A MAINTENANCE PLAN FOR STEREOLITHOGRAPHY RAPID PROTOTYPING PROCESS: METHODOLOGY AND TOOLS

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Abstract. Nowadays new product development uses technologies that help to reduce time-to-market achieving the quality expected by final consumers. The Rapid Prototyping (RP) technologies are capable to build prototypes directly from CAD data with high fidelity in few hours. This rapid feedback to engineering teams aloud many advantages as errors detection, assembly and functional tests and ergonomic evaluation. Although, RP machines have high costs for acquisition and maintenance. So it is necessary to keep the machine running fast and accurately to be advantageous to have or to use this kind of techniques. One of the most popular processes is the stereolithography that build up prototypes based on photo curable resins with an ultra violet laser beam. This paper presents the implementation of a basic maintenace plan to be used in the stereolithography process. It does not keep focused only in the machine but it tries to involve all step process from the workstation software until the prototyping delivery on the life cycle. The critical components from the process were identified and individual maintenance plans were stabilized. This maintenance plants was managed starting from the information obtained by the use of Fault Tree Analysis (FTA) and of Failure Modes Effects Analysis (FMEA). Computational tools and documentation were used to achieve quality, time and costs requirements. The final conclusion is that the systematic adopted, it can be applied in any system that represents fundamental importance for a production system, as much of the economical point of view as in availability.

Keywords. *maintenance, rapid prototyping, stereolithography.*

1. Introduction

Last decade, many technological processes appeared to improve the manufacturing of prototypes that are used on product development. These processes were denominate as Rapid Prototyping (RP) and they are characterized by the short manufacturing time to build up a prototype with accuracy and quality, directly from computer three-dimensional data from a CAD (computer aided design) system (Beal et al, 2002).

Rapid prototyping machines are highly automated and after start to build parts the presence of the operator is only required to take parts out from the machine at the end of the process. Manufacturing objects on RP systems may take from few hours to days depending of the process, material and object geometry. As in any other productive process, RP machines are very expensive and this is compensated by using it constantly, characterizing that a maintenance plan must be implemented to avoid failures in the process, specially during the objects manufacturing;

Furthermore, rapid prototyping machines acquisition is restricted to great organizations that are going to use it continuously. So, mainly RP machines are installed on bureaus that do services as prototyping to many others organizations that need sporadically of prototypes to evaluate their projects. The chart presented on Fig. (1) shows basically the interfaces between the organization and the rapid prototyping bureau to obtain a prototype.

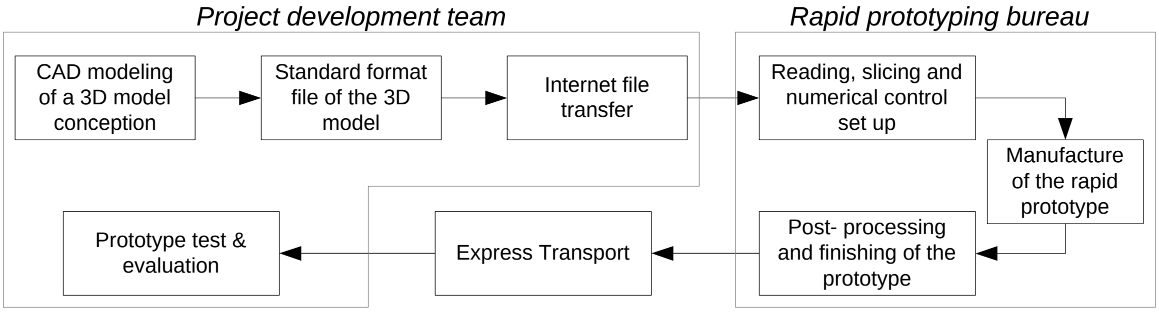


Figure 1. Interfaces and competences to obtain a rapid prototype (Ahrens et al, 2001).

Stereolithography (SL) is rapid prototyping processes that build prototypes quickly achieving high accuracy, quality and versatility. It works layer-by-layer deposition of a resin that is photo-cured by a ultra-violet laser beam (Jacobs, 1996). Due to the complexity of the sub-systems that make part of the stereolithography machines, SLA (stereolithography apparatus), many are the concerns about the machine operation. SLA machines should always by ready to operate and failures during the manufacturing of an object must be minimized because there is high costs to re-calibrate the machine if something gets wrong or a prototype is not delivered when it should be. A difficulty to maintenance the SLA is the high dependency of the machine manufacturer that tries to keep a strong dependency with the SL user. Another problem is the access to spare parts, which means that in Brazil at least 80% has to be imported and there is a lead time to obtain the part after the request to replacement.

