Additive Manufacturing for Cost Efficient Hybrid Welding Jigs

Kolja Lichtenthäler, Georg Bergweiler, Achim Kampker, Ansgar Hollah and Sebastian Leimbrink

Abstract The use of the Additive Manufacturing (AM) process Fused Filament Fabrication (FFF) for the manufacturing of pre-series welding jigs for car body assemblies shows potential in terms of cost reduction and design flexibility. A conventional welding jig consists of standard parts and machined parts which can cause high costs in manufacturing. Although many simpler 2D parts which can be cut very economically are used as well, some of those parts have to be machined again in order to integrate all functional features. Additional manufacturing steps cause additional costs and prolong the supply process of those parts. A hybrid jig system that consists of part specific FFF components and standard elements has been developed for the welding of car body assemblies in the pre-series vehicle production. In order to analyse cost and time advantages, an economic assessment is used. It is aimed to determine whether the use of a hybrid jig system for welding operations of car body prototypes generates lower financial and time expenditures compared to conventional welding jigs. The assessment includes a detailed comparison between the manufacturing of a hybrid welding jig and a conventional welding jig for car body assemblies. Additive Manufacturing (AM) of the complex and specific parts with FFF offers time and cost advantages because material and process costs are lower than with milling, and process chains can be simplified. This paper presents the results of the assessment on the hybrid welding jig system and shows the overall potential in the pre-series vehicle production.

Keywords Additive manufacturing · Body shop · Fused filament fabrication · Welding jig

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1 Introduction

In automotive body shops, welding jigs are used which are usually completely manufactured out of steel. This is a well proven way to ensure the stiffness and strength required to meet the prevailing quality requirements of the welded body assemblies. Since the jigs and fixtures have to meet accuracy requirements in the tenth of a millimetre range, the specific components of the jigs and fixtures are correspondingly expensive and time-consuming to manufacture (Fritzsche et al. 2012). These stiff but at the same time rigid and inflexible jigs are also used in pre-series production. However, the pre-series phase is often characterised by component changes and other adaptation measures, which means that the provision of this type of jigs is associated with high manufacturing costs. In general, the usual quantities in pre-production are also significantly lower than in series production. In a pre-series phase, no more than several hundred vehicles are built, in some cases even less than 100 units (Schuh et al. 2008). In this case, the steel jigs used are usually over-dimensioned and exceed the quantity requirements many times. Due to factors such as an increasing number of variants, shorter ramp-up phases and life cycles, as well as the rise of electromobility, there is an enormous cost pressure on the prototype and pre-series phase of automotive production, which to a large extent affects the body shops, including its complex jig technology (Bichler et al. 2018; Hansen et al. 2018; Zhang et al. 2009).

In conventional manufacturing, subtractive manufacturing technologies, such as CNC machining, are used. These remove material from a basic block until the final functional geometry is established. In additive manufacturing, parts are produced from 3D model data by joining materials in layers. With this layer-by-layer fabrication, AM differs from subtractive and forming manufacturing processes. The use of polymer-based AM for jig manufacturing in pre-series body shop offers potential to save costs and reduce provisioning expenses by shortening and thus accelerating the process chain from the first jig design to the operational welding jig. Existing approaches show the general suitability of polymer-based additive fabrication for the manufacturing of welding jigs for pre-series body shops but lack in a comprehensive economic evaluation and a detailed comparison with the costs of current jig production (Guo and Leu 2013; Markforged Inc. 2019; Stratasys Inc. 2019; Thompson et al. 2016).

2 Conventional Pre-series Welding Jigs

Pre-series welding jigs consist of standard parts and specific elements, which are adapted to the components to be welded. Typical standard elements are the base plate, manual clamps, location pins, stands and clamping spindles. In the following, only the manufacturing costs of the component specific elements are considered, since the standard parts are well available and do not offer much cost saving potential. The elements of a jig and fixture system are shown in Fig. 1 (Hesse et al. 2012).

