View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Universidade do Minho: RepositoriUM

# Redesign of machine component in polymeric matrix composite towards increased productivity

R. Figueirêdo de Sá & J.P. Nunes
*Institute of Polymers and Composites/I3N, Minho University*
L. Oliveira
*PIEP - Innovation in Polymer Engineering*
F. W. J. van Hattum
*Research Centre Design and Technology, Saxion University of Applied Sciences, The Netherlands*
J. M. A. César de Sá
*IDMEC – Institute of Mechanical Engineering, University of Porto*

ABSTRACT: This work is focused in the maximization of the acceleration a 2D Industrial Laser Cutting Machine (ILCM). The changes to be implemented are centered in the replacement of a metallic critical component: the gantry. This component largely influences precision and maximum acceleration. Finite Elements Analysis was performed to the current metallic part. From this analysis the maximum allowed deformations were established. A replacement composite component capable of an equally valid behavior was designed in carbon fiber.

To establish the maximum increase in acceleration that does not lead to precision losses, the working conditions were simulated and the acceleration to which the component was subjected to was varied. The variation of the thickness of layers with different orientations and locations in the part allowed for the understanding of how the mass varies along with the maximum possible acceleration. This analysis, asides with considering the maximum force allowed by the linear motor that is responsible by the gantry motion, establishes the limit in terms of maximum acceleration of the machine. An increase of 22% in the maximum acceleration while maintaining the precision is possible due to the higher specific rigidity of composite materials and the use of an optimization heuristic.

## 1 INTRODUCTION

Industrial Laser Cutting Machines (ILCM) are widely used in different manufacturing processes in industry due to advantages in cut quality and cost effectiveness through mass-production rate (Eltawahni, 2012). Their function is the production of a workpiece with required geometry, with an acceptable surface finish and accuracy and at a rate as high as economically possible (Lee, 2004). The main limitation of these machines are related to the need of maintaining high accuracy while withstanding high accelerations (Heisel, 1996).

One component (the gantry) of the ILCM that is the subject of this study has been identified as particularly critical for allowing to ensure a machine able of presenting high maximum accelerations and precision.

### 1.1 *Machine Description*

A schematic depiction of the Industrial Laser Cutting Machine (ILCM) is portrayed in Figure 1.

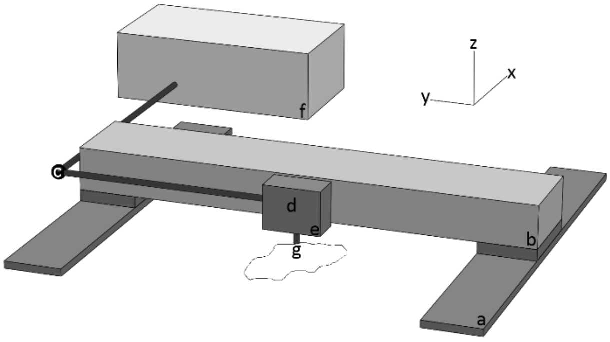

Figure 1. Schematic depiction of the ILCM and the cutting process. a) supporting structure; b) gantry; c) stationary optical components; d) movable optical components; e) cutting head; f) laser source; g) cutting spot.

As illustrated, the ILCM under analysis consists of three different main components: supporting structure (a), gantry (b) and cutting head (e). Attached to the gantry, on one of its ends, are the stationary optical components (c). These components project the laser beam to the movable optical components (d) that are contained in the cutting head (e). All these components have one main purpose: to ensure that the laser beam follows a path that takes it from the laser source (f) to the point where it must hit the target to allow for the production of the desired piece or cutting spot (g). The gantry moves along the length of the supporting structure and the movable components of the optical system move along the gantry. The combination of these orthogonal movements allows for the covering of the two dimensional space defined by the target (or part that is to be cut). The gantry is, therefore, a critical component in terms of the cutting performance of the ILCM.

### 1.2 *Gantry design principles*

The rigidity of the gantry must be such that it ensures deformations will not cause that the spot where the laser effectively hits the target distances from the cutting spot more than the machines accuracy.

The material in which the new gantry will be produced must allow for high stiffness while keeping a low mass. Multilayered polymeric matrix composites (composites) present more attractive specific stiffness (E/ρ) than metals and other polymers. Also, they ensure good damping characteristics. A composite material gantry was designed to ensure full compatibility with the current machine's structure while allowing it to present better performance in terms of maximum acceleration without degradation of the precision specifications. A 50% increase on maximum acceleration was defined as maximum possible limit, getting up to a maximum acceleration of 3 g. The external dimensions of the composite structure are to be the same as the current component, as to ensure compatibility with the current system.

