

# Die Casting Mold Repair by Hybrid Manufacturing

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**Abstract:** This paper describes the process of repairing a damaged die for injection molding using a 5-axis Hybrid Milling Machine equipped with a Direct Laser Deposition (DLD) tool. A software developed by the authors—DUOADD—is adopted to detect the location of missing material and to create a solid model of the damaged spot. The resulting CAD file is used to calculate the paths of the DLD nozzle for filling the damage spot with new material. Finally, to restore the original shape of the mold, the surplus of added material is removed by a milling operation. The paper describes every step of the repair process: from 3D scanning of the damaged component to the finishing operation. This repair method can be applied to extend the life of a costly component and to restore the original shape of valuable objects—e.g. historical or artistic artifacts. The material used for the mold repair is stainless steel 316L, while the mold is made of hot-die-steel. In this paper the functionality of the repair process has been investigated by checking whether all the damaged spots are properly filled with new material. Moreover, this work investigates how to perform the milling operations that allow restoring the original shape of the object, minimizing mismatches between the machined surface and the original one.

**Key words:** Additive manufacturing, repair, hybrid machine, direct laser deposition, octree.

## 1. Introduction

The integration between mechanical milling machines and Direct Laser Deposition (DLD) [1] technologies has recently resulted in the first generation of hybrid machines on the market. This type of combined machine paves the way for new approaches to the use of DLD additive technology. In particular, the ability to add and remove material without the need to change machines is the ideal starting point for repair operations. In fact, to repair a damaged component it is necessary to add new material where it is missing and then finish all the surfaces to get back the original shape.

The DMG MORI Lasertec 65 3D machine was used for this job. This 5-axis milling machine is equipped with a laser head for additive operations. Compared to non-commercial DLD machines, Lasertec is operated using toolpaths generated by the Siemens NX CAD/CAM software [2] which, for the moment, is the

only CAM capable of handling hybrid machines.

Generally, a repair operation begins with a three-dimensional scan of the damaged component. The final result of this operation, depending on the type of 3D scanner used, is a mesh or a point cloud (which will be transformed into a mesh with an additional operation). Siemens NX can not directly use meshes to calculate toolpaths for additive operations. To perform the calculation of the toolpaths it is necessary to have a solid model. It is therefore necessary to find a way to convert the information coming from the 3D scan and transform it into a solid model that can be used by the CAM.

The authors developed a software—DUOADD [3]—that compares the mesh of the damaged object with the nominal solid model. The output of this software is the solid model of the damaged volume. With DUOADD it is therefore possible to obtain the digital solid model that can be used in CAM to create toolpaths.

Other works tackled the problem of repairing with additive process [4, 5], however with different

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approaches because it was not necessary to obtain the solid model—as required by Siemens NX. Furthermore, using meshes to directly detect damages and create toolpaths is a difficult and error-prone task. For this reason authors decided to discretize through octrees both the mesh obtained with the 3D scan and the nominal solid model. Later on, it is possible to compare the two models without facing problems that occur when working with meshes.

Another characteristic of DUOADD is that it is not expected that the area to be restored is machined before adding new material. The volume detected by the software has the same shape as the damage spot and, through the DLD, it is possible to add the material voxel by voxel.

The new material is added by direct deposition of melted metal powder in the place to be repaired. Fig. 1 shows how the metal powder is ejected from the nozzle and becomes a layer of solid metal.

The DLD technology is particularly suitable for repair operations because:

- it is not directly affected by the electrical and thermal conductivity of the metal powder;
- it creates stronger bonds than welding;
- it introduces less heat into the part and, consequently, less thermal distortion.

### 1.1 Paper Structure

This article is structured in a way that explains the

whole repair process with particular emphasis on a case study. The main phases of the process are:

- The 3D reconstruction of the damaged component by 3D scanning (Section 2);
- The use of DUOADD for the comparison of the mesh with the nominal solid model (Section 3);
- The creation of the necessary toolpaths for the several operations (Section 4);
- The addition of new material to the damaged mold and the finishing of the worked areas (Section 5);
- Section 6 is dedicated to the analysis and discussion of the obtained results. Several conclusions and suggestions for future developments are provided.

## 2. From Damaged Mold to Mesh

This section describes the process required to obtain a mesh of the damaged mold. There are many ways to obtain a three-dimensional reconstruction of the object, however, for this job it has been chosen to use a structured light scanner to perform the 3D scanning of the component. The device used is the Creaform Metrascan [6]. This scanner is capable to reconstruct the surface of the mold with a precision up to 0.1 mm with a repeatability of 0.02 mm. The resolution of the 3D model obtained is adequate for further analysis.