This work tries to establish an efficient maintenance plan to the stereolithography system using methodology and tools to all sub-systems that are used in the SL process. This plan does not keep focused only in the SL machine but also in software, network and workstations that are necessary to the entire process. The implicit conceptual idea is the total quality control to the prototypes that are manufactured so parallel types of maintenance plans were applied to achieve manufacturing of parts with quality, in the shortest time at minimum costs. These maintenance plans are characterized as preventive, predictive and corrective. In this work, it will be considered the adaptive and perfective maintenance concept, normally used in the software area, to improve maintenance of data and performance of the system (Blanchard, 1995).

2. Background – The stereolithography process

Most of the manufacturing process that are denominated as "rapid prototyping" have a high degree of automation of the process specially in the CAM software (*computer aided manufacturing*) that aid to prepare and to generate the numerical control file to build a part in the machine. This is very common in processes like stereolithography, fused deposition modeling (FDM), selective laser sintering (SLS), Thermojet, laminated object manufacturing (LOM), 3D printing (3DP) and others (Beal, 2002). These processes called as rapid prototyping are know too as Layer Manufacturing Technologies. Despite they have diverse physical-chemical principles to generate and to add the layers they basically have a similar sequence to build up a 3D object. The first step is to obtain a three-dimensional CAD (*computer aided design*) data from the object that is going to be manufactured. This native CAD data has to be translated to a common data file, usually the STL file format is chosen. The STL (Structured Triangle Language) is a simple triangular mesh that represents the boundaries of the object. Most of the commercial CAD systems export using STL formats their 3D CAD models. After obtained the STL file it is necessary to read the file inside the CAM system that is specifically build to each type of rapid prototyping machine. This 3D file is sliced and each slice will represent a layer of the object. Each slice is processed to the numerical control and in the RP machine every layer is build and added over the previous layer (Fig. 2).

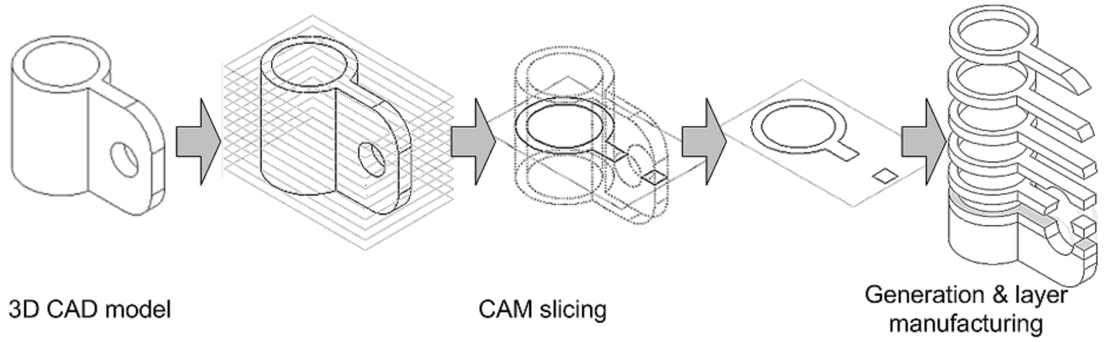


Figure 2: Basic manufacturing sequence of layer manufacturing technologies.

The stereolithography process is capable of build 3D objects by photo-curing a resin using a ultra-violet (UV) laser beam. A simplified sketch of the working-principle of the process is presented in Fig. (3). The UV beam is driven over the resin surface by mirrors. The resin photo reactor actives the chain reaction starting to polymerize and to turn the resin from liquid to solid. The lasers beam only draws inside the slice border obtained from the CAD data until it complete polymerize the layer. The platform dives and the liquid resin get over the solid layer. After few seconds, the platform raises to a new position, lower then the original position (between 0,02 and 0,15mm depending on the machine model). Due to the high viscosity a blade or other re-coater system is used to uniform the layer. So the laser beam starts to draw the sequenced layer gluing it to the previous layer and the process is repeated until all part is done. It is important to know that this is a basic description from the process. Jacobs (1996) and 3D Systems (1998) can explain in more close details all the stereolithography process.