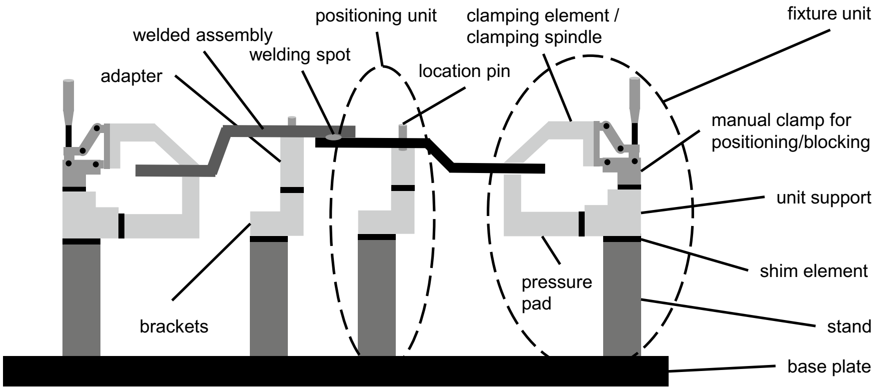

Fig. 1 Functional elements of a pre-series welding jig

2.1 Manufacturing of Conventional Pre-series Welding Jigs

In conventional pre-series welding jig manufacturing, the elements unit support, bracket, clamping arm, pressure pad and adapter are usually made of tool steel such as S235JR+AR using various manufacturing processes. In order to ensure that the respective elements fulfil their functions, it is often necessary to use manufacturing process chains with different manual steps. Cost-effective two-dimensional (2D) cutting processes such as water jetting and laser cutting are used to produce a large number of elements that can be functionally fulfilled with a 2D geometry. In many cases, pure 2D cutting is not sufficient to integrate all functional features, in which case cut-out holes have to be machined afterwards. Holes that are not in the cutting plane must be drilled in an additional step after the cutting process. To meet the accuracy requirements, some of the cut holes must be reamed in order to comply with the tolerances. Threading can also only take place in a post-machining step after the 2D cutting. In pre-series jig and fixture manufacturing, manual drilling and tapping is usually used. In the case of close-contour clamping and pressure pieces, the 2D elements are often post-machined by milling. With machining the 2D pieces, 2.5D or 3D contours can be created, which are required for the functional fulfilment of some of the jig elements. In case of adapter pieces that are needed to direct the force direction by a certain angle, without the availability of suitable standard angles, 2D components are welded together accordingly. This requires an additional manual manufacturing step (Hoffman 2004; Trummer and Wiebach 1994).

2.2 Manufacturing Costs of Pre-series Welding Jigs

The cost of manufacturing includes three terms. The material costs, the machine costs for water jetting and the costs for milling. Both process steps contain the personnel costs for both the CAM process and operation at the machine. Only the costs that can be assigned directly to the component to be manufactured are considered.

$$Total\,cost\;per\;part\;P[EUR] = MP + 1\text{st}\,P + 2\text{nd}\,P$$

with

$MP = Material\ cost\ per\ part\ [EUR]$
$1\text{st}\ P = Costs\ for\ the\ first\ process\ step\ per\ part\ [EUR]$
$2\text{nd}\ P = Costs\ for\ the\ second\ process\ step\ per\ part\ [EUR]$

In this paper, the manufacturing costs of two different welding jigs are analysed. The first jig is a welding jig for a smaller body assembly consisting of a lower sheet and a hat-shaped upper part. The jig is mounted with feet on a welding table and consists of a larger jig body structure that is connected to the feet. The jig body structure contains the location pins for positioning the parts as well as the connection features for the toggle clamp. The clamping arm is extended by means of a clamping element into which two clamping spindles are screwed. The jig positions and fastens the two parts and allows the targeted access of the welding gun for the welding of the parts with a total of four welding spots. The part specific components of the jig clamping element and jig body structure are designed once for fabrication with FFF and once for production with milling processes. This jig is called "small example welding jig".

