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Design for Additive Manufacturing (DFAM) applied in the manufacture of Master Sample for the automotive industry

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Abstract

In order to supply auto parts to the automotive industry the companies must meet all Advanced Product Quality Planning (APQP) requirements. One of the biggest difficulties in obtaining the approval of the APQP is in the preparation of the "Master Sample," which will be used for the validation of jigs, production, and dimensional control devices. The procedures for manufacturing Master Samples through conventional manufacturing processes are outdated, slow, and cost-effective, which goes against the concepts of Industry 4.0. Therefore, this work aims to propose a procedure for Design for Additive Manufacturing (DFAM) that analyzes the feasibility and systematizes the manufacture of Master Sample through Additive Manufacturing (AM). Two model parts were submitted to the procedure, manufactured by AM and validated as Master Samples. In this work, a comparative analysis between the parts produced conventionally and those produced by AM showed that the time and costs in order to obtain the Master Samples using the proposed procedure was significantly shorter. The reduction in time to obtain Master Samples speeds up the evaluation and validation of control devices from suppliers, can speed up the acquisition of APQP documentation and reduce the time in the development of the serial parts by manufacturing process. Furthermore, the use of the proposed DFAM procedure is innovative in the context of the automotive industry, as it suggests a change in the production concept and inserts AM as another option in the manufacturing process and not just as a rapid prototyping tool.

Keywords

Additive manufacturing, APQP, DFAM, jigs, Master Samples

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Introduction

The automotive industry is of great importance in industrial production as it impacts other service providers or component suppliers in general. Auto part companies, to be able to supply serial components to the automotive industry, must meet the Advanced Product Quality Planning (APQP), which is a concept that belongs to standardized quality management in the automotive industry (QS 9000). One of the challenges is the manufacture of a "Master Sample" that will be used for the validation of jigs and production and dimensional control devices. Aiming at the manufacture of a Master Sample by conventional processes can take time and involve large costs that, in an increasingly competitive market, compromise the launch of new products.

For more than a century, industrial products have been constrained by capabilities of traditional processes such as machining, forming, molding, and casting. Additionally, the economics of manufacturing have been limited by the need to invest in fixed tooling and equipment. The current concepts of industry 4.0 encourage the use of new technologies and the modernization of the manufacturing process. Additive Manufacturing (AM) fundamentally is a manufacturing process with a lot of potential that allows to create

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objects on demand, complex, free-forms, and with many previously unthought-of features. It allows factories to make more efficient reducing their time-to-market. AM is one of the major breakthroughs in the manufacturing domain over the last three decades.[1,2] According to Motyl and Filipi[3] interest in AM in general has increased both as a technical subject and for the working methodology that it involves, especially in recent years, given its strong link with the Industry 4.0 framework.

This manufacturing revolution leads to more freedom and alternatives in design, and then requires either an adaptation of current design practices or new design paradigms.[2] This has raised academic and industrial interests in the development and use of the Design for Manufacture Additive (DFAM) methodology with the main purpose of simplifying the topological structure of the products, generating weight reduction and providing accessible geometric conditions to be manufactured by AM.

Bassoli et al.[4] redesigned an aluminum component for automotive application through topology optimization and DFAM and fabricated it using metal by AM as well as CNC machining. An evaluation of time and cost of AM versus CNC pointed out that additive processes are an advantageous alternative to traditional subtractive processes and are economically more convenient than CNC, unless a single part had to be produced. Arleo et al.[5] used DFAM approaches to design a flexible one-arm pneumatic chamber to bellows-like shape to obtain huge deformations quickly with reduced cost and able to validate the design.