The mesh obtained—an STL file—must be handled to obtain a closed and topologically correct surface—i.e. watertight, coherently oriented, no overlapping faces, etc.

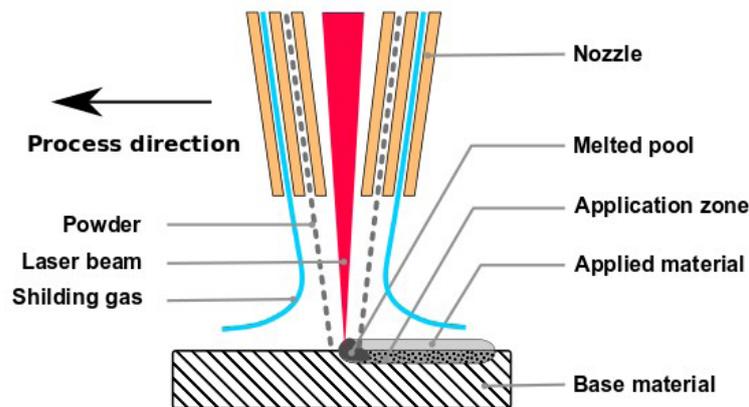
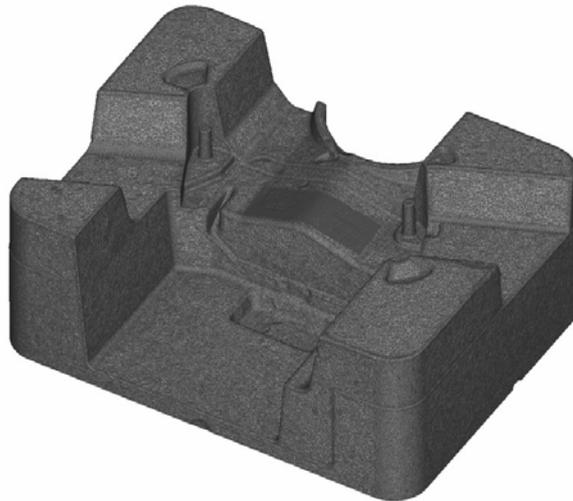


Fig. 1 Direct laser deposition.

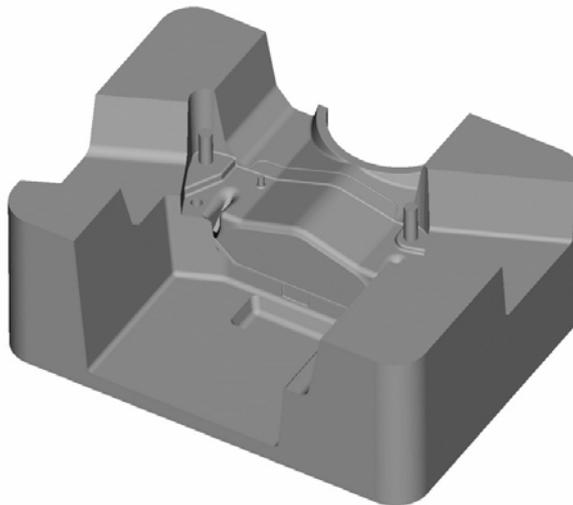
Before the scanning operation, the mold must be cleaned and, if needed, sprayed with a powder that avoids light reflections. It is possible to scan the whole mold in a single session or, for complex components, several sessions can be performed and then all results can be merged into a single mesh. There are several kinds of software available for correcting the obtained mesh; for this work the software provided by the scanner manufacturer—VX Elements—was used. Fig. 2 represents the nominal solid model while Fig. 3 shows the mesh obtained by 3D scan.

Authors developed the software that detects

damages by comparison between the mesh obtained from the 3D scan and the nominal solid model. To properly perform the comparison, the two models must be coherently positioned and oriented. To facilitate the operation described in Section 4, it is convenient to align the CAD solid model with a convenient reference system. Afterwards, the mesh of the 3D scan can be aligned with the model just referenced. Automatic algorithms that minimize the distances between the surfaces of the two models can be used to perform the alignment. The reference model—in this case the nominal one—is fixed in space while the mesh is moved and rotated for reaching



**Fig. 2** Mesh of the damaged mold.



**Fig. 3** Nominal CAD model.

the best match. The Cloud Compare [7] software was used to perform the alignment operation.

