Ring shaped laser for tape winding of an endless tube

Citation for published version (APA):

Document status and date:
Published: 01/01/2012

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.
• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 19. Oct. 2020
Ring Shaped Laser for Tape Winding of an Endless Tube
# RING SHAPED LASER FOR TAPE WINDING OF AN ENDLESS TUBE

AFPT BV - GmbH, 2012

by

Lucky Leonardus

23 Aug 2012

Confidential

One year project presented to Eindhoven University of Technology towards the degree of Professional Doctorate in Engineering in Design and Technology of Instrumentation


(Eindverslagen Stan Ackermans Instituut ; 2012/078)
Project Summary

AFPT is a start-up company that provides laser-assisted technology for the production of a pressurized component such as tube, pressure vessel, etc made from or strengthened by fiber reinforced plastic (FRP) tape. The tape is laid precisely by a machine head (connected to a robot), melted with a laser, and consolidated on to the surface with a pressure roller. This process is known commercially as tape winding/laying process.

The aim of this project is to wind a very long tube (endless tube) with the FRP tape. The problems are the current system has limitation in the movement (±4m length tube) and tape winding speed (±0.2-0.4 m/s). Thus, a new machine is required for this application. The new machine is consists of several tapes that are slided, feded, and consolidated at the nip point of a rotated doughnut roller and the endless tube. Hence the tapes will be wrapped around the tube when the tube is pulled out axially. The concept is designed by external contractor Absolid bvba.

For the heat source, the new machine is required to have a ring-shape laser beam with uniform intensity for uniform melting of all the tapes on the doughnut roller. This ring laser is constructed by passing several standard laser beams (rectangular beam) through special metal mask modeled by Solidworks. The problem is the thermal management due to the heating of the mask. Thermal model with Comsol Multiphysics and experimental test are performed for determining the material and for dimensioning of the mask. Based on the thermal simulation model and experiment, Copper is selected as the metal mask because of its high thermal conductivity (k) and its high melting temperature (Tm) compare to other commercially available material such as Aluminum and Steel.

On this project, first proof-of-principle prototype is also built and tested. Remaining work that still need to be done are conception of consolidation force, integration of the parts into the full machine, installation of the cooling unit (for cooling the aperture) and the control system (for the laser power regulation).
# Table of Contents

Project Summary .............................................................................................................. 3
List of Figures ..................................................................................................................... 5
List of Tables ....................................................................................................................... 6
Acknowledgements ............................................................................................................ 7
Chapter 1 - Introduction .................................................................................................... 8
  1.1 Company Background ............................................................................................... 8
  1.2 Project Background ................................................................................................. 12
  1.3 Design Analysis ....................................................................................................... 13
  1.4 Design Project Status ............................................................................................. 16
Chapter 2 - Geometry Model ............................................................................................ 17
  2.1 First Model – Estimation ......................................................................................... 18
  2.2 Second Model – Masking ....................................................................................... 19
  2.3 The Mask Experimental Test ................................................................................. 20
Chapter 3 - Thermal Management ................................................................................... 22
  3.1 Thermal Experiment ............................................................................................... 22
  3.2 Comsol Multiphysics Model .................................................................................. 25
  3.2.1 Model vs Experiment ....................................................................................... 27
  3.2.2 Final Mask Simulation ..................................................................................... 28
Chapter 4 - Test Prototype Design .................................................................................. 30
  4.1 Front Part – Ring Laser Beam ................................................................................. 30
  4.2 Back Part - Doughnut Roller with Spring Consolidation ....................................... 32
Chapter 5 - Conclusion & Recommendation .................................................................. 34
  5.1 Conclusion .............................................................................................................. 34
  5.2 Recommendation ................................................................................................... 34
References .......................................................................................................................... 36
List of Figures

