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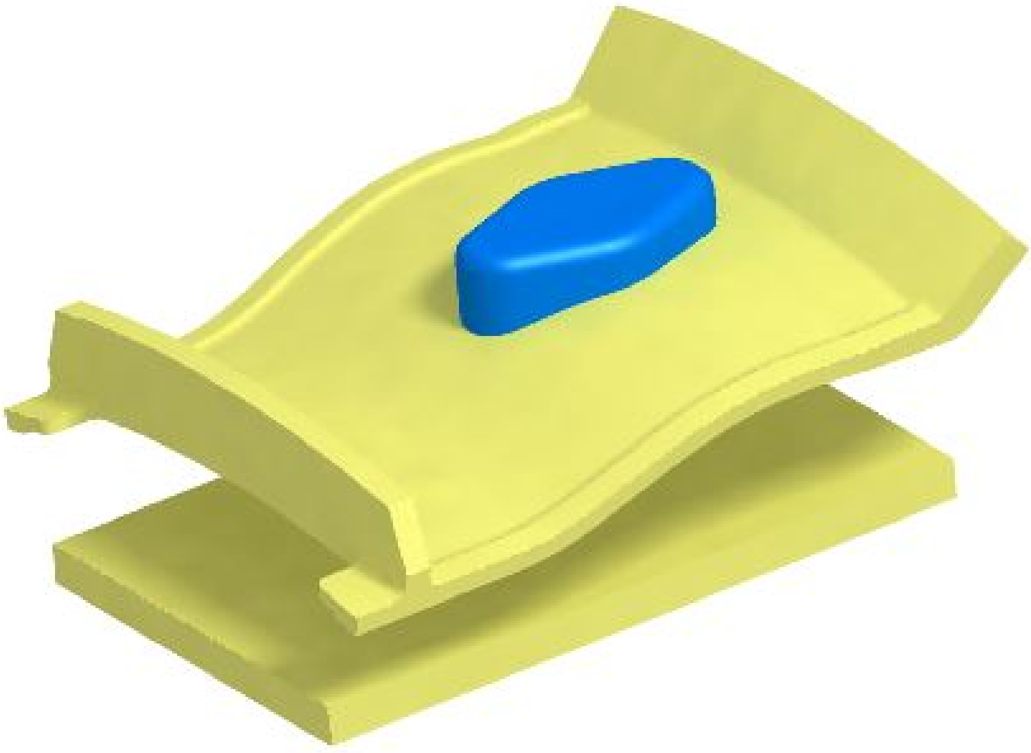

Geometrical Locating Scheme for Complex Hybrid Manufacturing

"Multiple Additive Manufacturing & Machining"

Master's thesis in Master's Program Product Development

ADVAITH MARAGOWDANAHALLI SOMASUNDAR

DAVID PAUL

Department of Industrial and Materials Science
Division of Product Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's thesis 2019

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David Paul

Supervisor: Johan Berglund, Research Scientist at RISE IVF
Supervisor: Vaishak Ramesh Sagar,Doctoral Student at Department of Industrial and Materials Science, Chalmers
Examiner: Kristina Wärmefjord, Deputy Head of the Department, Industrial and Material Science

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Department of Industrial and Materials Science
Division of Product Development
RISE IVF,Mölndal
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Advaith Maragowdanahalli Somasundar
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Abstract

The technology of additive manufacturing is rapidly developing as one of the most sustainable alternatives for the traditional manufacturing processes. Additive manufacturing technologies offer numerous advantages such as weight reduction, design freedom, reducing material waste and so on. But to manufacture complex components, the traditional manufacturing processes are still needed to obtain the final desired geometry.

DiSAM is one such project that is happening in Sweden, aiming to improve the technology readiness of additive manufacturing processes. A complex aircraft component is being manufactured in this project using both additive manufacturing and traditional manufacturing processes. In this process of complex manufacturing where, multiple additive manufacturing processes and machining processes are involved, the effect of the locating scheme in each step of manufacturing process plays a vital role in providing the desired geometrical accuracy.

This thesis work was carried out to develop a locating scheme that was most suitable to follow in this complex manufacturing process chain. The component from the engine exit structure of a gas turbine engine which is termed as "H-Sector" was the product in focus.

Information was collected through interviews with the stakeholders of the DiSAM project. The manufacturing process flow was studied to finalize on the parameters that affects the geometrical accuracy at different manufacturing steps. The critical areas of the components were identified which needs to be focused in developing locating scheme at each manufacturing step.

The software RD&T was used in evaluating the locating schemes. Different locating scheme strategies were developed. Sensitivity analysis was carried out to compare between the strategies and finalizing on the final locating scheme.

This thesis outcome will help in making decisions regarding the locating scheme for the DiSAM project. The same method can be followed in developing different locating scheme for different geometry in the future.

Keywords: H-sector,locating scheme,SLM,LMD,machining,RD&T

Acknowledgements

We would like to express our gratitude to all who have helped us in completing this project. Special gratitude to our examiner Kristina Wärmefjord for her instructions and guidance in the thesis project.

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Advaith Maragowdanahalli Somasundar & David Paul; Gothenburg,2019

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List of Acronyms

2D	Two dimension
3D	Three dimension
CAD	Computer-aided design
DiSAM	Digitalization of Supply Chain in Swedish Additive Manufacturing
EDM	Electrical discharge machine
LMD	Laser metal deposition
NA	Not applicable
NDT	Non destructive testing
PBF	Powder bed fusion
RD&T	Robust design and tolerences
RMS	Root mean square
RT	Radiographic testing
SLM	Selective laser melting
STL	Standard triangle language

1
Introduction

This chapter introduces the background of the project and different uncertain areas of the project. A number of research questions have been stated and addressed in this project. This chapter also includes a brief introduction to the DiSAM project of which this thesis is a part of.

1.1 Background

The technology of additive manufacturing is being used in prototyping, production equipment and end products but the application is still relatively limited. In order to get the maximum impact of the technology, it is important to explore it further. This helps the companies evaluate the advancement in technology before implementation. The DiSAM project is aiming to create such platform by developing the strategies that can make companies to understand the readiness of the technology of additive manufacturing to be implemented in their production process. This thesis study is a part of DiSAM project dealing with locating schemes and geometrical assurance. A Locating scheme is a strategy of positioning and supporting the parts for manufacturing process, assembly process or for inspection process.

Since, complex manufacturing involves many processes like additive manufacturing, machining and other post processing; it is important to have a common geometric locating scheme or a robust strategy for locating schemes throughout the process steps. There are challenges relating to geometries, limitations in machines and fixtures. Additionally, there could be variation propagation throughout the different processing steps depending on the chosen locating scheme. The purpose is to come up with a strategic solution to answer this problem.

1.2 Problem Formulation

As there are many processes involved in securing the finished part starting from additive manufacturing, machining and other post processing like polishing etc, it is important to study the effects of each manufacturing process step, on the geometrical quality of the final product. The contribution of the different manufacturing processes might bring in variations to the final product at different points. In order to overcome these problems, following points were listed to form the base of this thesis project.

- Study about the different processes involved in the manufacturing of the specified part to know about the possible variations that could occur in each process.
- Study about the present locating schemes for the processes involved in the manufacturing.
- Can some process be avoided or replaced with other process to avoid the variations to the final product?
- Can the same locating scheme be used throughout the process?
- How to have common locating scheme for additive manufacturing and traditional machining?
- If common locating scheme is not possible, how can it be compensated to provide required geometrical assurance?
- Work on the alternative solutions.

1.2.1 Purpose

The purpose of the project is to develop a locating scheme for all the processes involved in the manufacturing of the finished product. The report should serve as a base in development of a locating scheme when there are multiple hybrid manufacturing processes involved.

1.2.2 Objective

The objective of this project is to perform literature studies about locating scheme for manufacturing processes. This information is used to identify the parameters that possibly induce geometrical variation in the product at different steps. After specifying the parameters contributing to the geometrical variations, a locating scheme strategy is developed which practically will be used in the production of H sector using different manufacturing processes.

1.2.3 Delimitation

There are several factors involved in the project which is still unclear. In those cases, assumptions have been made to proceed further. Also, there are some dimensions that are not included in this thesis, as listed below.

- The scope of the project just includes two types of additive manufacturing processes, SLM and LMD and the geometrical variation contributors in different additive manufacturing process might have different effect on the geometry of the product.
- The study is conducted for only one material, the end results need to be tested when other materials are considered.
- The results of the study cannot be put out statistically, as the batch quantity of the produced part is very small.

1.3 RISE IVF

RISE IVF is a part of RISE, Research Institutes of Sweden. RISE offers publicly funded research as well as commissioned research for the industries. RISE IVF develops and implements new technologies and new working methods within a range of sectors focusing on product, process and production development. RISE IVF also offer in-depth expertise in relation to materials properties and applications for ceramic, polymer and textile materials. This thesis project was performed at the location in Mölndal.

1.4 H-Sector

The component chosen for the project of DiSAM is termed as H-sector and is shown in the below Figure 1.1. It is a component that has its function in the exhaust section of the gas turbine engine. Since, it is an aircraft component, the geometry has to be very accurate for its efficient functioning. Any variation in the geometrical quality will obstruct the flow of exhaust gases. The actual design has been changed to study the effect of additive manufacturing processes that is replacing some of the traditional manufacturing processes.

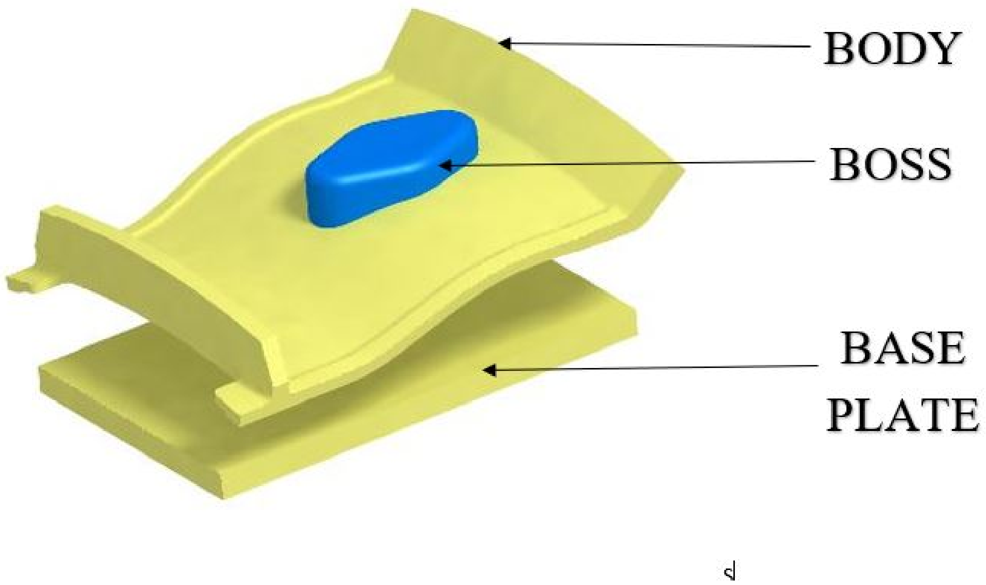


Figure 1.1: H-Sector

1.5 Inconel 718

Inconel 718 is a nickel alloy that contain columbium which is an age-hardening addition that provide high strength and low ductility. It is a high corrosive resistant that can be used in a wide range of temperature between -217^{0}C to 700^{0}C. The material has a good tensile, fatigue, creep and rupture strength which is why it is used in manufacturing components for rockets, air crafts turbine, cryogenic tank age etc. The chemical composition of inconel 718 is shown in the table below [1].

Cr	**Mo**	**Al**	**Ti**	**Fe**	**Nb**	**C**	**Ni**
18.4	4.2	0.3	0.9	17.7	5.1	0.08	Balance

Table 1.1: Chemical compositions of Inconel 718 powder (in weight percent, wt%) [1]

The material is considered to be difficult to machine because of the properties of the materials such as abrasiveness, low thermal properties, high work hardening and the values for the properties are shown below in the table [2].

PROPERTIES	**VALUE**
Elastic Modules	31.3GPa
Poission Ratio	0.3
Density	8193.252 Kg/M^2

Table 1.2: Properties of Inconel 718 [2]

2
Theory

This chapter reviews the literature study performed in the beginning of the project to gain deeper knowledge of additive manufacturing, traditional manufacturing processes and locating schemes.

2.1 Manufacturing Process

The production of the H sector of an aircraft engine involves different manufacturing steps. As the process defined in the DiSAM project, the first step is to print the part using an additive manufacturing process (SLM) and the printed part is heat treated to remove the residual stresses. The next step involves traditional process such as milling to get a smooth and flat surface for further additive manufacturing step. After the process of milling, the build plate from the part is removed using wire EDM process. There is an extra feature printed on the part using Laser Metal Deposition. After the laser metal deposition, the part is finally milled to the required dimensions. The manufacturing process flow is represented as shown in the figure below:

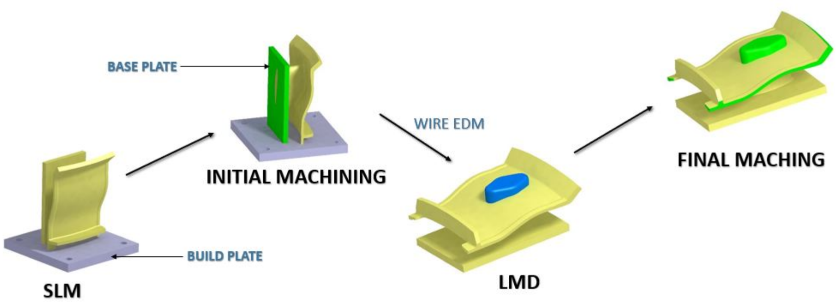


Figure 2.1: Work flow diagram

2.1.1 Additive Manufacturing

Additive Manufacturing is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to substractive manufacturing methodologies. Additive manufacturing is a developing technology launched in the 1980s. Currently, it has practical application in the fields such as manufacturing, medicine and art [3].