Although most of the additive manufacturing studies are based on conceptual approaches, it can be said that it is still in its infancy stage. DFAM methodologies is not defined well; there is insufficient understanding of the process method, strategies, and when to undertake design for AM. Even though DFMA faces many challenges, still new products, design possibilities, and manufacturing paradigms are born.[6]

Many companies still do not know how to properly incorporate AM into the production process in order to benefit from its characteristics. Furthermore, designers face new challenges in the conceptual design phase because of the increasing advance of AM.[7] According to Castillo and Siqueiros,[8] Gebisa and Lemu,[9] and Adam and Zimmer,[10] the development of DFAM knowledge, that is, tools, rules, processes, and methodologies is the main technical challenge and an opportunity to expand the AM use. Vaneker[11] presents DFAM methodologies and linked to commercial success of AM in industry. It is shown that for this introduction the role of product (re)design for AM is of major importance to successfully apply AM as a production methodology. Seepersad et al.[12] reported that to design more effective pieces for AM, designers need rules and methodologies that help to understand not only the limitations of a specific AM process, but also the design opportunities and freedoms provided by the process.

Therefore, the main objective of this work is to propose an innovative DFMA procedure that serves as a protocol to analyze the feasibility and systematize the design of Master Samples for manufacturing through AM. The feasibility of manufacturing Master Samples by AM is evaluated by the proposed procedure, considering the material requirements, available 3D printers and mechanical properties, and/or quality of the part. A comparison of time and cost of fabrication by AM and conventional processes will also be made to assess the economic impact of the process choice.

Development

A DFAM procedure to analyze the feasibility of manufacturing the Master Sample for AM is proposed. The motivation is to apply any type of Master Samples to this procedure. The feasibility of manufacturing Master Samples with different dimensions, materials, and technical requirements will be identified and limited according to the capabilities and characteristics of the 3D printers available for manufacturing. The DFAM procedure contains seven main steps (Figure 1). The first step consists of identifying the specific requirements of the product such as: dimensional characteristics, geometric tolerances, special geometries, fixation points, and applicability. The requirements are raised through the interpretation of the technical drawing and virtual analysis of the assembly in a 3D CAD system (Computer Aided Design). This initial step is important to later evaluate the AM manufacturing capability with the available 3D printers. In the second stage, the process limitations are analyzed, such as: manufacturing volume and processable materials by the available 3D printer, required dimensional accuracy and, also, the impact of factors inherent to the AM process, such as: support structure, ladder step effect, anisotropy, among others. In the third step, the possibility of solutions for the possible limitations identified above is analyzed. In the fourth step, it is verified if the part geometry is suitable to be manufactured using AM. This evaluation is carried out using the methodology proposed by Booth et al.[13] that, through a spreadsheet, points out characteristics of complexity, functionality, material and support structures, pointing out, among other things, if the part's geometry needs to be redesigned before proceeding to the next step. With a suitable project (original or re-engineered), in the fifth step, the process planning is carried out with the definition of the part orientation and definition of the process parameters in a CAM (Computer Aided Manufacturing) software. Some CAM systems allow process simulation to check parameters, estimate the time and volume of material needed. The next step involves physically manufacturing the part on the available 3D printer, followed by post-processing operations.

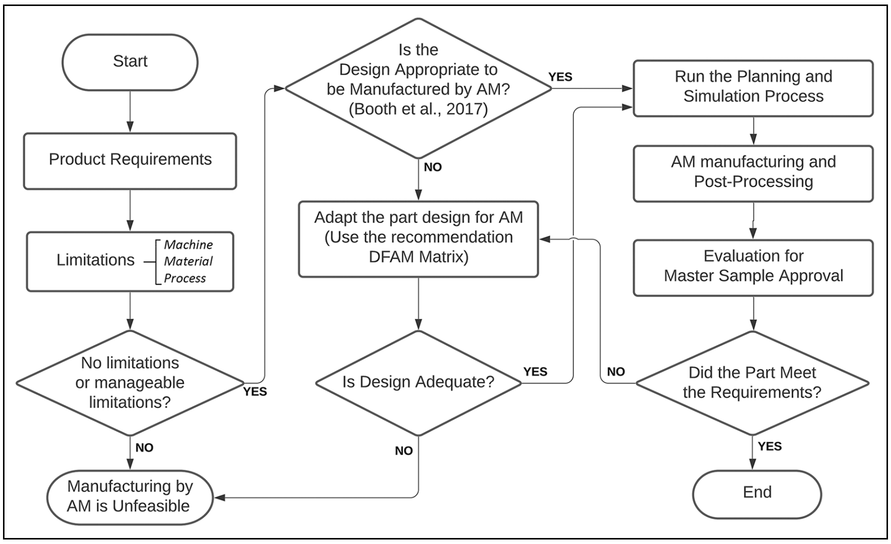

Figure 1. Flowchart of the manufacturing procedure for Master Samples by Additive Manufacturing.

