Journal of
Manufacturing and Materials Processing

MDPI

Review

A Review of Automotive Spare-Part Reconstruction Based on Additive Manufacturing

Enrico Dalpadulo , Andrea Petruccioli, Francesco Gherardini * and Francesco Leali

Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Vivarelli 10, 41125 Modena, Italy
* Correspondence: francesco.gherardini@unimore.it

Abstract: In the Industry 4.0 scenario, additive manufacturing (AM) technologies play a fundamental role in the automotive field, even in more traditional sectors such as the restoration of vintage cars. Car manufacturers and restorers benefit from a digital production workflow to reproduce spare parts that are no longer available on the market, starting with original components, even if they are damaged. This review focuses on this market niche that, due to its growing importance in terms of applications and related industries, can be a significant demonstrator of future trends in the automotive supply chain. Through selected case studies and industrial applications, this study analyses the implications of AM from multiple perspectives. Firstly, various types of AM processes are used, although some are predominant due to their cost-effectiveness and, therefore, their better accessibility and wide diffusion. In some applications, AM is used as an intermediate process to develop production equipment (so-called rapid tooling), with further implications in the digitalisation of conventional primary technologies and the entire production process. Secondly, the additive process allows for on-demand, one-off, or small-batch production. Finally, the ever-growing variety of spare parts introduces new problems and challenges, generating constant opportunities to improve the finish and performance of parts, as well as the types of processes and materials, sometimes directly involving AM solution providers.

Keywords: component reproduction; replacement parts; classic cars; restoration; reverse engineering; rapid tooling; Industry 4.0; original equipment manufacturer (OEM)

Citation: Dalpadulo, E.; Petruccioli, A.; Gherardini, F.; Leali, F. A Review of Automotive Spare-Part Reconstruction Based on Additive Manufacturing. *J. Manuf. Mater. Process.* **2022**, *6*, 133. https://doi.org/10.3390/jmmp6060133

Academic Editors: Siavash H. Khajavi and Mika Salmi

Received: 18 August 2022
Accepted: 25 October 2022
Published: 29 October 2022

1. Introduction

The automotive industry is characterised by high innovation, complexity, and competitiveness, and it involves large supply chains. Currently, Industry 4.0 is at the heart of the automotive industry, which benefits from digital enabling technologies for the trending demands of mobility services, autonomous driving, performance, and electrification [1]. Additive Manufacturing (AM) represents one of the "nine pillars" of Industry 4.0 [2] and it is tied to all the other pillars, whether they can be used directly (for AM applications) or indirectly (with AM processes) [3]. The key factors for AM spread in the automotive sector can therefore be identified. In addition to fast iteration design and prototyping, functional end-use parts such as high performance parts [4–6], customised parts [7] or customised tooling [8,9] can be produced. Moreover, AM processes can be used to repair components, or to make small-batch production and spare-part production feasible [10–12], or even on-demand production and distributed manufacturing [13–15]. AM can minimise the storage of both spare parts and tooling (e.g., moulds, dies, etc.). Therefore, it can lead to enhanced business models due to the supply chain shortening and overall lead time reduction [16,17]. Delic et al. [17] stated that applications in prototyping, tooling, direct part manufacturing, and maintenance and repair are going to spread within the next 10 years. In 2014, Deloitte [18] identified future applications for parts such as original equipment manufacturer (OEM) components, interiors, seating, wheels, tires, suspensions, electronics, frames, bodies, doors, powertrains, and drivetrains. Many milestones have been achieved. The 2019 Wohlers record confirms that 28.4% of AM output achieves functional end-use components [19]. A recent review highlighted current trends in the use of AM in the modern automotive sector and its relative advantages and drawbacks [20]. Deloitte's study [1] included OEM component production, but an application that was not mentioned is component replication. AM also has applications in the reproduction of "hard-to-find" parts [14]. Out-of-production spare parts and lost components or tooling can be reproduced in one-off applications or small batches with limited investments. For example, the demand for replicas of components for the restoration of classic cars is, interestingly, growing. Indeed, the sector provides the highest 10-year return on investment [21], cars with classic potential are continuously increasing, and interest in classic cars has never been greater [22].

The aim of this work is to provide a framework for the reproduction of automotive spare parts, based on the combination of digital technologies such as Reverse Engineering (RE) techniques and AM processes. The paper is structured as follows. Section 2 deals with digital processes, including RE and AM, formalising a generic digital and physical workflow. Section 3 collects the technologies used for the reconstruction of automotive spare parts based on AM, classifying them according to the materials (polymers, metals, composites) into direct and indirect AM processes. The results of this study are proposed and discussed in Section 4 and some final remarks close the paper in Section 5.

2. Digital Processes

The scientific literature provides sundry examples of part reproduction for different purposes. Physical reproductions can be developed just to obtain a physical high-scale model or to perform functional tests [23]. Moreover, reconstructions can be performed to repair and rework defective or worn components [24,25] or to replace damaged components [26–29]. Finally, reproduction processes can be embedded into methodologies for rapid manufacturing, discontinued and out-of-production part production [30–32], or even decentralised spare-part production [33–35]. Most of these component reproduction cases make use of digital technologies to acquire the shapes and dimensions/sizes of systems, generate virtual models and designs, and build tools and products.