With rapid, customized and low-cost products, 3D printing will make a considerable impact on the industrial world. Some other advantages of using additive manufacturing are product customization, ability to manufacture complex structures, minimum inventory turnover, reduction in time to market, less material waste and maximum flexibility.
Current limitations of additive manufacturing include slow building speed, restricted object size, restricted object resolution, high material cost and in some cases, restricted object strength. But there has been rapid progress in the additive manufacturing technology in reducing these limitations and making it a widely accepted manufacturing process [3] [4].

2.1.1.1 Selective Laser Melting

Selective Laser Melting (SLM) is an additive manufacturing process which has working principle based on the Powder Bed Fusion (PBF) technique. The printing in the SLM process is initiated primarily by spreading the material powder onto the base plate of the machine. The laser is then guided to the different points on the powder bed based on the CAD design. The laser melts the powder on the build plate and based on the layer thickness, the build plate is lowered to initiate the printing of the subsequent layer of the part. The process is repeated until the whole part is printed according to the CAD model [5]. The different components of the SLM machine is as shown in the figure below.

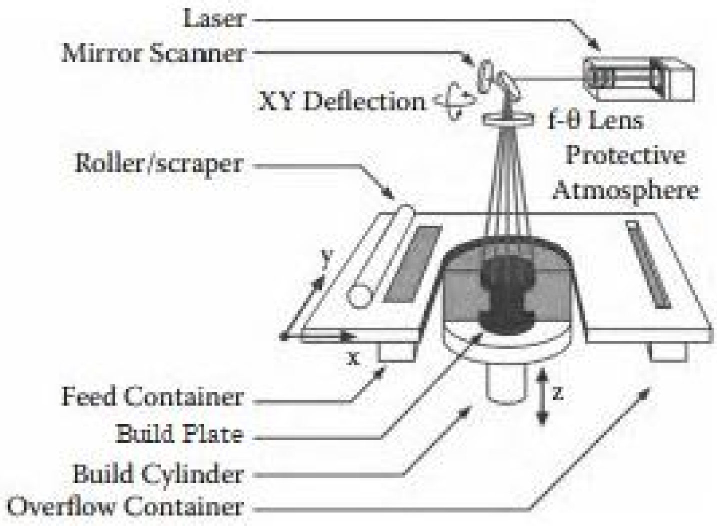
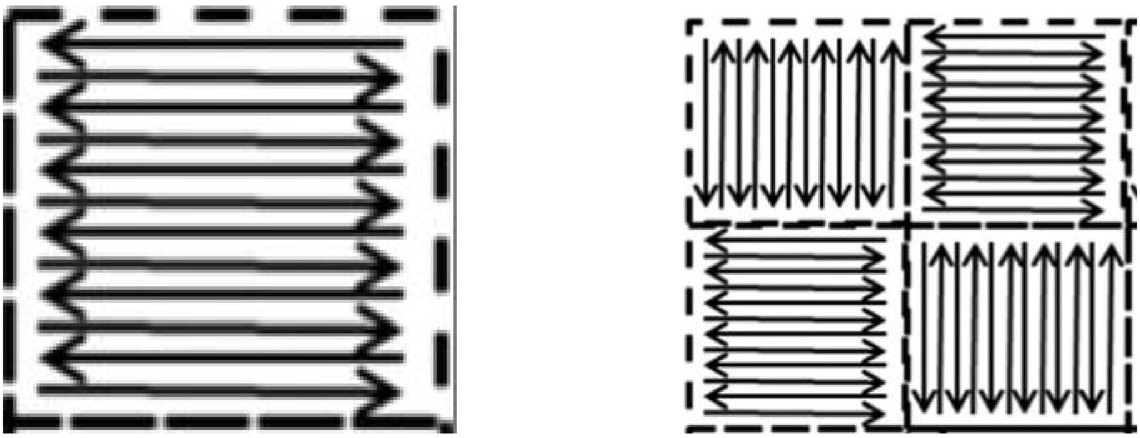


Figure 2.2: Selective laser melting [6]

There are several process parameters that influence the mechanical properties and the geometrical properties of the SLM printed part. Such parameters are:

- **Build direction:** The laser scanning pattern is parallel to the build direction. The direction of the grain growth is according to the thermal gradient. Thus, the orientation of the build model will have the influence on the mechanical properties of the part [5].

- **Scan strategy:** The laser scan strategy can make a considerable effect on the micro structure of the printed part. The two commonly used scan strategy are "Back-and-Forth" sequential scan strategy and the "Island" scan strategy. The Back-and-Forth strategy has the laser beam moving back and forth scanning the powder as shown in the below Figure 2.3(a). In the Island strategy, the print pattern is in the form of checker board that contains many small squares as shown in the Figure 2.3(b). These squares are then exposed to laser beam randomly. The choice of scan strategy will give rise to different micro structure [4] [5].



(a) Back and Forth **(b)** Island

Figure 2.3: Scan strategies [7]

- **Hatch angle:** Hatch angle is defined as the change in direction of the laser between consecutive layers. The hatch angle of 0° means the direction of the laser is in the same direction for every layer and if the hatch angle is 90°, it implies that the four layers needs to be printed until the laser comes back to the original direction [8] [5].
- **Energy density:** Energy density is the amount of heat per volume the powder bed is subjected to. It affects the melt characteristics of the powder. The four main parameters that governs the energy density are namely laser beam power, scanning speed, hatch distance and layer thickness. The relation between the four parameters and the energy density is expressed in the below equation.

$$E = \frac{P}{v \times h \times t} \tag{2.1}$$

  Where, E is the energy density in inJ/mm^3, P is the laser power in W, v is the scanning speed in mm/s, h is the hatch distance in mm and t is the layer thickness in mm.
- **Metal powder:** Apart from the process parameters, the AM powder used can influence the mechanical and physical properties of the final build. The main

powder characteristics that affects are powder morphology, powder granulometry, surface chemistry, packing density, powder rheology, thermal and optical properties [5].

2.1.1.2 Laser Metal Deposition

Laser metal deposition (LMD) is an additive manufacturing process which combines both laser and powder processing for high precision complex manufacturing. The commonly used lasers in a LMD process are diode lasers, CO2 lasers and Nd:YAG lasers which are controlled in z direction [9]. The high energy laser is focused on to the workpiece using a lens while the powder feeder delivers powder into a gas delivery system via the nozzles. The required geometry is obtained by moving the workpiece in the x-y direction by a computer-controlled system under the beam-powder interaction zone. The three-dimensional component is built by depositing consecutive layers one above the other [10]. The different components of the LMD machine is as shown in the Figure 2.3. The LMD process have several process parameters that are explained below which are of great importance.

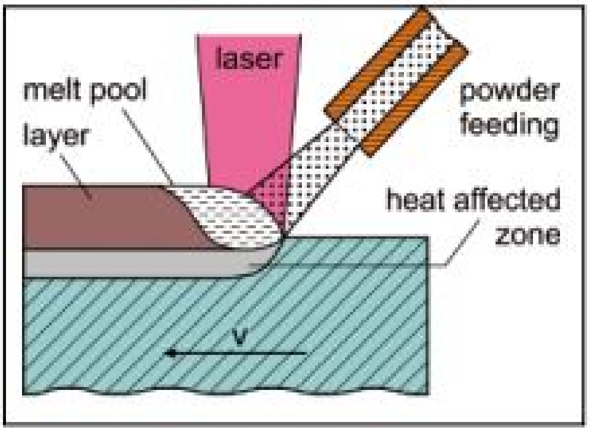


Figure 2.4: Laser metal deposition [11]

- **Laser power:** The power of the laser is an important process parameter in LMD, it effects the width of the deposition, penetration depth and surface finish. When the laser power is low it is then suitable for a columnar grain structure and if the laser power is too high it would lead to undesired keyhole weld [9].
- **Laser standoff distance:** The spot size of the laser is affected by the laser standoff distance which affect the energy density of the laser. According to the equation (2.2) radius of the laser spot has a squared relationship to the energy density [9].

$$I = \frac{L_{\mathrm{p}}}{{w_{\mathrm{o}}}^2 \times \Pi} \tag{2.2}$$

Where I is the energy density in W/mm^2,L_p is the laser power in watts and w_o is the laser spot radius in millimeters.

- **Scanning speed:** The scanning speed is the most important parameter in LMD process. A lower scanning speed give higher energy input which lowers the thermal gradient by increasing the temperature build up in the underlying layers. A lower scanning speed also lead to the solidification velocity which in turn lead to a more columnar structure [9].
- **Powder feeding rate:** The powder feeding rate has an effect on the built height, laser attenuation and powder particle temperature. A higher powder feeding rate would provide more material to the melt pool which cause large deposition [9].
- **Powder standoff distance:** The powder standoff distance is defined as the distance between the nozzle tip and the surface of the substrate where the powder is deposited. When the standoff distance is zero then the powder utilization efficiency is maximum [9].
- **Sheild and carrier gas flow:** The main purpose of the carrier gas is to transfer the metal powder from the feeder to the melt pool. These gases protect the metal powder from reacting to oxygen and nitrogen at high temperature preventing formation of oxides and nitrides. For a high velocity of the gas flow the powder density would be lesser which effects the efficiency of the process. The gas flow also protects the laser optics from repelling and damaging [9].
- **Overlap fraction:** When two adjacent deposits overlap each other, it could influence the grain structure, residual stress distribution and surface finish. At lower overlap the surface finish and dimensional precision is high but leads to more columnar grain structure [9].
- **Height step:** The distance moved by the equipment in the height direction between two deposit layers is called the height step. The value is set to be fixed which depend on the geometry of the wall [9].

2.1.2 Milling

Milling is a material removal process that is used to produce parts which are not axially symmetric and having additional features like holes, slots, pockets etc. The main components of a milling process are the milling machine, workpiece, fixture and cutter. The workpiece is fixed to the fixture and placed on the milling machine for the cutting process. The cutter which is the cutting tool with sharp teeth rotates at high speed and the workpiece is moved towards the cutter. The material is removed as chips to create the desired shape [12]. The process of milling is represented in the figure below.
In milling the parameters are selected according to the material, tool size, tool materials etc. The parameters of the milling process are:

- **Cutting feed:** The distance that the workpiece is advanced for one revolution of the cutting tool which is measured in inches per revolution [12].
- **Cutting speed:** The relative speed of the workpiece to the tool during a cutting operation is defined as cutting speed [12].
- **Spindle speed:** The rotating speed of the spindle to which the tool is attached which is measured in revolution per minute [12].

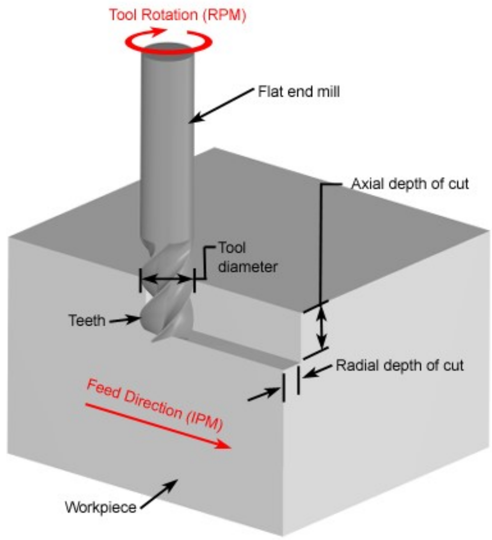


Figure 2.5: Milling [12]

- **Feed rate:** The rate at which the material is removed from the workpiece which is measured in inches per minute [12].
- **Axial depth of cut:** The depth of the tool that it advanced after each cut which is measured in the axial direction, with respect to the tool. The axial depth of cut is inversely proportional to the feed rate of the milling process [12].
- **Radial depth of cut:** The depth of the tool along the radius in the workpiece when it makes a cut. The radial depth of cut is inversely proportional to the feed rate [12].

2.1.3 Wire EDM

The electronic discharge machining comes under the non-conventional machining techniques. The process involves removing of unwanted material by electrical expulsion trapped between tool and the workpiece in the presence of dielectric fluid. In the machining process, tool is attached to negative, so called as cathode and the workpiece is the anode. Dielectric fluid used are distilled water, kerosene or transformer oil [13].
The wire EDM process involves eroding of the material using thin single stranded by guide metal wire surrounded by deionized water to conduct electricity. In this process, tool electrode will be in the form of wire. To avoid the breaking of wire, it is wound between two spools and the active part of the wire keeps changing throughout the process [13]. The typical wire EDM machine is as shown in the Figure 2.5.