Once the alignment process is complete, the two three-dimensional models are ready to be used by DUOADD to detect any damage.

### 3. DUOADD: From Mesh to a New Solid Model of the Damage

This section describes the steps required to obtain the solid model of the damage. Authors devised a process that allows comparing the two models by identifying the differences between them—i.e. the damages—while avoiding the problems that occur when working directly with meshes. To automate this process as much as possible, authors developed C++ software—DUOADD—that allows extracting the solid model of the damage from the mesh of the damaged mold. This model is suitable to be used within the CAM.

The main phases of the process are:

- conversion of the two models into octrees; filling procedure;
- Boolean comparison between the two octrees; filtering of results;
- merging all nodes into one solid;
- exporting the obtained result as a STEP file.

#### 3.1 Geometry Discretization by Octree

The two three-dimensional models obtained in Section 2 are discretized with a data structure called octree [8]. An octree is a hierarchical tree structure

that is obtained by recursively subdividing a cubic volume—i.e. the mesh bounding box—called the root node into eight cubes, each with dimensions equal to half the size of the father. Recursive means that the children that contain faces of the mesh are also split into eight more cubes and so on until the desired resolution is achieved. If a child node does not contain any mesh faces, it is not subdivided any longer. The nodes belonging to the last level of the tree that contains parts of the mesh are called “leaves”. The set of all leaves represents the shell of the mesh made by voxels. Fig. 4 shows an example of the structure obtained.

The resulting shell is empty inside but in order to perform the Boolean comparison between the two octrees it is necessary that both are “filled”. All the nodes inside the mesh must be marked as belonging to the object. A ray-triangle intersection algorithm [9] was used to define whether a node is located inside or outside the mesh. From the center of each node, a ray is drawn to the outside of the root node and the number of intersections of that ray with the triangles of the mesh is counted. If the number of intersections is odd, it means that the node is inside the mesh; otherwise the node is external. One of the disadvantages of octrees is that at each further iteration the maximum number of nodes  $N$  increases exponentially according to equation:

$$N = \sum_{i=1}^n 8^{n-1}$$

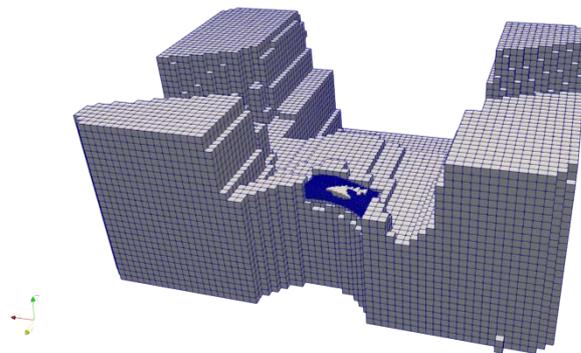


Fig. 4 Octree of the mold.

To avoid this problem, which increases the computational time, a method was developed to increase the resolution of the octree only in correspondence of the damaged area. Fig. 5 shows the increased resolution and the damaged area.

### 3.2 Octrees Comparison and Ltering of the Results

Once the octrees of the 3D scan and the nominal solid model are created, they can be compared. By iterating both octrees at the same time, it is possible to check if both nodes belong to the object or not. By applying a NOR Boolean operation, it is possible to identify all the nodes where the two octrees mismatch.

Fig. 6 depicts the result of a Boolean difference between the octree of the nominal CAD part and the one that represents the damaged mold.

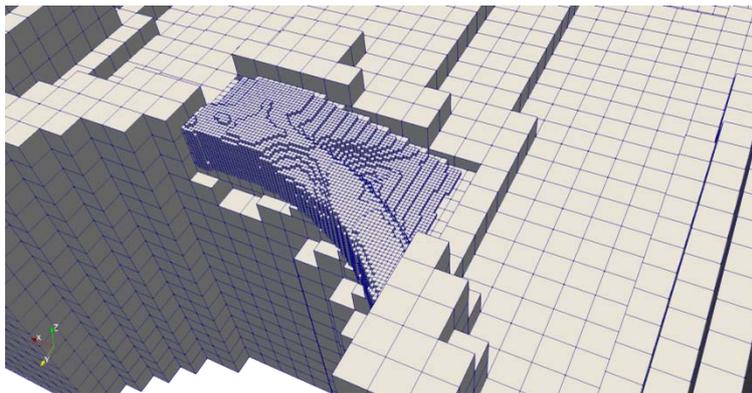
The red volume in Fig. 6 is, at the moment, a set of nodes of the octree, namely, a set of disjointed cubes. In some cases after the comparison the result contains

some disconnected and scattered nodes that must be removed. To address this problem, the authors developed a routine that clusters the nodes and eliminates all the outlier cubes that are created by very small geometric discrepancies.