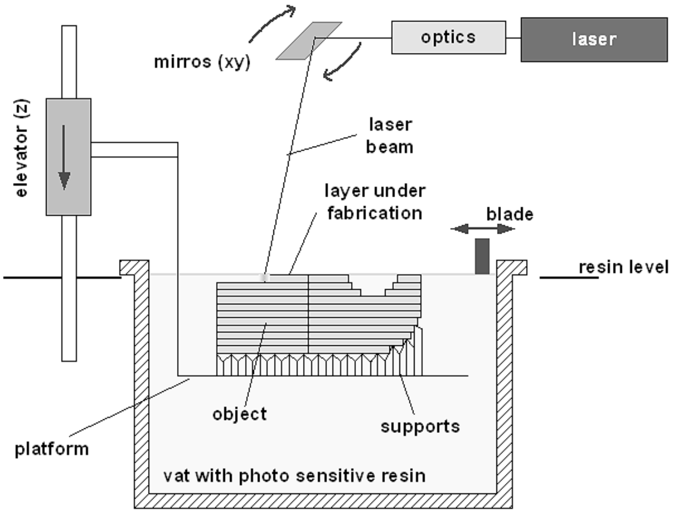


Figure 3. The stereolithography system developed by 3D Systems (Beal et al, 2002).

After the complete object manufacturing there are few procedures to finish the object. It is necessary to break-off supports, to clean the liquid resin that remains in the object surfaces and to complete the cure of the object placing it inside a ultra-violet oven. If necessary it is possible to adjust some dimensions and to apply coatings, to paint or to sand to achieve a better surface quality.

As this work intend to apply maintenance plans to the entire stereolithography process, Fig. (4) shows an detailed flow diagram of the steps and parameters that make part of the stereolithography process.

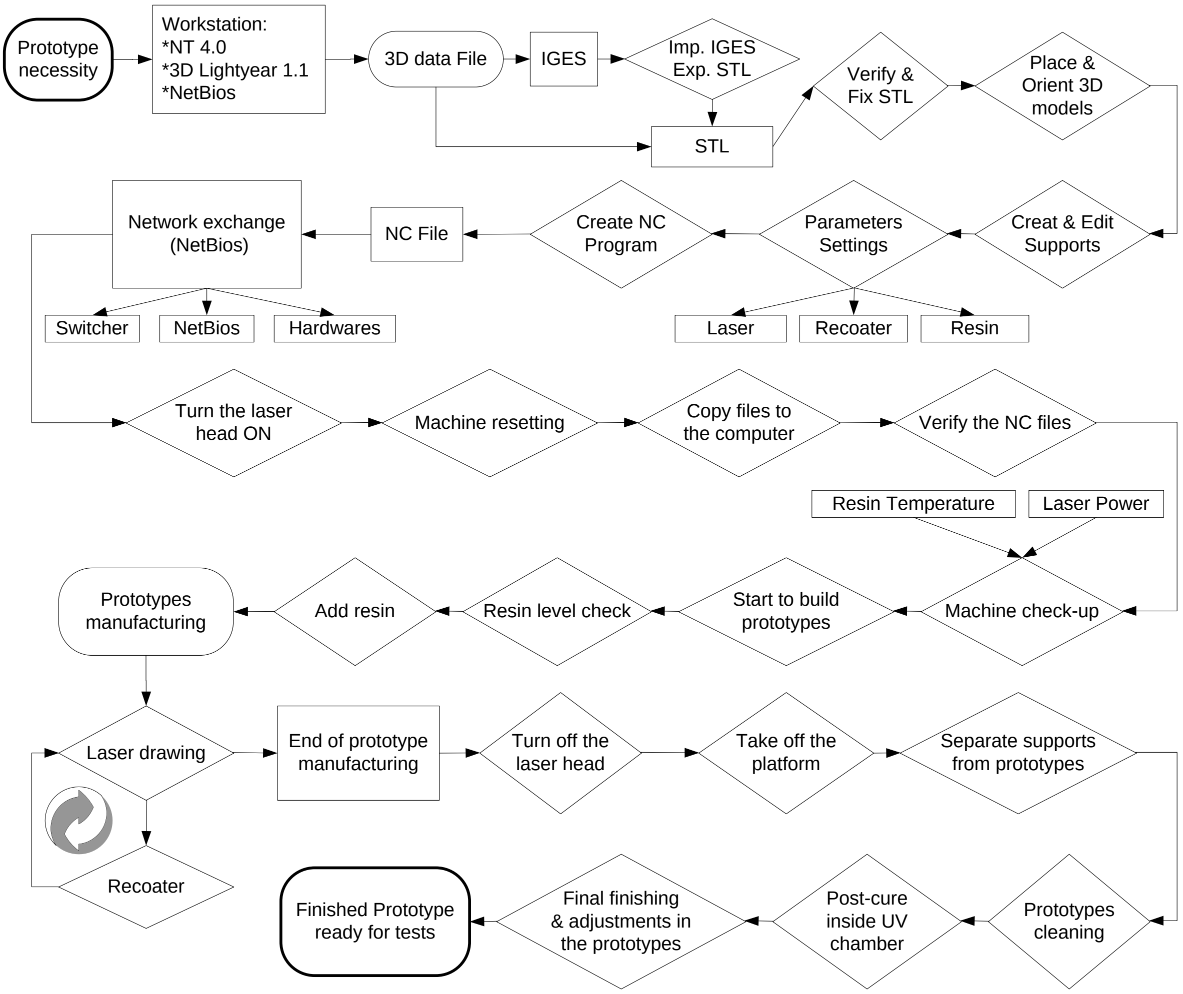


Figure 4: Flow diagram of the stereolithography process.