## 2 ANALYSIS DESCRIPTION

### 2.1 *Analysis of the current part*

In order to ensure that the new part is capable of leading to a machine working with an equivalent level of precision, the current metallic part was studied.

The current machine's gantry presents essentially a rectangular tubular section. The visible part is the exterior shell, produced in metal sheet of uniform thickness. This shell has both aesthetic and functional purposes. Contained in the shell are several reinforcements.

The analysis was performed using Finite Elements Method (FEM). The software used was Abaqus/CAE 6.11-1. The geometry of the current metallic component was obtained from the producer and, in order to reduce computational cost, both external shell and interior reinforcements were considered as a single part. This approximation requires no contacts to be defined and assumes rigid connections between different parts. This is very similar to what is verified in reality. A midplane mesh was generated in ANSA pre-processing software. The powerful meshing capabilities presented by this software allowed for a better discretization of the domain, thus leading to more reliable outcomes from the FEM software.

The geometry was subjected to loading conditions that are representative of the machine's working conditions (interaction with surrounding components and the acceleration it is subjected to). As the components move along the gantry, the loading cases change. In the context of this study only one will be considered:  the gantry suffers maximum acceleration and the cutting head is in the center, while the cutting head is also subjected to maximum acceleration. This has been identified as the critical loading case (capable of causing higher deformations in the gantry). In all load cases there are also other concentrated loads that come from the interaction with surrounding components. All of these loads were taken into account but will not be specified in this paper.

None of the surrounding components are geometrically represented in the numerical model. Instead their masses are applied to points represented at the same coordinates as their centers of gravity. These masses are subjected to the same gravities as the bodies are in working conditions. The connections between center of gravity of each component and the gantry are represented by kinematic coupling. This way to model the connection between the gantry and surrounding components consists of a group of slave nodes (the nodes where the components are attached to the gantry) constrained by the translation and rotation of a master node (the point to which the loads are applied). From this simulations the considered outputs was the displacement (both translational and rotational) of the point located at the center of gravity that represents the cutting head. This point was selected since it is both the endpoint of the optical system and the component that applies higher loads to the gantry.

### 2.2 *Composite material gantry development*

Initial estimations of the thicknesses of the external walls of the composite gantry were performed to allow for part that, without interior reinforcements, would present equivalent deformations and, therefore, equivalent machine performance. Because of the loads known to be applied to the gantry, two fiber orientations were selected. The unidirectional fibers will be able to give higher bending rigidity. ±45° fibers are used for their higher Shear Modulus. Calculations were performed considering that only the unidirectional fibers would be subjected to the bending loads and that the rotation of the beam would only be dictated by the thickness of the ±45° fibers layer. A combination of thicknesses that create a structure rigid enough to support the loads but as light as possible was selected.

The initial results from the numerical model in which the composite model was subjected to loads portraying the working conditions showed concentrated deformations near the interface with some components. Local reinforcements had to be placed. It is important to notice that the dimensioning of the composite gantry aims at maximum accelerations of 3G and that this factor has impact in the loads applied to both the gantry and the points representing the center of mass of the surrounding components.

The strategy followed to overcome the local deformations consisted in the introduction of ribs along the axis of the gantry. These ribs increase the rigidity of the shell structure by transferring the loads that are applied to one face to the opposite one. Two distinct types of ribs are considered: the external and internal ones. The external ones are aimed at supporting two structures located near the extremities of the gantry. The internal ones deal basically with the loads applied by the cutting head as it moves along the gantry's length and is subjected to the accelerations imposed by the linear motors. Figure 2 displays the different sections that are considered in the gantry design.

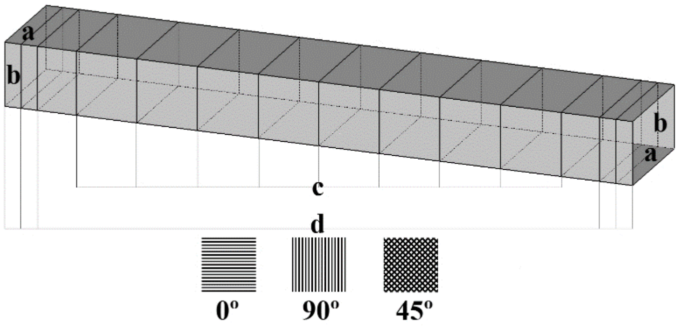

Figure 2. Different sections of the gantry. a are the horizontal walls; b are the vertical walls; c are the internal ribs and d the external ones. Each of these sections may have fibers with at least one of the illustrated orientations.