2.1.4 Heat Treatment

Heat treatment is a process of heating the material to certain temperature and cooling it down in a particular manner to obtain desired mechanical and physical

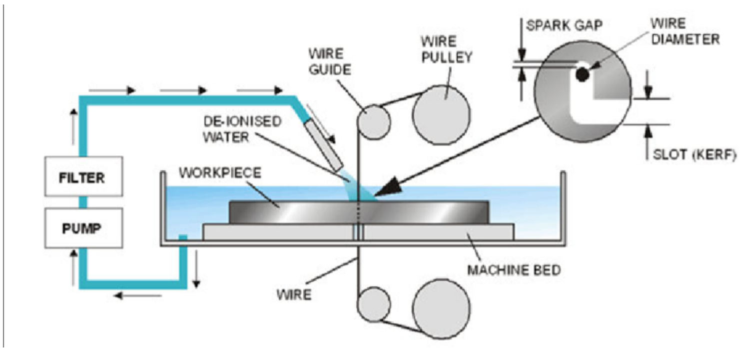


Figure 2.6: Wire EDM [14]

properties.
In additive manufacturing-built parts, there are internal stresses produced because of the heat cycles caused by laser melting and inhomogeneous cooling that happens during the process of fusion of the laser melted material. This will cause plastic deformation and residual stresses.
To get rid of the residual stresses induced in the part, the part is heat treated. The part is heated up to certain temperature and then slowly cooled to remove the residual stresses. The slow cooling is very important as it will avoid emergence of new stresses [8].

2.1.5 Non Destructive Testing

Non-Destructive Testing (NDT) is an analysis technique that is used to evaluate the properties of a workpiece without causing damage. This technique is used for resolution of doubts related to the quality of the materials and their manufacturing process. There are different kinds of NDT techniques which are selected according to the availability and requirement [15].

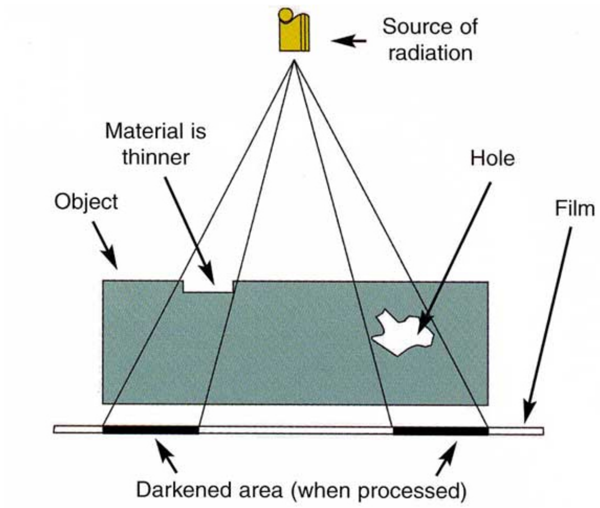


Figure 2.7: Radiographic testing(RT)-Non Destructive testing [16]

In this case, Radiographic Testing (RT) is used to examine the H-sector. RT is a NDT method that examines the volume of the workpiece using the X-rays and gamma-rays. These rays form a radiograph of the workpiece which shows the thickness, defects and assembly details. Compared to other NDT methods RT is considered to be slow and expensive but it detects porosity, inclusions, cracks and voids [17].

In RT technology the X-rays are produced by a X-ray tube and the gamma rays are produced by the radioactive isotopes. These rays are transmitted through the workpiece which fall on to the radiographic film, which measures the various quantities of radiations. The film is processed to develop the image which is used to detect the defects. The defects in the workpiece would affect the amount of radiations received by the film which is interpreted using the developed image as shown in the Figure 2.6. [17].

2.1.6 3D Scanning

3D Scanning is a technology used to capture the shape of an object, person or environment using a 3D scanner to study the geometrical deviations. It produce a 3D file that can be saved, edited and 3D printed. The 3D scanning process are done with respect to physical principles described below.

- **Laser triangulation 3D scanning technology:** The process of projecting the laser beams on to a surface and the measurement is done through the deformation of laser rays.
- **Structured light 3D scanning:** The process of measuring the deformation of light pattern on a surface to 3D scan the shape of the object.
- **Photogrammetry:** The process of reconstructing an 3D object from the 2D captures with help of computational geometry algorithms.
- **Contact-based 3D scanning technology:** The process of sampling the points on the surface which are measured by the deformation of probe.
- **Laser pulse:** Also called the time of flight, the 3D technology is based on the time of flight of the laser beam. The time travel of the laser beam is between the emission and reception which provides the required information [18].

2.1.7 Locating Schemes

A locating scheme is a strategy of positioning and supporting the parts for manufacturing process, assembly process or for inspection. A rigid body has six degrees of freedom which are three translations and three rotations. The purpose of different locating scheme is to lock these degrees of freedom [19]. In an ideal scenario each degree of freedom should be controlled by each point to have an uncoupled system. But in actual case each locating scheme are often coupled by nature since one locating point control more than one degree of freedom [20]. For non-rigid components it requires more than six locators compared to the locating schemes of the rigid bodies. This is done by providing extra supports and it is called as N-2-1 locating scheme [21]. Some of the locating schemes strategies for the rigid bodies are:

- **Orthogonal locating schemes:** In locating scheme, the locating directions are orthogonal to each other. This is one of the most commonly used locating scheme since it is easy to analyze and understand. There are two types of orthogonal locating schemes:

  I) 3-2-1 locating scheme: In this, there are six different points that locks six degrees of freedom. Depending upon the way in which these points are arranged decides which degree of freedom is locked by the particular point. For example see Figure 2.7; there are three primary points (A1, A2, A3) that defines the plane which locks the translation motion in Z direction and rotation motion in X and Y directions. There are two secondary points (B1, B2) that define a line to lock the translation motion in Y direction and rotation in Z direction. The last is a tertiary point (C1) that locks translation motion in X direction [19]. This scheme is suitable for the prismatic parts with orthogonal locating surfaces [20].

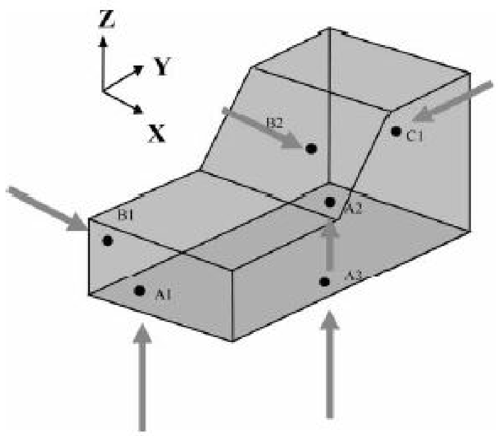


Figure 2.8: 3-2-1 locating scheme [20]

II) 3-point locating scheme: In this locating scheme there are only three points A1, A2 and A3 that control the six degrees of freedom. See Figure 2.8, points A1, A2 and A3 define the primary plane and control translation motion in Z direction and rotation motion in X and Y directions. Points A1 and A2 define the line and control the translation motion in X direction and rotation motion in Z direction. Point A1 controls the translation motion in Y direction. In this locating scheme all three planes are orthogonal to each other [20].

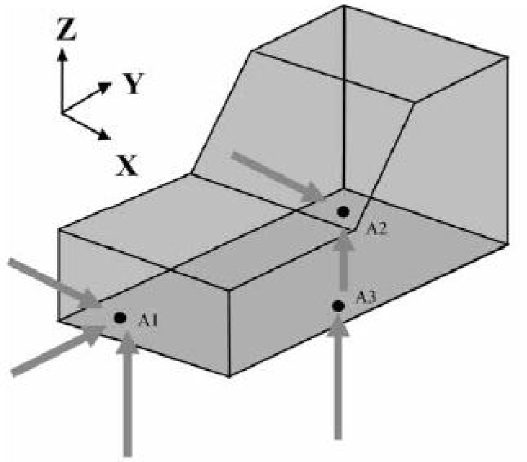


Figure 2.9: 3-point locating scheme [20]

- **Non-Orthogonal locating scheme:** Unlike the orthogonal locating scheme the locating directions are non-orthogonal to each other in this locating scheme. This locating scheme is suitable for prismatic parts that have three non-orthogonal locating surfaces. It is difficult to analyze with respect to robustness and how good the six degrees of freedom are locked. There are two types of non-orthogonal locating schemes [20].

  I) 3 direction locating scheme: In this scheme there are six points which are located in different planes to lock six degrees of freedom. See Figure 2.9, points A1, A2 and A3 are the primary points but A2 is located in a different plane. These points control the translation motion in all three directions and rotation motion in X and Y directions. The secondary points are B1 and B2 control the translation in X direction and rotation in Z direction. Point C1 is the tertiary point which controls the translation in Y direction [20].
  II) 6 direction locating scheme: There are six points D1, D2, D3, D4, D5 and D6 defines the locating directions which are perpendicular to the locating surfaces of the part as in Figure 2.10. Each point on the locating scheme controls all the three translation and rotation motions [20].

- **Locating schemes for curved surfaces:** These are locating schemes which are suitable for non-prismatic parts as shown in Figure 2.11. Similar to the non-orthogonal locating scheme these are difficult to analyze with respect to the robustness and how good the six degrees of freedom are locked.There are six points D1, D2, D3, D4, D5 and D6 defining the locating directions which

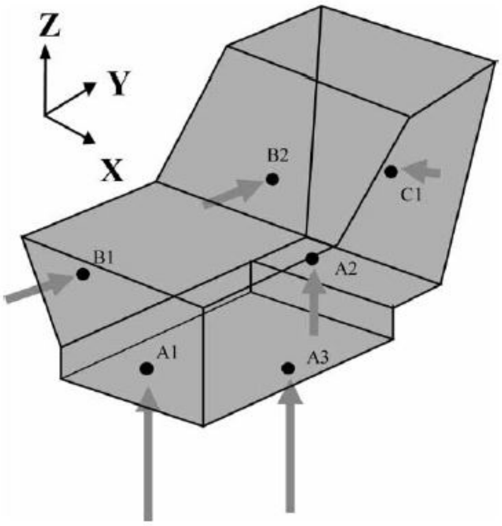


Figure 2.10: 3 direction locating scheme [20]

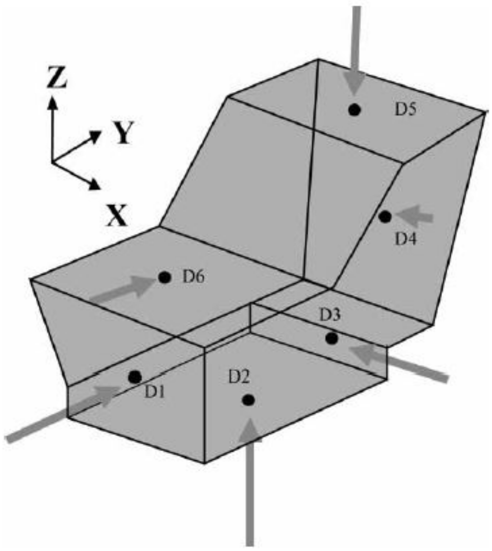


Figure 2.11: 6 direction locating scheme [20]

are perpendicular to the curved locating surfaces of the part. Each point on the locating scheme controls all the three translation and rotation motions [20].

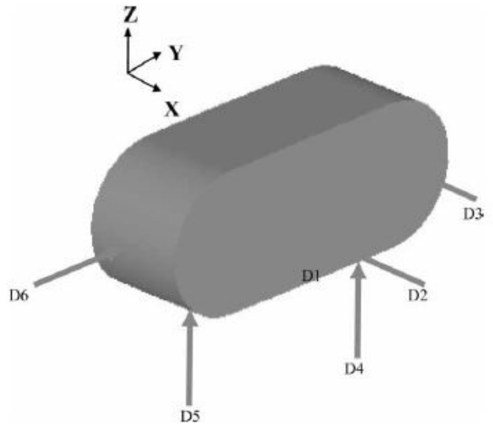


Figure 2.12: Locating scheme for curved surface [20]

2.1.8 Robust Design and Tolerance

RD&T (Robust design and tolerance) is a software that allows to simulate and visualize the effect of manufacturing and assembly variation before creating any physical prototypes. It is a tool that is used to compare the different design concepts and to make a quality decision among the designs [22]. From the early phase of designing to pre-production and production, RD&T software can be a support to have a geometrical assurance for the design concept.

In the initial stage of designing when the manufacturing data are limited the software helps to maintain the geometrical robustness of the design. Later when the manufacturing data is available, it optimizes the selection of tolerance to meet the design, manufacture and cost constrains. RD&T software mainly provide three types of analysing functions that can be used in different stages of design process as explained in detail below.

- **Stability analysis:** Analyze the geometrical robustness of the design by controlling different locating schemes. The stability analysis results are represent by different colour coding. Colour coding is an important tool for communicating the effects of geometrical variation as represented in Figure 2.12. Showing the results as different colour makes it easy to explain the consequences of different locating schemes and compare among different locating schemes [23].