In the last step of the procedure, the part is subjected to dimensional evaluation for validation purposes as a Master Sample.

The proposed procedure was applied in the fabrication of two master samples of different geometries. The first part is a metallic support called “handcuffs” conventionally manufactured by stamping processes and the second part, called cooling tube, conventionally manufactured with the aid of CNC (Computer Numerical Control) bending machines and welding processes.

Definition of product requirements

Tolerated dimensions and alignment datum targets that represent the initial points of the dimensions were identified and pointed with arrows in the technical drawings of the products (Figure 2) and were used in the final validation step of the procedure.

Process limitations

A SethiS2 filament material extrusion 3D printer with print volume of $200 \times 200 \times 200$ mm and printing accuracy of ± 0.1 mm, with heated table, closed chamber was available for fabrication. ABS filament was the chosen material because it has adequate mechanical and thermal properties for the use of the parts in a manufacturing environment. Neither the material chosen nor the inherent process characteristics of the technology were considered limiting for the fabrication of the part. However, a limitation in the Cooling Tube print volume that exceeded the 3D Printer’s available manufacturing volume was identified. The DFAM procedure pointed the possibility to solve this limitation.

As it is only a print volume limitation that presents some contouring possibilities, the procedure led to the next step of analyzing the need for design adequacy. When there are many limitations and with no possibility of changes, the procedure indicates the non-viability of manufacturing the part by AM.

AM design evaluation

Analysis of the feasibility of manufacturing through AM was performed applying the DFAM procedure proposed by Booth et al.[13] as shown in Figure 3. The procedure consists of eight main parameters that are filled in and scored according to the physical characteristics of the part to be manufactured. The result of this analysis guides the decision making regarding the manufacture of the component. Results higher than 33 points indicate that the design of the part should be modified, between 24 and 32 suggest a revision in the part’s design, between 16 and 23 points indicate a moderate probability of being successful in the manufacture of the part and between 8 and 15 it indicates a greater probability of successful part manufacturing through AM and the part can proceed to the manufacturing step.

Handcuffs and Cooling Tube parts had scores 19 and 18 respectively, indicating a moderate probability of the parts being successfully produced by AM. Because the cooling tube exceeds the manufacturing volume it was directed toward a design fit.

Design adequacy for AM

A matrix of design fit recommendations was developed based on practical experience by the authors with automotive industry’s most recurrent problems (Figure 4). It is intended to assist the designer in planning regarding the suitability of the design for AM manufacturing. The lines of the matrix point out usual manufacturing problems and the columns for possible solutions to the problems. At this stage of the procedure, it is necessary to identify the problems for manufacturing the part by

