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REDESIGN OF METAL PARTS FOR ADDITIVE MANUFACTURING: A REVIEW OF CASE STUDIES

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Abstract: *Additive material (AM) technologies are an emerging manufacturing technology with a large degree of design freedom. They provide the possibility of further product improvement beyond the limits of conventional manufacturing methods. To exploit this to the full it is necessary to identify component classes that are most suited to be "designed for AM". Systematic research of the kinds of components and factors for a successful product with additive technologies is still lacking. This work presents an attempt to categorize the applications for AM in which the advantages of the method provide the greatest economic and production benefits for industry. In addition, it presents the main design goals, difficulties, solutions, side benefits as well as common materials and post processes for each of the specified categories among with a summary of the mail design rules.*

Key words: *Additive Manufacturing, design rules, case studies.*

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LEGEND

General engineering terms

DfAM	Design for Additive Manufacturing
DfM	Design for Manufacturing
FEA	Finite Element Analysis
MCD	Multi-Criteria Decision Analysis
TO	Topology Optimization

Manufacturing Processes

AM	Additive Manufacturing
CMP	Chemical / Mechanical Polishing
DMD	Direct Metal Deposition
EBM	Electron Beam Melting
HT	Heat Treatment
MC	Machining
EDM	Electro Discharge Machining
LPBF	Laser Powder Bed Fusion
SLM	Selective Laser Melting

DfAM goals / side effects

BTR	Build Time Reduction
CR	Cost Reduction
DF	Design Flexibility (rapid iterations)
EF	Eco-friendliness
FPO	Flow Path Optimization
HTE	Heat Transfer Enhancement
IBE	Internal Burr Elimination
MCR	Material Consumption Reduction
ME	Maintenance Elimination
MFI	Main Function Improvement (generic)
MI	Manufacturability Improvement
PC	Part Consolidation
RRD	Reliable/Robust Design
SI	Stiffness Increase / Adjustment
SR	Space/volume Reduction
TDM	Thermal Distortion Minimization
WR	Weight Reduction

DfAM difficulties

AC	Assembly complexity
BDO	Build Direction Optimization
CMS	CAD Model Size
DC	Design Complexity
HVE	Hollow Volumes Elimination
LD	Lattice Design
NMM	Nozzle Move Minimization
PPA	Post-Processing Avoidance
PPR	Post-Processing
PS	Part Size
SAP	Suitable AM Process
SMR	Support Material Reduction
STR	Stress Reduction
TA	Tolerance Achievement

DfAM solutions

FCD	Feature Class Definition
GDR	General Design Rules for AM
LRC	Large Radius Curves
NIP	Non-circular Internal Passage
SCE	Sharp Corner Elimination
SMS	Suitable Material Survey
SP	Splitting of Part
SSA	Suitable Software Application
TPMS	Triple Periodic Surfaces
VPI	Vertical Profile Inclination
VWA	Vertical Wall Addition
VWT	Variable wall thickness shell

1. INTRODUCTION

Although initial inception of AM was for design visualization and rapid prototyping, it has been progressively become a manufacturing method capable

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of producing end user products from diverse materials including metals. This is considered a manufacturing technology breakthrough exhibiting benefits that are not realized in conventional manufacturing techniques, in connection to various types of complexity as follows:

- Shape complexity: It is possible to build near net shape, complex shape geometry including interconnected internal channels.
- Material complexity: parts can be built one layer at a time consisting of a single material or even one region at a time yielding complex multi-material compositions locally altering physical, chemical, or mechanical properties.
- Functional complexity: Fully functional multi-part devices can be produced in one build, thus reducing difficulties associated with the assembly process.
- Hierarchical complexity: Features can be designed across multiple size scales. Internal cellular structures can be employed such as honeycombs, foams, or lattices. This increases a part's strength to weight or stiffness to weight ratios towards cost saving.

In addition to these capabilities, there exist many others, such as mass customization, weight reduction, part consolidation, personalization of products and decentralization of production that provide benefits by opening new design space that cannot be exploited with conventional DfM methods.

Part or product design strategy can be distinguished into manufacturing-driven and function-driven as presented in [1]. According to the former, AM is primarily used as a manufacturing technology with cost benefits for complex shapes and small batch sizes. Once the product is established in the market and sales increase, production can easily be transferred to a conventional process implementation. According to a function-driven strategy the designer neglects all conventional design rules and designs the part only according to the requirements of the application and the AM process. The resulting design can only be produced by Additive Manufacturing; a change of production method requires a complete redesign. The benefit is product improvement in terms of weight, number of assembled part and functional efficiency.