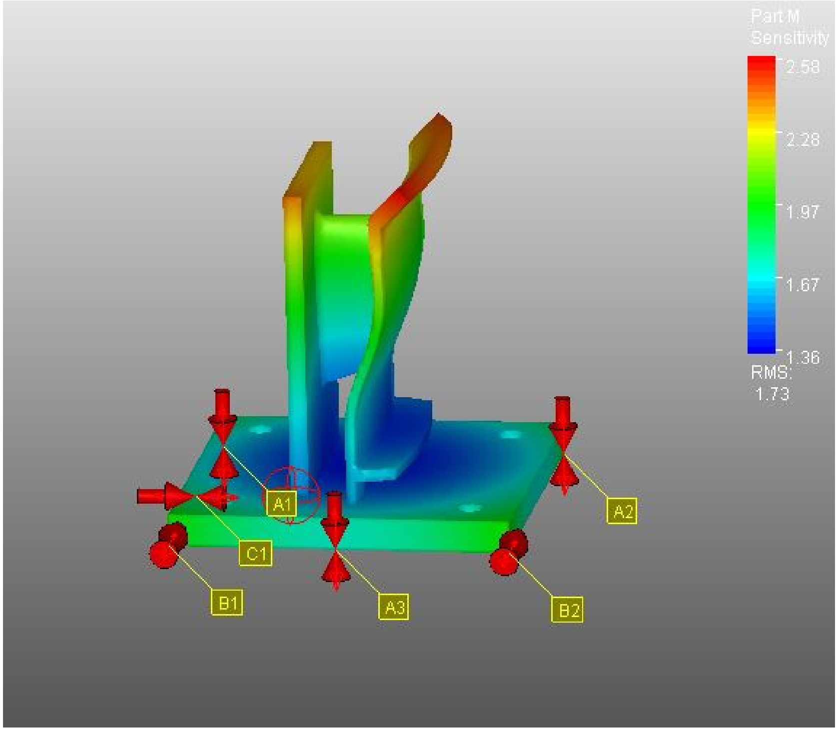


Figure 2.13: Stability analysis in RD&T software

- **Variation analysis:** It analyze the variations in critical dimensions of the design by using Monte Carlo simulation technique. The results are presented in a bar chart that represents the values of total range of variation, six standard deviations, eight standard deviations, mean value of variations, shift of mean value and capability [23].
- **Contribution analysis:** It gives a ranked list of points and corresponding tolerances contributing to the measured variations. The analysis is mainly used to optimize the value of tolerance when sufficient data related to the manufacturing process is available. The analysis also reflects the total influence of the locating points, variation direction and the variation range which suggest improvement for the robustness of the design and reduce variations [23].

3
Method

This chapter gives the detailed overview of how the information regarding the project was collected and structured to list down the factors that can induce the geometrical variation. Also, the tool used to develop the locating scheme strategies and the selection criteria to choose amongst the developed locating scheme strategies are explained in detail.

In the beginning of the thesis, the problem statement was very unclear as there were no established practices of having locating scheme for complex hybrid manufacturing processes. Initially, the efforts were put in to acquire the details about the DiSAM project, stakeholders of the project and responsibility of each stakeholder. The schematic of the procedure followed is illustrated in the below diagram.

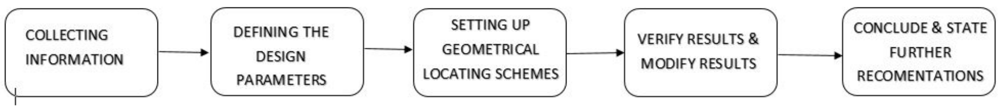


Figure 3.1: Process flow chart

Once the process flow for the production was known, the locating scheme that is generally used for additive manufacturing and traditional manufacturing was observed. Several literature were studied in order to understand the basic principle of locating scheme. This formed the base of the project and several iterations were tried in the RD&T software to understand the trends of sensitivity with different locating schemes. Each step involved is explained in detail in subsequent steps.

3.1 Collecting Information

Since, there are many stakeholders involved in this research project and each one of them had different roles and responsibilities, meeting was arranged with the team to know about the project better and the manufacturing processes involved. Information about several engineering and technical aspects were acquired from literature studies.

3.1.1 Literature review

At the beginning, literature studies were conducted to mainly acquire deeper knowledge on additive manufacturing, traditional manufacturing and robust design. Some literature regarding the locating scheme were studied to understand the theory of locating scheme and the important factors to be considered while developing a locating scheme for any component for traditional manufacturing processes. Literature regarding the SLM machine were studied to understand the different parameters involved in the process of printing as explained in chapter 2. Once after printing, the post processing like heat treatment and 3D scanning was studied as well for the better understanding of the complete process flow for the SLM printing. Few literature survey was also made on the deformation of the printed parts and also the deformation of the build plate. Then, literature were studied on the LMD process about the machine parameters and the general way of orienting the part in the LMD machine. Also, the literature survey was conducted on the milling process and wire EDM to know the basic principle, since it was involved in the manufacturing process chain. Since, the development of the locating scheme was of the main focus, many literature regarding the locating schemes were studied and the literature regarding the software RD&T was also studied as it was supposed to be the software used to conduct the simulations of locating scheme.

3.1.2 Interviews

Some of the key information were collected from the semi structured interviews with the people from the companies involved in DiSAM project. The information about the artifact was given by the GKN as they are the owner of the component. The CAD geometry was shared with everyone once it was finalized. Companies doing process simulations shared the trend of deformation after printing of the artifact, based on which some recommendations are made in the report for further improvement of the locating scheme. The manufacturing company that is involved in DiSAM was able to give valuable inputs about the practicality of the locating schemes that were being developed. The developed locating scheme were practical as it was possible to manufacture the fixtures and have the locating points as proposed. The process flow for the production of the artifact was from the interview at RISE IVF.

3.1.3 Observations

Some of the information was captured through observations of the SLM printing at RISE IVF. Also, some knowledge regarding the milling process were acquired by observing the milling process at RISE IVF. Observing the fixture design for the similar part at Brogren Industries was very helpful in realizing the locating scheme that was being developed keeping the practicality in consideration.

3.2 Mapping Quality Related Parameters

From all the information gathered from the previous steps, it was summarized and structured further to list down the factors that can induce geometric variations in the final artifact. There are numerous processes involved including additive manufacturing and traditional manufacturing for the production of the artifact. The process flow is as shown in the below diagram:

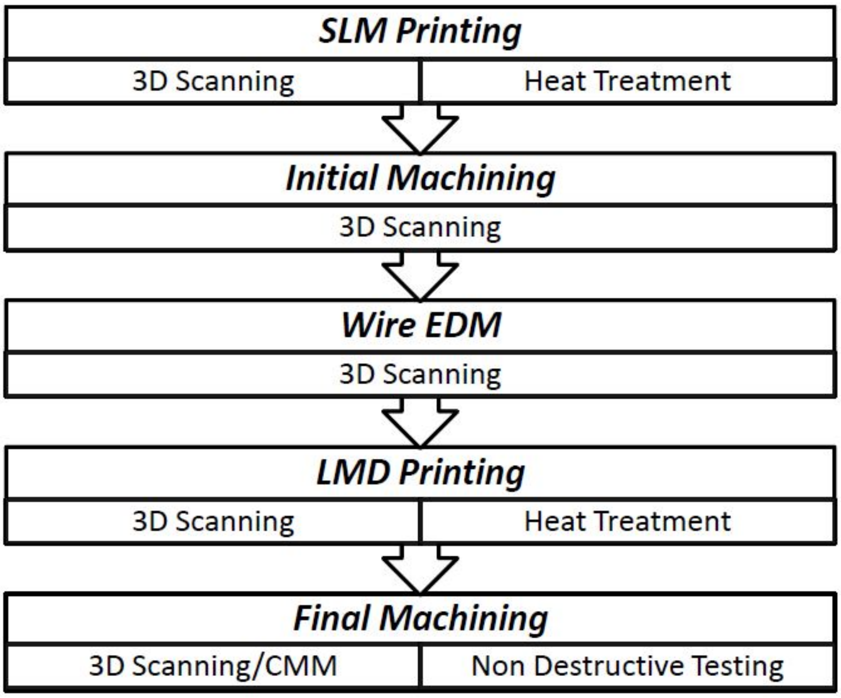


Figure 3.2: Process Flow Chart

As there are many processes involved in the production, each step has the possibility of inducing the geometrical variation in the part. These variations can propagate further throughout the process and effect the complete geometry of the part.

For easier understanding and better representation of the factors contributing to the geometrical variation. Ishikawa diagram was created considering all the factors that is going to contribute for the geometrical variation in each step of manufacturing. The contributors of geometric variation is as shown in the figure 3.3:

The main contributors of the variation can be classified under six main heading namely; Man, Materials, Method, Environment, Machine and Measurement as shown in the ishikawa diagram.

- **Man:** There can be several minor errors from the human that can affect the geometry of the part. These variations can be from human errors, usage of wrong units in the drawings or mistakes in the time of preparation of CAD

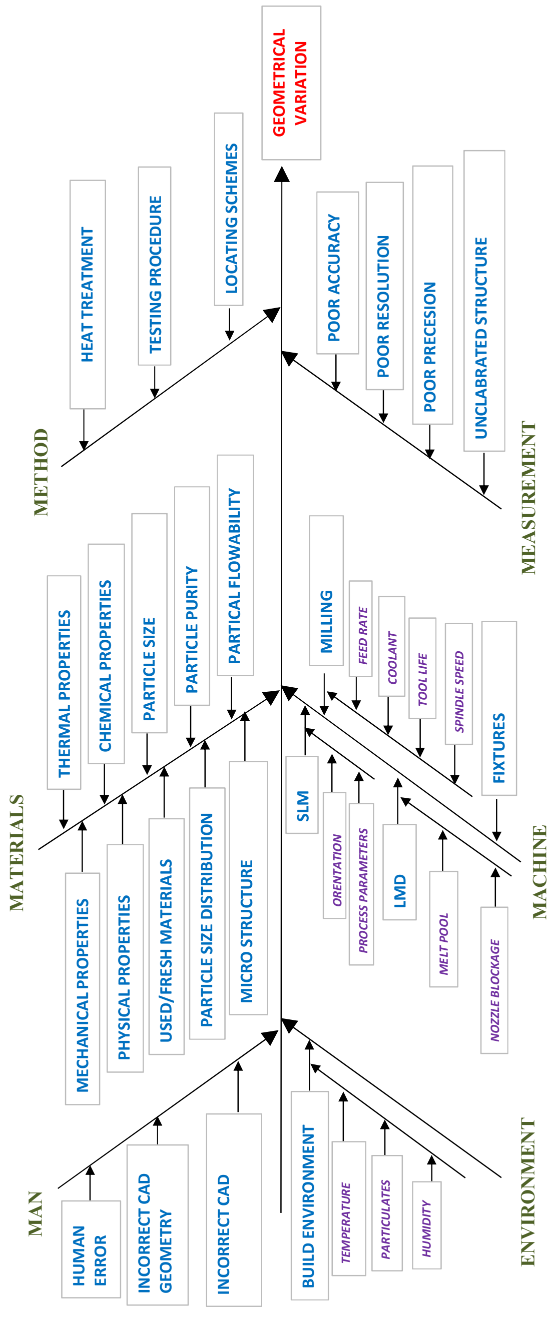


Figure 3.3: Ishikawa Diagram

models. By careful execution and rechecking after each step will eliminate the errors escalating into subsequent steps.

- **Materials:** Materials play a major role in the geometrical quality of the part. In this particular project, since additive manufacturing technologies are involved; the mechanical, thermal, chemical and physical properties can affect the geometry of the final part in different ways. Hence, considering the properties of the material in case of design and using different simulations for such properties might help reducing the variation. The powder characteristics as such as flowability, particle size distribution, microstructure, reused/fresh batch of powder will still affect the geometry of the part and to completely eliminate such contributing factors is too expensive.
- **Method:** Some of the methods used in the process of manufacturing can cause variation in the part if not followed properly. The method for heat treatment, testing and locating scheme can be a crucial factor in maintaining the geometry. The method of heat treatment is decided based on the material used. Since, heat treatment is carried out for 3D printed parts to get rid of the residual stress and to obtain desired physical and chemical properties, it is very important to follow the right heat treatment cycle for the artifact.
  The process of testing, that is 3D scanning which is generally used to compare the dimensions between CAD drawing and the actual part, if the wrong reference points are chosen for the measurement, it might give wrong results and actual geometrical variation becomes hard to calculate. In this particular project, as there are many processes involved including additive manufacturing and traditional manufacturing, the locating scheme plays a vital role in obtaining the geometrical accuracy. The locating scheme has to be in such a way that the geometric variation is not propagated to the subsequent step. So, developing a locating scheme for the different process in this project will be a major contribution in maintaining the geometrical accuracy.
- **Environment:** The building environment includes humidity, temperature, particulates that might influence the quality of the part that is being produced. In case of additive manufacturing processes, the environment is almost maintained inert and there will be negligible effects on the part. During traditional manufacturing processes, the environment remains stable and it is also monitored to be in favorable condition throughout so that it has negligible effect on the geometrical accuracy of the manufactured part .
- **Machine:** The machines involved in this manufacturing processes are SLM printing machine, milling machine, LMD machine, wire EDM machine and 3D scanner. In case of additive manufacturing, process parameters play a major role in maintaining the geometry of the part. There will be a recommended parameter and build orientation that needs to be followed for different materials according to the machine manufacturer. Any mistake in process parameters will induce geometrical variations in the printed part. In LMD process, the melt pool should be maintained adequately and the nozzle should be clear always in the time of printing, otherwise it results in poor geometry. In case of traditional manufacturing, there are numerous parameters as tool life, coolant used, feed rate and spindle speed to concentrate on to get best accuracy.

The fixtures used in this complex process flow is an important factor to be considered. Based on the desired locating scheme, the fixture has to be designed and manufactured. Any variation in the fixture will directly induce the geometrical variation in the part artifact. Even the wrong design of the fixture can lead to poor accuracy of the part.

