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Evolutionary-based optimization strategy in a hybrid manufactured process using LMD

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Abstract

We investigate a hybrid manufacturing strategy combining laser metal deposition (LMD), and milling or turning. LMD is an additive manufacturing process, which can be used for surface cladding, repair, and 3D build-up of parts. One of its advantages is the creation of near net-shape parts on variable ground geometries.

The strategy focusses on manufacturing a part by choosing the appropriate wrought material with the remaining volume being added by LMD to minimize used resources and manufacturing time. This is done by adapting an evolutionary algorithm that varies the size, orientation, and position of wrought material with respect to the remaining volume.

Keywords: hybrid manufacturing, laser metal deposition, evolutionary algorithm, additive manufacturing,

1. Introduction

Weight critical applications, like parts in the aerospace industry, are driven by lightweight design. Today structural parts are manufactured by milling processes. These parts lose up to 95% of the wrought material as waste, which costs time and energy, and is not sustainable. [1]

The buy-to-fly ratio defines the rate between the raw stock material and the final part. Additive manufactured parts have a buy-to-fly ratio of nearly 1. Only functional planes have to be post processed by milling. Conventional milled parts can have a buy-to-fly ratio of up to 20 if 95% of the raw stock has been machined. The additive manufacturing process lacks in productivity compared to milling. The economical manufacturing of parts is only possible with high buy-to-fly ratios. [1]

Laser Metal Deposition (LMD) is a powder-bed-less layer-by-layer manufacturing process for the production of three-dimensional complex parts [2]. The process solidifies a nozzle fed powder by a laser. This allows the repair of damaged parts or building on wrought material.

The researched hybrid manufacturing process combines LMD with mechanical machining, where the LMD process adds the needed material to the wrought to manufacture a near-net shape stock, which will be machined to its final shape. Zhu et al., 2013 assign the process to the hybrid manufacturing group "hybrid additive and subtractive manufacturing processes". [3]

The advantage of the hybrid manufacturing process is shown in the sketches of Figure 1. The left sketch shows a fully milled part. In the upper area most of the wrought material has to be milled, which costs time. On the other hand, the right sketch shows a completely additive manufactured part, where the massive lower section is built by the productivity lacking additive process. The central sketch

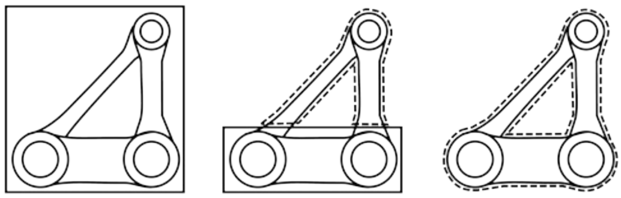

Fig. 1. Sketch of (a) subtractive, (b) hybrid and (c) additive manufactured

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demonstrates the combination of both strategies towards the mentioned manufacturing of a near-net shape stock to minimize the time and energy of either single processes. [4]

An adapted design approach for this hybrid manufacturing process has been defined by Ewald et al., 2017. It consists of 6 steps in 2 categories. Figure 2 shows the process flow chart. In the first category "Shape design" the volume part will be designed under usage of topology optimization and FEM tools considering the boundary conditions of the work space, the material properties, and the manufacturing restrictions. In the second category, the designed part has to be optimized for the hybrid manufacturing process. This contains the optimization of the additive and subtractive amounts as well as verification of the buildability of the hybrid part under the mentioned boundary conditions. Followed by the preparation of the manufacturing plan. [4]