Design guidelines, principles and rules have been reported for parts manufactured using AM [2]. These are paving the way to a new DfM concept, namely DfAM requiring designers to think differently and pertinent methods, methods, tools and techniques to be developed to deal with the inherent association between geometry, materials, and quality in AM systems [3].

TO is a methodology that optimizes material layout within a given design space and for given boundary conditions such that the resulting shape meets a prescribed set of performance targets. Essentially, it removes any material that is not performing a useful function within a part [2], materializing lightweight engineering. TO has been leading redesign methods, yet further progress from specialized 3D CAD systems is expected for decreasing calculation time especially in relation to lattice feature manipulation.

In a DfAM context, work is needed towards suitably pitched instructions for non-experts [4]. This can result in rules, benchmarks or knowledge-based software. A pertinent first attempt for metal parts follows. First, some generic rules are assembled together. Then, for generic part families and functionally specific part classes are considered as separate categories. For every category the traditional manufacturing method and associated problems are briefly mentioned. Then AM main goals, difficulties and solutions are coded in pertinent Tables, whereas the main points are briefly mentioned in textual form. Side benefits, common materials and post processing for each of category are added. All codes are included in the Legend section.

2. REDESIGN RULES FOR METAL PARTS

There are a number of fundamental principles that can be applied to almost any form of additive manufacturing. These are described also in [2]. Some generic rules to consider in DfAM context are as follows:

- Establish the right build strategy, i.e. part orientation, down-skin areas, support structures.
- Integrated design: explore functional, assembly and manufacturing constraints.
- Design for facilitating powder removal.
- Minimize supports.
- Avoid support material in internal features, e.g. channels, as this can be difficult to remove.
- Use integral design features, e.g. walls, to both replace supports and improve strength and rigidity.
- Consider post processing, e.g. stress relief annealing, machining for shape accuracy, etc.
- Use internal lattice section as required.
- Use overhang angles of 60° for internal lattice structure to avoid additional supports.
- Use TO to determine the best build orientation beforehand instead of testing orientations afterwards.

3. REDESIGN OF GENERIC PART FAMILIES

In plenty of cases AM has been selected as a primary method for manufacturing mechanical metal parts in replacement of conventional methods. In order to do so, redesign of parts was necessary.

Parts fall into generic families in terms of use, namely aerospace parts, automotive/original equipment manufacturing (OEM) parts and in terms of function, namely complex assemblies. The pertinent data gathered are summarized in Tables and Figures and briefly discussed next.

3.1. Aerospace parts

The aviation and space industries are interested in particular in SLM, since in conventional manufacturing costs are primarily determined by production volume. As aircraft are not built in large quantities and operating costs and payload put a constant pressure to save weight. Aerospace parts are traditionally manufactured by forging, casting and machining. AM methods provide some advantages as summarized in Table 1 and Fig.1.

Key difficulties which have to be addressed in DfAM concern optimal material distribution using TO software, part orientation in early stages and possible numerical problems linked to freeform surfaces of complex parts.

Table 1

Analysis of DfAM aerospace part cases

Fig.	Ref	AM	Goals	Difficulties	Solutions	Side benefits	Materials	PPR
1a	5	LPBF	WR HTE	-	VWT		AlF357	-
1b	6	SLM	WR	TO	-	-	-	-
1c	7	SLM	WR SR	CMS	SSA	-	TiAl6V4	-
1d	8	LPBF	SI WR TDM	-	TO SSA	-	TiAl6V4	-
1e	9	SLM	WR CR	LD TO	SSA	SR	AlSi10Mg	HT MC CMP

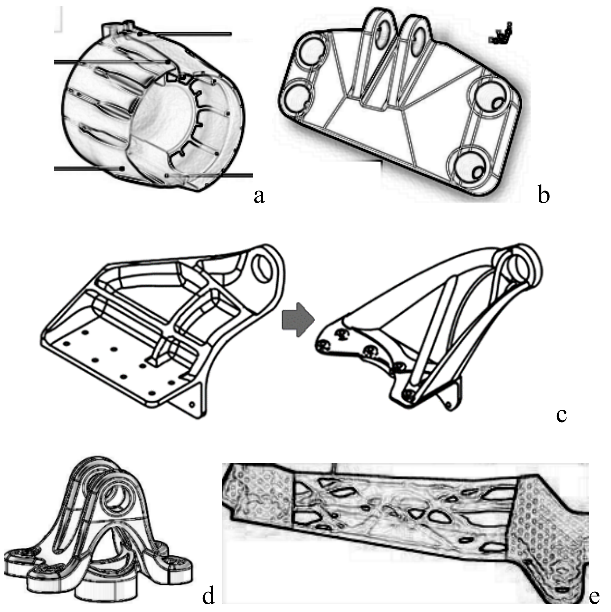

Fig. 1. DfAM aerospace part cases.

