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Procedia CIRP 93 (2020) 62–67

www.elsevier.com/locate/procedia

53rd CIRP Conference on Manufacturing Systems

Topology Optimisation and Metal Based Additive Manufacturing of Welding Jig Elements

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Abstract

Topology optimisation (TO) and Laser Powder Bed Fusion (LPBF) for the manufacturing of welding jigs used in automotive body shops shows high potential regarding material efficiency, weight reduction, and the integration of additional functions into the metal LPBF jig elements. For conventional series production, steel or aluminium jig elements are manufactured by using water jet cutting and machining processes, such as milling, drilling, and turning. To determine the economic efficiency of the topological optimised jig elements, the manufacturing costs for using LPBF with steel powder is compared to the costs for using conventional manufacturing processes. Based on the results, the application of TO and LBPF for jig elements is discussed.

Keywords: Laser Powder Bed Fusion; LPBF; fixture; automotive body shop; welding jigs; Jigprinting; Additive Tooling; Selective Laser Melting (SLM); Additive Manufacturing (AM)

1. Introduction

The increasing number of vehicle variants, the appearance of the electric vehicle, and the global diversification of the industry, all are increasing the need for more flexibility in the automotive industry. This holds especially true for the body in white production with its high degree of automation and high production volumes. Given this situation, traditional manufacturing (TM) technologies are starting to not be able to cost-efficiently cope with the manufacturing of production equipment for prototypes, pre-series, and series production. Today's automotive industry demands for variant-specific production equipment that require a high economic investment when manufactured using traditional processes. Research is done on cost-efficient production solutions, but besides the fixtureless body shop approach, many solutions for flexibility increase still have high investment costs regarding welding jigs [1]. In this scenario, Additive Manufacturing (AM), specifically metal based processes like Laser Powder Bed Fusion (LPBF) are a promising solution to produce more complex production equipment, such as jigs without rising costs. However, previous studies show that using LPBF for traditionally designed jig elements is not economic yet. Polymer based AM such as Fused Filament Fabrication (FFF) with polylactide (PLA) can be used to produce part-specific jig elements in order to reduce the manufacturing costs and the total weight of pre-series welding jigs [2]. Since polymer elements might not be suitable for serial welding jigs designed for large quantities, the application of LPBF for jig manufacturing is investigated. Due to the high costs of LPBF, metals based AM of welding jig elements is not used in the industry and there only little research about it, which has been discussed in previous studies [3] [4]. The novelty of this of this work is the combination of state of the art topology optimisation (TO) and LPBF of welding jig elements in order to make the AM parts cost-competitive in comparison to TM (water-jet cut and machined) and reduce the overall weight of the welding jig. The weight reduction allows important robot jig applications that are demanded by the industry [5].

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10.1016/j.procir.2020.04.066

2. Objective

The objective of this work is to analyse the applicability of LPBF in combination with TO for the manufacturing of welding jig elements. The task is to find out whether this combination is a superior engineering solution to reduce weight and costs, allowing the manufacturing of jigs with improved functionality and adaptation capability for each case. This assessment will be achieved by completely redesigning a manually operated welding jig, replacing most of its TM elements with TO elements manufactured with LPBF. A subsequent economic analysis is performed in order to evaluate the economic efficiency of this manufacturing solution, considering that LPBF is cost intense.

3. State of the Art

The automotive body in white production consists of several body assembly lines, as well as numerous sub-assembly lines which are each composed of a large number of stations. These stations consist of various interlinked welding jigs. Studies have shown that an average automotive welding line contains more than 500 of these jigs [6]. Welding jigs play an important role in the manufacturing process, as they have a direct effect in productivity, and product quality and cost. These costs account for the material, assembly, operation and design of the jigs [7] and, according to research, can sometimes equate to as much as 10 to 20 % of the total manufacturing costs of products [8]. Also, as [9] shows, around 70 % of geometric deviations of welded assemblies are caused by jigs. This illustrates that welding jigs for automotive body shops have potential of improvement regarding their variant specific manufacturing costs.

