material with a high strength-to-weight ratio, stiffness, and lightweight, have made significant progress in displacing traditional materials [1].

There are several processes developed for the mass production of these materials. Among the manufacturing techniques, Resin Transfer Molding (RTM) is widely used to achieve good impregnation of complex shaped parts [2]. Various materials and process parameters influence the quality of the final product in the RTM process. Permeability of the fiber reinforcement is an important parameter that measures the flow resistance offered by the fiber reinforcement by determining the resin flow in the porous preform[3]. Therefore, the measurement of the permeability of the fiber preform is essential for the simulation and optimization of the RTM process [4], which can help the designer to optimize the injection process to achieve a robust production process in the shortest time. The problem with the RTM process is the presence of voids in the finished part [5], which affects the mechanical performance of the fabricated structure [6-8], such as compressive strength, impact resistance, and shear strength [9,10]. The formation of voids depends on the capillary and viscous forces [61], resin velocity [11], molding temperature [12], and variation of permeability values [13]. Manufacturing techniques also have a significant influence on the performance of composite materials [14]. Good strategies for efficient RTM manufacturing increase production volume and reduce time and cost [15].

The estimation of permeability has been the subject of several research papers. The permeability was estimated from the relationship between pressure and flow velocity [16]. Based on the optical measurement of real weight fields, the in-plane permeability fields were measured [17]. A prediction method shows that the change in permeability is mainly influenced by the change in the number of layers [18]. A strategy for measuring permeability with gas flow and pressure was proposed by [19].

A mixed numerical/experimental technique to determine full in-plane permeability was used by [20]. Other researchers used ANOVA analysis to study the main parameters affecting the permeability coefficients [21]. Online estimation and monitoring method of local permeability by developing a visualization system to record the positions of the flow front and using a pressure sensor array mounted in the mold to measure the local pressure values in real-time [22].

A comprehensive permeability prediction tool that considers the influence of geometric variations was done by [23]. Permeability prediction as a function of fiber volume fraction and fiber diameter was presented in [24,25].

Individual studies have shown that there is no predominant technique for measuring permeability [26,27].

A study has shown that advanced optical techniques can be helpful in estimating permeability [28], and the local values of the permeability/porosity ratio can be estimated [29]. A theoretical model was developed to calculate the permeability of porous media with two approaches using the Navier-Stokes and Kozeny-Karman equations [30].

The permeability was analyzed by experimental and numerical methods for different textiles, carbon, glass, and natural fibers [31]. Permeability prediction for 1D, 2D, and 3D flow in porous media was performed [32]. Other studies involving theoretical analysis of the permeability of fluids in two orders of magnitude using Darcy's law and Stock's equations for a transverse and longitudinal flow were presented [33,34]. Permeability predictions using an X-ray micro-computed tomography-based voxel model were performed [35-39] and based on virtual models [40,42].

An overview of different methods for measuring permeability was proposed by [43]. There are many other studies dealing with the determination of permeability [44-46].A new analytical model for estimating permeability for hybrid composites were proposed [47].

The principle of controllability and observability to control and estimate permeability in the RTM process was adopted in [48,49].

With the development of computing hardware and software, especially in the fields of image processing technologies, computer vision techniques for automatic tracking of tool conditions started to be largely adopted in manufacturing [50]. Control and monitoring are becoming more and more important in today's manufacturing sector.

Observers are software sensors that are central modules in online monitoring systems and make an important contribution to process safety, control, and fault detection. The design of observers essentially depends on the inherent system properties, especially observability.

The first question to be addressed in any estimation problem is the observability property of the system. In control theory, a system is defined as observable if it is possible to reconstruct its initial state by knowing the control inputs and the outputs [51], and the state estimation can be used for control, diagnostic, or monitoring purposes.