3.2. Automotive/OEM parts

Application of TO in automotive and general mechanical parts such as beams, brackets, hooks etc. is a very common activity. Different studies show the capability of lattice structures regarding their mechanical properties.

Conventional manufacturing processes meeting pertinent quality standards include, e.g., low-pressure permanent mold casting followed by machining. Such processes involve high investment costs, long time-to-market and very low flexibility. These are incompatible with small batches, where variable costs, that are still high in the case of AM, can be allocated / distributed easier than fixed costs (Table 2, Fig. 2).

Key difficulties in DfAM are implementation of TO, redesign by lattice, exploration of functional, assembly and manufacturing constraints, selection of build orientation, application of FEA and MCDA with client-defined criteria.

Table 2

Analysis of DfAM automotive / OEM part cases

Fig.	Ref	AM	Goals	Difficulties	Solutions	Side benefits	Materials	PPR
2a	10	SLM	PC	AC BTR	SSA	PC SR		
2b	11	SLM	TO WR SI	BDO	SSA	PC	EOS GP1 UNS S17400	HT
2c	12 13		WR CR SI	TO	SSA	SR	AlSi10Mg	-
2d	14	SLM	WR SR	BDO	SSA	WR	AlSi10Mg	MC
2e	15	LPBF	WR	SMR BDO SI	MCD	-	AlSi10Mg	-
2f	16	DMLS	WR RRD	DC	SSA	-	AlSi10Mg	-
2g	17	DMD	SR	HVE NMM	LRC SCE GDR	-	Ti6Al4 SS 316L	-
2h	18	LPBF	WR MFI	SAP	FCD	CR BTR	AlSi10Mg	-

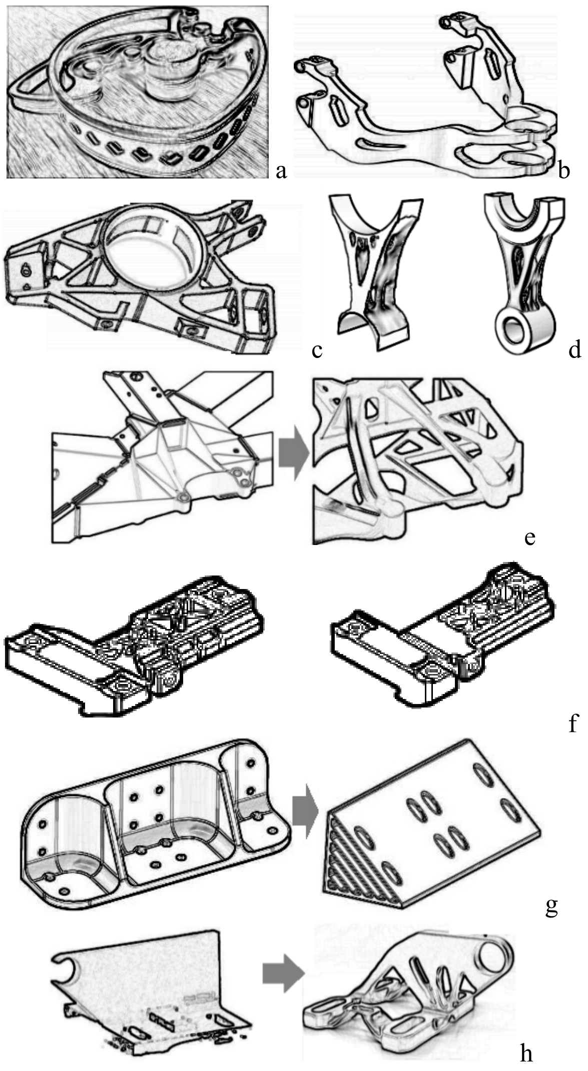

Fig. 2. DfAM aerospace part cases.