The 4 sections represent: the horizontal external faces (a), the vertical external ones (b), the internal ribs (c) and the external ones (d). Each one of these sections contains one or more of the three possible fiber orientations. Each of these fiber orientations in each of the sections is treated as a continuous variable. This comes to a total of 12 variables. The calculation initially performed resulted in the dimensioning of a gantry with the thicknesses and weight presented in the third column of Table *1*.

With the initial setup of the thicknesses required to create a gantry that allows for enough rigidity, a trial and error approach was followed as to understand if the introduction of new layers would allow for the creation of a gantry with equivalent rigidity while decreasing its mass. It was observed that the inclusion of fibers perpendicular to the vertical walls in both sections c and d (the ribs) would allow for an increased rigidity that allows for the reduction of the ± 45º fibers in the outer walls (both sections a and b) as depicted in the fourth column of Table *1*. This way it was possible to reach to a configuration that comprises a variety of fibers orientations on its sections but a lower total mass (reducing by 17.6% the total mass of the gantry).

Table 1. Thicknesses of the layers of the different sections of the gantry and corresponding masses.

| Section | Fiber orientation | Calculated initial thickness (mm) | Thickness after numerical model experimentation (mm) |
|---|---|---|---|
| a | 0º | 4 | 4 |
| | 90º | 0 | 0 |
| | ±45º | 11.785 | 8 |
| b | 0º | 6 | 6 |
| | 90º | 0 | 0 |
| | ±45º | 12.155 | 8 |
| c | 0º | 0 | 2 |
| | 90º | 0 | 0 |
| | ±45º | 3 | 3 |
| d | 0º | 0 | 2 |
| | 90º | 0 | 0 |
| | ±45º | 3 | 3 |
| Total Mass (kg) | | 82.3 | 67.8 |

## 2.3 *Linear motor analysis*

The movement of the gantry is controlled by Linear motors. Linear motors are chosen for they provide an optimally tuned linear direct drive system capable of meeting the requirements of precision machines such as the ILCM here focused (SIEMENS, 2013). They are capable of extensively avoiding the effects of elasticity, play, and friction, as well as natural oscillation in the drive train. Higher dynamic response and increased precision come from these characteristics (SIEMENS, 2013).

Linear motors have characteristic curves (Figure 3). These curves show that the motor is capable of producing a constant force ($F_{max}$) up to a certain value of velocity ($v_{max(Fmax)}$). After this value is reached the force drops reaching the feederate force ($F_{rated}$). The ratio between $F_{max}$ and $F_{rated}$ depends on the desired working conditions: continuous load – lower ratio – or peak load.

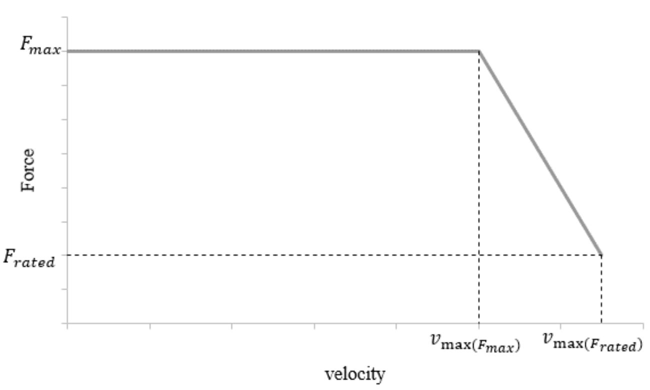

Figure 3. Example of a Linear Motor characteristic Curve

The current machine comprises a motor that moves the gantry and the surrounding objects with $F_{max}$ of roughly 9760N and well within the scope of velocities that allows it to employ its highest force. It was possible, by accounting for the mass of the surrounding components that are also moved by this motor, to calculate the maximum mass from the gantry that the motor can move at a given acceleration.

By assessing the minimum mass that allows the gantry to keep the minimum desired rigidity through an array of accelerations it is possible to determine what the maximum acceleration reachable by this approach is.