Figure 1.1 Principle of tape laying/winding [1]................................................................. 8
Figure 1.2 Single tape winding head (STWH) [2]............................................................. 9
Figure 1.3 Schematic production process of the FRP tube............................................. 10
Figure 1.4 Schematic working concept of the machine for winding an endless tube............. 12
Figure 1.5 Metal mask to sort the rectangular laser beams............................................. 13
Figure 1.6 Part functionalities of the tape wrapping machine......................................... 14
Figure 1.7 Machine prototype for the tape winding of an endless tube........................... 16
Figure 2.1 Zemax simulation result from the supplier.................................................... 17
Figure 2.2 Side view of the SW model............................................................................ 18
Figure 2.3 The SW model to estimate the laser(s)............................................................ 19
Figure 2.4 The SW model for masking........................................................................... 20
Figure 2.5 Test Setup based on the SW model............................................................... 21
Figure 2.6 Verification of the SW model.......................................................................... 21
Figure 3.1 Thermal test construction................................................................................ 22
Figure 3.2 Real setup and measurement points............................................................... 23
Figure 3.3 Thermal experimental T(t) test result............................................................. 25
Figure 3.4 Comsol model geometry - 3D transient heat transfer in solid module............... 26
Figure 3.5 T(t) profile for various metal mask with Comsol model.................................. 27
Figure 3.6 The simulation result of Cu mask with Comsol model.................................... 28
Figure 3.7 T(t) comparison between experimental test and Comsol model....................... 28
Figure 3.8 The Comsol simulation for the metal mask.................................................... 29
Figure 4.1 Real setup for the front-part of the machine.................................................. 30
Figure 4.2 Test setup for the back-part of the machine................................................... 32
Figure 4.3 Two tapes side by side consolidated with spring consolidation....................... 33
List of Tables

Table 1.1 Part functionality in the single tape winding head (STWH)............................................. 10
Table 1.2 Components functionality concept, requirement, problem and solution. .................... 14
Table 2.1 Measurement result with ruler (mm accuracy)................................................................. 21
Table 3.1 Test setup overview. ........................................................................................................ 24
Table 4.1 Test parameter for the back-part of the machine. .............................................................. 32
Table 5.1 Recommendation list for the project.............................................................................. 34
Acknowledgements

For this project, I would like to acknowledge all AFPT team member in the project for the kind support and assistance, especially to Mr. Coert Kok, dr. Patrick Koelzer, and Mr. Frank Rittenburch for the opportunity. I am very appreciate for: Solidworks help provided by Mr. Erik Emmen and Mr. Thomas Mayer; technical physics design advise by dr. G.J.H. Brussaard, dr. J.J. Koning, and Prof.dr. E.J.E. Cottaar; and also for experimental test help in AFPT GmbH by all the team member.
Chapter 1 - Introduction

1.1 Company Background

AFPT is a start-up company that provides automated technology for laser-assisted tape placement. This technology enable the production of a component made from or strengthened by the fiber reinforced thermoplastic tape (known as ‘prepreg’). This prepreg tape offers benefit in terms of the light-weight functionality (for large surface area part), and performance (strengthened the part). Some of the components that produced by AFPT are for example: tube & pressure vessel (major products), and other component for automotive and aircraft industries.

The production process of the component is known as tape laying (or tape winding for rounded component such as tube & pressure vessel) and depicted schematically in below Figure 1.1. The homogeneous laser intensity is used as a heat source to melt the matrix of both fresh incoming prepreg and laid prepreg underneath. Then, the melted tape is pressed by the consolidation roller, and finally form a solid composite structure on the mold when the matrixes cool down. The quality of the product is determine by the temperature at nip point - the point where the consolidation roller, the tape and the mold converge. AFPT is able to monitor and to control the process temperature of the nip point real-time.

Figure 1.1 Principle of tape laying/winding [1].
The tape winding is operated by a machine head called as Single Tape Winding Head, (STWH) - because it is only supplying one prepreg tape. This prepreg comes from the spool carrier that is connected to the head. Inside the head, mechanical parts are guiding the prepreg tape into the pressure roller. Besides mechanical functionality, this head also contain electronic box for software and control management. The schematic overview and part of the head is shown in below Figure 1.2.

![Figure 1.2 Single tape winding head (STWH) [2].](image)

The STWH is attached to the robot that functioning as system maneuvre and movement (for winding orientation angle and winding the prepreg tape as far as tube length). The tube production of the FRP tube is depicted in Figure 1.3. The metal clutch is clumping and rotating the tube, while STWH is maneuvering the winding angle and moving axially along the tube length. This figure also gives an insight that since the robot movement is limited, then the tube produced by the STWH is also limited in the length (± 4 m length tube).
Figure 1.3 Schematic production process of the FRP tube.

Technical specifications and functionalities of the production system is explained in Table 1.1. In general, the production system consists of materials (various type of prepreg tape), mechanical parts (roller & tube), optical system (diode laser & homogenizer optics), and control system (IR camera for feedback of laser power regulation).