It is clear that the process is quite complex and there are many sub-systems that have to be applied specific maintenance plans. In this paper is presented basically the maintenance plans to the helium-cadmium laser head due to the high costs associated with it and its particular influence in the process speed and quality.

3. Methodology

It is possible to organize the flow diagram (Figure 3) in different and appropriate sub-system to maintenance. Each of the sub-system had specific plans for the maintenance but it was strongly focused on the corrective maintenance. Obviously the corrective plan is not appropriated to a process that claims to be rapid. Consequently it was necessary to implement and to adapt maintenance plans to all sub-systems looking forward to speed, quality and low costs target. Figure (5) presents the arrangement of maintenance plans that were used for each 10 main sub-system and the objective that is presented in this work changing from corrective plans to predictive, preventive, adaptive and perfective maintenance plans. The division between each type of maintenance plan is based on those found in Blanchard et al (1995).

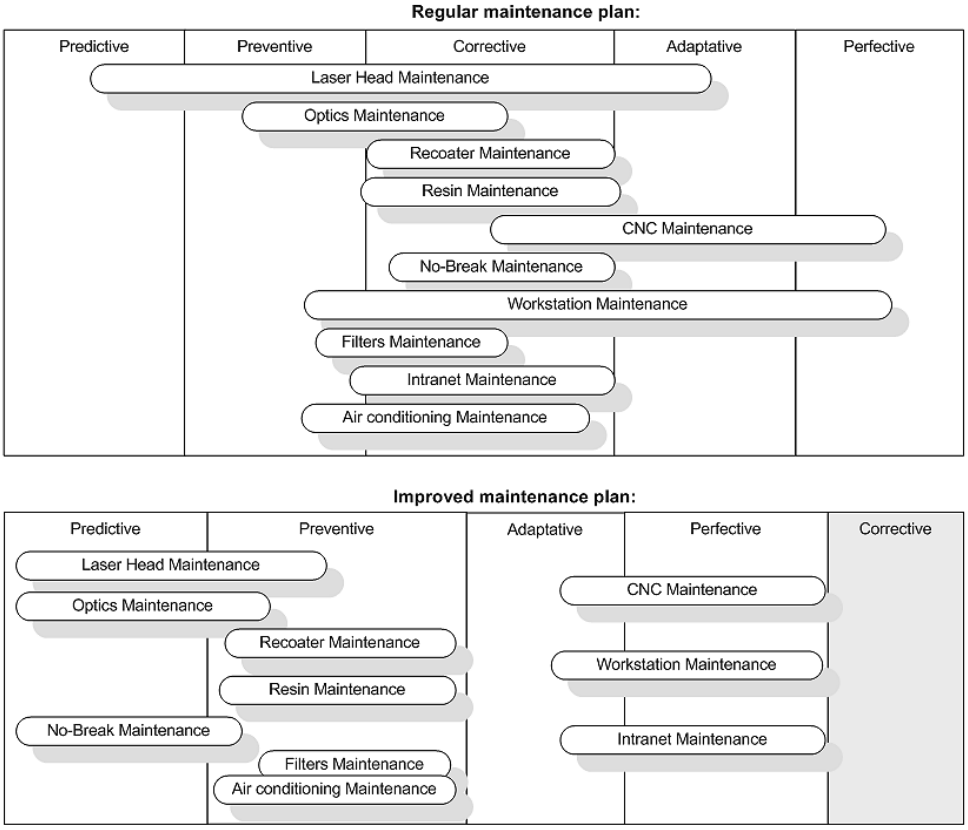


Figure 5: Differences between the corrective maintenance plans and the new strategy to avoid corrective actions.

Since there were establish the type of plans that should be implemented for the sub-systems it was necessary to apply tools to identify the critical components of each system, how they affect the process and what would be more appropriated actions to implement.

Although there different levels of impacts of each sub-system, this paper presents the use of FTA – Fault Tree Analysis and FMEA – Failure Mode and Effects Analysis tools applied to the sub-system related to the laser beam head, considering all parameters involved to it.