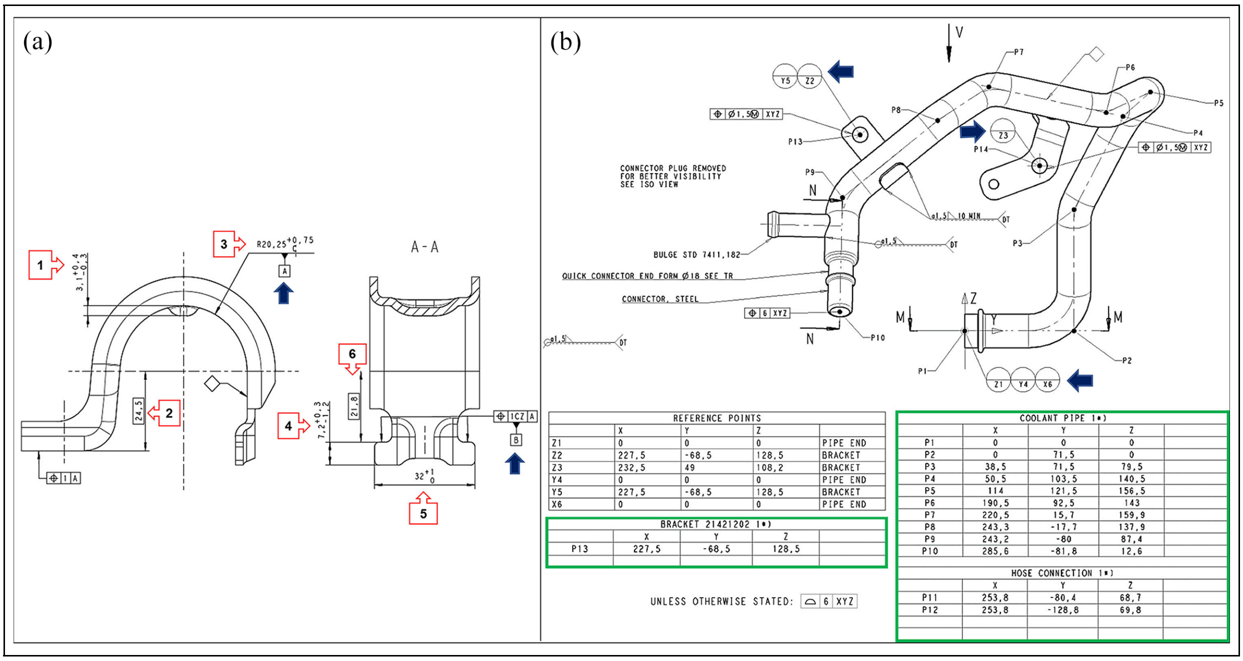

Figure 2. Parts technical drawing with indications of datum targets and tolerated dimensions in: (a) handcuffs and (b) cooling tube.