Digital technologies promote the development of digital inventories and repositories of 3D model data files, enabling on-demand and on-location production [36]. This virtually eliminates the need for maintaining large backstock, reduces the costs of unsold items, and starts the dismantling of outdated production facilities and tools, which are often not as environmentally friendly as modern technology such as AM [37].

Different techniques can be exploited and, thus, many related approaches can be provided, depending on the application requirements. Mainly, the digital threads are based on the integration of RE and AM [38].

2.1. Reverse Engineering

RE is the first step of the product redesign process and must comply with the need to predict what a product should do in terms of form, functionality, manufacturability, and assemblability [39]. RE comprises several actions to address this purpose, from observations and predictions to tests and analyses, to the disassembly of existing products [40]. RE is an integral part of product development processes, commonly practised by OEMs as a competitive approach for ensuring product performance [26]. According to this global aim of understanding and developing the set of specifications that the product must comply with, different techniques and tools can be adopted, depending on the specific application; generally speaking, it consists of capturing the surface data of existing components by means of scanning or measurement devices [38]. Concerning the automotive field, the design of new products, the redesign of existing products, quality control, and the design of custom-fit parts are the most common areas of RE application [41,42]. Moreover, RE is the key approach to reconstructing digital models from measured data to provide spare parts and maintenance support for no-longer-available components (e.g., when the 3D CAD model is not available) [28,43].

RE techniques are classified as contact and non-contact (generally optical) methods, depending on the 3D acquisition process and the technology adopted [44]. Contact methods, including manual measurement, co-ordinate measurement machines (CMMs), and numerical control (NC) machines, are commonly used by automotive OEMs for quality control and inspection phases, providing high accuracy; however, they are also expensive [41]. Non-contact methods use sensors and cameras for easier and faster acquisition [42]. Even if they are less accurate than contact methods, optical techniques are more common, affordable, and scaled for a wide range of applications thanks to different tools and technologies—mainly active sensors such as 3D scanners, and passive sensors comprising image-based techniques such as photogrammetry [45].

The literature provides the major steps of a generic RE process [41,42,46]:

- Scanning and data capturing.
- Point cloud processing and segmentation.
- Feature classification and extraction.
- The generation of analytical surfaces and features.
- CAD model reconstruction.

With respect to these, a pre-acquisition phase is commonly required to define the correct strategy, based on the component geometry (dimensions, surface, materials, etc.), required accuracy, and output application of RE (i.e., the kind of result expected) [47]. Concerning CAD model reconstruction, this phase is critically affected by the previous one, and several strategies are available, generally classified as feature-based (parametric and non-parametric) and surface-based (freeform) reconstruction methods [48]. To improve integration and interoperability during RE, available software packages comprise dedicated modules to interact with 3D-scanned data and support models' reconstruction processes [42].

2.2. Additive Manufacturing

AM is a set of technologies that can produce parts by adding material layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [49]. AM technologies are not so innovative, since the first patents concerning layer-by-layer fabrication were deposited in the early 1980s. From the late 1980s, AM technologies started to spread, giving rise to applications that are known as rapid prototyping (RP) (first 1990s), rapid tooling (RT) (late 1990s), and rapid manufacturing (RM) (early 2000s). The roadmap from RP to the foreseen Direct Digital Manufacturing (DDM) scenario [50] goes hand-in-hand with technological improvements and, thus, it is based on digital processes. From product concepts or aesthetic prototypes, the evolution of machines and materials enabled the construction of parts that can both fit in assemblies, due to the improvements in accuracy, and perform functionally, due to the better mechanical properties. This process is the achievement of the so-called "3 Fs" rule: form, fit, and function [50]. Currently, AM technologies can be used to transform almost every material, such as polymers, metals, ceramics, and composites [51]. They can represent either additively manufactured final components or tools to support the most common manufacturing technologies (e.g., models, inserts, cores and moulds for injection moulding, casting, and composite lamination). Nowadays, innovation is the path to their extension to a real manufacturing system for final products, leading to many potential advantages [51,52]. The direct connection between a CAD model and a functional part provides a reduction in investment cost and improved product development lead time. The layer-by-layer construction provides enhanced design freedom and "complexity for free", which go hand-in-hand with high differentiation, high flexibility, high specificity, and high customisation [53–55]. This is why the technologies are at the heart of the "mass customisation" third industrial revolution and, more recently, Industry 4.0 [54,56]. Moreover, they can be matched with Generative Design (GD) approaches, i.e., design exploration methods based on algorithms that provide design variants according objectives and constraints specified by the user [57,58]. It is necessary to remark that these characteristics, together with enhanced part performance and process reliability, can be obtained using Design for Additive Manufacturing (DfAM) methodologies [53,59]. DfAM approaches [60,61], guidelines [62], and design methods [5,63] can be used to develop optimised parts. Moreover, process-specific DfAM rules should be considered as well, and in particular, they must be used to build parts with high-quality requirements, as in the case of the reconstruction of automotive components.