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Function</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Laser.</td>
<td>Heat source.</td>
<td>- Laser diode 980 nm, $P_{\text{max}}=3$ kW ($P_{\text{at}}$ production $\approx 2$ kW).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- The power module is connected with fiber optic to the optic homogenizer.</td>
</tr>
</tbody>
</table>
laser beam in rectangular shape is the product from this homogenizer optics.
- For production, laser intensity is ≈ 0.5-1 W/mm².

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Impregnated carbon or glass fiber on polymer matrix. The most known parameter process are for matrixes PA-12 &amp; PEEK (T_{production PA-12}≈220°C, T_{production PEEK}≈380°C).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- The tape thickness≈0.125 mm, and the width varies from 12 mm to few cm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- The tape winding speed 0.2-0.4 m/s.</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Pressurized roller correspond up to ≈ 400 N.</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.</td>
<td>Temperature measurement system (IR camera).</td>
<td>Temperature monitoring as a feedback system for laser regulation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Monitoring temperature for laser power, laser angle, and laser height regulation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- The T_{production} is fixed (±30°C variation) and then the laser power regulated within period 0.5 ms.</td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- 1st run the substrate is the flat surface or the tube. It is required T_{substrate/tube} &gt; T_{Roller} so the melted prepreg is not stick to the roller. At the 1st run, the prepreg is merely stretch on the surface (not attached). Sticky tape at the beginning and the end of the prepreg is necessary to stretch the prepreg.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 2nd run the substrate is the previous laid prepreg. It is necessary to melt both incoming prepreg and laid prepreg while consolidated them as fast as possible.</td>
</tr>
</tbody>
</table>
1.2 Project Background

The aim of this project is to wind a very long tube (endless tube). It is expected that the STWH will not be suited for this application due to the limitation in the reach (± 4 m length) and in the speed (tape winding speed of STWH is ≈ 0.2-0.4 m/s). A new machine concept is developed by external contractor Absolid bvba [2].

The machine is designed where multi-prepreg tapes slid through, melted, and then consolidated at the nip point of a rotating doughnut-roller. To melt these tapes, the uniform intensity (hence uniform heating) of laser beam in a ring-shape is required. This because ring shape laser beam able to heat all over the surface of the doughnut-roller regardless at how many and at which orientation those tapes are fed. When the liner (endless tube) is pulled in axial direction and passed through the doughnut roller, those tapes are wrapped around the liner. This schematic working concept of the machine is depicted in Figure 1.4.

![Figure 1.4 Schematic working concept of the machine for winding an endless tube.](image)
The problem is that the ring-shape laser beam with uniform intensity is not available at this moment. Hence AFPT try to develop its own way to produce the ring-shape laser beam. This is depicted in Figure 1.5 where multiple standard homogenizer optic (rectangular laser beams) are arranged in a ring holder and those laser beams are sorted with a special shape of metal mask. The purpose of the metal mask is to prevent an overlap between the laser beams. However since this metal absorb some portion of the laser beams, it gets heated. The shape (for preventing beams overlap), material selection, and dimensioning are the requirement for the metal mask design.

![Figure 1.5 Metal mask to sort the rectangular laser beams.](image)

**1.3 Design Analysis**

It is easier to analyze the tape wrapping machine by disassembling it into components based on the functionality. Refers to below Fig 1.6, the main components of this machine can be divided into five: laser beam (optics), liner, metal mask, guider doughnut, and consolidation doughnut. Notice that the doughnut roller (Fig 1.4 and Fig 1.5) is divided into the guider doughnut and the consolidation doughnut only because of its functionality and not necessarily true in the real machine. The metal mask is located between the optics and the guider doughnut. Defining the shape of the metal mask is one of the main tasks in this project, and will be discussed in the next Chapter 2.
Figure 1.6 Part functionalities of the tape wrapping machine.

The component’s function, requirement, problem, and design solution of the tape wrapping machine are described in below Table 1.2. This table is useful as an insight for the overall design requirement of the machine.