3.1. Functions and features of welding jigs

A jig is a device with the function of locating, holding, and supporting a workpiece during a specific manufacturing operation as for example welding. They are essential tools for production, as they are required in most of the manufacturing, inspection, and assembly processes. In particular, welding jigs are the most used devices to align and retain various parts during welding [10]. Welding jigs are specifically made to hold multiple parts together, resist high heat as well as sputter and, in case of arc welding, conduct electricity to provide grounding. They ensure the correct welding dimensions and minimise thermal distortion [11]. Welding jigs have the following main features [12]:

- **Principle of location:** Welding jigs generally make use of the 3-2-1 principle of location, also called the six point principle, as a way to restrict the degrees of freedom (DOF) of the workpiece.
- **Opening ability:** Because welding is a process in which various parts joined, the welded structure gradually grows in size. This requires a good opening ability to make loading and unloading of welding jigs as convenient as possible.
- **Adjustability:** Welding jigs are subjected to a great number of loading and unloading cycles throughout their lifetime. Because of that, welding jigs must be adjustable. The adjustability of the jig is usually solved with shim plates and allows the correction of the manufacturing tolerances of the jig elements.

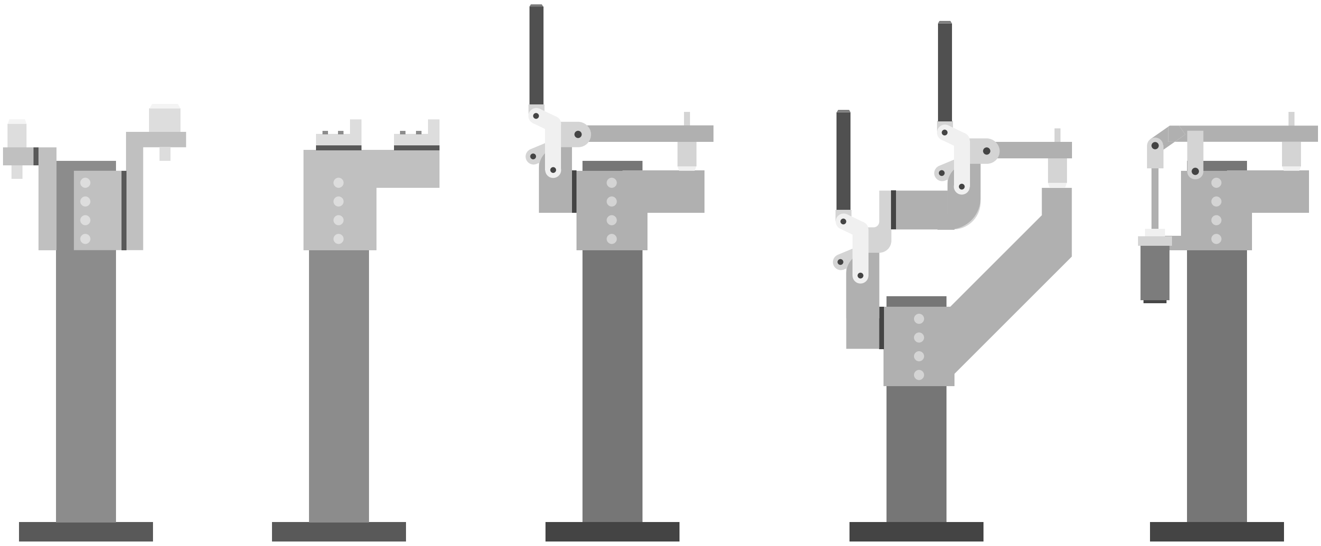
The same standard parts can be identified in the principal assembly of most jigs. Since most standard parts are well available at reasonable cost, only the structural part specific jig elements are suitable for additive manufacturing [4]. They make up the main body of the different jig units. They ensure the correct position and orientation of the clamping and positioning elements. These are the parts which are topology optimised and assessed for the manufacturing with LPBF.