3.1. Fault Tree Analysis - FTA

The FTA was applied to identify the lowest failure levels in all process. The top event that was considered was a defective part made in the machine. A defective part could be a part with dimensions outside from the tolerances limits, a part with material properties outside the specifications, a complete deformed part or even a power failure leaving an uncompleted part. Figure (6) shows the Fault Tree Analysis obtained to the stereolithography process.

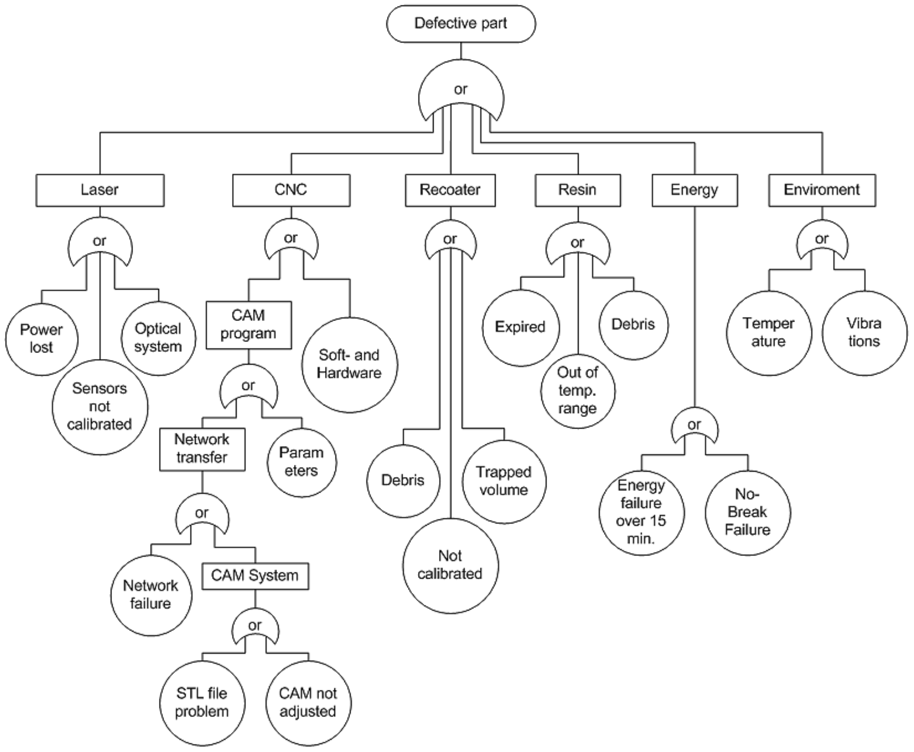


Figure 6: FTA to the stereolithography process considering the top-event a defective object manufactured in the machine.

Using FTA was possible to identify and to analyze the better the failures that affects object manufacturing. It is possible to see that are several basic events that can affect the high performance of the stereolithography process. Nevertheless it does not show how critical these failures are, how often they happen and if they are easy to identify. So it was necessary to apply a second tool: the FMEA.

3.2. Failure Mode & Effects Analysis – FMEA

The FMEA was used to detect those sub-systems that need more attention in the process, analyzing for each failure identified in the FTA what was it impact in the process, how often it happen and how easy to identify. Each failure is classified with scores. High scores indicate that the analyzed item has to be studied to diminish its effect in the process reliability. Also it is possible to observe the direct impact of maintenance actions in the item score. Table (1) is extracted from a complete FMEA table to all sub-systems of the stereolithography process.

Table 1. A part of the FMEA table for the laser head only considering the “power lost” failure mode.

Item	Failure mode	Effect	Severity	Causes	Occurrence	Current control	Detection	RPN(*)	Recommended actions:	Action results			
										Severity	Occurrence	Detection	RPN(*)
Laser head	Power lost	Longer build time	7	Cadmium deposition in diode front	7	Monitoring and documentation	3	147	Re-melt procedure;	1	7	3	21
				Diode misaligned	6		3	126	Diode alignment;	1	6	3	18
				Sensors not calibrated	5		3	105	To calibrate sensors;	1	5	3	15
				Helium lost	4		3	84	Replacement of the laser head;	1	4	3	12
				Dirty optics or defocused	3		5	105	Optics Maintenance;	1	1	4	4

(*) RPN – Risk Priority Number = Severity x Occurrence x Detection

Using the results obtained form the FTA and the FMEA it have been started actions to implement an improved maintenance plan to the sub-systems of the stereolithography process. Furthermore is presented an implement plan to the maintenance of the laser head of the stereolithography machine.