<table>
<thead>
<tr>
<th>No.</th>
<th>Component</th>
<th>Function</th>
<th>Requirement</th>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
</table>
| 1.  | Laser beams       | Projected as a ring in the guider doughnut. | -No beams overlap on the guider roller.  
- Laser intensity up to 1 W/mm² (~1.5-2 kW per AFPT’s optic).  
-Melted both consolidated tape and fresh tape. | -After beam homogenization at the optic, the beam dimension is rectangular [3]. | -Metal mask to sort out the beams.     |
|     | (optics)          |                                 |                                                                                                       |                                                                        |                                        |
| 2.  | Liner             | Shape forming the tube.         | -Able to stretch the tape for consolidation (keep the precision of tape)                              | -Thermal: it is a must that $T_{\text{liner}} > T_{\text{roller}}$ (to prevent the tape sticking to the | -Preheating.                           |


<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Melts and coincides both consolidated tape &amp; fresh tape at the nip point</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>placement)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>roller)</td>
</tr>
<tr>
<td>3.</td>
<td>Metal mask</td>
<td>Ring forming the beam.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-No beams overlap on the roller.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Withstand the heat.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Heating problem.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Material selection &amp; dimensioning.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Cooling system.</td>
</tr>
<tr>
<td>4.</td>
<td>Guider doughnut roller</td>
<td>Guiding the tapes without crossing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Low surface roughness.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Withstand the heat from lasers.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Friction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Thermal: it is a must that $T_{\text{roller}} &lt; T_{\text{tape matrix}}$ melting, so the tape will not stick to the roller.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Chrome layering (if necessary) commercially provides surface roughness $\pm 2\mu m$, $T_{\text{operating max}} \pm 200^\circ C$</td>
</tr>
<tr>
<td>5.</td>
<td>Consolidation doughnut roller</td>
<td>Consolidate the prepreg tapes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-As fast and as close as possible to the nip point (before the tape gets cold).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Uniform circular pressure.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Friction: able to passed the tapes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Thermal: the $T_{\text{consolidation doughnut}} &lt; T_{\text{tape matrix}}$ melting to prevent sticking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Doughnut bellows with hydrostatic pressure.</td>
</tr>
</tbody>
</table>
1.4 Design Project Status

The project is started at Aug 2011 and aimed to build the machine prototype. At this moment (Aug 2012), the prototype is not finished yet. Some remaining problems are remains, such as:

1. The ring-shape laser beam can be obtained from the special mask built by the Solidworks model (discussed in Chapter 2) as shown in below Figure 1.7. The doughnut roller is unseen (located behind the metal mask). In this prototype, six customized homogenizer optics (with internal specification code 27x60, wd=165 mm) are required for a specific dimension of the roller and the liner (60 mm diameter tube). However, the reflection of the laser light because of shiny surface of the metal part (roller, steel liner, and the back of the aperture) is still an issue. It is not clear yet the implication of the reflected laser light to the heating.

2. The guiding and the consolidation doughnuts are still not yet tested and finalized. An experiment in Chapter 4 is designed to start observing the design of the doughnut roller.

Figure 1.7 Machine prototype for the tape winding of an endless tube.
Chapter 2 - Geometry Model

The geometry model is related to the dimensioning of the rectangular laser beam(s) into the ring shape. As mentioned before in Table 1.1, the laser system includes both laser module and the homogenizer optics supplied by Laserline GmbH. In the current system, one laser source corresponds to one homogenizer optic. This is because the laser power module cannot divide the beam to several fiber optics at this moment. Hence one laser module is limited to one optic only.

The homogenizer optic produces rectangular beam shape that has flat-top (uniform intensity) beam profile. When the laser beam emerges from the optic, its dimension (the initial size and the axes spreading angle) is determined by the cylindrical and the collimator lenses that are used.

The laser beam dimension is given as a result from Zemax simulation (ray tracing software) performed by the Laserline. For example, Figure 2.1 is the simulation result after the beam emerges as far as 165 mm from a certain optic. The color plot and color scale represents the laser intensity. At this distance (165 mm), the laser beam has spread from initial size of 10 mm x 15 mm to 60 mm x 27 mm. The color plot and the color scale (upper right corner) represent the laser intensity. Other optics has different rectangular sizes than this one.

Figure 2.1 Zemax simulation result from the supplier.
The ring-laser beam will be constructed from many of this homogenizer optics. The problem is to determine which optic type and how many of this optic is needed to encircle the doughnut-roller. This problem can be solved with the Solidworks (SW) model. Various types of homogenizer optics that used in AFPT are stored in the SW model. The aim is to observe and to select the type of the optic based on the highest beam coverage on the doughnut roller (thus minimize the number of lasers and optics) and the optic availability. This model is discussed in the sub-section Chapter 2.1.

The problem remain in the first SW model is the overlap between the laser beams. This is solved by the second model which is constructed by Absolid bvba. The aim of this model is to determine the shape of the mask for shaping many of those rectangular beams on the doughnut roller into a ring shape. This model will be discussed in the Chapter 2.2.