3.2. Types of jig units

A classification of welding jigs units can be made according to kinematics and the mechanism itself. Two different types of jig units will be presented according to [13]. The first type are non-driven jig units and the second type are driven jig units. The non-driven jig units are also called positioning units. They consist of fixed support parts which do not require driven power. Depending on the type of support parts they can be subdivided in three types. First, there are pin positioning units with cylindrical pins used to position the welded parts by holes. Units with one or various pins can be differentiated. The second type are locator positioning units with locator elements positioning a face of the welded component. Mixed positioning units as the third type have a combination of positioning pins and locators [13]. Driven units have a movable mechanism (usually some type of clamp) which requires a power unit to be actuated. Two types of power are generally used: Manuel driven units and pneumatic driven units. With manual driven units, the clamp mechanism is operated by hand. These clamps, called toggle clamps, usually make use of a four-bar linkage with a self-locking function [14]. Pneumatic clamps use a pneumatic cylinder driven by compressed air to lock the welded components in place. Both manual and pneumatic jig units can be divided in two types depending on the kinematics of the clamping motion. One-swing units with only one motion is needed during clamping and on the other side two-swing units. In two-swing units, clamping parts are moved by two clamps. Figure 1 shows examples of location jig units and driven jig units.

3.3. Topology optimisation of structural parts

Topology optimisation (TO) is a computer assisted method used in product development to identify potentials of optimisation. It works out the placement and amount of material needed inside a design domain in order to achieve the best structural performance [15]. TO starts with a mechanical element inside said 3D design domain Ω in $\mathbb{R}^3$ which is subjected to some forces and boundary conditions (supports) [16]. With TO, an



(a) Various pins (b) Various locators (c) Manual one-swing (d) Manual two-swing (e) Pneumatic one-swing

Fig. 1: Examples of non-driven and driven jig units (adapted from [13])

optimal material distribution can be achieved for each specific case. The method is used in the field of lightweight design, which focuses on achieving the lightest systems possible. Because of that, TO is a well-established method in aerospace and automotive industry. However, the main drawback of TO is that the optimisation results are often very difficult or even impossible to manufacture with TM. With the rising technology of AM it is possible to fabricate TO structures directly from the optimised CAD data [17].

3.4. Additive Manufacturing of jig elements

There is only little research interest in manufacturing welding jig elements with LPBF. As mentioned earlier, polymer-based AM with FFF can be used for cost-efficient pre-series welding jigs, but metal-based AM seems to be not yet economic [2]. Currently, series welding jigs in automotive body shops are manufactured using TM technologies, for example with water jet cutting and subsequent machining as part of the case studied in this project. However, TM technologies have some disadvantages regarding the manufacturing of welding jigs for two main reasons. Because of their characteristics, TM technologies often require part specific equipment, such as tooling, molds or in some extreme cases even specific machines. In the case of body-in-white welding jigs, which usually are unique because of their part-specific characteristics, TM implies high manufacturing costs. Second, car body production is very complex from the production process standpoint, and this complexity is carried over to the used welding jigs. Design demands such as difficult clamping positions, volume restrictions or movable parts result in very complex shapes of the welding jig elements. TM is not efficient for the fabrication of these elements, as complex parts are expensive and require long process chains with different technologies. AM technologies, on the other hand, are a very well-established way of manufacturing parts with a high complexity at low production volumes [4].

4. Approach

The TO, redesign for LPBF, and evaluation is done on an existing conventional jig, which is provided by an automobile manufacturer (see Figure 3). All simulations and TO are done with SOLIDWORKS 2019 Education Edition. A static analysis of the existing parts is done to extract the load conditions for the redesign and TO of the LPBF jig elements. The results of the TO are interpreted and included into the optimised design. A static analysis of the TO LPBF parts is done to check that mechanical requirements are still fulfilled. The model for the mechanical simulation is prepared by considering the load cases and restrictions of each selected jig element. The optimisation process consists of an iteration of TO, constantly modifying the constraints and objectives until a satisfactory result is achieved. The TO results are post processed by smoothing the raw mesh elements. Finally, the topology study results are interpreted, and the final geometries of the elements are designed. Due to the greater geometrical freedom of LPBF parts, in some cases several parts are merged into one to improve the simplicity of the system. The redesigned AM elements are quantitative compared to the TM parts by total weight and part volume. In addition to that, some qualitative aspects, such as simplicity and functionality are analysed. As a conclusion, an economic analysis and comparison of the TM and redesigned parts and their manufacturing costs is carried out.