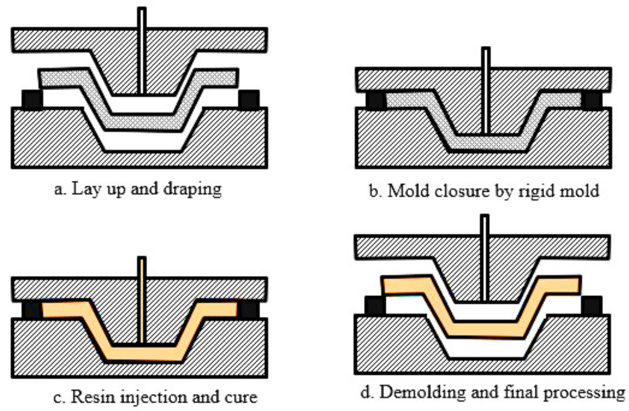

Fig. 1 RTM Process

In this paper, we deal with the design of an observer. After testing the system's observability, a high-gain observer is designed to estimate the permeability. The stability analysis is verified theoretically, and the convergence is proved using the Lyapunov approach. Simulations illustrate the permeability estimation.

2. The RTM Process and Modeling

2.1.The RTM Process

The RTM process uses rigid molds packed with dry fiber preforms. These preforms are impregnated progressively by the resin injected through the injection ports of the mold. After the mold is filled, the resin solidifies in the curing phase, and the product is taken out of the mold [52]. Fig 1 shows the RTM process.

This process has several advantages as the use of rigid molds gives good production in comparison with other liquid composite molding (LCM) processes, closed mold molding significantly reduces gas emissions of volatile organic compounds (VOC) [53], and parts manufacture using RTM has a good surface finish on both sides with high dimensional tolerances [54,55]. The cost of labor is reduced [56].

2.2. RTM Modeling

The resin flow in the RTM process is described by Darcy's law [57]:

$$u = \frac{-K}{\mu} \nabla P = \frac{Q}{A} \quad (1)$$

Where u, K, μ, P, Q, and A are Darcy velocity, permeability, viscosity, pressure, flow rate and area, respectively.

It should be noted that there is a difference between Darcy velocity u and seepage velocity v; the relationship between these two velocities is:

$$v = \frac{u}{\varphi} = \frac{\partial x}{\partial t} \quad (2)$$

The resin flow is described with the following one-dimensional equation:

$$v = \frac{-K}{\mu\varphi}\frac{\partial P}{\partial x} \quad (3)$$

From(3) we have:

$$\frac{\partial P}{\partial t} = -\frac{\mu\varphi v^2}{K} \quad (4)$$

3. Observability Analysis

The following notations are introduced:

$$\begin{cases} x_1 = P \\ x_2 = K \end{cases} \quad (5)$$

Thus we have

$$\begin{cases} \dot{x}_1 = \frac{-\mu\varphi v^2}{x_2} \\ \dot{x}_2 = \frac{\partial K}{\partial t} = \delta(t) \end{cases} \quad (6)$$

System (4) can then be re-written under the following condensed form:

$$\begin{cases} \dot{x} = g(x) + B\delta(t) \\ y = Cx = x_1 \end{cases} \quad (7)$$

Where:

$$g(x) = \begin{pmatrix} \frac{-\mu\varphi v^2}{x_2} \\ 0 \end{pmatrix}$$

And

$$B = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

This is no canonical observability form. Exists a Lipschitzian diffeomorphism: $\varphi: R^n \longrightarrow R^n$, that puts system (7) under an observable canonical form z as follows:

$$\begin{cases} \dot{z} = Az + B\delta(t) \\ y = Cz \end{cases} \quad (8)$$

We will introduce a classical state transformation that puts system (6) under a known observable canonical form. This analysis will emphasize the Jacobian matrix and consider this change of coordinates. $x \longrightarrow z = \Phi(t)$

$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \Phi_1(t) \\ \Phi_2(t) \end{pmatrix} \quad (9)$$