4. Results

The Helium-Cadmium laser head has a minimum life-time warrant of 2000 hours. The laser head manufacturer claims a warranty for the power of the laser beam remains at least 75% of the nominal value after the 2000 hours or during one year. For example, a laser head with 40mW of nominal power have to be, at least, at 30mW after 2000 hours otherwise the manufacturer will exchange the laser head. The laser power fades with the time as it goes down and the time to polymerize the stereolithography resin increases. Laser power lower than 15mW gives an instable laser beam diameter and it is not economically viable to build parts.

Based on documentation and data about the laser head power variation along its time life it is possible to follow how the power changes in time as showed in Fig. (7).

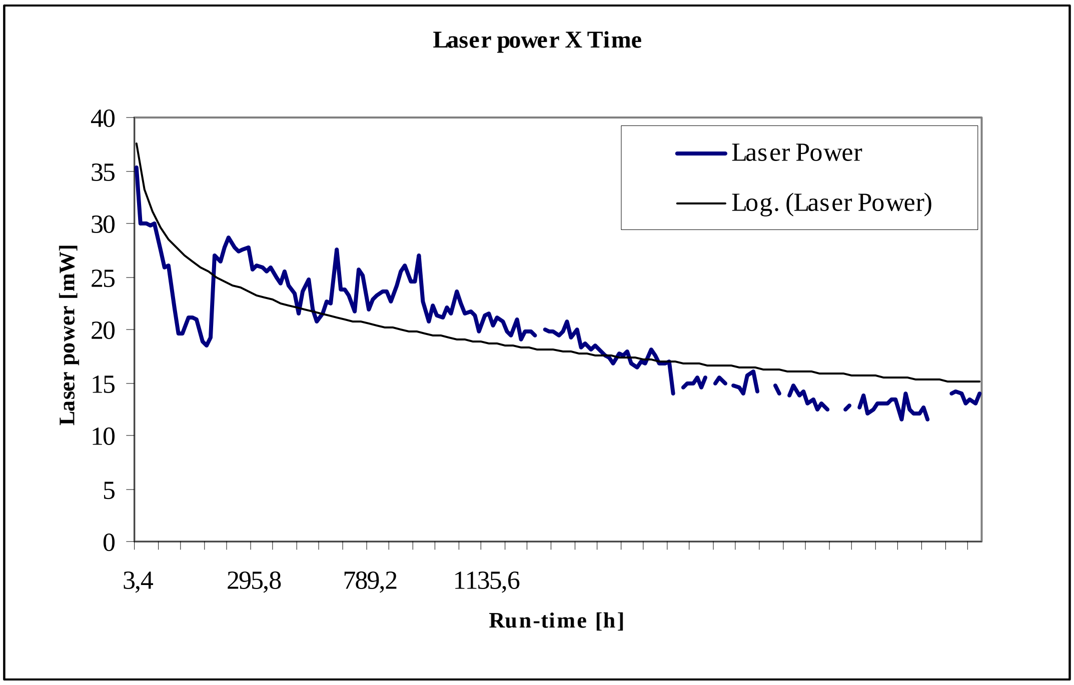


Figure 7: Power lost data from the laser head.

The graph in Fig. (7) shows that the laser power has a strong variation and it decreases quickly. Using this kind of data and documentation it is possible to identify many anomalies in the laser beam. The anomalies identification activates predictive maintenance plans and the documentation helps to apply preventives plans. Moreover, the anomalies and natural changes in the laser beam activates perfective maintenance plan for the CAM system in the workstation.

To manage all the information it was necessary to place the sensors readings inside one database software that could store and associate programmed actions to each identified anomaly. So a database was created and prompted actions are automatically showed to the user as he feeds the database with the latest readings. Figure (8) presents the logical sequence to filter the data and identify the more appropriated action.