3.3. Complex assemblies

Traditionally assemblies grow larger due to complexity of functionality demands and manufacturing constrains. Part consolidation objectives concern reduction of the number of components inside an assembly to create a more compact product, with enhanced performance and lower cost of production.

Key difficulties in DfAM concern pinpointing parts with the potential to merge into a single one, often encompassing advanced concepts such as self-lubrication and possible to produce only by AM.

4. REDESIGN OF FUNCTIONAL PART CLASSES

Specific part classes have been particularly addressed by AM methods and reported in literature as detailed next.

4.1. Hydraulic housings (manifolds)

Hydraulic housings conventionally have a compact, square design with multiple internal channels controlling oil distribution in machinery. They are traditionally manufactured by casting and machining. Constraints associated with these processes may lead to poor functionality because of long and/or non-optimal flow paths causing even flow stagnation and thus inefficiency, inadvertent dirt reservoirs, emergence of sharp edges at junction channels and leakages in adjacent channels. In addition, block failure may result due to edges, which are associated with stresses concentration.

Table 3 and Fig. 3 present characteristic cases from literature on how AM provides for optimized shape design and consequently alleviate these problems in addition to consolidating the assembly and reducing its weight. Key difficulties in DfAM are (a) reduction of support material through the extended use of features with inclination lower than 45 ° from vertical, (b) shape optimization using fluid dynamics principles and models.

4.2. Heatsinks

Heat sinks are widely used for cooling electronic components. Heat removal from heat sinks can be enhanced by modifying the characteristics of either the solid or the fluid domain. An effective way to enhance heat transfer is geometry modification. Miniaturization of electronic systems adds the additional challenge of designing efficient systems operating in limited space. They are traditionally manufactured by extrusion, machining and casting and their combinations.

Traditional manufacturing of heatsinks may lead to large weight and volume and thus high manufacturing costs. AM Methods reduce overall weight and size, enhance heat dissipation by incorporating biomimicry in design, which also provides a turbulent flow path for more efficient natural convection. Key DfAM difficulties concern efficiency of heat dissipation and size constraints satisfaction. Table 4 and Fig. 4 demonstrate a pertinent case.

Table 3

Analysis of DfAM hydraulic housings cases

Fig	Ref	AM	Goals	Difficulties	Solutions	Side benefits	Materials	PPR
3a	19	DMLS	WR IBE MFI SR ME	-	-	DF	Al	-
4b	20	SLM	WR MFI SR	SMR	VWA VPI	CR DF	Al	-
3c	21	SLM	WR IBE MFI ME	FPO	DF	DF BTR MCR	-	-
3d	22	PBF	WR SR MFI	SMR PPA	NIP WR SR	PC RRD	EOS-GP1™	HT EDM MC
3e	23	-	WR MFI MI	IBE STR	SSA	-	-	-