- **Measurements:** Proper measurement techniques and well calibrated equipments are very important. In the process of manufacturing, there are measurements taken after each step of the process and according to those measurements, the processes are adjusted for better accuracy if there is any deviation. If the measuring equipment has poor resolution, poor accuracy or uncalibrated then, there are high chances of reducing the accuracy of geometrical assurance. To avoid this, proper care should be taken about the quality of the measuring instruments and it needs to be calibrated at certain intervals as defined by the manufacturer.

3.3 Robust Design and Tolerance

As described in section 2.1.8 RD&T is a software that allows to simulate and visualize the effect of manufacturing and assembly variations before creating any physical prototypes. In this section the application of RD&T software will be discussed.

The software was used to recognize the geometrical variation corresponding to different locating schemes and compare these results to select the locating scheme for different processes. Orthogonal locating scheme (3-2-1 locating scheme) was used for the project, since this strategy would help to lock all the six degree of freedom. The orthogonal strategy is explained in detail in section 2.1.7.

For creating different location schemes for all the three manufacturing processes considered in the project some basic rules were followed. Firstly, the primary three points were considered in a plane, placed such a way that the it covers maximum area. Secondly, the two secondary points are selected in a line and thirdly, the tertiary point was selected in the same plane of primary points. The locating schemes for different manufacturing processes is discussed in detail in coming sections.

3.4 Selection Criteria for Locating Scheme

There were factors like practicality of the fixture design and tool accessibility for the machining of the part were considered in the development of the locating scheme strategies. Based on these factors, many locating scheme strategies were developed that was practical. Later on, critical points were identified which would be an important feature on the part. These are the features that are either machined in a particular manufacturing process step, or a surface on which the printing is going to happen. These features of the part are considered as the critical area of the

H-sector. But, still we are left with numerous locating scheme strategies and to choose the best ones out of them was very important. To choose between the large number of strategies that were developed, few criteria were made that would help in screening. The factors considered for concluding with two strategies are listed below:

- **Root Mean Square value of part sensitivity:** Using the RD&T software, the optimized RMS value was found out. Observing those locating points, strategies were developed and compared to the value of the RMS value. It is not possible to have locating points as shown in the optimized locating scheme because of very complex fixture design and tool accessibility. Hence,the locating points were chosen by carefully observing the location of the primary, secondary and tertiary points of the optimized simulation. It was made sure that the primary points are widely spread out forming a plane and is also practical to have a fixture accordingly. Same procedure was followed in choosing secondary and tertiary points as well.
- **Uniform sensitivity:** To have well distributed sensitivity is one of the main factors to be considered while developing the locating scheme. Uniformly distributed sensitivity on the part minimizes the effect of geometric variation. So, uniform sensitivity was one of the factors taken into account to choose the best among the many strategies.
- **Sensitivity at the measuring point:** The measuring points were selected at the critical areas that needs to be considered for each process step. The stability at these points are very important as they are going to be machined and if these points are not stable then it is obvious to increase geometrical variations. So, over the multiple iterations of the locating scheme, it was focused to reduce the sensitivity at the measuring points.
- **Complexity of the fixture:** The different locating scheme requires different fixture designs. The increase in complexity of the fixture will in turn increase the cost of manufacturing. One of the factors that was considered is to reduce the complexity of the fixture. The locating scheme was developed keeping practicality of having the fixture design that would be easy to design and manufacture.

3.5 Locating Scheme Strategies

As mentioned before, the 3-2-1 locating scheme was used throughout in all the strategies, since it was the most suitable strategy for rigid body. The CAD file of the H-sector was converted to the STL (Standard triangle language) format for using it in the RD&T software. The six points was selected on the H-sector and the target points was selected on the fixture which is an imaginary fixture created in the software. The points were picked manually on the part and these points were copied locally on the fixtures. The tolerance was defined for each point and it was assumed to be 0.1 linear. In order to analyze the effect of the locating scheme stability analysis was conducted and the colour coding was set between the range of 0-3. The reason why the range was fixed to 0-3 was, in all the trials the RMS value

was always around two.
The sensitivity of the part was examined in general and on critical measurement points in the stability analysis. The measurement points was selected in areas where the machining was about to start and on the critical spots on the part. For the three-manufacturing process different strategies was tried and these strategies was screened according to the criteria mentioned in the above section. The strategies were screened down into two main strategies which is explained in the following sections.

3.5.1 Initial machining

After the part is made in the SLM machine, it is taken out for the machining of the sides and for removing the SLM build plate. The machining is supposed to be done by milling process and the build plate is removed by wire EDM. The first strategy was set for the milling process. The area where the part is going to be machined is highlighted by the color green in the picture below.

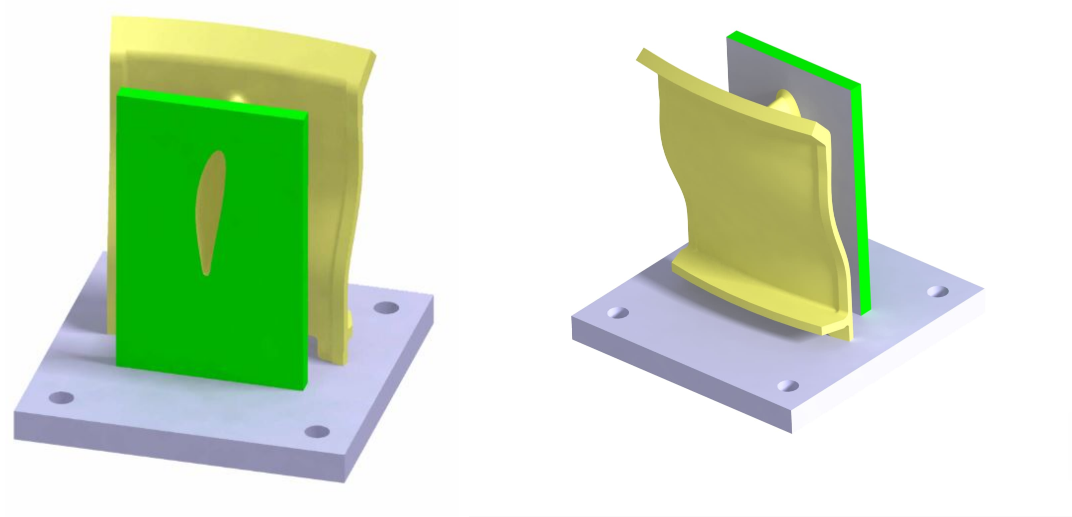


Figure 3.4: Initial machining area

In order to do the machining operation, after screening all the strategies, there are two final strategies which will be discussed below.

Strategy 1:
In the first strategy the aim was to have the most effective and simple locating system for the robustness of the design. The first strategy is shown in the picture below.

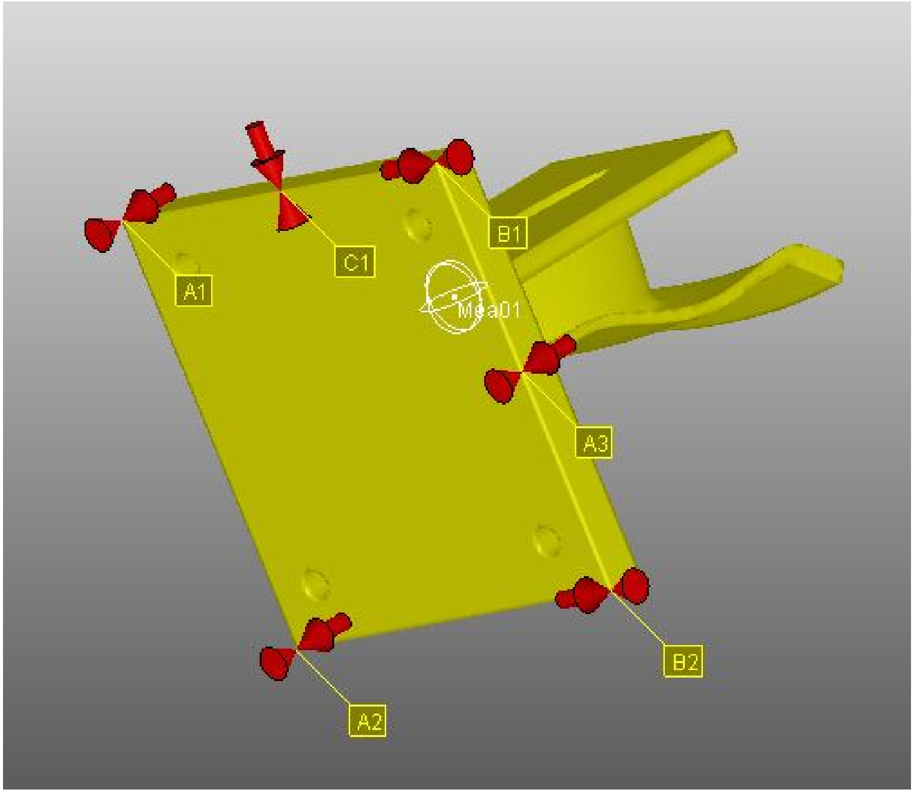


Figure 3.5: Strategy 1 for initial machining

Here the primary points A1, A2 and A3 are on the SLM build plate, arranged in such a way that the points cover maximum area of the plane. The secondary points B1 and B2 are placed on the edge of the SLM build plate which forms the line. The tertiary point C1 is placed on the edge of the SLM build plate. In this strategy all six points are placed on the same plane, and these points were given same linear tolerance of 0.1.

Strategy 2:
The importance of the critical features of the part was unknown at this stage of the project, therefore there was need for providing the process with more strategies. The second strategy is as shown in the figure below :

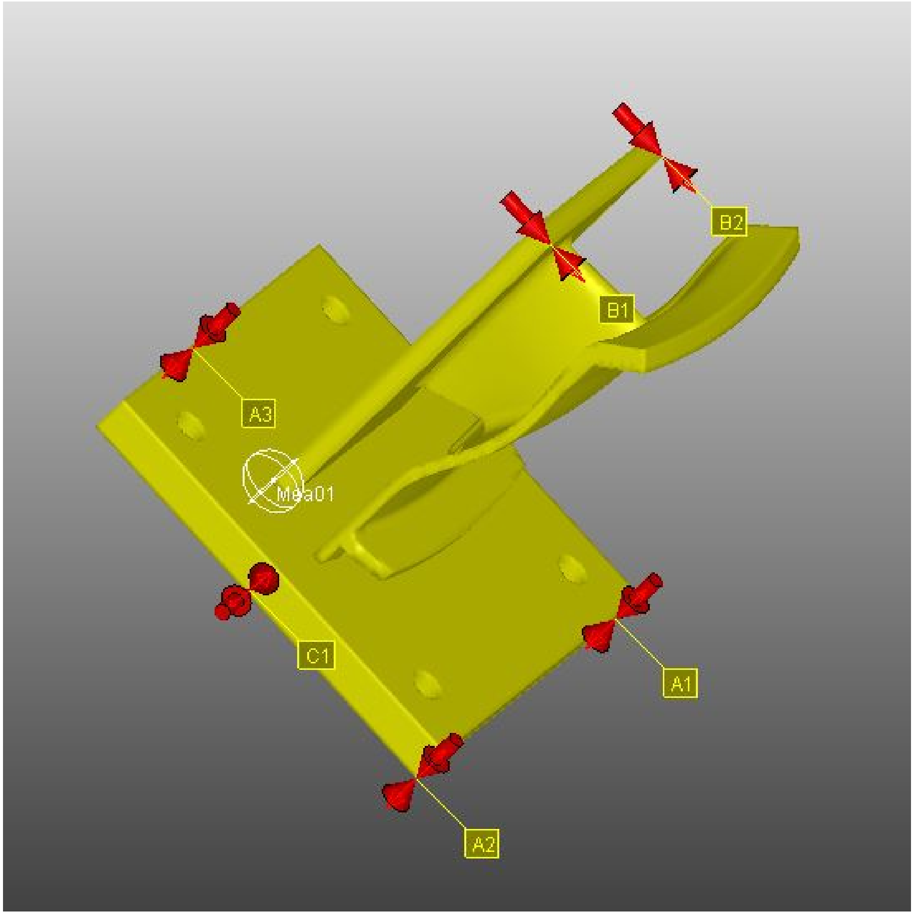


Figure 3.6: Strategy 2 for initial machining

Compared to the strategy 1, the primary and tertiary points are placed in similar manner but the secondary points are placed differently. In strategy 2 the secondary points are placed behind the SLM base plate which is printed and unmachined feature. The secondary points are placed in a different plane compared to the primary and tertiary points.

3.5.2 Laser metal deposition

After the initial machining process, the part is moved for the LMD process. The LMD process is done on the surface shown in green in the figure below.

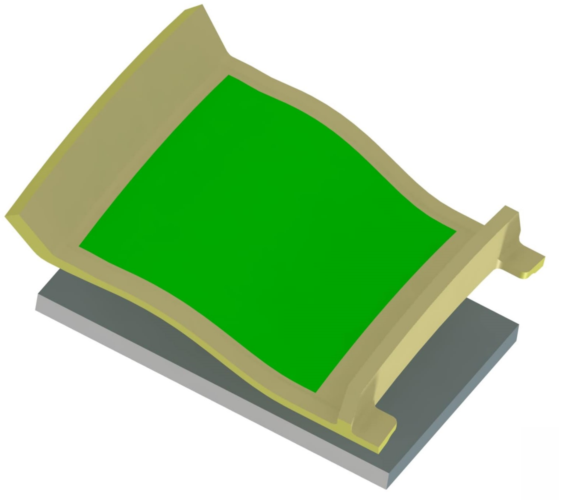


Figure 3.7: Area where LMD process occur

Similar to the initial machining process there are two strategies for this process also and these are discussed below.