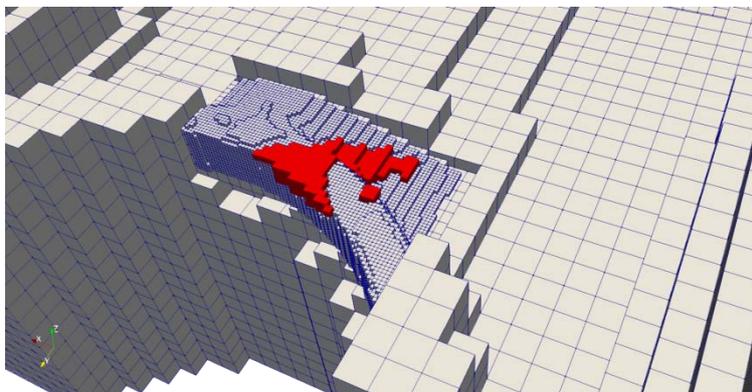
### 3.3 Create and Export the Solid Model

The result of the previous section is still an octree where only the nodes representing the damage are kept. In order to work on these data with CAM, it is necessary to convert the information contained in the octree into a virtual solid model. Authors developed an algorithm that allows to convert an octree node into a geometric element in STEP [10] format.

In order to have a manageable STEP file, it is important that all nodes are represented as a single solid. It is thus necessary to merge all the nodes in a single compound that represents the volume of the damage. DUOADD uses the Open CASCADE [11]



**Fig. 5** Octree of the damaged area.



**Fig. 6** In red the octree of the damage.

library [12] to merge all nodes and create a single solid model. Notice that the exported model describes the damage with arbitrary approximation, depending on the resolution of the octree selected by the operator. In addition, the exported model is already located and oriented consistently to the solid CAD model used to align the 3D scan in Section 2.

#### 4. The Creation of Toolpaths

The toolpaths are created with the Siemens NX CAM software. The operations to be carried out are the following:

- import all solid models into the manufacturing environment of NX;
- position and fix CAD solids according to the actual position inside the Lasertec;
- modify the solids needed for additive operations to ensure that sufficient new material is applied;
- create toolpaths for additive and finishing operations.

Once the files represent the original mold, the damage and various fixtures have been imported, it is possible to proceed with the correct virtual positioning of the models in the workspace. At this stage, it is important to check that the areas to be machined can be reached by the tools and that there is no risk of collisions. When the models are positioned, the solid that represents the damage must be modified—in accordance with DMG MORI use guidelines—by

offsetting the lateral and upper surfaces. By this way Lasertec adds some excess of material to the area to be repaired while ensuring complete coverage of the volume. Without this operation, there would be the risk of not perfectly covering the nominal volume of the damage with enough material, especially in thin spots or where there are sharp edges. Moreover, a surplus of matter is required by the forthcoming milling operations. Fig. 7 shows the solid model of the damage placed in the right position on the CAM environment.

The last operation to be performed is the creation of toolpaths. During this phase, all process parameters such as scanning strategy, laser power, stepover, layer height, etc. must be entered. The parameters used are based on tests carried out previously by the authors. The generated part-program is saved and sent to the CNC machine for the actual repair. Fig. 8 shows a simulation of the additive process performed on the Siemens NX.

#### 5. Perform the Repair

This section describes the steps required to add the new material to the mold and restore the surfaces to their original state. Fig. 9 shows a detail of the damaged area: three distinct worn areas can be recognized. The same three spots can be easily individuated also in Fig. 8.