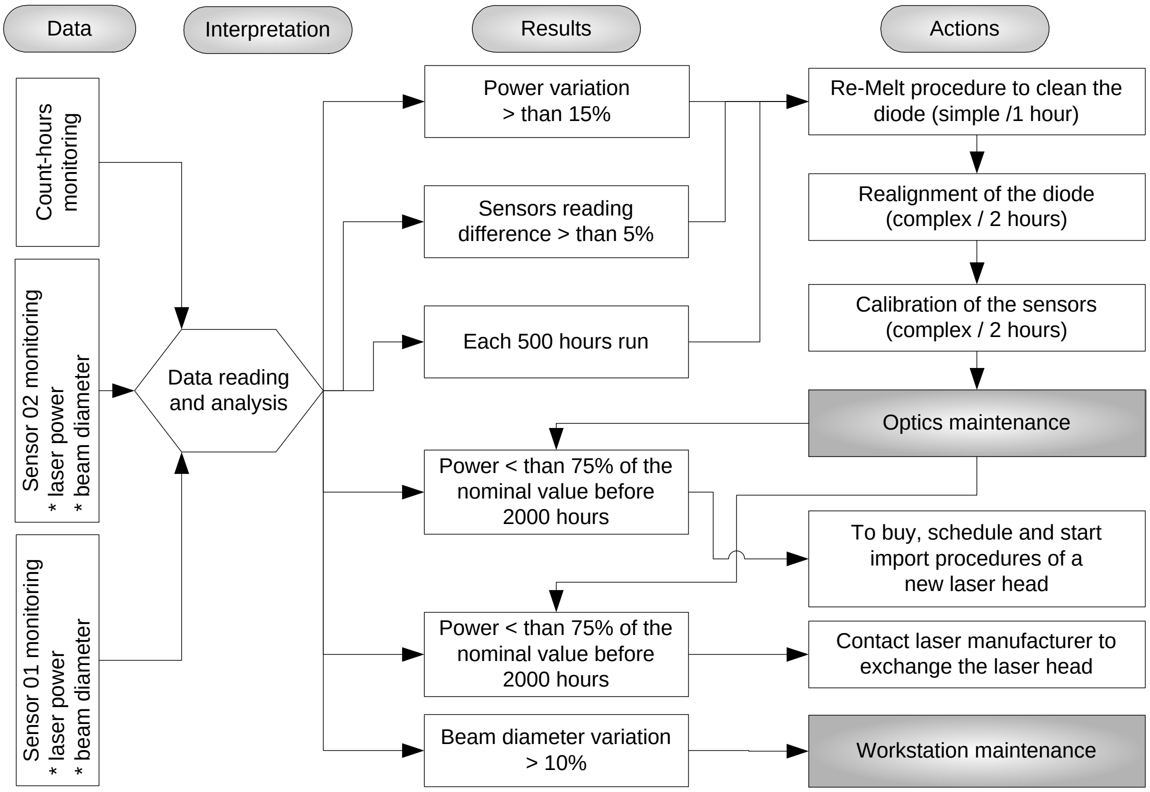
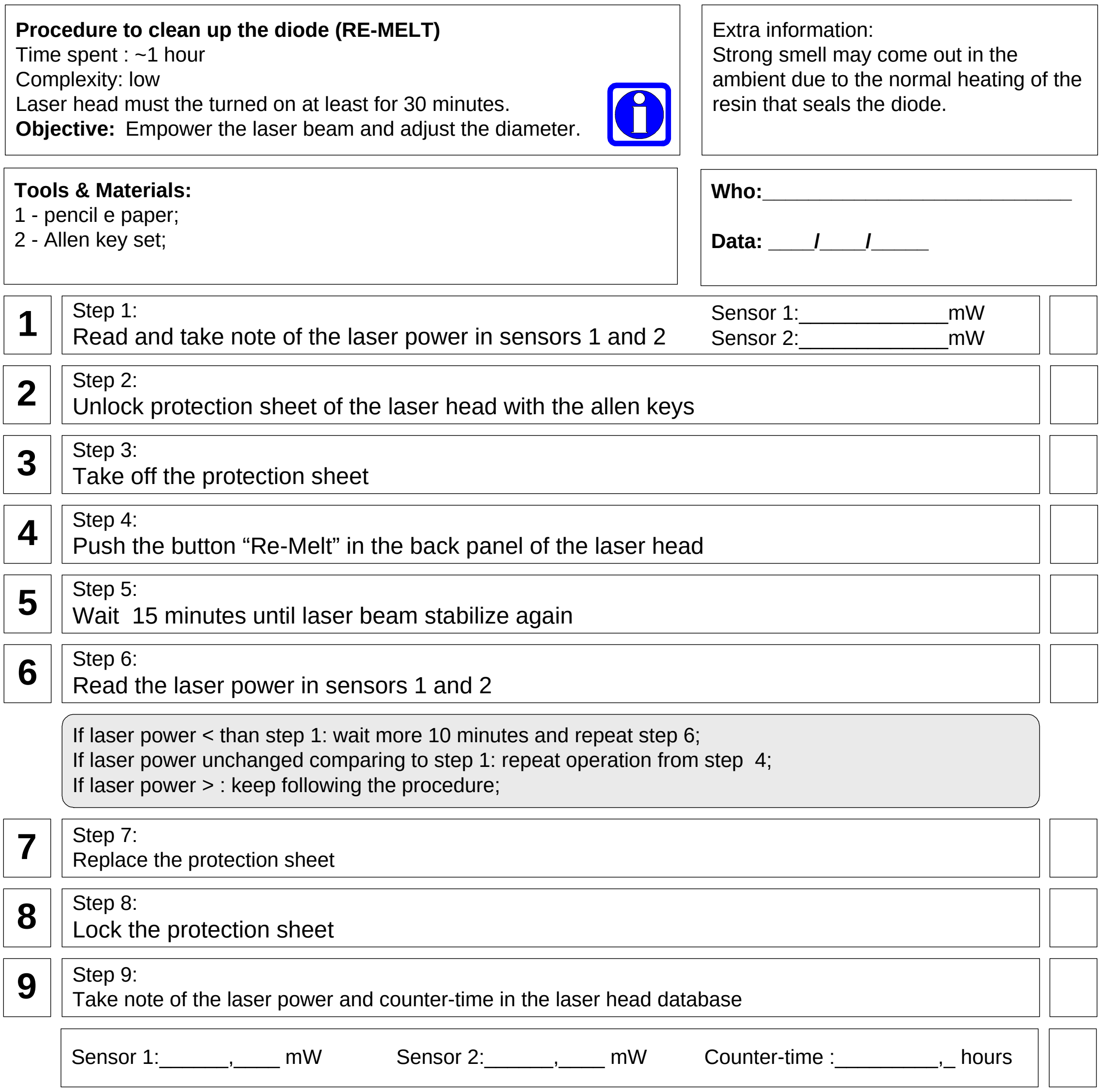