Strategy 1:
The first strategy has the simplest locating scheme for the LMD process which is shown below.

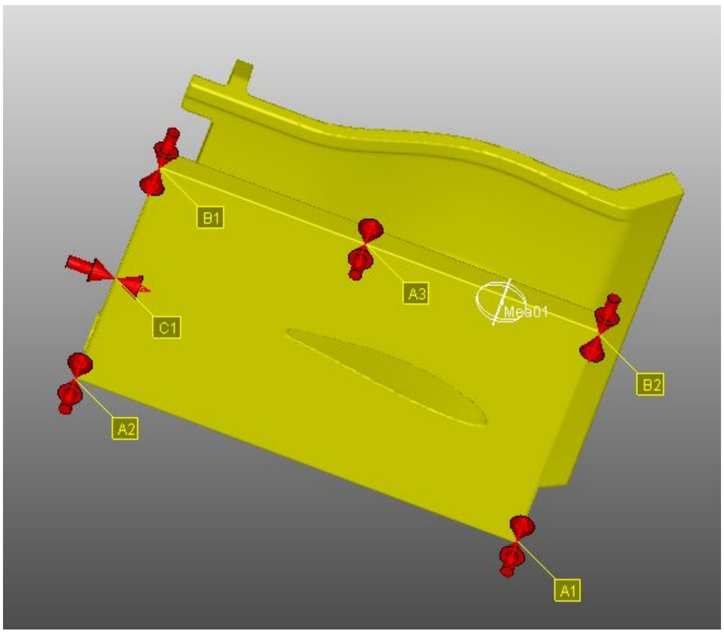


Figure 3.8: Strategy 1 for LMD

In this strategy, all the six points are placed in such a way that all comes in a single plane. The primary points A1, A2 and A3 are placed on the edges of the base plate to cover maximum area of the part. The secondary points B1 and B2 are placed on one of the edges of the base plate and tertiary point on the other edge. All the points are given same linear tolerance of 0.1.

Strategy 2:
As explained in section 3.3.2 the second strategy is complex in terms of the fixture design but it clears the cons of the first strategy. The strategy is shown in the figure below.

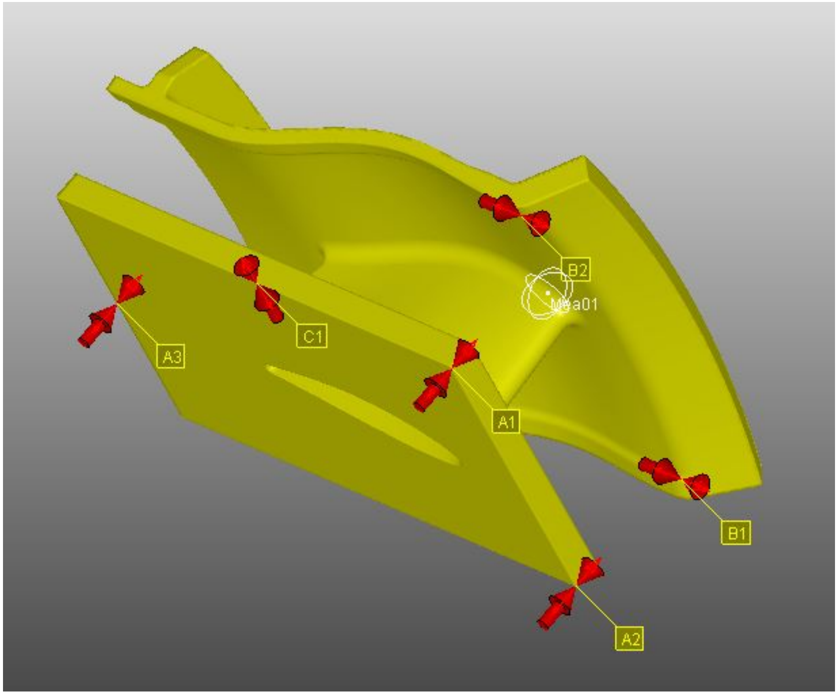


Figure 3.9: Strategy 2 for LMD

Compared to the strategy 1, the secondary points are moved to the body of the H-sector. The primary points and tertiary points remain in the same location as that of the strategy 1.

3.5.3 Final machining

In the final machining process, there are two features which are being machined, first is the boss of the H-sector and second is the sides of the body of the H-sector. The area which is machined in the final machining process are shown in colour green in the figure below.

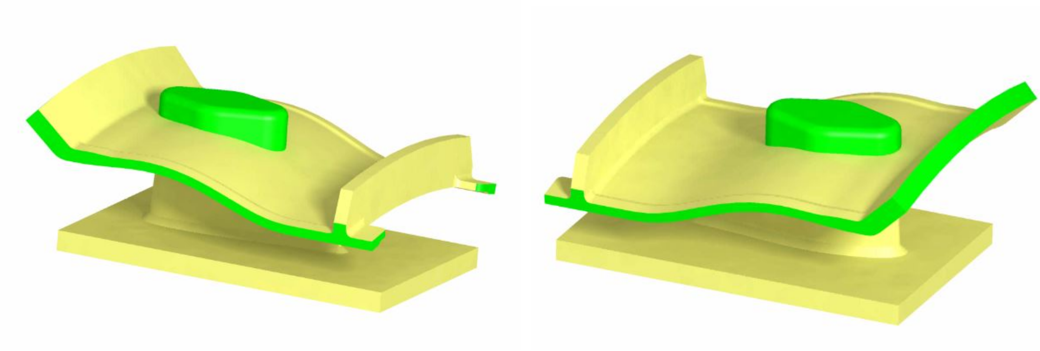


Figure 3.10: Final machining area

There are two strategies for the final machining process.
Strategy 1:

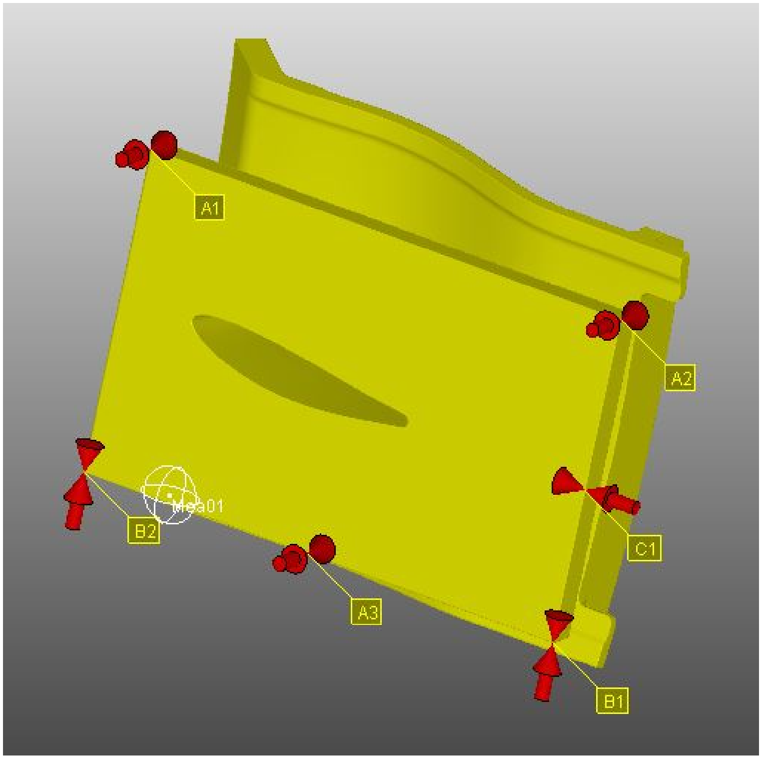


Figure 3.11: Strategy 1 for final machining

In this locating scheme, the points are placed on the same plane of the base plate. As shown in the figure above the strategy is quite similar to the first strategy of the LMD process. The primary points A1, A2 and A3 are placed on the edges in such a way that the points cover maximum area of the plane. The secondary points B1, B2 and tertiary point C1 are placed on the edges of the base plate. The figure above shows the first strategy for the final machining process.

Strategy 2:

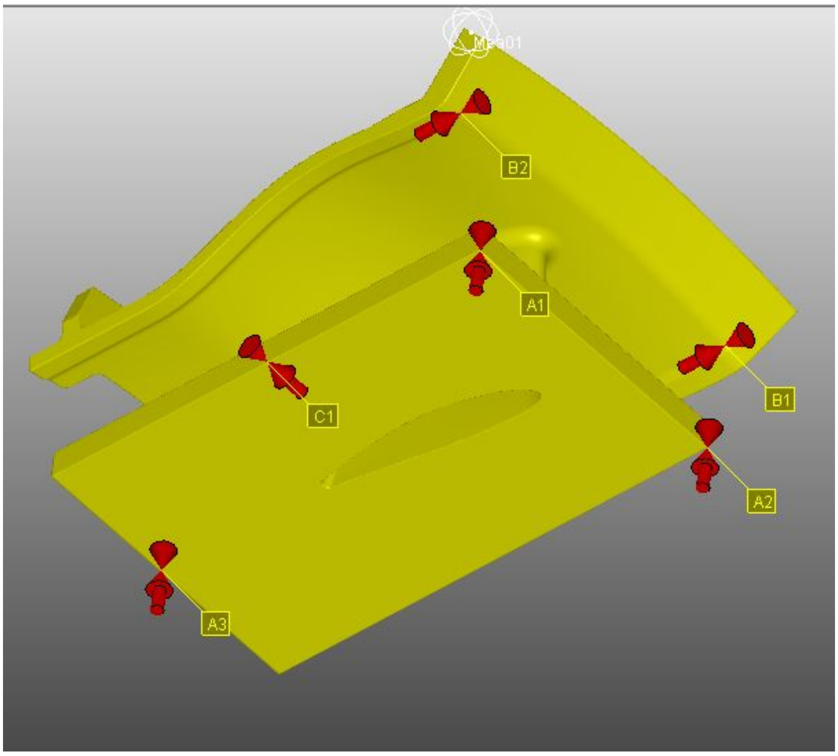


Figure 3.12: Strategy 2 for final machining

Compared to the first strategy, the primary and tertiary points are placed on the same locations but the secondary points are moved to the body of the H-sector. In this locating scheme, the fixture design could be complex compared to the fixture required for the first strategy. The strategy is shown in the above figure.

4

Results

In this section, the results obtained from the simulations are presented. There are two strategies of locating scheme best suited for the manufacturing process of this particular part artifact as explained below.

4.1 Initial Machining

The locating scheme strategies for the initial machining is as shown in the figures below:

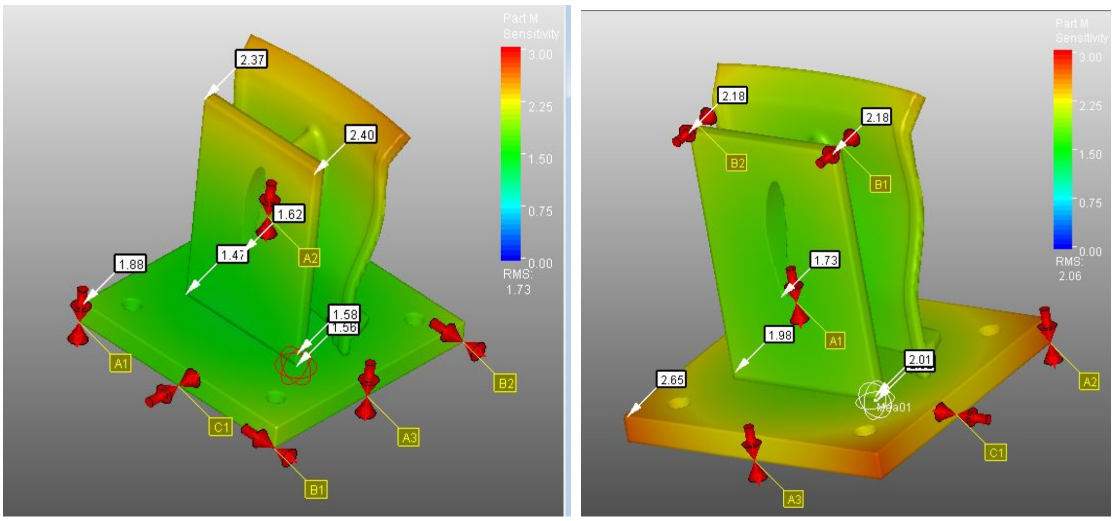


Figure 4.1: Results of initial machining

The table below represents the complete evaluation of each strategy for the initial machining and also the comparison made with the optimized value for the part artifact geometry.

PARAMETER	STRATEGY 1	STRATEGY 2	OPTIMIZED
RMS Value	1.73	2.06	1.66
Sensitivity	Less Uniform	Uniform	More Uniform
Sensitivity on Build Plate	1.88	2.65	2.03
Sensitivity on Base Plate	2.4	2.18	1.60
Sensitivity at Tool Initiation Point	1.56	2.02	1.55
Locating Points	All on Build Plate	Secondary points(B points) on the part artifact	Random
Tool Force	NO Locators against tool force	Locators against tool force	NA

Table 4.1: RD&T simulation results for initial machining process

The RMS value for the strategy 1 is 1.73, which is almost nearing the optimized value. The strategy 2 has little higher RMS value of 2.06 but it is found to have uniform sensitivity throughout the part. The sensitivity on the build plate for strategy 1 is 1.88 which is again almost towards the optimized value. For strategy 2, the sensitivity is more on the build plate, which is a least critical part in this machining process. The sensitivity at the base plate and at the measuring points, the strategy 1 has least sensitivity of 1.56. The base plate and measuring points are the critical parameters in this machining step. The measuring points are located where the machining is going to begin and on the base plate as it is also being machined. For strategy 1, all the locating points are on the build plate and there are no locators against the tool force. In case of strategy 2, the secondary points are on the part artifact, which is against the tool force.