### 2.1 First Model – Estimation

This model is an assembly type SW model consists of two main parts. The first part is the doughnut roller (center radius 40 mm) and the liner (tube 60 mm diameter), and the second part is the laser beam (from the optic). The dimensions for the model are depicted in the Figure 2.2. The optic is located at the angle 25° and at the distance 250 mm from the nip point (with 1 mm tolerance between the doughnut roller and the liner).

![Figure 2.2 Side view of the SW model.](image-url)
The spreading of the laser beam is depending on the optic [4]. Based on the suitability (able to encircle the doughnut roller) and availability (not used for production), the optics 60 mm x 27 mm (with distance 165 mm) is selected for the design of the machine prototype. By using six of this optic (six lasers), it is shown that the lasers sufficiently covers the doughnut roller (Fig 2.3a), while other type of optic need more than six (Fig 2.3b).

![Figure 2.3 The SW model to estimate the laser(s).](image)

### 2.2 Second Model – Masking

Second model is designed for the mask. The aims of the mask are to shape the laser beams, and to prevent overlaps between beams. In this model, the doughnut roller and the liner are divided from the center point into six sections. One representative section is imposed with the laser beam from the optic (in this case optic 27x60) at given distance and angle (Figure 2.2). This imposed section is shaped as a ring and then is projected into the aperture plane (is located between the optic and the roller). This plane projection is therefore represents the geometry of the mask.

The real mask is just an extruded 3D of this plane projection (for the thickness of the mask). It is assumed that the laser beam spreading angles (both horizontal and vertical) remains constant after passed through certain thickness object – the mask with thickness ±5 mm. Thus, this assumption is ignoring the diffraction effect on the edges of the mask. This assumption is proven to be quite accurate from the test setup experiment described in sub section Chapter 2.3.
And the thickness of the mask is necessary for sustaining the heat (through heat conduction). The final mask design is depicted in the Figure 2.4 below.

![Figure 2.4 The SW model for masking.](image)

### 2.3 The Mask Experimental Test

A test setup is build to verify the SW model of the mask design (see Fig 2.5). The particular mask is made to prevent overlap between laser beams if the six optics (and six masks) are arranged to a ring-shape. The laser beam chord length ($L_{\text{chord-roller}}$) and arc length ($L_{\text{arc-tube}}$) are compared between the SW model (Fig 2.6a) and the real setup (Fig 2.6b). From the measurement result with ruler (mm-accuracy) on Table 2.1, it is shown that the SW model represents actual condition within ± 1-2 mm accuracy. From this verification, it is expected that a ring laser beam configuration can be built based on this model.
Figure 2.5 Test Setup based on the SW model.

Table 2.1 Measurement result with ruler (mm accuracy).

<table>
<thead>
<tr>
<th></th>
<th>$L_{\text{chord-roller}}$</th>
<th>$L_{\text{arc-tube}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW model</td>
<td>63.62 mm</td>
<td>30 mm</td>
</tr>
<tr>
<td>Real setup</td>
<td>64 mm</td>
<td>31 mm</td>
</tr>
</tbody>
</table>

Figure 2.6 Verification of the SW model.

(a) Laser beam on the SW model.
(b) Laser pilot on the real setup.
Chapter 3 - Thermal Management

This chapter mainly discuss for the thermal part of the mask. Since the mask is exposed to the laser(s), the heat of the mask will become the main concern. Includes in this chapter are thermal test (sub-chapter 3.1) and thermal model (sub-chapter 3.2) with Comsol Multiphysics to estimate the heat of the mask and to determine the material selection of the mask. More detail about the experimental test and the model can be read at Appendix A.

3.1 Thermal Experiment

The aim of this experiment is to test how the heat is accumulated in the metal mask when subjected to high laser power (from 0.5 kW to 1.5 kW). The experimental results then are fitted with heat transfer simulation model with Comsol Multiphysics for the estimation of the steady state condition.

The experimental setup is constructed in the SW and schematically depicted in Figure 3.1. The laser is exposed to the mask, and the temperature plot as a function of time $T(t)$ at a different position of the mask is recorded with a thermocouple data logger. To reduce an excessive heat due to the laser exposure, the water is flowing through the Copper cooling block.