One can represent that the above state transformation puts system (6) under the following canonical form [58]:

$$\begin{pmatrix} \dot{z}_1 \\ \dot{z}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{\mu\varphi v^2}{x_2} \end{pmatrix}\delta(t) \quad (10)$$

Where:

$$\begin{cases} z_1 = \Phi(x) = x_1 \\ z_2 = \Phi(x) = \dot{x}_1 \end{cases}$$

and:

$$\begin{cases} \dot{z}_1 = \frac{-\mu\varphi v^2}{x_2} = z_2 = \dot{x}_1 \\ \dot{z}_2 = \frac{-\mu\varphi v^2}{{x_2}^2}\delta(t) \end{cases} \quad (11)$$

One can conclude that the system (6) is observable for whatever input x. System (1) shall be observable as the transformation Φ(x) exists and is regular almost everywhere [59].

If an observer is synthesized for the system, at that point, its execution in the first coordinates requires processing the inverse of the Jacobian transformation as follows:

$$\wedge = \begin{bmatrix} 1 & 0 \\ 0 & \frac{\mu\varphi v^2}{\dot{x}_2} \end{bmatrix} \quad (12)$$

Or, we know that:

$$det\wedge = \frac{\mu\varphi v^2}{x_2^2} \quad (13)$$

So this determinant is non-zero because μ and φ are constants, also v # 0 and x 1 # 0

4. High Gain Observer Design

This section aims to design a high-gain observer for the system represented by (4). The observer inputs are the inputs of the RTM molding process, and the outputs are the estimated states.

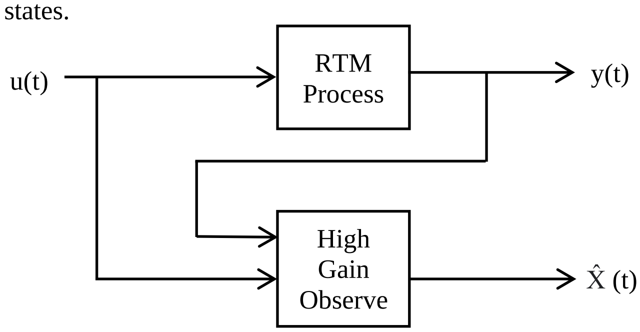

Fig. 2 Observation Scheme

4.1. High Gain Observer Structure

For convenience, the system model (6) is given the following more compact form:

$$\begin{cases} \dot{z} = Az + B\delta(t) \\ y = Cz = z_1 \end{cases} \quad (14)$$

Where :

- $z = \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} \in R^n$
- $\delta(t)$ an unkown bounded function

The matrix A, B and C are defined as follows

$$\begin{cases} A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \end{cases}$$

$$B = \begin{bmatrix} 0 \\ \frac{\mu\varphi v^2}{K_2} \end{bmatrix}$$
$$C = [1 \quad 0]$$

The observer could be:

$$\dot{\hat{z}} = A\hat{z} - \theta\Delta_\theta^{-1}S^{-1}C^TC(\hat{z} - z) \qquad (15)$$

Where:

- Δ_θ is the diagonal matrix in which $\Delta_\theta = diag(I, \frac{1}{\theta}I)$
- $\theta\rangle 0$ is a design parameter.

So, we have:

$$\begin{cases} \Delta_\theta = \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{\theta} \end{bmatrix} \\ S = \begin{bmatrix} 1 & -1 \\ -1 & 2 \end{bmatrix} \end{cases} \qquad (16)$$

4.2. Stability Analysis

The dynamics of the states include an uncontrolled linear part and a controlled nonlinear part, generally verifying the Lipschitz condition with respect to z:

$$\left\|\dot{\hat{z}} - \dot{z}\right\| \leq \beta \left\|\hat{z} - z\right\| \qquad (17)$$

We consider the dynamic system defined by (10); the system (12) is an asymptotically stable observer if$\theta\rangle\theta_0$