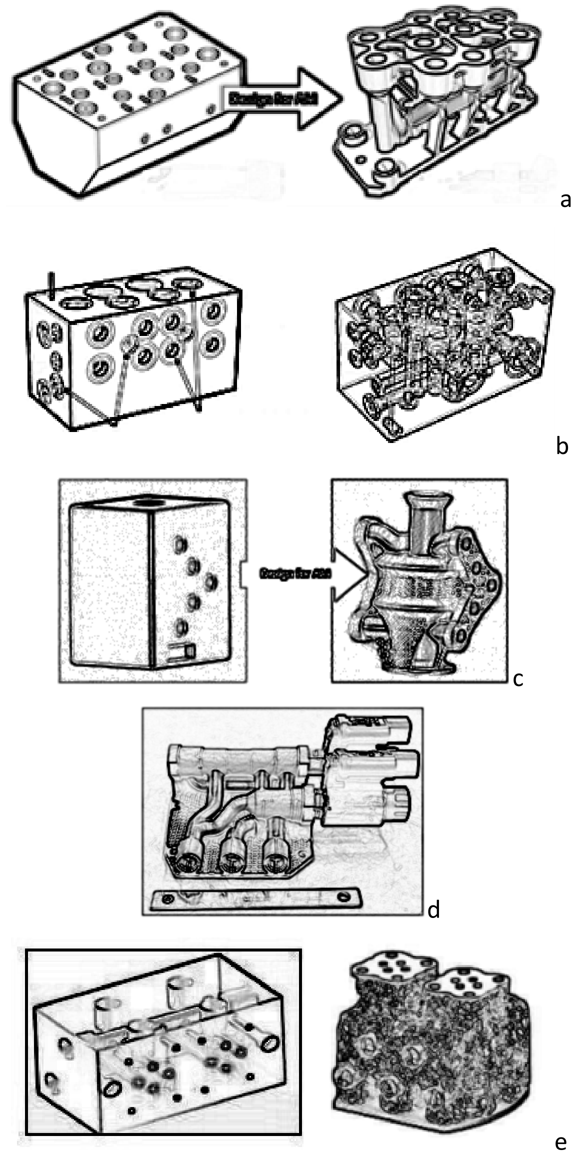

Fig. 3. DfAM hydraulic housings cases.

Table 4

Analysis of DfAM heatsink cases

Fig	**Ref**	**AM**	**Goals**	**Difficulties**	**Solutions**	**Side benefits**	**Materials**	**PPR**
4	24	LPBF	HTE SR	-	TPS	MCR	AlSi10Mg Cu alloys	

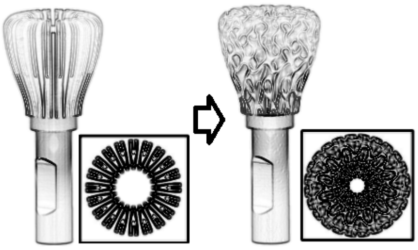

Fig. 4. Analysis of DfAM heatsink case.

Table 5

Analysis of DfAM robot link case

Fig	**Ref**	**AM**	**Goals**	**Difficulties**	**Solutions**	**Side benefits**	**Materials**	**PPR**
5	25	SLM	WR SR SI	-	SMS TO	PC	AlMgSc	

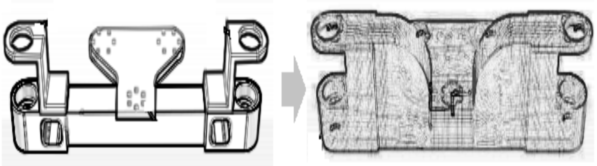

Fig. 5. Analysis of DfAM robot link case.

4.3. Robot links

Robot links are traditionally manufactured by metal cutting (milling, laser) and forming (bending), leading to large weight and volume and requiring large number of parts. DfAM objective is to optimize already conventionally manufactured existing structural components with TO equivalent parts to be manufactured by AM. Key DfAM difficulties are associated with topology optimization (Table 5, Fig. 5).

4.4. High pressure die casting inserts

Die Casting Inserts are used for Aluminium casting in huge variety of applications. They are usually made from high strength steel, e.g. AISI H13 or similar and are usually interchangeably fixed on a holder plate. They are traditionally manufactured by the combination of cutting, EDM and polishing. Cooling channels in them are manufactured by drilling. The main pertinent problem is not optimized conformal cooling leading to expensive and low accuracy production.

AM Methods improve heat exchange, but also require finishing operations since fits are demanding Key difficulties in DfAM are associated with internal lattice and cooling channel optimisation as well as the avoidance of additional supports (Table 6, Fig. 6).

Table 6

Analysis of DfAM die casting insert cases

Fig	**Ref**	**AM**	**Goals**	**Difficulties**	**Solutions**	**Side benefits**	**Materials**	**PPR**
6a	26	SLM	FPO	DC LD	SSA	WR	Maraging Steel	MC
6b	27	SLM	CR BTR	FC TA	SSA	-	Corrax	MC HT

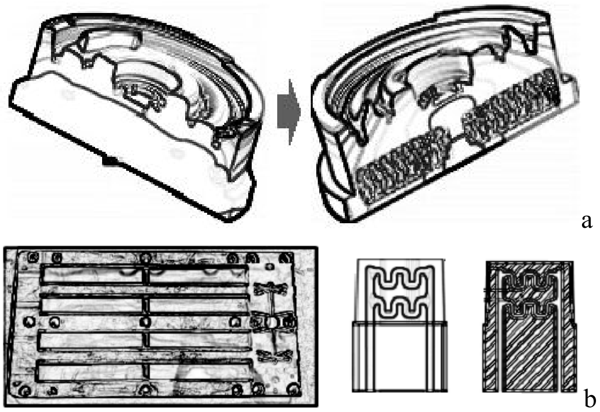

Fig. 6. Analysis of DfAM die casting insert cases.

4.5. General fixtures (clamping/tooling)

Table 7 and Fig. 7 summarize pertinent cases selected from literature.