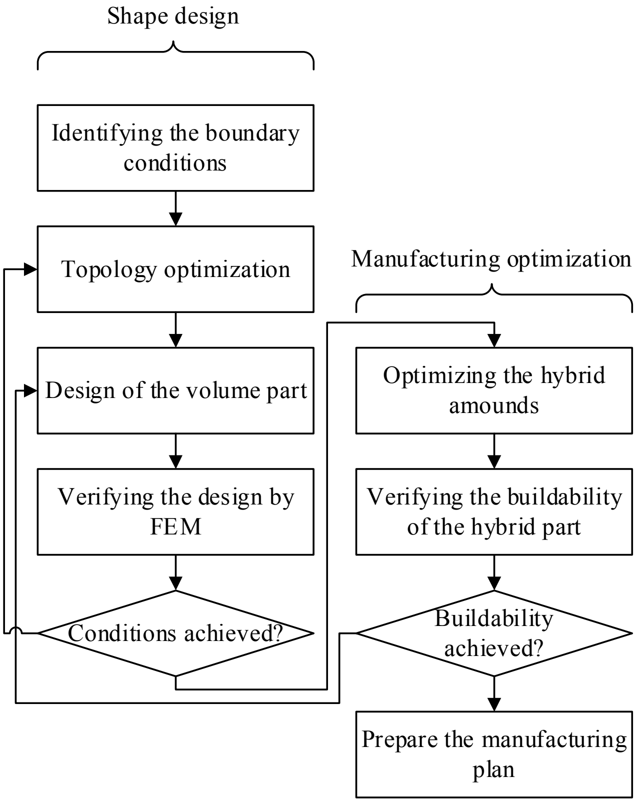

Fig. 2. Flow chart of the adapted design process for near-net shape stock using the hybrid manufacturing process.

The optimization of the ratio between the raw stock and the LMD added material is a key aspect of the material and cost efficiency of the hybrid manufacturing process. The determination of the optimal ratio between the two quantities can be achieved by a minimization of the costs.

2. Optimization Process

As already pointed out, the hybrid manufacturing process in this case is a combination of machining and additive manufacturing. In order to determine the optimal rates of material removed by machining and generated material, an optimization tool is developed with the help of MATLAB R2016a. The objective function is the calculation of the production costs. These shall be minimal. The cost model by Krantz and Sjöö, 2015, states, that overall production costs are the sum of both the additive manufacturing and machining costs. Each of these parts are calculated as an addition of volume-dependent cost factors and overheads like set-up costs [5]. In the end, the cost function is able to calculate the production costs of the whole hybrid manufacturing process with regard to the amount of machined and generated volume as well as the material. The tool includes three basic materials: steel, aluminium and titanium.

Despite handling the same material, the costs for the additive manufacturing process is higher than the wrought material due to the need for it to be powder.

Assuming that one hybrid machine is used for both individual processes there is only a single overhead for the rechucking.

The first step, see fig. 3, of the MATLAB procedure is the import of geometry data of the product. Therefore, STL data, which is a standard format to export triangulated surfaces of geometries from CAD programs, is used. In order to calculate the mentioned production costs, it is essential to determine the volume of the geometry. Hence, the STL model is converted to a volume model that is discretized into many small tetrahedrons in step 2. So the model volume and, looking forward to the optimization, the volume of an arbitrary area of the geometry can be calculated by the sum of the tetrahedron volumina in the third step.

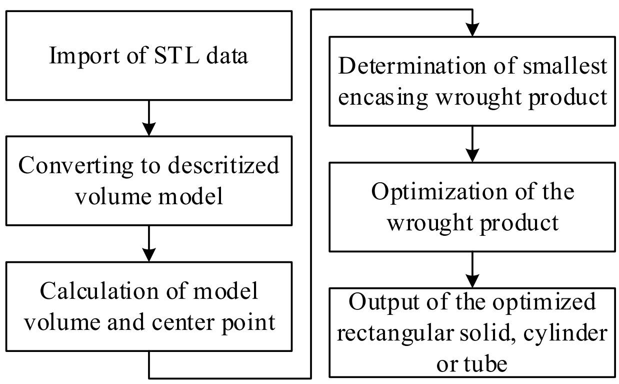

Fig. 3. Flow chart of the optimization algorithm

In the fourth step the tool considers the complete machining of the product with the goal to determine the smallest wrought product which encases the geometry.