Consider the estimation error:

$$\varepsilon = \hat{z} - z$$

In view of (10) and (11), the estimation error dynamic is given by:

$$\dot{\varepsilon} = \dot{\hat{z}} - \dot{z} \qquad (18)$$

$$\dot{\varepsilon} = (A - \theta\Delta^{-1}{}_\theta KC)(\hat{z} - z) - \beta\delta(t)$$

Where $C\Delta^{-1}{}_\theta = C$ and there exists a gain $K \in R^+$, such as $K = S^{-1}C^T$ Introducing the following variable change:

$$\bar{\varepsilon} = \Delta_\theta\varepsilon$$

and $$\dot{\varepsilon} = \Delta_\theta{}^{-1}\dot{\bar{\varepsilon}}$$

Where we have used the fact that:

$$\Delta_\theta A\Delta_\theta{}^{-1} = A\theta$$

and $$C\Delta_\theta{}^{-1} = C$$

Considering this change of variables, we have:

$$\dot{\bar{\varepsilon}} = \theta(A - KC)\bar{\varepsilon} - B\delta(t) \qquad (19)$$

There exists a positive definite matrix $P \in R^+$, and the Hurwitz matrix is defined as (A-KC); the choice of the Hurwitz matrix is always possible since the pair (A, C) is observable, such that,

$$P(A - KC) + (A - KC)^TP \leq -2I \qquad (20)$$

We demonstrate the asymptotic stability of ε, so that we consider the Lyapunov function candidate:

$$V = \bar{\varepsilon}^TP\bar{\varepsilon}$$

Taking the derivative of V:

$$\dot{V} = 2\bar{\varepsilon}^TP\dot{\bar{\varepsilon}} \qquad (21)$$

Applying (18) on (15) gives:

$$\dot{V} = 2\theta\bar{\varepsilon}^TP(A - KC)\bar{\varepsilon} - 2\bar{\varepsilon}^TPB\delta(t) \qquad (22)$$

According to (16), we have:

$$\dot{V} = \theta\varepsilon^T((A - KC) + (A - KC)^TP\bar{\varepsilon} - 2\bar{\varepsilon}^TPB\delta(t)$$

Bounding the right-side terms in (20) with norms, we get:

$$\left\|\dot{V}\right\| \leq -2\theta \quad \|\bar{\varepsilon}^T\|\|I\|\|\bar{\varepsilon}\| - 2\|\bar{\varepsilon}^T\|\|P\|\|B\delta(t)\| \qquad (23)$$

On the other hand, we have:

$$\left\|\dot{V}\right\| \leq -2\theta \quad \|\varepsilon \quad\|^2 - 2\lambda\|\varepsilon \quad\|\|B\delta(t)\|_{max} \qquad (24)$$

$\lambda_{\max}$ is the largest eigenvalue of the matrix P, where:

$$\left\|P\right\| \leq \lambda_{max}$$

and $$\left\|B\delta(t)\right\| \leq \beta$$

The following inequality holds because P is a positive definite matrix:

$$\lambda_{\min}\|\varepsilon\|^2 \leq \left\|V\right\| \leq \lambda_{\max}\|\varepsilon \quad\|^2 \qquad (25)$$

We have:

$$\|\varepsilon\|^2 = \frac{\|V\|}{\lambda_{min}} \qquad (26)$$

Then:

$$\left\|\dot{V}\right\| \leq -2\theta\frac{\|V\|}{\lambda_{\min}} - 2\beta\lambda_{\max}\frac{\sqrt{V}}{\sqrt{\lambda_{\min}}} \qquad (27)$$

For θ ≥θ_0 inequality (21) can be written under the following form:

$$\dot{V} = -\alpha_1V + \alpha_2\sqrt{V} \qquad (28)$$

with,

$$\alpha_1 = \frac{2\theta}{\lambda_{min\,i}}\rangle 0$$

and,

$$\alpha_2 = 2\beta\frac{\lambda_{max}}{\sqrt{\lambda_{min\,i}}}$$

This condition ensures asymptotic convergence of the observation error.