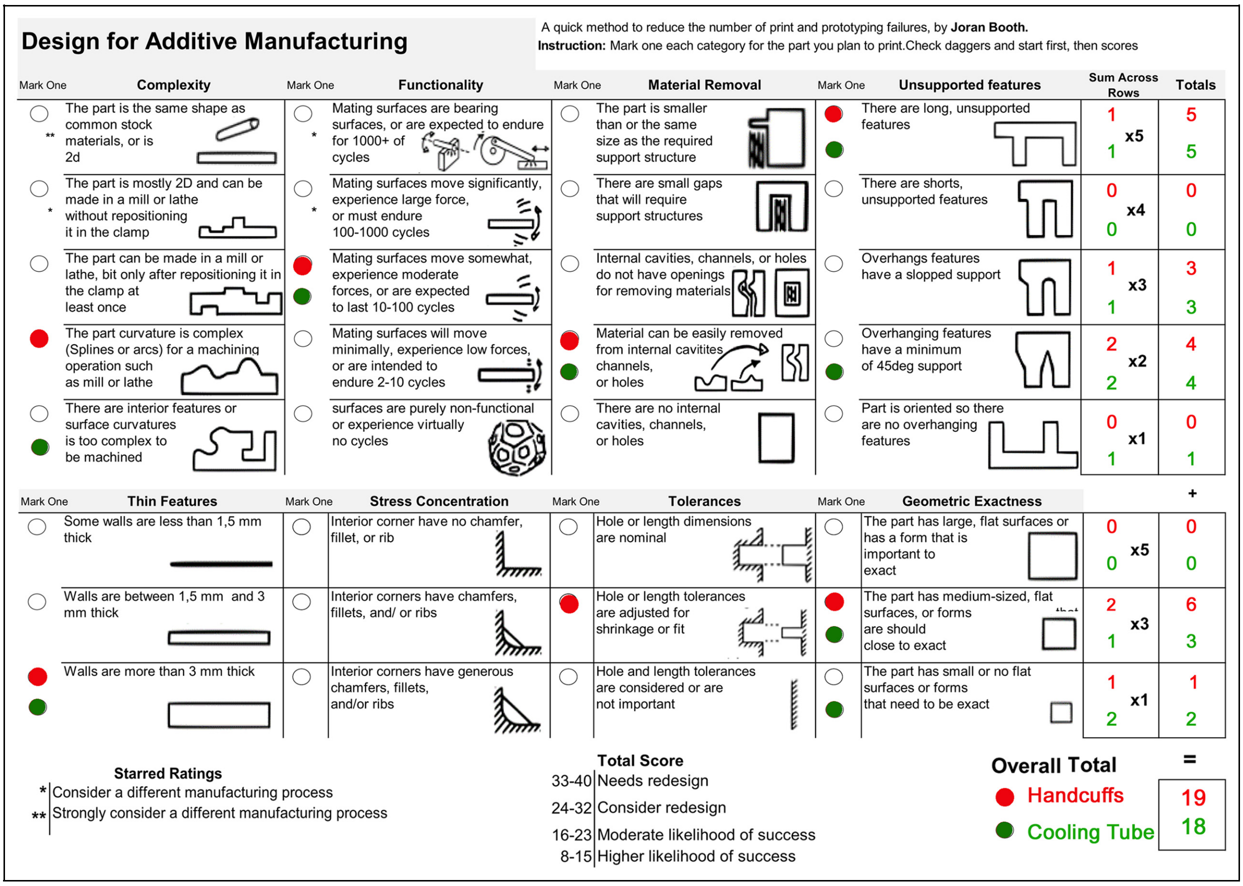

Figure 3. The DFAM worksheet applied to evaluate the design of parts, adapted from Booth et al.[13]

AM and the most recommended solutions. The solution recommendation is divided into Highly recommended (HR), Recommended (R), and Not Recommended (NR).

Recommendation / What's the problem?	Change material	Reduce thickness	Reduce mass by extracting known geometries	Split the piece into parts	Change product scale	Topologically optimize design using biomimetic design	Topologically optimize the design using lattice structures	Develop a new design concept
								
Part´s dimensions is greater than the manufacturing area	NR	NR	NR	HR	NR	NR	NR	NR
Geometry has a high level of complexity	NR	NR	NR	R	NR	HR	HR	HR
Part has dimensional deviations	R	NR	NR	NR	R	R	R	R
Part has an excessive amount of subcomponents	NR	NR	NR	R	NR	R	R	HR
Piece presented overweight	NR	HR	HR	R	NR	HR	HR	HR
Mechanical resistance less than desired	R	R	NR	NR	NR	R	HR	R
Thermal resistance less than desired	HR	NR	NR	NR	NR	NR	NR	NR
High production cost	R	HR	HR	R	NR	HR	HR	HR

(HR) Highly recommended (R) Recommended (NR) Not recommended

Figure 4. Recommendation matrix to guide design suitability for AM manufacturing.

To get around the problem of the Cooling Tube exceeding the available manufacturing volume, the proposed matrix strongly recommends splitting the part into parts to allow AM manufacturing.

The Cooling Tube was divided into 10 parts, as shown in Figure 5(a). There are seven parts of the main tube and three parts referring to the welded supports and the perpendicular tube. The divisions of the main tube were carried out in the straight regions of the tube and because it only needed the external region of the product, the tube was modeled solid to eliminate internal support structures and improve the mechanical resistance of the part.

Process planning

The first stage of the process planning consisted of choosing the process parameters for the available material extrusion 3D printer. The most important decision in the process was the proper orientation of the part on the printing table to ensure better dimensional accuracy and surface finish. If 3D printers of other technologies were available to manufacture the parts, a process planning dedicated to these technologies needed to be done. The process parameters used are listed in Table 1. Only conventional 3D printing parameters with ABS filament were defined and average values were used. No special 3D printing setups were used.

Manufacturing and post-processing

After AM fabrication, which is an automated step and requires only visual monitoring, the parts were removed from the 3D printing table and went through small post-processing operations to remove the support structures and burrs. The handcuff was sanded and painted with thin acrylic paint to improve their appearance. The seven parts of the Cooling Tube were assembled and glued with cyanoacrylate and the peripheral fixation brackets were mounted with screws. Proper positioning for assembled and gluing the Cooling Tube parts was ensured thanks to hexagonal male-female fittings designed into each interface.