![Figure 3.1 Thermal test construction.](image)
The mask in Figure 3.1 and the mask that is used for thermal test is not the final mask design that has been shown in Figure 2.6. This is because the SW model for the mask (Chapter 2.2) is not available yet at that time.

In the real setup, the thermocouple cables are placed in the pits on the back of the mask and are isolated with thermal paste and kapton tape. To record the temperature difference, the K-type thermocouples cables are placed in the different positions, which are: close to or in contact with the copper cooling block (Position 1), in the middle of the mask (Position 5), and in the edge (Position 9). It is expected that the Position 1 and the Position 9 are the lowest and the highest temperature profile respectively. An overview for this experimental setup can be seen below on Figure 3.2.

In the real setup (Fig 3.2), the mask is made from Copper due to high thermal conductivity coefficient (k) and relatively high melting point compare to Al & Stainless Steel (Table 3.1). Thus it is expected least heat will be accumulated in the Cu mask. This is later confirmed by the heat simulation (Comsol Multiphysics) and Cu is the material preferred for the final design of the mask.
Table 3.1 Test setup overview.

<table>
<thead>
<tr>
<th>Optic used</th>
<th>15x10→27x60 (at working distance 165 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mask material properties (commercial type of materials)</td>
<td>k(Cu/Al/St.Steel) = (400/160/44.5) [W/(m*K)]</td>
</tr>
<tr>
<td></td>
<td>Tmelting (Cu/Al/St.Steel) = (1080/660/±1500) [°C]</td>
</tr>
<tr>
<td></td>
<td>Cp(Cu/Al/St.Steel) = (385/900/475) [J/(kg*K)]</td>
</tr>
<tr>
<td></td>
<td>ρ(Cu/Al/St.Steel)=(8700/2700/7850) [kg/m³]</td>
</tr>
<tr>
<td>Area of the mask</td>
<td>45 mm x 20 mm</td>
</tr>
<tr>
<td>Angle/distance from the optic to the mask</td>
<td>0° (horizontal) / 150 mm</td>
</tr>
<tr>
<td>Area of the mask exposed to the laser (front view)</td>
<td>= Area of the laser beam – Area of the mask = 55 x 30 – 45 x 20 = 750 mm²</td>
</tr>
<tr>
<td>Laser intensity</td>
<td>= Laser power / Area of the laser beam = 1500 W / (55 x 30) = 0.9 W/mm²</td>
</tr>
</tbody>
</table>

The record of this measurement is the T(t) profile. The temperature increment during the five minutes laser power exposure until it reached the steady state temperature is shown in Figure 3.3 at the constant ambient temperature ±20°C. The T(t) profiles for the three pits on the back of the mask showed the gradient of the temperature difference due to the cooling. Because of pits proximity relative to the cooling block, the pit on the Position 9 (blue lines M1-1500-C_Pos9) is the hottest steady-state point at 220°C while the Position 1 is the coolest at 70°C (black lines M1-1500-C_Pos1).

The time constant (τ) that represents how fast the system become stabilized is obtainable by fitting the T(t) profile to the asymptotic equation (Equation 1). The most common engineering practice is to determine the time constant as a time when the temperature reach 63.2% of the Tmax. The time constant for the hottest point (Position 9) at this experiment is 40 seconds.
\[ T = T_0 \left( 1 - e^{-\frac{t}{\tau}} \right) \]  

(Equation 1)

From the information based on the T(t) profile, the heat transfer model can be built in the Comsol Multiphysics software. This model can provide an insight for the heat accumulation of the metal mask because of laser exposure. Later, even the model can be tailored for the multi-lasers exposure to the mask (for real prototype). The heat transfer model will be discussed in the next sub-chapter 3.2.

Figure 3.3 Thermal experimental T(t) test result.

### 3.2 Comsol Multiphysics Model

Based on the experiment, the 3D transient heat transfer in solid is built in Comsol. The physics of this model is formulated in Equation 1 as the heat storage in material over the time equals to the heat conduction (depends on the material thermal properties) and incoming heat flux (Q).

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \]  

(Equation 2)
The model geometry is shown in Figure 3.4, with an assumption that the laser beam only hit the front and not the inside edges of the mask. The water that flow continuously through the cooling block is assumed to keep the cooling block temperature constant at 20°C.