The second jig is a pre-series welding jig for a larger welded assembly. The function of the jig is the positioning and fixing of two smaller components, a holder for the brake hose and a second holder for the ABS system, on a longitudinal member. The holder for the brake hose is joined with resistance spot welding and the ABS holder is joined with a gas metal arc welding (GMAW) process. This jig is called "larger welding jig". Figure 2 shows the two welding jigs.

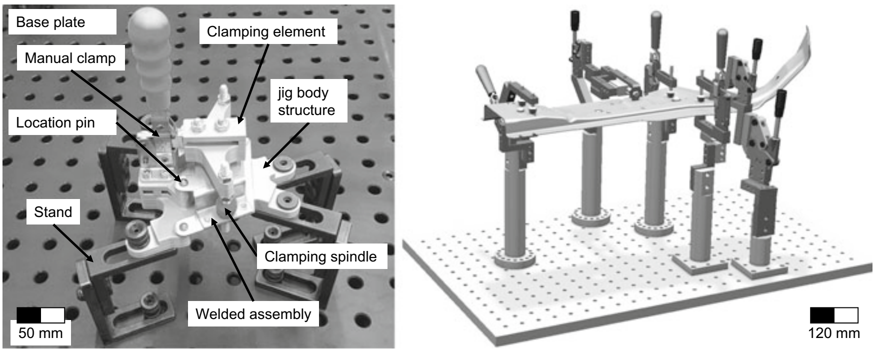

Fig. 2 Small example welding jig (left) and larger welding jig (right)

3 Hybrid Welding Jigs with Additive Manufactured Elements

The idea behind hybrid welding jigs with AM elements is to keep standard elements and some of the simple 2D elements by only using water jetting and add polymer AM elements to reduce the manufacturing costs of the jigs. In order to get a better understanding of why metal based AM is not yet economical, the costs of metal AM of the specific jig elements are estimated as well.

3.1 Polymer Additive Manufacturing

Common AM processes are Stereolithography (SLA), Fused Filament Fabrication (FFF), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Selective Laser melting (SLM), Polygraphy (Polyjet), Direct Light Processing Printing (DLP) and Laser Metal Deposition (LMD). In addition, there are other and related processes for which reference is made to the available literature (Gebhardt et al. 2016). Since the FFF process has significant low manufacturing and material cost among the polymer-based AM processes, the available materials are examined in more detail below. The focus on the FFF process is substantiated by the good results with FFF welding jigs elements that have already been achieved. In Fig. 3, the filament costs of different FFF materials are plotted double-logarithmically above the material stiffness.

The diagram shows that of the wide range of FFF materials, PLA and ABS are among the cheaper ones. At the same time, they have good stiffness properties. PLA continues to work well with common support materials, and its suitability as a