Dimensional analysis and validation

To validate the parts manufactured in this work by AM as Master Samples, the product requirements raised in the first step of the procedure were analyzed. A dimensional evaluation was performed on a ZEISS coordinate measuring machine model ACCURA with a measurement uncertainty of 2.2 μm. Finally, Master Samples manufactured by AM using the proposed procedure were compared with Master Samples manufactured by conventional manufacturing methods (tube forming, sheet metal stamping, welding, and machining). The times and costs involved in manufacturing and validation were compared, starting from the CAD file of the parts until the part is considered approved as Master Sample.

Results and comparison AM process versus conventional process

The validation of Master Samples is traditionally done on parts manufactured through conventional

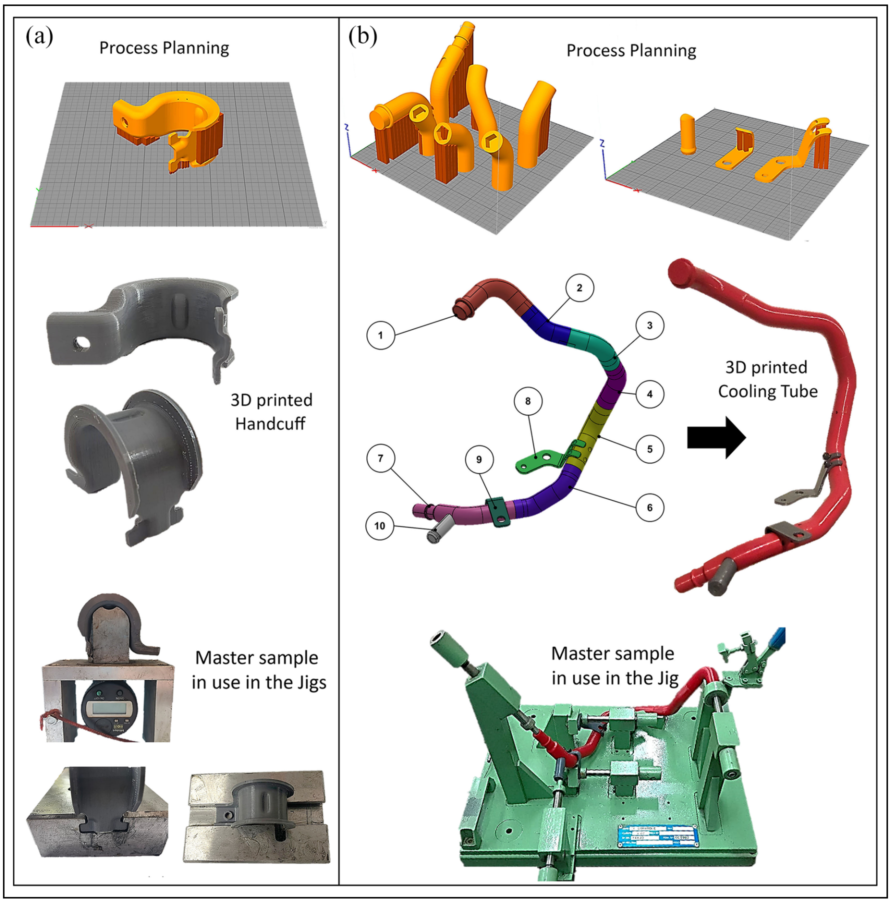

Figure 5. CAM system process planning, parts manufactured by AM and later used in the templates in: (a) piece handcuffs and (b) cooling tube.

Table 1. Process parameters used for printing the two Master Samples.