Jigs and fixtures are required in most of the manufacturing, inspection, and assembly processes, including welding. They are traditionally manufactured by machining, sheet metal deformation processes and their combinations including press fit accessories and fasteners.

Table 7

Analysis of DfAM jig and fixture cases

Fig	**Ref**	**AM**	**Goals**	**Difficulties**	**Solutions**	**Side benefits**	**Materials**	**PPR**
7a	28	SLS	MFI PC WR BTR	SAP	-	RRD	Steel ALSi10Mg	-
7b	29	LPBF	MFI WR SR CR	-	TO	PC STR	SS 316L	-
7c	30	LPBF	WR STR	BDO WR	-	BTR	Steel AlSi10Mg	-
7d	31	LPBF	WR PC SR	SMR PS	SP	EF	Steel AlSi10Mg	HT MC EDM
7e	31	LPBF	MFI SI PC WR	TO	SSA	EF	Steel AlSi10Mg	HT MC

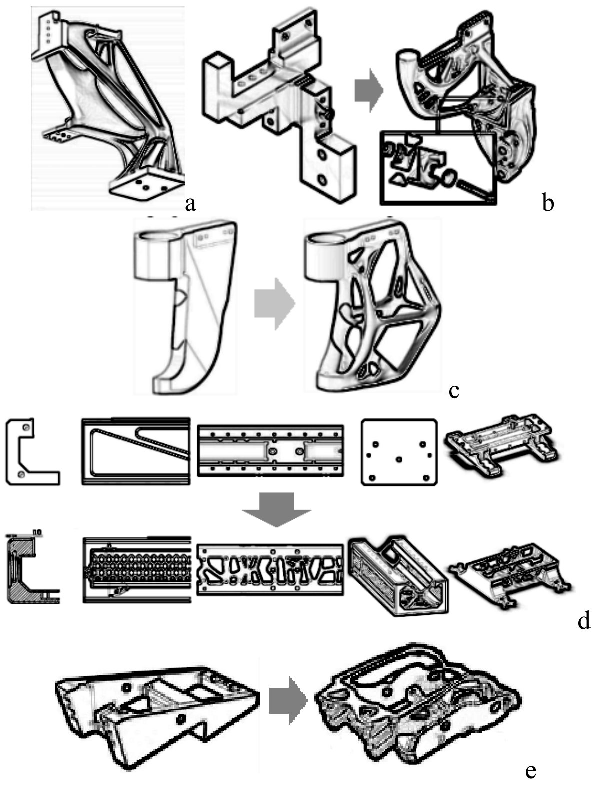

Fig. 7. DfAM hydraulic housings cases.

It is important to note that jigs and fixtures may account for high cost, as much as 10 to 20% of the total manufacturing costs since they consist of different parts, they require precision and they may sometimes be large and/or heavy.

DfAM methods have been employed to provide significant weight reduction of jigs, alleviate precision in assembly by part consolidation and achieve much needed reduced lead time for jig development especially concerning small production batches in flexible manufacturing.

Key difficulties in DfAM for jigs and fixtures are similar to those for mechanical parts, see section 3.2.

5. CONCLUDING REMARKS

This article represents an attempt to categorize the applications for AM which demonstrate economic and production benefits for Industry.

AM has been proved extremely advantageous for Aerospace and Automotive Industry. Aerospace industry needs are small quantities and low weights for saving operating costs. Automotive industry has in many cases needs for very complex parts in low quantities (i.e. race cars) and high flexibility/adaptability. Also traditionally large assemblies for both industries can be simplified with part consolidation for more compact products and lower cost production.

The main functional part classes which are best served from the advantages of AM are hydraulic housings (manifolds), heatsinks, robot links, high pressure die cast inserts and general fixtures for clamping/tooling.

Parts which are produced from combination of complex castings (high or low pressure) and machining and have relative low volumes of production needs, are usually the most appropriate candidates for replacement with AM methods. In addition, parts with large volumes and many hours of precision machining, e.g. manifolds, or high quality certified welding also fall into the above category.

SLM and LPBF are the main AM methods which are used for producing these parts and the main common goals for re/design sums up to weight/built time reduction, cost reduction, design flexibility, heat transfer enhancement, part consolidation and improvement of main function and manufacturability.

Further steps under way concern developing and implementing an advisory system helping the designer to implement the redesign taking into account the capabilities and limitations of AM methods and specific machines.

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