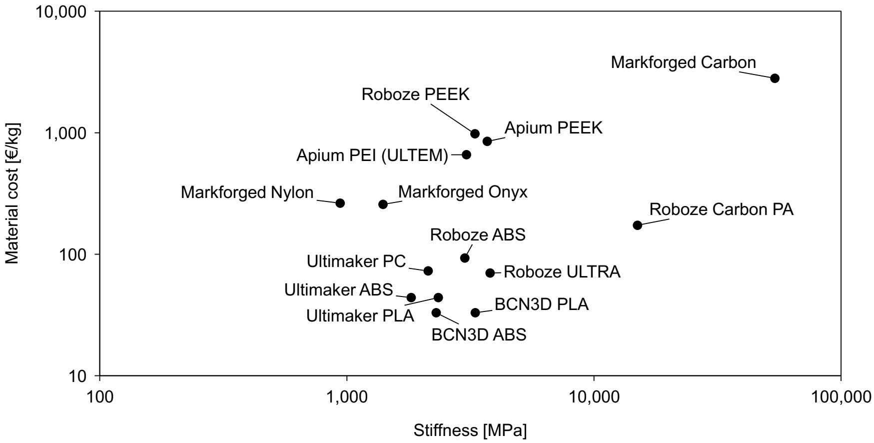

Fig. 3 Filament costs and Young's modulus of selected FFF materials

Table 1 Calculation of hourly rate of a FFF printer

Hourly rate of a FFF printer		
Cost type	Value	Unit
Acquisition cost	5075	€
Runtime	3	a
Operating hours	4768	h
Residual value	400	€
Interest rate	1	%
Maintenance cost	300	€
Electricity cost	0.02	€/h
Space requirement	0.5	m^2
Space cost	30	€/(m^2a)
Annual depreciation	1573.92	€/a
Annual depreciation per hour	0.33	€/h
Space cost per hour	0.00315	€/h
Maintenance cost per hour	0.02098	€/h
Total hourly rate	0.3542191	€/h

feedstock for the jig manufacturing has been demonstrated in a previous study. High performance polymers such as PEEK and fibre-reinforced nylon have a significantly higher stiffness but are much more expensive. Not only the filament costs of those materials are much higher than PLA and ABS, also the investment costs for the printers are higher.

The operating costs of a typical FFF printer are exemplified in Table 1. An AM printer can be used almost around the clock, since during production no personnel deployment is needed. The investment is much smaller than with conventional production machines. This results in an hourly rate of well below one euro per hour of operation.

The typical process chain of part manufacturing with the FFF process begins with the import of the STL file into the software environment of the FFF printer. After adjusting the process parameters, the paths of the print head are calculated and the machine code is generated by the postprocessor. Since the printing process runs smoothly in general, continuous monitoring of the printing process by the operator is not necessary. The finished printed part must then be manually removed from the building platform. Depending on whether support material was used, this must be removed in a post-processing step. Supporting material is always used when the geometry of the part to be printed has overhangs that exceed an angle of 60°.

There are different types of support material. Water-soluble support material has the advantage that the part has a very low risk of damage caused by the removal of the support material. The part surrounded by support material is placed in a water bath in which the support material dissolves. The disadvantage here is that this process takes some time and in case of part faults water can get into the inside of the part. The dissolution of the supporting structure in water is associated with time expenditure, but the costs are low. A simple container, which is filled with water and into which the part is placed, is sufficient. Many support materials are biodegradable; thus, the disposal into the drain is not critical. Supporting material for manual "break away" has the advantage that it is much faster than with the water-soluble process, but it is a manual work. In addition, especially with filigree structures, there is a risk that the part will be damaged. Problems can also often arise because the support material cannot be completely removed. Another option is to print support structures from the same material as the part. This option is usually used when the melting temperature of support and base material differ too much or only single extruders are available. The same disadvantages of "break-away" support occur in this case in a stronger form. An AM-equitable construction can counteract this.

The manufacturing costs of an FFF part consist of the costs for the preparation of the print job, the material costs, the process costs with the machine cost per hour as well as the costs for the post-processing, essentially the removal of the support material.

3.2 Metal-Based Additive Manufacturing

In metal-based AM, Selective Laser Melting (SLM) is the most widely used process alongside Metal Binder Jetting and Laser Material Deposition (LMD). In the SLM process, metal powder is located in a moveable powder bed. An optical system consisting of objectives and mirrors deflects a laser beam to the corresponding points in the powder bed. At this point, the powder is completely melted. This allows the forming of a solid material layer after solidification. The building platform is then lowered by the height of the layer and a new layer of powder is applied. The powder bed is smoothed with a roller to obtain a homogeneous layer. The process steps are repeated until the finished part is fabricated. The part is removed from the building platform and from the supporting structure, which in this case consists of the same material. The support structure is shaped in thin chains which support the overhangs of the part (Atzeni and Salmi 2012).