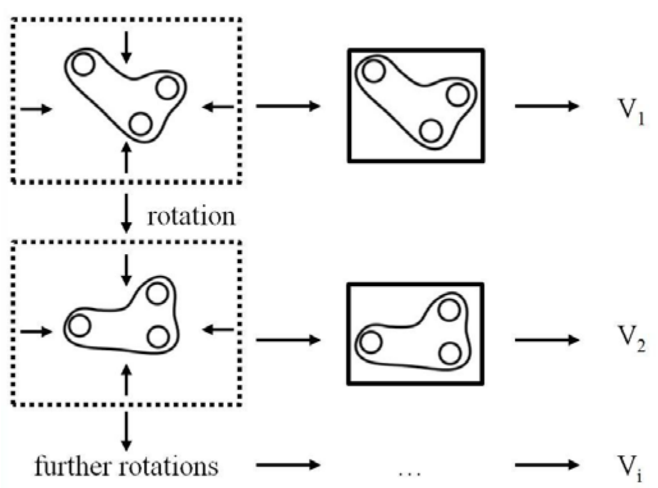

Fig. 4. A rectangle encases a product in different positions and generates different volumina.

The results are the lowest machining costs for the production due to the small amount of chips. In general, there are two common types of wrought products, which can encase a product: rectangular solids and cylinders. These are only available in particular sizes. Then, step by step the product geometry is turned around its axes in all directions. After every rotation, the encasing wrought product is calculated and compared to the available size. That process simulates a real-life order of wrought products from a supplier. In detail, the point of the geometry, which is furthermost from the model center will be found for each direction of space. After that, the model length can be calculated in each direction and the program determines the dimensions of the encasing wrought product next in available size. When the appropriate wrought product for the actual model position is found, the program saves the wrought volume. Then the geometry will be turned and the fitting process starts again. At the end of this full factorial optimization the smallest wrought product with the corresponding model position is found. That leads to the lowest production costs for the complete machining process. Figure 4 shows a two-dimensional example, where a product is encased by a rectangle, which represents the wrought product.

In step 5 it will be identified, at which areas which manufacturing process is preferred to achieve the overall lowest production costs for the hybrid manufacturing process. The optimization problem is defined with the size and position of the wrought product as the parameters and the minimization of the production costs as the objective. With respect to the discrete lengths of the wrought product and the number of parameters, the mixed-integer genetic algorithm, which belongs to the evolutionary algorithms, is chosen. Evolutionary algorithms develop individuals, i.e. sets of parameters, and evaluate them. The individuals with the best value, in our case with the smallest production costs, are transferred into the next generation, where they will be compared with new individuals, see Figure 5. When the deviation between the best values of the last twenty generations is less than a certain stopping criteria, the iteration is stopped.

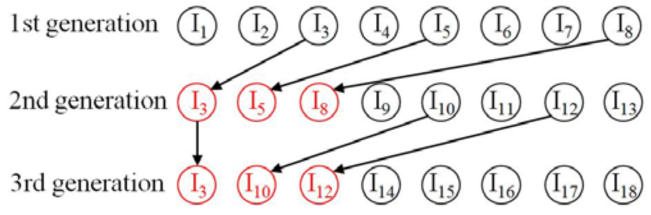

Fig. 5. Procedure of the genetic algorithm. Individuals which were transferred from the previous generation are marked in red.

Three kinds of wrought products are available for the optimization process: rectangular solids, cylinders, and tubes. In general, tubes, i.e. hollow cylinders, were not appropriate for the procedure of the encasing wrought product, but they may be appropriate for the hybrid process for cylindrical elements in the final product geometry. The upper boundaries for the optimization parameters are derived from the encasing wrought dimensions. Thus, the optimized wrought product for the hybrid process can be the same size as the encasing ones, but not bigger. All smaller particular sizes and lengths are suitable for the optimization. In order to evaluate a set of parameters, the tool has to calculate the model volume, which is beyond the actual wrought product described by the parameters. This volume is the amount of material, which has to be manufactured additively to the wrought product. In Figure 6, the additively manufactured volume is illustrated in red and the wrought product is represented by a rectangle.