4.2 Laser Metal Deposition

The locating scheme strategies for the laser metal deposition process is as shown in the below figures:

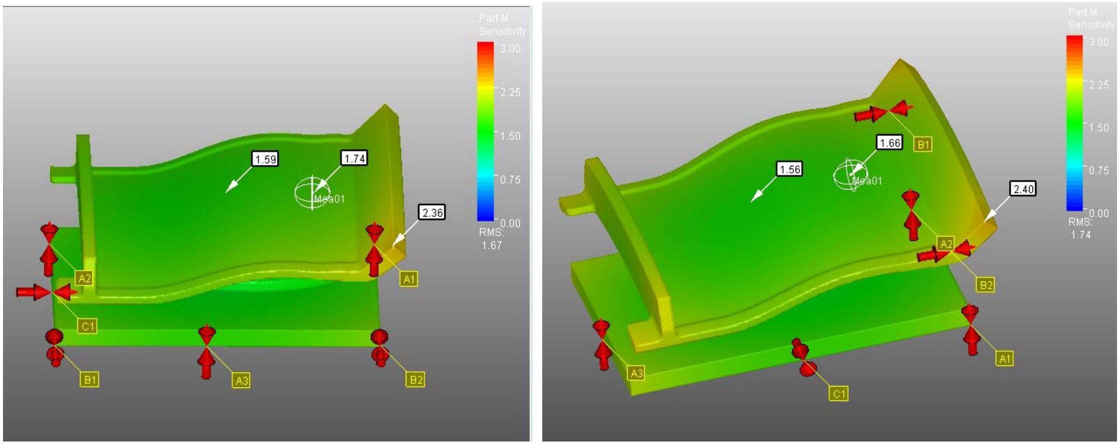


Figure 4.2: Results of laser metal deposition

The table below represents the complete evaluation of the two developed locating scheme strategies for the process of laser metal deposition.

PARAMETER	STRATEGY 1	STRATEGY 2	OPTIMIZED
RMS Value	1.67	1.74	1.61
Sensitivity	Less Uniform	Uniform	More Uniform
Sensitivity at Critical Feature	1.74	1.66	1.43
Locating Points	All on Build Plate	Secondary points(B points) on the part artifact	Random

Table 4.2: RD&T simulation results for LMD process

The RMS value of strategy 1 is 1.67 which is almost equal to the optimized value. All the locating points in the strategy 1 is on the base plate and it has no locators on the part. The most critical area for this process is the area on the part, where the laser metal deposition is taking place as shown in the Figure 3.7. The measuring point is taken at the same area. The sensitivity at the measuring point is 1.74 in strategy 1.
The RMS value of the strategy 2 is 1.74, which is almost in the same range as the strategy 1. The locating points in strategy 2 has B points on the part. The sensitivity at the measurement point is 1.66 and the sensitivity is spread out uniformly on the part.

4.3 Final Machining

The locating scheme strategies for the final machining process is shown in the below figures:

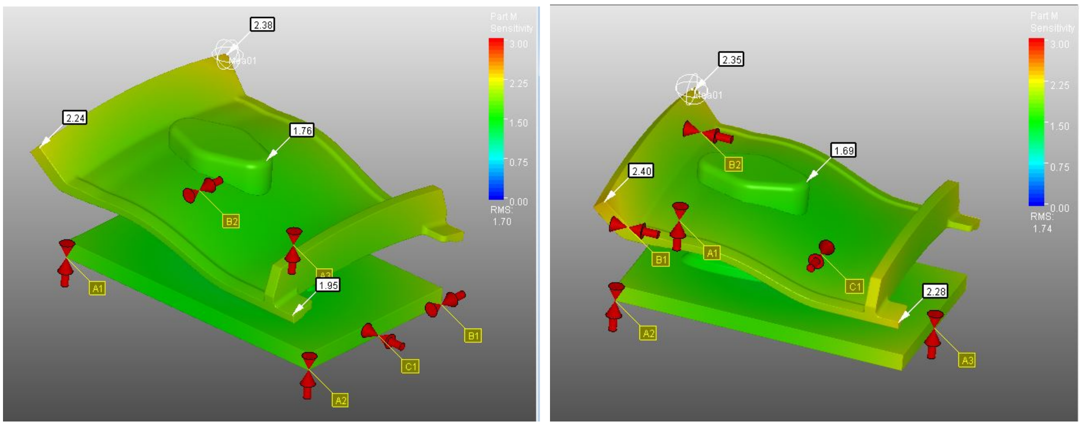


Figure 4.3: Results of final machining

The table below represents the complete evaluation of the two developed locating scheme strategies for the process of final machining.

PARAMETER	STRATEGY 1	STRATEGY 2	OPTIMIZED
RMS Value	1.70	1.74	1.56
Sensitivity	Less Uniform	Uniform	More Uniform
Sensitivity at Tool Initiation Point	2.38	2.35	1.71
Sensitivity at Boss	1.76	1.69	1.46
Locating Points	All on Base Plate	Secondary points(B points) on the part artifact	Random
Tool Force	No Locators against the tool force	Locators against the tool force	NA

Table 4.3: RD&T simulation results for final machining process

The RMS value for the strategy 1 is 1.70 against the optimized value of 1.56. The critical areas in this step is the area that is getting machined. The machining areas are is shown in the method section using figures. The sensitivity at the measuring point is 2.38 and at the boss area is 1.76. In the strategy 1, all the locating points are on the base plate and there are no locators against the tool force.
The RMS value for the strategy 2 is 1.74 and the part in whole has more spread out sensitivity. The secondary locators are on the part acting against the tool force. The sensitivity at measurement points and at boss are 2.35 and 1.69 respectively.

5 Discussion

The purpose of the project was to support the DiSAM project, who are aiming to develop the platform for additive manufacturing in production process. This thesis study is mainly about the locating schemes for different manufacturing processes and geometrical assurance. Hybrid manufacturing process is the combination of additive manufacturing processes and traditional manufacturing processes. Therefore, it is important to have a common geometric locating scheme or a robust strategy for locating scheme throughout the process steps.

In the initial stage it was difficult to collect data related to the locating scheme of the additive manufacturing. Most of the data collected was related to the traditional manufacturing process which influenced to bring out the different strategies discussed above. The study was conducted based on the ideal scenario because of the unavailability of the process simulation data. The properties of the material were not considered in the process.

The manufacturing of H-sector consists of four main manufacturing processes which are: SLM, initial machining, LMD and final machining. For the thesis project locating scheme for the two machining processes and for LMD process was considered. The SLM process will be held on the SLM build plate in the SLM machine which does not need a locating scheme. 3-2-1 orthogonal locating scheme was used for all the strategies since it is easy to analyze and understand, also it is commonly used for rigid bodies. The locating schemes were tested using the stability analysis in RD&T software and the screening of the different strategies was based on these results.

For each manufacturing processes number of different locating strategies were tried out and these were screened down to two strategies which was explained in chapters 3 and 4. The screening were done based on the parameters explained in section 3.3.1 and the stability analysis in the RD&T software.

Considering the results of locating scheme for the initial machining step from the result section, it is evident that the sensitivity at the critical features are reduced in the strategy 2 and the build plate becomes the most sensitive part which is going to be taken off in the next step. But, in the strategy 2, there are locators on the unmachined surface which might contribute to the geometrical variation itself. Whereas, in case of strategy 1, all the locating points are on the build plate, which is a machined part. Since, all the locating points are on the build plate, it easier and cheaper to design and manufacture fixtures for the initial machining compared to the fixtures required for strategy 2. The difference in results between the two strategies 1 and 2 are not very significant and also, the quantity that is being produced in this project is very less and therefore going with strategy 1 makes it very much feasible.

In case of the process of laser metal deposition, the feature of the part where the boss is being printed becomes the most critical feature. Observing the results from the two strategies as shown in the results section, there is no much difference in the sensitivity value at the critical point. By providing the secondary locators on the part will make the strategy 2 more robust as the sensitivity is spread out uniformly over the surface. Considering the batch quantity that is being manufactured, for this step it is feasible to go with strategy 1. In future, when the number of parts being produced reaches considerable quantity, it becomes reasonable to go for the complex and expensive fixture.

For the final machining step, the critical features and the sensitivity distribution for each strategy can be seen from the results and method section. The locating scheme for the process of laser metal deposition and the final machining is kept same. It is evident that, the strategy 2 gives more uniform distribution of sensitivity but the difference is not very huge. Even at this step, strategy 1 can be used and the same fixture can be used from the previous step.

6
Recommendations

Since, the manufacturing is not happening in sync with this thesis project, few of the factors might miss out from list of contributors considered in developing the present locating scheme.

Since, DiSAM is of the prime focus for this thesis project, recommendations are made based on the requirements of DiSAM.

The manufacturing process flow is going to start with SLM printing. After the printing is completed, the build plate is not removed. Build plate is used to locate the part for the next manufacturing process of initial machining.

For the process of initial machining, two strategies are developed. Considering the DiSAM project where the quantity of the part produced is very less, it is recommended to use the strategy 1. In strategy 1, all the locators are on the machined surface and the complexity of the fixture needed is very simple. This brings the advantage of lower cost for fixture design and manufacturing. After the initial machining, the build plate is removed using wire EDM.

The next manufacturing process step is the LMD. Even in this step, it is recommended to use the strategy 1, where all the locators are on the base plate. This makes the fixture design very simple and all the locators are on the machined surface. Also, the difference between the results of strategy 1 and strategy 2 is very small.

In case of final machining, where the part is machined to its final dimension, it is recommended to use strategy 1. In final machining, the fixture from the previous step can be used. Even though strategy 2 gives slightly better results, it is cheaper to use the strategy 1. Also there is no need of design and manufacturing of the new fixture.

7
Conclusion

Additive manufacturing is still an emerging technology and there are many dimensions of additive manufacturing that needs to be explored more in detail. Geometry assurance for the complex manufacturing process where multiple additive manufacturing and traditional machining are used in order to manufacture a part is an important aspect to make additive manufacturing widely acceptable in manufacturing industries.

In this thesis project, the contribution from the locating scheme for the geometrical variation is studied in detail and locating scheme strategies were developed in order to increase the geometrical accuracy. There are numerous locating scheme strategies that were developed. To choose the best among the developed strategies, some screening criteria were developed based on the critical features, RMS value and complexity of fixture as explained in the chapter 3.3.1.

For each manufacturing step, there is an important feature and the stability of that feature is very important. These are the features that are either going to be machined, surfaces where the printing is happening and the point of tool initiation. So, the locating scheme strategies which resulted in high sensitivity at those critical features were eliminated. The lower the RMS value, better the robustness of the locating scheme. Also, for some developed strategies, the fixture design was very complex or impractical. Thus, these criteria helped in fair screening of the locating scheme strategies.

After the screening process, two best strategies for each manufacturing step were decided and explained detail in the chapters 3.4 and 4.

The deformation of the part after printing is not considered for the development of the locating scheme. The process simulation results need to be considered to know the trend of deformation of the part. Based on the deformation trend, for respective additive manufacturing processes, locators can be adjusted to get the best geometrical accuracy.

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A

Appendix 1

A.1 Optimized Locating Schemes

As mentioned earlier, the RD&T software provides an option to find out optimized locating scheme for the particular part by itself. Even though, these are not practically possible and theoretically incorrect, these locating schemes were used for the comparison between different strategies. The values of sensitivity and RMS from the optimized locating scheme were used to select the best strategy among different combinations. Here are the optimized schemes for the three processes discussed in this report.

A.1.1 Initial Machining

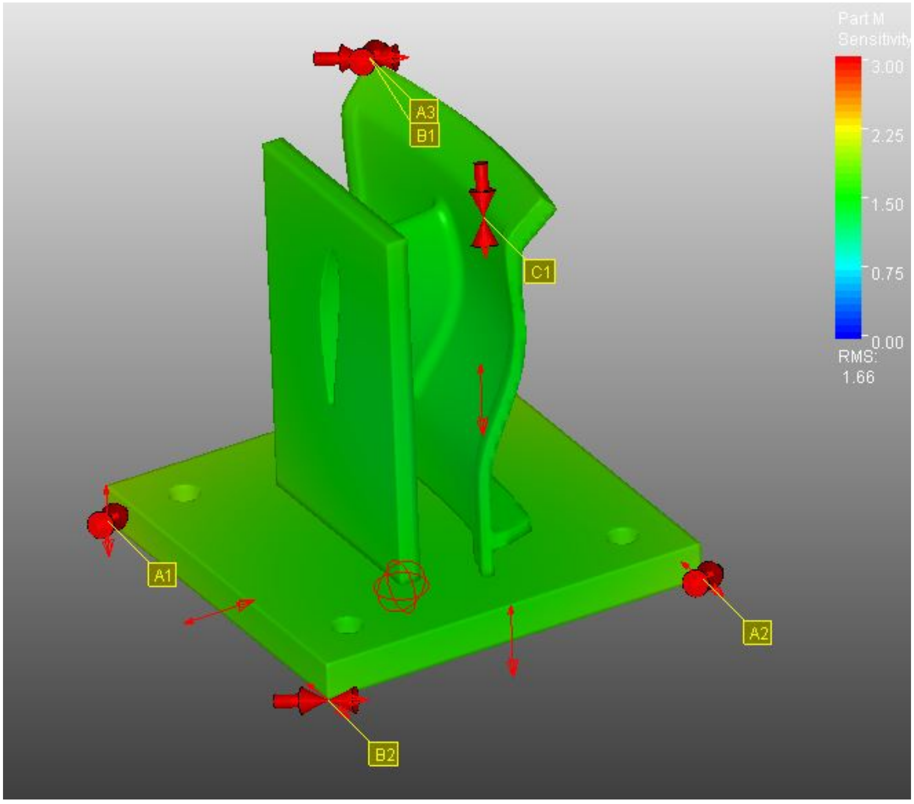

Figure A.1: Initial machining

In the figure above the primary points A1, A2 and A3 is forming a plane which is practically not possible. Similarly the secondary point B1 and B2 does not form a line in a plane, also point A1 and B2 overlap each other which is against the principle of the 3-2-1 locating scheme. Here the RMS value is 1.66 which is considered to be the optimal value.