3.3 Manufacturing Costs of AM Parts

The manufacturing costs of AM parts are given as follows (Schmidt 2015).

$$Total\ cost\ per\ part\ P[EUR] = MP + AP + CP + BP$$

with

$MP = Material\ cost\ per\ part\ [EUR]$

AP = Pre-processing cost per part [EUR]
CP = Processing cost per part [EUR]
BP = Post processing cost per part [EUR]

The pre-processing cost consists of the time the system operator spends preparing the print and the corresponding hourly rate. The post-processing cost of SLM consists of the costs for the subsequent heat treatment of the printed part and the time for the rework multiplied by the hourly rate of the operator. The post-processing cost of FFF consists of time for support removal multiplied by the hourly rate of the worker.

4 Cost Analysis and Comparison

To compare the cost of the pre-series jigs, the smaller example jig and the larger jig are used. The effort invested in development and designing is assumed to be the same for every production process and is excluded in the calculation.

4.1 Manufacturing of Conventional Pre-series Welding Jigs

The material costs for the specific elements of the conventional pre-series welding jigs include only the cost of the actual component, not the cost of material to be removed. These are 2.38 € for the small example welding jig. In the first process step, a 2D shape is created with the use of the water jetting process. The expenses in the first process step consist of approximately one third of machine costs for a total cutting length of 1100 mm (3.76 €) and two thirds of personnel costs (8.80 €). To calculate the machine part, the costs are taken from Table 2 (Kühn et al. 2018). The staff costs of a worker in the German automotive industry are estimated at 60 € per hour.

This results in an amount of 14.86 € in the first processing step. In the second step, the milling process follows to produce the functional geometry with one 2.5D milling process (8 h) and four drilling and threading operations. This consists of 376 € for the milling machine costs and 96 € of personnel costs. Overall, the small example welding jig costs 487 €. This shows that for small jig for the second processing step 97% of the cost must be incurred. The total manufacturing costs of the component

Table 2 Process characteristics of water jetting

Sheet thickness	Traverse speed (mm/min)	Costs (€/m)
5 mm steel	800	0.625
10 mm steel	500	1
15 mm steel	325	1.54
20 mm steel	150	3.33

specific elements of the larger jig are 1420.48 €. For the larger jig, the cost of the second step is about 91% for a summarised milling and drilling process time of 22.9 h, while the proportion of water jetting is 7% with a summarised cutting length of 9040.75 mm.

4.2 Manufacturing of Hybrid Welding Jigs with FFF

The manufacturing costs of the small example hybrid with jig and the large one are analysed with FFF and the polymer PLA. The costs for water jetting remain the same as described above. The costs for AM are composed of material, machine and personnel costs. However, the proportion of personnel costs is higher, since in AM the post processing happens mostly manually. In total, the costs of FFF are significantly lower than those of the milling process. A standard FFF printer prints at approximately 0.028 cm^3/min. This value is to be understood as a guideline because the printing time depends on many parameters. These include the print settings, as well as geometric properties such as protrusions, overhangs or special shapes. The exact consumption values and real machine duration are used for the analysis.

The total FFF-printing costs for the small example jig are 48.91 €. This price consists of 8.20 € material and 10.80 € machine costs. In addition to this, there are the personnel costs for the CAM process, the loading of the printer and the post-processing. These amount to 30 €. The total FFF-printing costs for the larger jig are 649.68 €.

4.3 Manufacturing of Hybrid Welding Jigs with SLM

Another possibility to fabricate the specific jig elements of the small jig is using SLM with steel powder. Due to the more expensive process, the total cost increases to 379.30 €. The material costs are 101.86 € and the machine costs amount 227 €. The personnel costs for preparation and post processing are 60 €. SLM is a process close to end geometry. However, some functional surfaces have to be reworked in a second process step (e.g. threads).