Process parameters	Value (unit)	Process parameters	Value (unit)
Layer height	0.2 mm	First layer temperature	230°C
Printing temperature	230°C	Print direction	Inside-Outside
Bed temperature	110°C	Fill pattern	Linear cross
First layer extrusion speed	15 mm/s	Retraction distance	5 mm
Perimeter extrusion speed	20 mm/s	Retraction speed	40 mm/s
Fill extrusion speed	30 mm/s	Filament diameter	1.75 mm
Solid contours on the wall	3	Support pillar resolution	2
Solid layers on the floor	3	% Fill support	30%
Solid layers on top	3	Dense support layers (80%)	2 e 5
% Filled	30%	Use of fan	100%

manufacturing processes, which can involve high costs and long delivery times, which are a major problem in a highly competitive market such as the automobile industry. The proposed procedure allowed to analyze the feasibility of manufacturing two Master Samples using AM offering a more versatile manufacturing alternative. In the process limitations analysis stage, it was observed that the Cooling Tube exceeded the available printer manufacturing volume and the application of the design adequacy recommendation matrix allowed the part division and manufacturing in the available equipment. If the analysis of the recommendation matrix for design adequacy did not indicate a viable alternative, or if there were any other limitations that could not be contoured, the procedure would indicate the impossibility of manufacturing by AM and the part would proceed to manufacturing by conventional methods.

In the analysis step of the design for AM fabrication proposed by Booth et al.[13] the result for both parts were scored between 16 and 23 indicating a moderate probability of success in manufacturing by AM. The most

Table 2. Comparison of manufacturing time and cost of Handcuffs and Cooling Tube parts by AM and the conventional method (C).

Development stage	Conventional		AM		Result
	Time (h)	Costs ($)	Time (h)	Costs ($)	
Handcuff Master Sample					
Design adequacy	0	0	0	0	C = AM
Part manufacturing	440 h	10,868.00	4 h 45 min	117.16	AM < C
Part validation	30 min	19.85	30 min	19.85	C = AM
Total	440 h 30 min	10,887.85	5 h 15 min	137.01	AM < C
Cooling tube Master Sample					
Design adequacy	0	0	8	0	C < AM
Part manufacturing	416 h	10,275.23	14 h	345.80	AM < C
Part validation	1 h 10 min	46.84	1 h 10 min	46.84	C = AM
Total	417 h 10 min	10,322.07	15 h 10 min	392.64	AM < C

critical points pointed out were the tolerances required in drawing, the contact surfaces and the geometric profiles of the parts. The 3D printer used with printing accuracy of ±0.1 mm, the orientation on the printing table, together with the proper definition of the process parameters ensured the manufacturing of the parts according to the product's requirements shown in Figure 2. Both parts were approved as Master Samples in the dimensional analysis stage and could be used in the validation of production jigs (Figure 5).

The total cost and time taken to manufacture the Handcuff and Cooling Tube parts by AM and by conventional processes are shown in Table 2. Costs refer to the amount charged by manufacturing companies that were hired and the time they spent manufacturing them. Master Samples manufactured by AM using the proposed procedure were ready for use in less than 2% (Handcuff) and 4% (Cooling Tube) of the time taken to manufacture them by the conventional manufacturing process. In just 5 h 15 min, the handcuff part was ready to be used in the validation of the control jigs and the cooling tube was manufactured in 15 h 10 min. This reduction in time to obtain Master Samples ensures greater agility in the evaluation and validation of jigs and dimensional control devices and speeds up obtaining APQP documentation and consequently reduces time in the development of the serial parts by manufacturing process. The cost reduction was also expressive, the manufacture of Handcuff by AM cost a little more than 1% than by the conventional process and the Cooling Tube less than 4%. The higher cost with conventional manufacturing can be further aggravated when there is a need to adapt or modify the tooling for manufacturing the model part. On the other hand, additive manufacturing allows greater flexibility and agility in implementing modifications directly on the part.

According to Thomas,[14] there are three primary aspects to the economics of additive manufacturing: measuring the value of goods produced, measuring the costs and benefits of using the technology, and estimating the adoption and diffusion of the technology. This work showed how the proposed DFAM procedure was able to enable the manufacture of industrial parts by AM, bringing economic benefits but also encouraging the adoption and diffusion of AM in the context of the automotive industry.