5. Topology Optimisation of selected Jig Elements

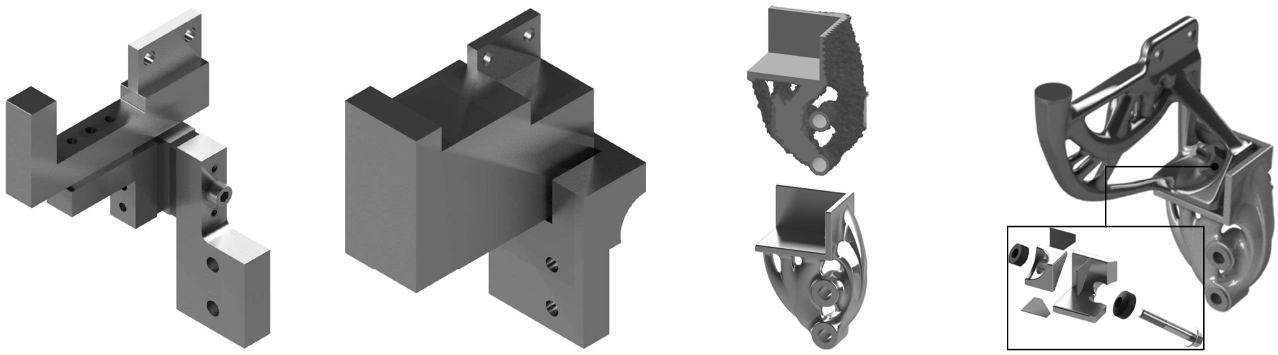
One of the objectives of the welding jig redesign and TO is to reduce the number of necessary elements, which in most cases is achieved by combining various parts into one complex part. For that, the elements in the simulation model were replaced by a single rough part, which represented the design domain (Ω) for the TO. The simulation model consists out of the following main fields:

- **Material:** it provides essential information about the behaviour of the part under stress. In this case, the original parts were manufactured out of S235JR structural steel. The LPBF parts are designed based on the material properties of 316L stainless steel. The material data is taken from the SOLIDWORKS database.
- **External loads:** in this field the loads that the mechanical elements are subjected to are modelled. In this project the loads were set, when possible, as the maximum loads that the clamps can withstand and the subsequent reaction forces. Part weight was neglected, as it was minimal compared to clamp loads.
- **Fixtures:** this field refers to the connections that the subassembly has to the other parts of the welding jig. They could be referred to as 'outer connections'. These fixtures are screw and bolt connections, either with clamps, with other body parts or with stands. They are modelled as fixed hinge fixtures, which allow the rotation of the bolted surface but not its translation.
- **Connections and contacts:** they model the interactions between the different parts of the subassembly. Three different connection types can be identified. They are welded connection, screw connections, and dowel pin connections.
- **Mesh:** meshing refers to the division of the parts to be simulated into smaller simple elements. A blended curvature-based mesh is applied. This mesh type has the advantage of allowing to define a maximum and minimum size for the mesh elements, which increases meshing flexibility and improves calculation precision in areas, such as small fillets or thin walls. A mesh element size between 1.5 mm and 4.0 mm is generally chosen, which shows a good compromise between precision and calculation time. Additionally, mesh controls are applied in order to refine the mesh, that is, reduce element size, in critical interface areas.

The design domain (Ω) is modelled to embody the maximal volume that the final redesigned part could take up, considering restrictions, such as the jig opening ability or the accessibility of the welding spots. The same forces and fixtures as in the previous static structural analysis are applied, and the mesh is created with the same parameters. However, some additional fields must be set in order to perform the TO. The first field is the optimisation goal with the geometrical constraints. For the goal, the default best stiffness to weight ratio goal of the TO software SOLIDWORKS is used, which looks for the stiffest geometry possible given a specific weight reduction. A mass constraint is applied, which sets the target mass that the resulting geometry should have. The second field includes manufacturing controls such as preserved regions with selected faces that cannot be removed by the solver, for example functional faces or connecting surfaces to other parts. Additionally, faces on which loads and fixtures are applied are also preserved during TO. Another manufacturing control are symmetries. One or various symmetry planes can be set, which cut the body into identical parts in order to reduce calculation time, as only one part of the design domain is calculated. The topology studies are iterative processes based on the continuous density method in which the solver progressively reduces geometry weight and volume by adjusting individual mesh element density by assigning pseudo-density values between 0 and 1. In this method, a value of 0 is assigned to the elements with the smallest stress values, that is, the ones which contribute the least to the overall stiffness of the geometry. A value of 1 is assigned to necessary elements for the structural integrity of the resulting geometry. The study is ended when a value within the stopping threshold (convergence tolerance) is reached.