### 2.4 *Mass of the gantry as a function of machine acceleration*

In order to estimate the minimum thickness of each layer of the above defined sections (and, therefore, the associated minimum masses) a routine was created. This routine was implemented in Python programing language and is explained in Figure 4.

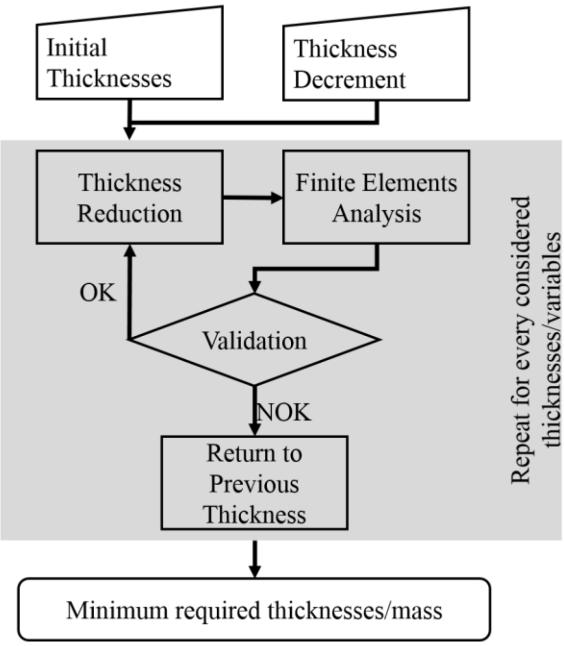

Figure 4. Routine to implement the iterative reduction of the layers' thickness

Python language is commonly used to create scripts for Abaqus. This approach allowed for a more robust and automated mass reduction process. This heuristic has severe limitations when it comes to accounting for the effects of the interdependence between variables. It can also be highly influenced by the order in which the thicknesses are reduced. A study was performed to understand to which variables are the results more sensible to. With this information it was possible to determine the order by which the thicknesses should be varied.

This analysis started with the definition of how many variables should be considered. Given knowledge previously gained during the process described in section 2.2 and the loads applied to the gantry, the layers with 90º fibers all of the sections where ignored and kept at 0 through the whole process. One other simplification was also defined: the same thickness would be applied to the ±45º fibers layers of both section a and b. Section c and d are to be considered as one single section. Therefore, the total number of variables to be considered is 5.

The next decision to be taken was regarding the order in which to test the reduction of thicknesses as to minimize the mass required for ensuring sufficient stiffness at a given acceleration. This order was decided based on the influence that the reduction of each layer had in the stiffness loss as a function of mass reduction. The lower the influence, the earlier its thickness will be varied in the routine described in Figure 4. Each of these variables was tested separately.

Each of the five thicknesses was repeatedly reduced by 10% of its initial value. For each of its values, both the mass of the gantry and the variation in stiffness were assessed. The stiffness variation was considered to be represented by an indicator that accounts for the changes in the 6 degrees of freedom of the point represented in the center of gravity of the cutting head. The stiffness indicator is calculated according to Equation 1:

$$\sum_{i=1}^{6} abs\left(dof_{i_{ini}} - dof_{i_{test}}\right) \qquad (1)$$

in which $dof_{i_{init}}$ is the value of the deflection or rotation suffered in the degree of freedom i by the initial metallic structure and $dof_{i_{test}}$ is the deflection or rotation suffered in the same degree of freedom by the composite structure with the thicknesses being tested. The higher this indicator is the larger are the deflections and rotations suffered by the center of gravity of the cutting head and, therefore, the lower is the stiffness. The results are shown in Figure 5.

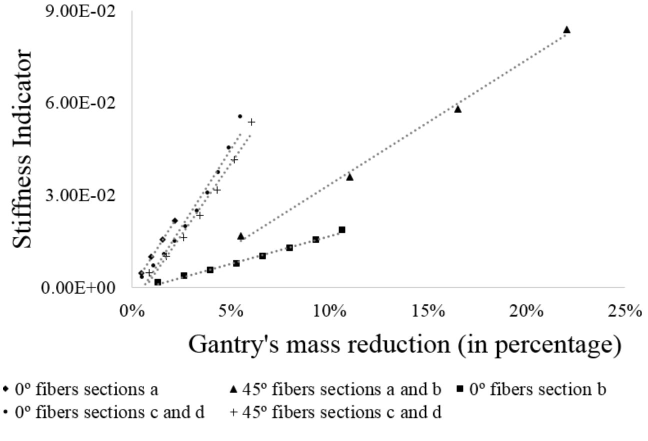

Figure 5. Relationship between Gantry's mass reduction by reduction of thickness of each layer and the reduction of stiffness.