![Figure 3.4 Comsol model geometry - 3D transient heat transfer in solid module.](image)

There are some problems remained with the model. First problem is the assumption of constant cooling block temperature. This assumption is not true since the water gets heated and reached more than 20°C (confirmed by the experiment data of M1-1500-C_Pos1 at Figure 3.3). Other problem arise with the Comsol model is to model the heat flux. The heat flux (Q) ideally should be mainly determined by the laser intensity and other heat losses. The number for the laser intensity (0.9 W/mm²) can be easily obtained. However, other heat loss because of reflection is not possible yet to be obtained since it can vary from 10-90% depends on the wavelength of the laser, incident angle, and the surface roughness of the mask [5]. Experimental test to estimate the reflection of the laser on the metal shows inconsistency of the reflection coefficient (attached in Appendix B). Thus, the model inserted the heat flux Q equals to laser intensity (0.9 W/mm²). This model therefore not accurate but serves its purpose for intuitive estimation for the hottest (worst) possible condition. An improvement of this model is recommended for better estimation of the temperature.
3.2.1 Model vs Experiment

With Comsol, the material of the mask can be easily assigned to the geometry. Thus simulation for various metals, e.g. Cu, Al, & St. Steel can be performed. The result of this simulation at the hottest point is plotted in Figure 3.5. The requirement for the mask is to have as low temperature as possible, especially in the part where it has direct contact with the prepreg tape (temperature processing of the tape is maximum at 380°C). The simulation result shows that Cu is the most suitable for masking the laser beam(s) application.

![Temperature profile for various metal masks](image)

Figure 3.5 T(t) profile for various metal mask with Comsol model.

From the simulation result, the steady state temperature of the hottest point for the Cu is 330 °C with the time constant of 30 seconds. This simulation result is still overestimated the temperature compare to the experimental test result (220°C, τ = 40 seconds). The simulation result is shown in below Figure 3.6 and plotted in Figure 3.7. The overestimation of the temperature of the hottest point is due to unknown reflection factor.
Figure 3.6 The simulation result of Cu mask with Comsol model.

Figure 3.7 T(t) comparison between experimental test and Comsol model.

3.2.2 Final Mask Simulation

The final mask at Figure 2.5 is simulated with the same model Comsol Multiphysics. The concern is the heat accumulation on the peaks of the metal. The assumptions are still the same only different in the geometry of the mask. This simulation is only to estimate the worst condition that can be happened to the peaks.
Figure 3.8 The Comsol simulation for the metal mask.

(left): The geometry boundary condition.
(right): The simulation result, with temperature max at 590°C and time constant ± 40 seconds.

In the real setup, the mask is exposed to the laser for 5 min with increasing power up to 2 kW. The T(t) profile cannot be recorded experimentally because the thermocouple is not available afterwards. The peaks can sustain the heat but the overall Cu mask is oxidized (Appendix C).
Chapter 4 - Test Prototype Design

There are two main prototypes that built and tested during this project. First prototype is the front-part of the machine, with aim is to build the projection of the ring laser beam on to the doughnut roller. This has been schematically depicted in the Figure 1.7. The second prototype is the back-part of the machine, with aim to get an insight how the doughnut-roller should be designed. Both prototypes are constructed by Absolid bvba.

4.1 Front Part – Ring Laser Beam

After the mask has been finalized (in Figure 2.5), six of these mask are arranged into ring configuration. The real setup of this device is shown in below Figure 4.1. A test with the aim to investigate the overlap between laser beams is performed. The test is only using one optic and one laser source, because Laserline is not ready yet at that time to provide the six optics (and six laser source).

Figure 4.1 Real setup for the front-part of the machine.

Similar to the test performed in the Chapter 2.3, the position of the laser pilot on the doughnut roller is marked. Then the optic is disassembled and moved to its closest neighbor optic, and then the laser position is marked again. With this experiment, it is expected that the overlap between two consecutive laser beams (shaping by the masks) can be measured.
However, due to the limited space in construction, the marking is not accurate enough. The result test in Figure 4.2 below shows that although the arc length of the beam on the roller is accurately at 63 mm, it cannot determine whether there is an overlap or a gap between these beams.

![Figure 4.2 The arc length measurement of the beam.](image1)

Other effort to measure the dimension of the beam is also shown in Figure 4.3. The linagraph paper is glued following the contour of the doughnut roller. This paper then exposed to 2 kW laser power (correspond to laser intensity 0.65 W/mm^2) for 10 sec. From this test, the beam photo is obtainable. However, the laser intensity is still too less for blackening the linagraph paper, hence the photo is not so clear. The arc length on the roller is 63 mm while the arc length on the tube is not obvious.