In order to maintain a better control over each step

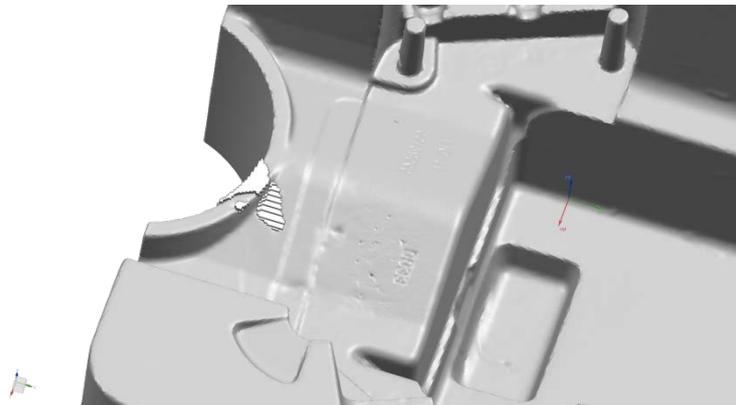


Fig. 7 Solid model of the damages inside the CAM.

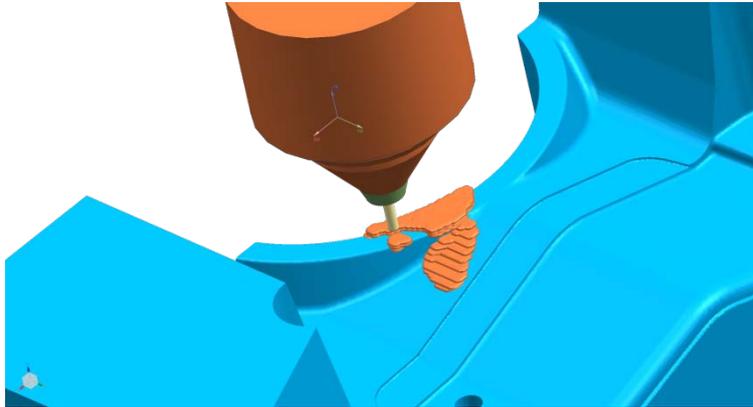


Fig. 8 Simulation of the additive operations.



Fig. 9 Damaged areas on the mold.



Fig. 10 The new material added to the mold.



**Fig. 11** Mold after finishing operations.

of the process, three depositions were carried out sequentially. The three additive operations took about six minutes while the next finishing process took about 20 minutes. Fig. 10 shows the three damaged areas after adding the material. It is easy to identify the surplus of material that is needed to have sufficient overlap with the mold substrate.

One of the most important advantages of a hybrid machine is that it is not necessary to move the component to another CNC machine to finish the part. The finishing task was performed using the capability of Lasertec to perform 5-axis milling. The surfaces were finished according to the solid CAD model provided by the company that owns the mold. By this way, no errors were introduced for the milling operations. Fig. 11 shows the damaged areas after repair and finishing operations.

## 6. Results and Conclusions

This work illustrates the first application of DUOADD for the repair of a real die-casting mold. The results demonstrate the effectiveness of the newly developed software and highlight a number of pros and cons of this approach. One of the most important advantages is the speed of repair process compared to other techniques. DUOADD takes only a few seconds

to compare the two models and reconstruct the virtual damage of the model. The entire repair process took just a little more than two hours, split in:

- 40 minutes for 3D scanning and cleaning the mold, 20 minutes for mesh alignment;
- few seconds to run DUOADD, 40 minutes to create toolpaths;
- 6 minutes for the deposition of the new material, 20 minutes for finishing operations.

The computing times used by DUOADD are almost negligible when compared with the amount of time required by the other operations.

The time saved, along with the reliability and repeatability of the DLD process, can potentially make the repair process more cost-effective. Increased efficiency and convenience in repair processes can lead to an increase in this practice with significant material and energy savings, which is also very positive from an environmental point of view.

A further positive aspect of the developed procedure is that it does not require the premachining of the damaged area before the addition of the new material, since DUOADD detects the exact shape of the damage. This makes the repair process even easier. However, it is important to take into account that the accessibility of the work area is crucial. In fact, when

it is necessary to machine occluded areas, such as particularly narrow or deep features, there is the risk that the DLD tool can not reach the area to be repaired. DUOADD developers think that one of the future developments of DUOADD can be to make a prior analysis of the feasibility of the repair.

Another very important area of investigation to take into account is the quality of the adhesion between the mold material and the added material. Authors are carrying out tests for analyzing the interface between the two materials; soon the results of these studies will be published.

One further issue in using octrees to detect damages is that the external surface of the obtained models is not smooth.

This makes the laser-head to follow a jagged profile during the deposition process. Authors performed a number of tests that show that this behavior does not represent an issue for the forthcoming milling operations. However, one of the next steps in DUOADD development can be a method to make the volume of the damage smoother.

In conclusion, the repair process of a damaged mold using DUOADD is not only possible, but also advisable, effective and fast.

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