4.3. Observer Equation in the Original Coordinate

By multiplying (8) with the Jacobian ∧, one can find the observer in x-coordinates:

$$\dot{\hat{x}} = g(\hat{x}) - \theta \Delta_\theta^{-1} \wedge^{-1} S^{-1} C^T C(\hat{x} - x) \quad (29)$$

Following structural representation of our high gain observer:

$$\begin{cases} \dot{\hat{x}}_1 = -\frac{\mu\varphi v^2}{\hat{x}_2} - 2\theta(\hat{x}_1 - x) \\ \dot{\hat{x}}_2 = -\theta^2 \frac{x^2}{\mu\varphi v^2}(\hat{x}_1 - x) \end{cases} \quad (30)$$

5. Numerical Observer Validation

The observer scheme is tested in numerical simulations to verify the theoretically assessed functioning. For this purpose, an experiment application was made for unidirectional injection to fabricate a rectangular laminate by RTM process [60], with length L=1 m, width W = 0:2 m, and thickness H=3 mm. The process parameter values are given in Table 1.

Table 1. System characteristics

Characteristics	Symbol	Value	Unit
Viscosity	μ	0.1	$Pa.s$
Porosity	φ	0.1	
Flow rate	Q_{inlet}	2	cm^3/s
Inlet pressure	P_{inlet}	2	bar
Permeability	K	250	darcy
Tracking gain	θ	10	

According to the observability analysis presented in the preceding section, the states are observable.

The observability results are meant to provide guidance on the RTM state variables, and a main application would be to design an observer to estimate and forecast unmeasured variables.