![Figure 4.3 The linagraph paper test result.](image2)
4.2 Back Part - Doughnut Roller with Spring Consolidation

The aim of this test is to investigate the proof of concept of the doughnut roller design [2] and to observe if the tapes can be guided without crossing each other. Two tapes are passed through the roller and the liner. The liner and the tapes are made from HDPE/Glass Fiber70. The liner is pulled by the robot. Attached on the back of the doughnut roller is the spring consolidation. Since the area of the spring consolidation is limited, the liner should be clamp tightly so that it is not rotate during the robot pulling (only move in the axial direction). The test setup is depicted in the Figure 4.4 while the test parameters are listed in the Table 4.1. The laser power is increasing iteratively from 300 W, 500 W, to 1 kW.

![Figure 4.4 Test setup for the back-part of the machine.](image)

<table>
<thead>
<tr>
<th>Table 4.1 Test parameter for the back-part of the machine.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optic used</strong></td>
</tr>
<tr>
<td><strong>Angle/distance from the optic to the mask</strong></td>
</tr>
<tr>
<td><strong>Liner material/Diameter</strong></td>
</tr>
<tr>
<td><strong>Tape material/width/thickness</strong></td>
</tr>
<tr>
<td><strong>Liner pulling speed</strong></td>
</tr>
<tr>
<td>Spring force</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>Power (iteration)</td>
</tr>
</tbody>
</table>

It is found that with 1 kW laser power, two tapes side by side can be consolidated (Figure 4.5). From this experiment, some remarks are noted that are:

1. The guiding roller from Al does not need any surface polishing. The tapes can be sliding through this guiding roller. This device is still need an improvement for rotational movement & all rounded consolidation part.
2. The fitting tolerance of the roller and the liner is difficult. It is recommended to have a tolerance within 0.5 – 1 mm to sliding the tape for the consolidation process.
3. Tape tensioning is necessary for the good quality consolidation.

Figure 4.5 Two tapes side by side consolidated with spring consolidation.
Chapter 5 - Conclusion & Recommendation

5.1 Conclusion

At this moment, the prototype for ring laser beam has been constructed. The remaining tasks are to configure the working concept of the rotational doughnut roller, to finalize the back-part machine, and to integrate the IR camera and electronic system.

5.2 Recommendation

The project is still unfinished. For the continuation of the project, remaining problems and recommendations are summarized in below Table 5.1.

Table 5.1 Recommendation list for the project.

<table>
<thead>
<tr>
<th>No.</th>
<th>Possible Problem</th>
<th>Possible Root Cause</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-Water temperature is increasing.</td>
<td>-Measure the flow rate of the water from the cooling machine.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-Other difficulty is the 3D drawing in Comsol.</td>
</tr>
<tr>
<td>2.</td>
<td>Beam overlap difficult to determine.</td>
<td>-Construction limited.</td>
<td>-Modify the construction.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Only have 1 laser source.</td>
<td>-Adding more lasers.</td>
</tr>
</tbody>
</table>
|   | Reflection – ring laser beams failed due to beams overlap and additional heat. | Shiny & smooth surface of the doughnut roller. | -Not clear yet if the reflected beams induce additional heat.  
-Blackening the surface of the roller.  
-If necessary, the reflected laser beam can be measured with power meter from Laserline. |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Construction dimensioning issue.</td>
<td>In between the doughnut roller and the liner (rough surface ± 0.5 mm) is difficult and time consuming to fit them precisely. Too big means there is no nip point for consolidation. Too small then the tape is stuck when it is fed to the nip point.</td>
<td>-Concepting the doughnut roller for both tape guiding and tape consolidation functionalities.</td>
</tr>
<tr>
<td>4.</td>
<td>Tapes crossing.</td>
<td>The guiding function of the doughnut roller. Especially if the doughnut roller is designed for rotation.</td>
<td>-Produce the route for sliding the tape (threading the doughnut roller).</td>
</tr>
<tr>
<td>5.</td>
<td>Poor consolidation</td>
<td>The consolidation functions of the doughnut roller.</td>
<td>-Fitting and tolerance problem.</td>
</tr>
</tbody>
</table>
References


3TU. School for Technological Design, Stan Ackermans Institute offers two-year postgraduate technological designer programmes. This institute is a joint initiative of the three technological universities of the Netherlands: Delft University of Technology, Eindhoven University of Technology and University of Twente. For more information please visit: www.3tu.nl/sai.