# 3 RESULTS AND DISCUSSION

## 3.1 *Order of thickness reduction*

Figure 5 shows the outcome of the analysis that intended at defining the order by which the thicknesses should be reduced. The order is defined based on the influence that mass reduction by thickness reduction has on stiffness variation. The higher the influence the latest this reduction will be tested. This is due to the fact that a reduction by this order is expected to conduce to higher weight reduction before leading to a loss of stiffness that implies a loss of machine performance. In the plot of Figure 5, the higher the slope, the higher the influence. Therefore, the order by which the layers' thickness will be reduced, is (1) 0º fibers in section b, (2) ±45º fibers in section a and b, (3) ±45º fibers in section c and d, (4) 0º fibers in section c and d, and (5) 0º fibers in section a. With this order and following the heuristics here described, it was possible to minimize the mass of the gantry for each acceleration.

## 3.2 *Maximum achievable thickness*

The minimum mass that allows for the desired rigidity of the gantry for different accelerations was plotted. Also plotted was the maximum mass that the gantry can move under $v_{max(Fmax)}$ and at a given acceleration. The interception of the two plots shows the maximum acceleration achievable by replacing the current metallic part by a composite one. These curves are shown in Figure 6.

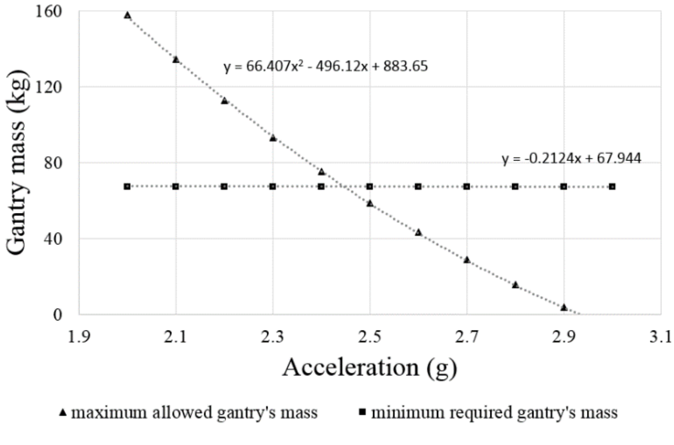

Figure 6. Plot of the curves of maximum mass allowed by the linear motors and the curves of minimum mass that allows for the required stiffness.

While the maximum allowed mass can be approached by a quadratic equation, the minimum required mass varies in a linear fashion as a function of the acceleration. The two equations shown in Figure 6 have they intersection point for an acceleration with a value of 2.44 g. This is the value for the maximum acceleration reachable by replacing the current metallic part with a composite component by the use of the explained heuristic.

# 4 CONCLUSIONS

By replacing the current metallic gantry by a composite fully compatible one it is possible to increase the machine's maximum allowed acceleration without loss of machine accuracy. A heuristic was used to estimate the maximum acceleration that this approach is able to reach. Following this heuristic the acceleration can be increased by 22%.

In Figure 6 it was possible to understand that, at least by following this heuristic, the variation of gantry mass as a function of the acceleration it is subjected to is quite low.

Anyway, this heuristic approach only considers the separate decrease of layers that are considered as fully independent. As shown by the study performed in Section 2.2, it is possible to decrease the general required mass of the gantry despite the increase of the thickness of a specific layer. In this situation, the initial mass increase was overcome as it allowed for a reduction in other layers.

This shows that an optimization strategy must be followed as further mass reductions might be possible.

# 5 ACKNOWLEDGMENTS

This work was supported by FCT (SFRH / BD / 51106 / 2010).

# 6 REFERENCES

Eltawahni, H.A., et al., Effect of CO2 laser cutting process parameters on edge quality and operating cost of AISI316L. Optics & Laser Technology, 2012. 44(4): p. 1068-1082.

Heisel, U. and M. Gringel, Machine Tool Design Requirements for High-Speed Machining. CIRP Annals - Manufacturing Technology, 1996. 45(1): p. 389-392.

Lee, D.G., et al., Novel applications of composite structures to robots, machine tools and automobiles. Composite Structures, 2004. 66(1–4): p. 17-39.

SIEMENS A.G., SIMOTION, SINAMICS S120 & SIMOTICS: Equipment for Production Machines. 2013.