As the result, a meshed body with the optimal geometry for the given set of loads and boundary conditions is generated. In it, a colour code is used to identify the relative importance of particular mesh elements, from 'must keep' to 'OK to remove'. The resulting smoothed mesh is used as a guide for the design of the new parts. Regarding the design phase, first, all the functional features, such as holes for bolt connections or force application surfaces, are modelled to ensure that the intended functionality of the specific parts is preserved. After all functional features of one element are modelled, they are connected. The reference smoothed mesh is interpreted in order to find organic shapes that flowed from one feature to the others. These shapes are modelled with the SOLIDWORKS tool 'lofted surface', which is used to create surfaces that transition from one profile to another following one or several guide curves. The surfaces are then converted to solid bodies, combined with the previous geometry and finally fillets are applied to their resultant edges for a seamless transition between bodies. Finally, minor adjustments are made to the parts in order to optimise their design based on the static structural analyses. Figure 2 shows the described optimisation process for one example jig element.

Out of all the functional features that the redesigned parts have, the new developed 3D shimming is probably the most important one. The key improvement of 3D shimming over conventional shimming is that it only uses one interface to adjust the position of parts in the three different directions, whereas with traditional shimming three of them are needed, increasing the number of jig and fixing elements, such as bolts and nuts. This is achieved with the use of a concave spherical bolt connection, in which three shimming plates of various thicknesses are placed in order to individually adjust the relative position of the two jig elements in the different axes. A bolt with a custom-made convex spherical nut and washer is used to fasten everything together. The 3D shimming is illustrated in Figure 2 (d).



(a) Original jig elements (b) Design domain (c) Redesign of jig element (d) Final Design of TO jig elements

Fig. 2: Optimisation of welding jig elements

6. Results of Topology Optimisation

The TO is performed on all selected jig elements of the conventional jig. The optimised welding jig (see Figure 3) is then analysed and compared to the key characteristics of the conventional jig. Table 1 shows the characteristics of the comparison between both jigs made by TM and TO LPBF.

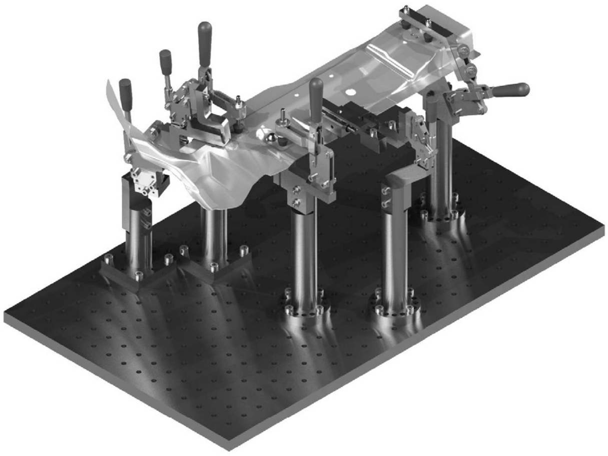
Table 1: Comparison between TM and TO LPBF welding jig elements

Characteristics	TM	TO LPBF
Total mass of jig elements [kg]	9.87	4.82
Total volume of jig body elements [cm^3]	1265.0	602.8
Number of jig elements [#]	21	12
Total manufacturing costs [€]	1420.50	2244.89