Conclusion

The proposed DFAM procedure allowed to analyze the feasibility of manufacturing by AM of two Master Samples previously manufactured by conventional processes. The procedure contains seven main steps, and initially requires the evaluation of product requirements so that, in view of possible limitations (equipment, material, and process), the feasibility of manufacturing by AM is verified. The two Master Samples analyzed were considered viable for AM manufacturing. The Cooling Tube part was directed to a design readjustment to overcome a limitation in the printing volume of the available equipment. Afterward, the planning of the process, the fabrication of ABS material, postprocessing and, finally, the dimensional evaluation was carried out. The results of the dimensional evaluation of the two parts confirmed the fulfillment of the product's requirements and could be used in the evaluation of jigs and control devices.

In this work, a comparative analysis between the parts produced conventionally and those produced by AM showed that the time and cost to obtain the Master Samples using the proposed procedure was significantly shorter. The reduction in time to obtain Master Samples speeds up the evaluation and validation of control devices from suppliers, can speed up the acquisition of APQP documentation and reduce the time in the development of the serial parts manufacturing process. Furthermore, the use of the proposed DFAM procedure is innovative in the context of the automotive industry, as it suggests a change in the production concept and inserts AM as another option in the manufacturing process and not just as a rapid prototyping tool.

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References

1. Thompson MK, Moroni G, Vaneker T, et al. Design for additive manufacturing: trends, opportunities, considerations, and constraints. *CIRP Ann Manuf Technol* 2016; 65: 737–760.
2. Sossou G, Demoly F, Montavon G, et al. An additive manufacturing oriented design approach to mechanical assemblies. *J Comp Des Eng* 2018; 5: 3–18.
3. Motyl B and Filipi S. Trends in engineering education for additive manufacturing in the industry 4.0 era: a systematic literature review. *Int J Interact Des Manuf* 2021; 15: 103–106.
4. Bassoli E, Defanti S, Tognoli E, et al. Design for additive manufacturing and for machining in the automotive. *Field Appl Sci* 2021; 11(16): 7559.
5. Arleo L, Stano G and Percoco G. I-support soft arm for assistance tasks: a new manufacturing approach based on 3D printing and characterization. *Prog Addit Manuf* 2021; 6: 243–256.
6. Durakovic B. Design for additive manufacturing: benefits, trends and challenges, periodicals of engineering and natural sciences 2018; 6(2): 179–191.
7. Haruna A, Yang M and Jiang P. Design for additive manufacturing: a three layered conceptual framework for knowledge-based design. *Proc IMechE, Part B: J Engineering Manufacture* 2023; 237(9): 1405–1421.
8. Castillo M and Siqueiros Z. Design and manufacturing strategies for fused deposition modelling in additive manufacturing: a review. *Chin J Mech Eng* 2019; 32: 53.
9. Gebisa AW and Lemu HG. Design for manufacturing to design for additive manufacturing: analysis of implications for design optimality and product sustainability. *Procedia Manuf* 2017; 13: 724–731.
10. Adam GA and Zimmer D. Design for additive manufacturing—element transitions and aggregated structures. *CIRP J Manuf Sci Technol* 2014; 7: 20–28.
11. Vaneker THJ. The role of design for additive manufacturing in the successful economical introduction of AM. *Procedia CIRP* 2017; 60: 181–186.
12. Seepersad CC, Allison J and Sharpe C. The need for effective design guides in additive manufacturing. In: *Proceedings of the 21st international conference on engineering design (ICED17) Vol. 5: Design for X, Design to X*, Vancouver, BC, Canada, 21–25 August 2017.
13. Booth JW, Alperovich J, Reid TN, et al. The design for additive manufacturing worksheet. In: *Proceedings of the ASME 2016 international design engineering technical conferences & computers and information in engineering conference (IDETC/CIE)*, Charlotte, NC, USA, 21–24 August 2016.
14. Thomas D. Costs, benefits, and adoption of additive manufacturing: a supply chain perspective. *Int J Adv Manuf Technol* 2016; 85: 1857–1876.