Figure 8: Flow diagram to the maintenance plan for the laser beam head.

In Fig. (8) there are actions that activate the maintenance plans to other subsystems (optics & workstation). In this logica3l procedure also is inserted the necessary time to execute the task and its complexity. The workstation and optics maintenance are not activated only after the maintenance of the laser head. They have also different maintenance and actions but their plans may be activated after the maintenance of the laser head. Furthermore, each action needs a documented procedure to follow. The document is a check-list that gives information to the operator about the sequence that needs to be follow and what should be expected. Figure (9) shows a document for the Re-Melt procedure to the laser head.



Procedure to clean up the diode (RE-MELT)
Time spent : ~1 hour
Complexity: low
Laser head must the turned on at least for 30 minutes.
Objective: Empower the laser beam and adjust the diameter.

Extra information:
Strong smell may come out in the ambient due to the normal heating of the resin that seals the diode.

Tools & Materials:
1 - pencil e paper;
2 - Allen key set;

Who:______________________________

Data: ____/____/_____

1	Step 1: Read and take note of the laser power in sensors 1 and 2 Sensor 1:______________mW Sensor 2:______________mW	☐
2	Step 2: Unlock protection sheet of the laser head with the allen keys	☐
3	Step 3: Take off the protection sheet	☐
4	Step 4: Push the button “Re-Melt” in the back panel of the laser head	☐
5	Step 5: Wait 15 minutes until laser beam stabilize again	☐
6	Step 6: Read the laser power in sensors 1 and 2	☐
	If laser power < than step 1: wait more 10 minutes and repeat step 6; If laser power unchanged comparing to step 1: repeat operation from step 4; If laser power > : keep following the procedure;	
7	Step 7: Replace the protection sheet	☐
8	Step 8: Lock the protection sheet	☐
9	Step 9: Take note of the laser power and counter-time in the laser head database	☐
	Sensor 1:______,____ mW Sensor 2:______,____ mW Counter-time :_________,_ hours	☐

Figure 9: Re-Melt procedure guide.

Every technical intervention a detailed procedure was created and it is easy to access because it is connected to the database. The executed procedures that are printed are placed inside the machine book log for future research of past actions.

5. Discussion & Conclusions

The results obtained using tools like FTA and FMEA are very interesting. First of all they aid to identify clearly the weak links in the process. The FTA helped to identify and separate the process in smaller parts (sub-systems) that are easer to control, understand and to apply maintenance plans. The FMEA had characterized the critical sub-systems and how simple actions may reduce they impact over the process.

Centering the information inside a database will be very useful to estimate the MTBF (Mean Time Between Failures) for the sub-systems and components of the machine. With the MTBF values will be possible to apply better preventive plans to the process.

Moreover the database with programmed actions after processing readings from sensors has proven to be an effective tool. Connected to the procedure documents, it is very easy to use and establish a documentation procedure in the maintenance actions of the process. So information is not lost when turnover of people happens.

Implementing maintenance plans is not simple and requires cultural exchange. The database does not read by itself the sensors and it is useless without the data. Also it is necessary to continuously improve the procedures of the actions from the maintenance plans to keep it clear and easy to manage.

As a result of the maintenance plans implemented to the stereolithography have proven to turn the process more reliable. It is important to note that a maintenance plan can not be used only in the machine but to the complete process as empathized in this work otherwise it is not possible to achieve time, quality and costs required to this manufacturing technology.

6. References

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