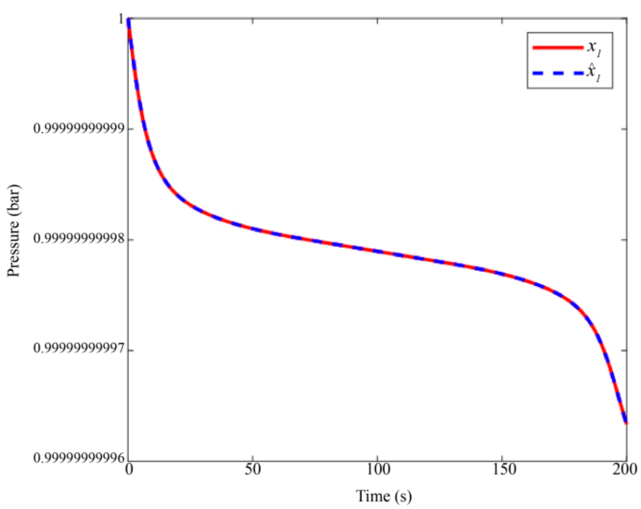

Fig. 3 x_1 with its estimated

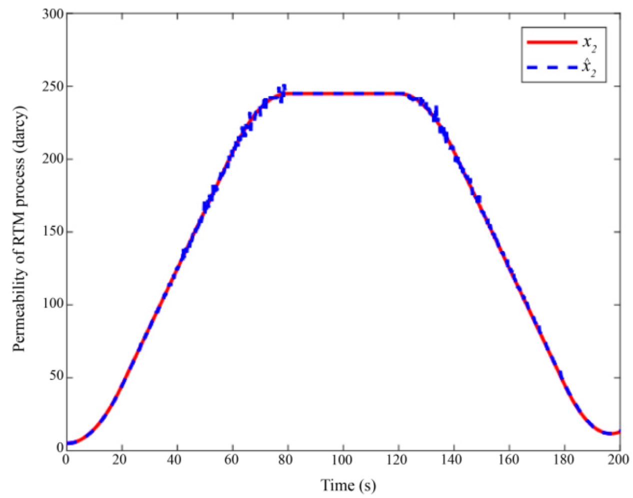

Fig. 4 x_2 with its estimated

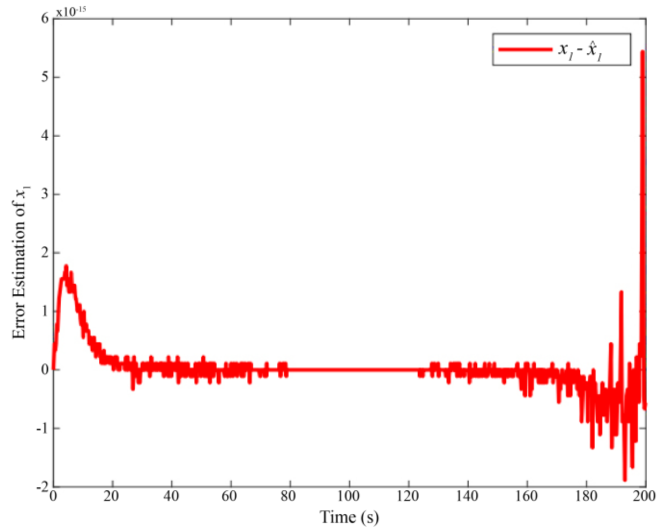

Fig. 5 Error simulation for x_1

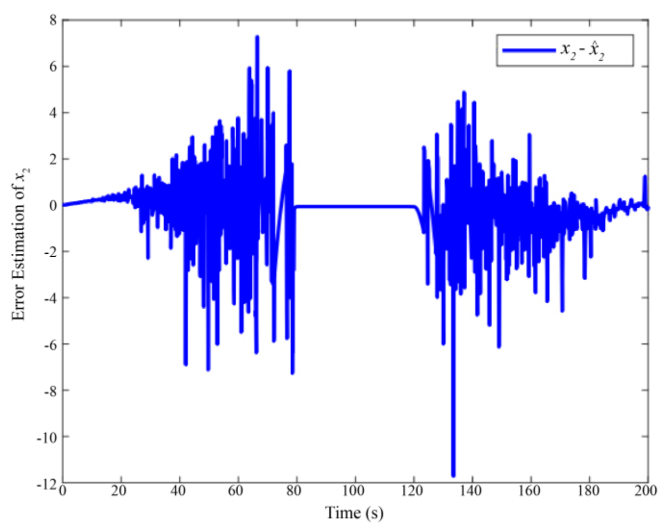

Fig. 6 Error simulation for x_2

The observation approach associated with an observer design is simulated under the software Matlab / Simulink environment to validate the proposed approach. The obtained results clearly demonstrated the estimation of pressure values without the need to use sensors and the estimation of permeability that is inaccessible to measurement.

6. Discussion

The performance of the high-gain observer will be devoted in this section. The studied system and the proposed control strategy are implemented using MATLAB/ SIMULINK environment. The output parameters of the RTM process are illustrated in Table 1. Simulation results show that the estimation states converge to their corresponding state variables.

Fig. 3 shows a simulation result of $x_{1,}$ which represents pressure. It can be seen that the observed pressure matches the measured values (the estimated value (blue line) converges to the real value (red line)). This approach shows the estimation of pressure values without the need to use sensors. So, due to cost considerations, it allows overcoming the need to use mechanical sensors. Fig.4 represents the permeability variation (unmeasured state), which is inaccessible to physical measurements. The estimated value (blue line) converges with the real value (red line).

Fig. 5 & Fig. 6 show that the observation error vanishes asymptotically to zero, confirming that the observation method has given satisfactory performance, improving the RTM reliability.

7. Conclusion

We have considered the problem of controlling parameters for the Resin transfer molding process. The problem has been addressed using a high-gain observer. This latter has been analyzed using the Lyapunov stability approach. To illustrate the observation quality of the proposed high-gain observer, theoretical results have been confirmed by numerical simulations. The estimated variables immediately converged to their true values with almost negligible error. The proposed sensorless control scheme emphasized extra robustness. Application of the observer design to RTM process monitoring has the potential to reduce the production of scrap parts which do not meet the required specifications.

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