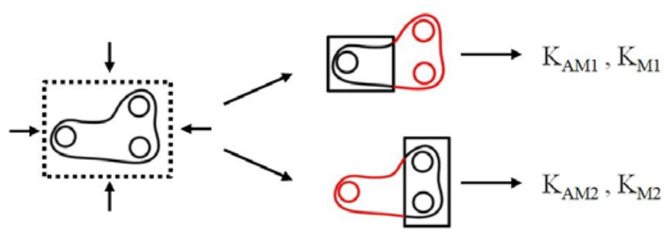

Fig. 6. A Product is manufactured by two different hybrid processes, which leads to different costs for the additive manufacturing and the machining.

As already mentioned, the STL model is converted to a volume model discretized by tetrahedrons. For identifying the volume beyond the wrought product, the MATLAB tool has to allocate every tetrahedron to either the inner or the outer volume by considering the boundaries of the wrought product. The tetrahedrons, which are neither on the outer nor on the inner side of the boundary, are divided into twelve smaller tetrahedrons, see Figure 7. Those have to be allocated to the inner or outer volume again. The small tetrahedrons, which are located on the boundary this time, are divided in the same way into even smaller tetrahedrons. So the model volumina beyond and inside the wrought product are the sum of the allocated tetrahedrons´ volumina. The volume of the tetrahedrons, which still remain on the boundary after the second decomposition, is split equally to both areas. Referring to the size of the validation model, which is presented below, the equal splitting leads to a maximum error in volume calculation of 0.9%. But it also prevents from a huge increase of model data, i.e. number of tetrahedrons. Hence, in that case the amount of the error is acceptable.

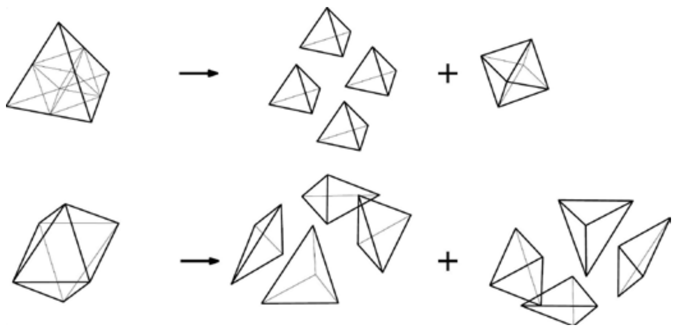

Fig. 7 Decomposition of a tetrahedron into twelve smaller tetrahedrons.

In general, the accuracy can be improved by choosing a smaller size of the tetrahedrons for the discretization at the beginning.

In the last step this procedure enables the tool to divide the overall product volume into the generated volume and the machined volume for every available wrought product size that the optimization parameters determine. By calculation of the volume parts, the production costs for the hybrid manufacturing process can be identified and the parameters can be evaluated. Using that procedure, the genetic algorithm determines the optimal wrought product with the lowest production costs.

3. Validation

For validation purposes, the MATLAB optimization tool is applied to a wheel carrier, which is developed by the help of the adapted product development process. The wheel carrier is made out of titanium and several points indicate forces and torsional moments to the component. That leads to a complicated curved structure along the paths of forces after the design phase is finished. In the center of the wheel carrier there is a basic cylinder included. That geometry is shown in Figure 8 on the left-hand side.

In the first step, the tool determines the smallest encasing wrought products in the form of a rectangular solid and a cylinder. As shown in Figure 8, both wrought products have a large volume, which has to be removed to create the requested structure. The volume of the smallest encasing cylinder is approximately twice as big as the volume of the rectangular solid. Because of the large size, the cylinders are the main driver of the production costs. Hence, the costs for machining the cylinder are also approximately twice as big as the costs using the rectangular solid.