4.4 Comparison

The different costs of the small example jig are illustrated in Fig. 4.

It turns out that using small hybrid welding jigs directly brings a cost savings potential. The greatest potential is shown by the machine costs. This can be explained by the fact that the second processing step in the conventional process requires 97% of the total machine costs. This step will be eliminated through AM. However, as

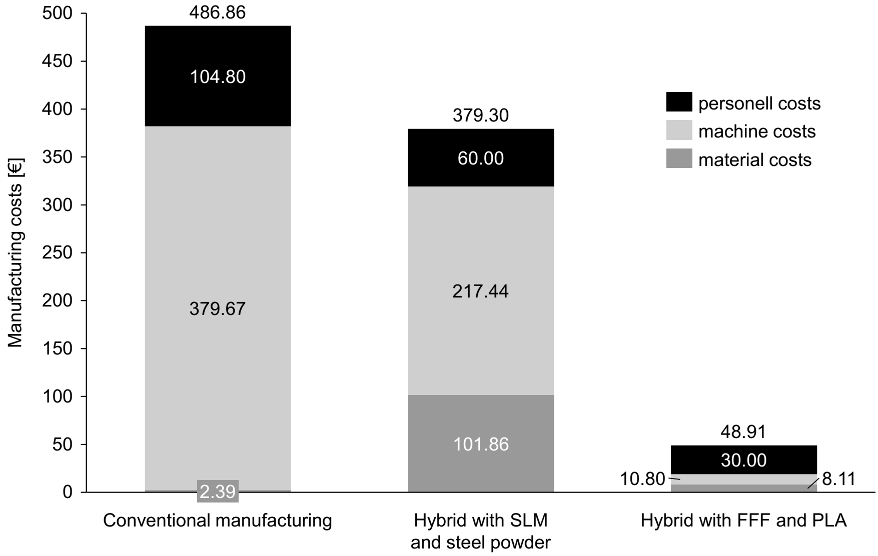

Fig. 4 Manufacturing costs of small example welding jig

described above, the machine cost of commercial SLM is higher compared to FFF printers. The figure also shows that machine costs account for the largest share of costs in the two metal processes. In polymer additive manufacturing, on the other hand, personnel costs account for the largest share of total costs. According to the current state of the art, post-processing in FFF processes is a manual process and thus personnel cost-intensive. Overall, it can be said that with small components, all the cost advantages of the FFF process come fully to grips with the highest potential. Since it is a small jig made up of few parts, differences in production time and assembly time play no role in this comparison.

That changes when considering the larger jig. The mere machine utilization time for conventional production is just under an hour for water jetting and 22 h of subtractive manufacturing. The printing time for an equivalent hybrid jig with FFF is over 370 h. This increases production time by 1600%, while the staff costs stay the same at about 5.5 h. The significant increase can be explained by the fact that a single printer does not have the same productivity as a comparable conventional machine. This increase in provisioning time can be reduced by the parallel use of several printers or by outsourcing the FFF production to external additive manufacturers. The manufacturing costs and time of the larger jig with the different manufacturing processes are shown in Fig. 5. Figure 6 portrays the hybrid jig with FFF elements for welding the longitudinal member assembly.

The largest savings can be found in the machine costs. There, the costs drop to almost 10%. This is due to the significantly lower investment and operating costs of the machines. The higher material price at AM can be explained by the larger volume, which is needed for the same strength, but also by the use of expensive support