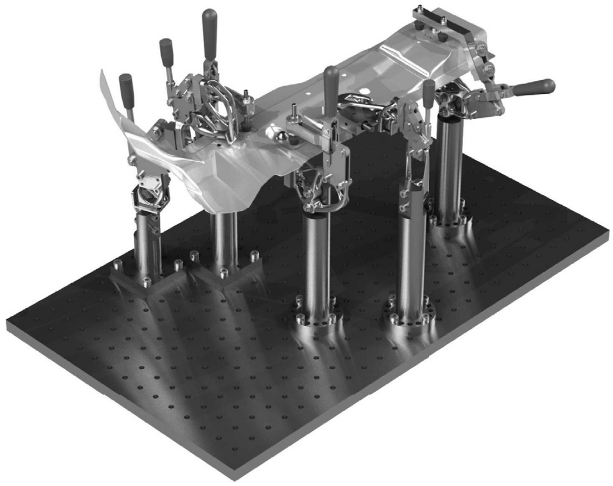
A reduction of mass by 51 % to 4.82 kg and volume by 52 % to 602.80 cm^3 has been achieved in comparison to TM. The small difference between volume and mass savings is because 316L stainless steel has a marginally higher density (8.0 g/cm^3) than the original material, S235JR structural steel (7.8 g/cm^3). However, the volume reduction that TO achieved greatly compensates the slight increase in density. TO also leads to an improvement of the behaviour under load of most of the parts. The optimisation of the geometry for the particular load cases achieved a reduction of maximum stress values between 14 % and 78 % at the elements with improved mechanical behaviour. A much more homogeneous stress distribution was achieved, avoiding the high stress concentration points that could be seen in the original ones. For these parts, the reduction of stress values led to an increase in safety factors. The safety factors of TM elements reach from 0.6 to 3.29 at maximum, whereas the safety factors of the TO elements reach from 1.87 to 11.7. That means that most of the TO parts can withstand higher loads without reaching its failure limit. The economic efficiency of the redesigned elements in relation to the original ones is analysed by using the data from a previous study performed on the same welding jig [2] and performing a manufacturing time and cost calculation on a SLM®280HL machine from SLM Solutions. The total manufacturing costs are divided in machine costs (C_{mach}), material costs (C_{mat}) and labour costs (C_{lab}) for all observed jig elements. The manufacturing costs of the TO LPBF parts are higher than the TM costs of the conventional jig parts. The cost of the TM processes, which consists of a water-jet cutting and a machining, were calculated to add up to 1420.50 € [2]. This price (when considering the amount of manufactured parts) is a direct consequence of TM having been well-established processes for a long time. On the other hand, LPBF has proven itself to be a cost intensive technology. The total manufacturing costs of the redesigned parts were estimated to be 2244.89 €. This means an increase of 58 % when compared with the original parts. The total printing time is estimated to 36.5 hours, which results in C_{mach} = 1058.50 € at a machine hour rate of 29 €. C_{lab} are 660 € including the time for post-processing (support removal and finishing of drill holes). C_{mat} are calculated to 526.39 € for the steel powder.

7. Summary and Outlook

The results confirm that TO and LPBF elements have better physical and structural properties than the original elements. They not only achieve a remarkable reduction in volume and mass, ranging from around 30 % up to more than 65 %, but they also show a better behaviour under load. This shows the great potential of metal AM technologies in combination with TO for lightweight design, especially in applications where highly demanding loads are applied to the parts. Potential applications can be robot gripper jigs whose currently high weight limits the travel speed and thus the process time. Another important application can be jigs of different variants that a stored next to a body shop welding cell and changed in by a handling robot. Currently, this solution for flexibility increase is limited by the weight of the jigs. However, the improvement in physical and mechanical properties results in an increase of manufacturing costs. LPBF, being a recently developed technology, is a cost



(a) Existing conventional welding jig



(b) Topological optimised welding jig

Fig. 3: Example welding jig with Topological optimisation and LPBF of welding jig elements

intensive manufacturing process. This, however, could change in the following years, as the technology is further developed, and costs are reduced. As a further development of the findings of this study, strategies for the economic optimisation of LPBF manufacturing processes should be carried out. Some promising areas of improvement are the optimisation of part orientation, in order to reduce the need for support structures, as well as the increase of build platform utilisation. This, combined with future developments in cost reduction of LPBF technology, could lead to a much broader application range of LPBF in jig manufacturing.

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