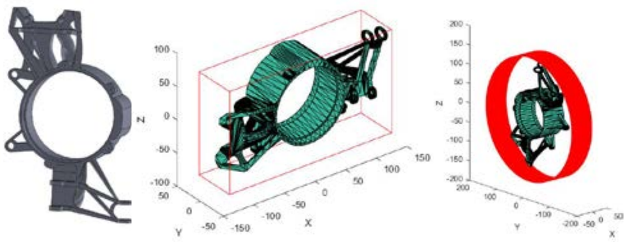

Fig. 8 Structure of the wheel carrier with an encasing rectangular solid and a cylinder (marked red).

In the next step, the tool determines the optimal combination of machining and additive manufacturing volume. The tool considers the rectangular solid, the cylinder, and the tube as possible wrought products successively. The optimal results for the first two wrought products are a very small solid or cylinder, with hardly any material of the wheel carrier inside. Hence, the cheapest production process only uses the additive manufacturing, when there are only rectangular solids or cylinders available. That seems plausible, since the requested structure of the wheel carrier is not formed like those objects. Instead, the center of the component is formed like a hollow cylinder, so a tube might be an advantageous wrought product to use in a hybrid manufacturing process.

And that is also how the optimization results for the tube look like. As shown in Figure 9, the tube is approximately concentric with the hollow cylinder, but has not the same length. All the structures beyond the wrought product have to be added to the tube by additive manufacturing. For the hybrid manufacturing process, this optimized wrought product leads to production costs, which are 42% less than the costs for the completely additive manufactured option. Additionally, the production costs constitute only 5% of the costs, which arose, if you would manufacture the wheel carrier out a cylindrical encasing wrought product by machining.

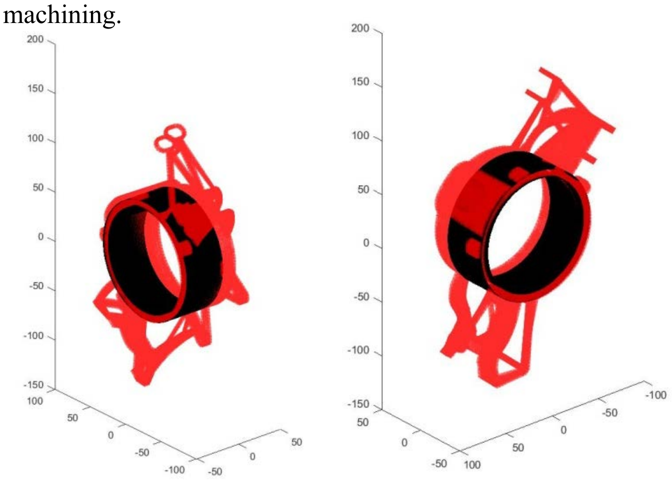

Fig. 9 Structure of the wheel carrier (red) and the optimized wrought product (black) for the hybrid manufacturing process.

The efficiency of the algorithm can be illustrated by counting the number of calculations during the optimization. The optimization for the tube finished after 79 generations with 60 individuals each. Every individual contains a set of parameters, that describes one available tube. Taking into account, that the best three individuals of one generation are shifted to the next generation, this leads to 4506 single calculations. On the other hand, a full factorial experiment, which would mean to evaluate every possible combination of available tube lengths, diameters and positions would lead to $1{,}34 \cdot 10^{17}$ calculations. Compared to that number, the genetic algorithm only needs a percentage of $3 \cdot 10^{-14}$.

4. Conclusion

We developed an optimization tool to determine the additive and subtractive amounts in a hybrid manufacturing process which

- Calculate the smallest encasing wrought material of a part,
- Determine the optimal proportions of the hybrid amounts based on a volume based cost function,
- Require a minimal calculation time by using a genetic algorithm.

The introduced tool enables a complete automation of the fifth step of the hybrid manufacturing process and allows the time and cost efficient application of hybrid additive and subtractive manufacturing processes.

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