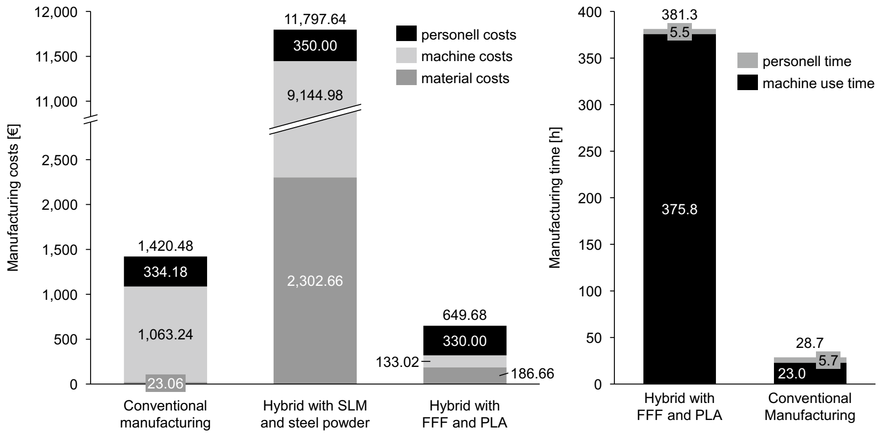

Fig. 5 Manufacturing costs and time of the larger welding jig

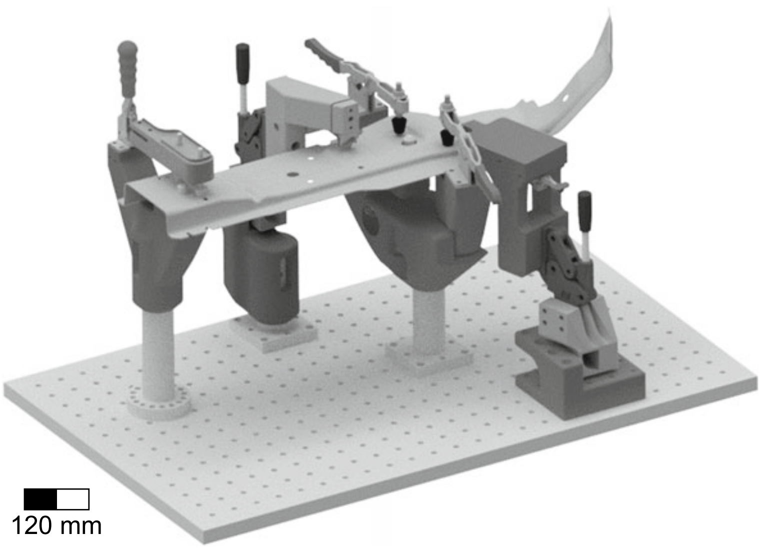

Fig. 6 Larger welding jig as hybrid version with FFF elements

material. The use of SLM to manufacture the jig is by far the most expensive. The total cost with 11,797.64 € is eight times as expensive as conventional production. The cost advantages of the FFF process are not to be borne by SLM, since the machine investment is very high. Another disadvantage are the material costs. These are, at the same volume, already factor 100 above, as in the conventional production process. Especially with SLM the costs of AM are sensitive to the part volume since large parts cause long building times and a high material consumption. This is the reason why the costs of SLM for the large jig are much higher than for the small jig and the proportion to the costs of the conventional manufacturing is inverse in the case of manufacturing the large jig. With conventional manufacturing, the complexity of the parts and the resulting manufacturing steps increases the costs. The influence of size of the parts on the total costs is low.

5 Conclusion

The cost comparison shows that using hybrid welding jigs with FFF elements is a way to reduce the manufacturing costs for pre-series welding jigs by almost the half for larger welding jigs. The cost saving potential gets bigger by using the hybrid welding jigs for all jigs in a pre-series body shop. For welding a complete car body, around 70 different jigs are used. Therefore, using hybrid welding jigs for the prototype und pre-series production allows to reduce costs of the industrialization of new car models and opens possibilities to meet the current challenges within the automotive industry. The cost analysis show that using metal AM is still too expensive, especially for large jigs, but the powder material costs as well as the machine operating costs are decreasing. Using it for the production of series welding jig might be possible soon. The next steps include a comprehensive testing of the hybrid jig system with focusing on the lifetime and the reproducibility of the welded parts.

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