A.1.2 Laser Metal Deposition

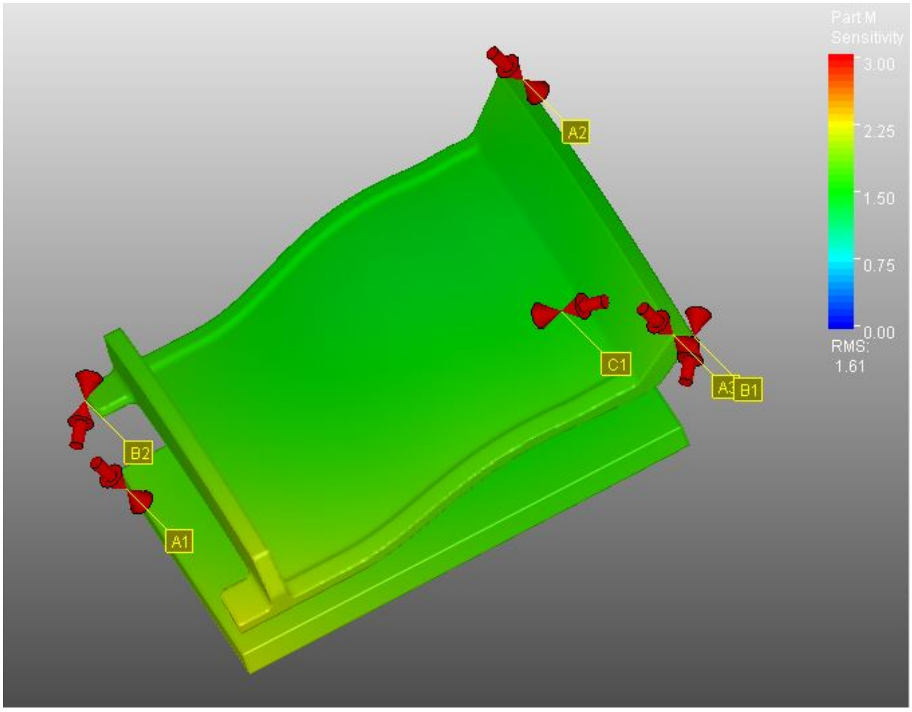

Figure A.2: Laser Metal Deposition

The figure above shows the optimized locating scheme for LMD process. The points have similar issues faced in the initial machining process. Also, the sensitivity is not uniform through out the part. There is a yellow shade on the corner which shows the part is more sensitive than the other areas. In this process the optimal RMS value is 1.61

A.1.3 Final Machining

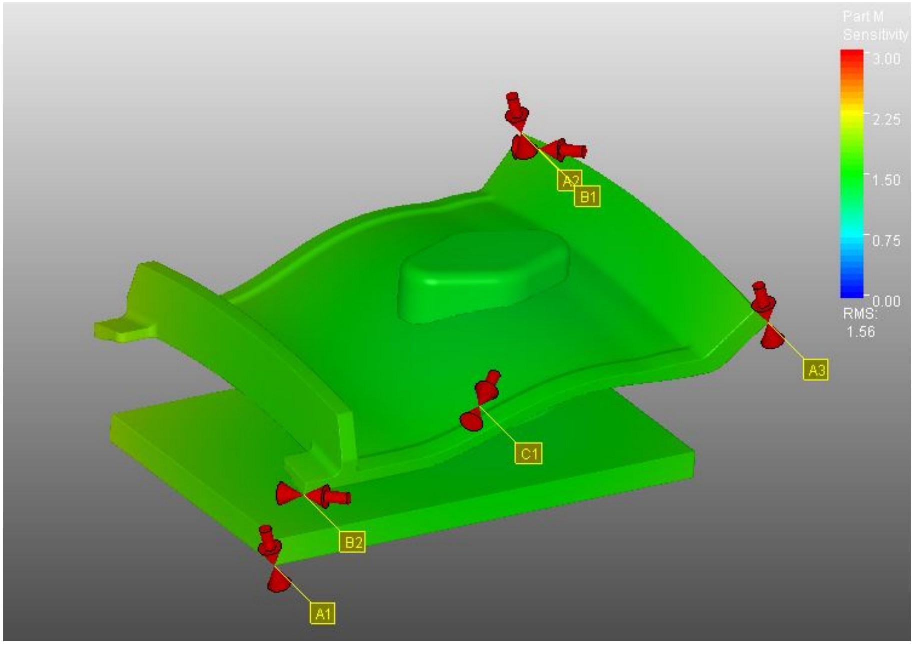

Figure A.3: Final Machining

The figure above shows the optimized locating scheme for final machining. The sensitivity is not uniform in the part and the points A2 and B1 overlap each other. The optimal RMS value is 1.56 in the final machining process.

A.2 Other Strategies

There were different strategies for the three different process from which two was selected according to the selection criteria. Figures below are some of the other strategies which are omitted during the selection procedure. These figures would give a insight about the role of locating scheme.

A.2.1 Initial Maching

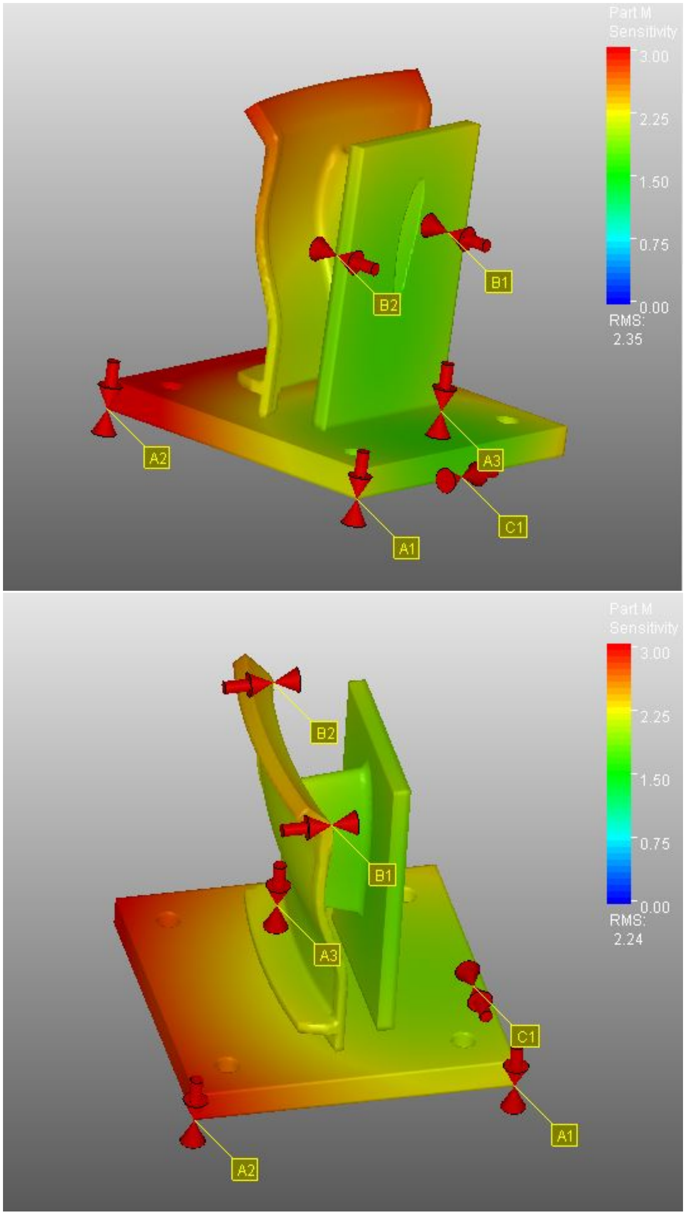

Figure A.4: Initial Machining

A.2.2 Laser Metal Deposition

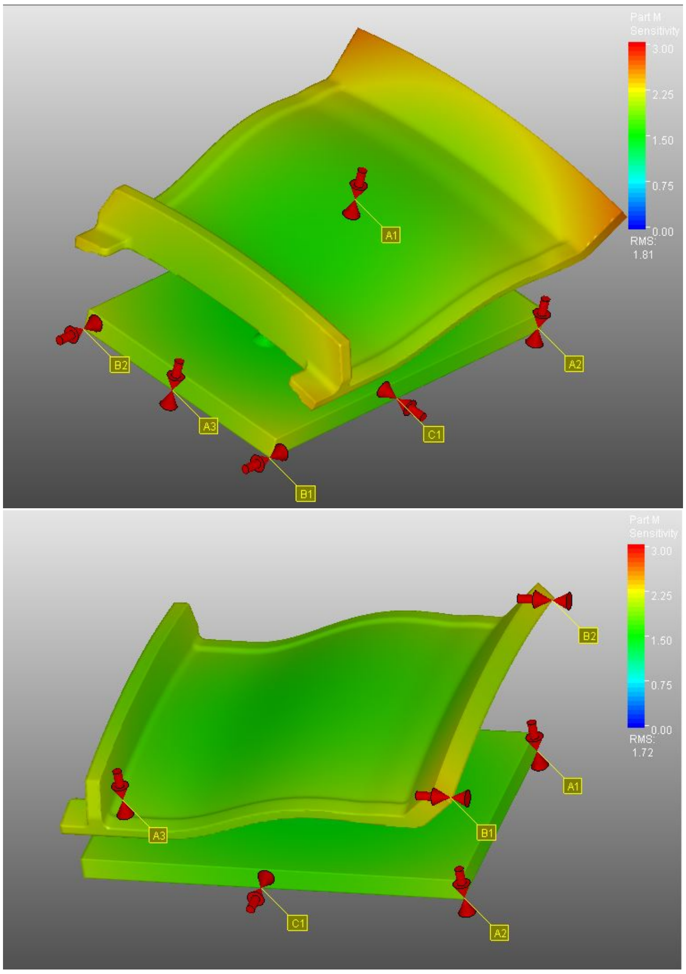

Figure A.5: Laser Metal Deposition

A.2.3 Final Machining

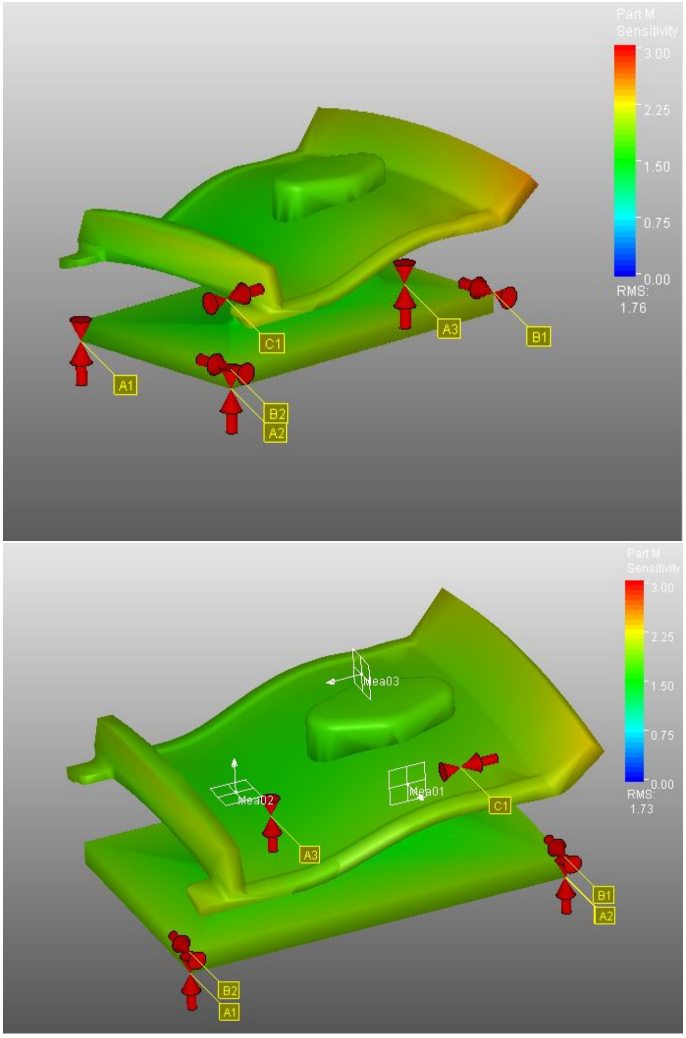

Figure A.6: Final Machining