For the purpose of this work, AM technologies and acronyms are summarised according to the ASTM F2792 [64]. In 2009, the American Society for Testing Materials (ASTM) committee F42 published a document containing the standard terminology on AM that classified all the technologies into seven categories, with which each specific process can be associated.

- Binder Jetting (BJ):
- 3D printing (3DP), S-Print, M-Print, etc.
- Directed Energy Deposition (DED):
- Laser Deposition/Laser Metal Deposition/Direct Metal Deposition (LD/LMD/DMD), Laser Engineered Net Shaping (LENS), etc.
- Material Extrusion (ME):
- Fused-Filament Fabrication/Fused Deposition Modelling (FFF/FDM), etc.
- Material Jetting (MJ):
- PolyJet, Nanoparticle Jetting (NPJ), Drop On Demand (DOD), etc.
- Powder-Bed Fusion (PBF):
- Selective Laser Melting/Direct Metal Laser Sintering (SLM/DMLS), Electron Beam Melting/Electron Beam Powder-Bed Fusion (EBM/EB-PBF), Selective Laser Sintering (SLS), Multi-jet Fusion (MJF), etc.
- Sheet Lamination (SL):
- Laminated Object Manufacturing (LOM), Ultrasonic Additive Manufacturing (UAM), etc.
- Vat Photopolymerisation (VP):
- Stereolithography (SLA), Digital Light Processing (DLP), Continuous Liquid Interface Production (CDLP), etc.

This classification is shared by the ISO [65] and further integrated by other authors [66–68]. Holmstrom et al. collected information for each of the seven categories, such as the basic working principle, the processed materials, and the main technology examples [69]. Considering the adopted classification, Tofail et al. [70] and Calignano et al. [71] provided comprehensive analyses of processes and applications, while Razavykia et al. [72] enriched the overview with related modelling approaches.

As seen for RE, literature provides the generic process steps of AM [50,61], which can be encased into (i) a digital workflow and (ii) a physical workflow [53]. The digital workflow begins with digital models, obtained through RE (from images, scans, metrology) or direct 3D CAD modelling, the models are converted into tessellated formats (e.g., the STL file) that discretise the geometry, and then, processed to generate the AM machine instructions. This is performed through the build preparation step, where the process is designed by defining part orientation and part positioning/nesting, generating the support structures, setting the construction and machine parameters, performing the slicing into layers, and returning the NC code to drive the process. Afterwards, the physical workflow starts, involving the AM hardware, which relies on the seven process categories; the build phase; and the subsequent required operations to meet the expected product requirement. This is achieved through post-processing, where the parts and supports are removed, and improvements are made to the surfaces (e.g., via sandblasting, polishing, machining, etc.) and/or materials (e.g., via thermal treatments, infiltration, coating, etc.) depending on the specific application.

2.3. Generic Digital and Physical Workflow

The literature provides a few component-reproduction or repair examples based on digital technologies, mainly related to industrial, aerospace, defence, or automotive applications. From the analysis of the existing state-of-the-art cases, a general framework for spare-part reconstruction concerns a digital and a physical workflow (Figure 1).

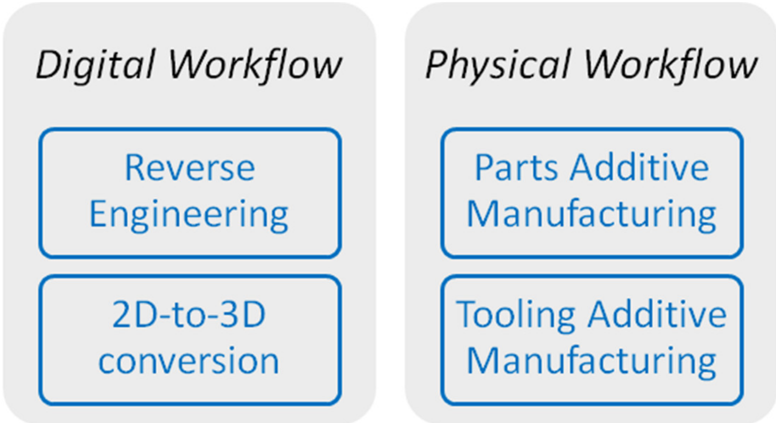

Figure 1. Key strategies of component-reconstruction workflow.

The digital workflow can be based on:

- An RE (or reverse modelling) process of an existing physical part.
- A 2D-to-3D conversion process.

An RE process transforms an existing physical component into its digital copy (3D model), through intermediate phases such as 3D scanning or an image-based process. It is necessary for "hard-to-find" components or out-of-production spare parts, even if they are broken. On the other hand, a 2D-to-3D conversion process can be performed if spare parts are missing but the original drawings or technical documentation do exist. This process produces a 3D representation of the object, transferring the dimensions and the geometric 2D shapes into a 3D CAD model.

The common goal of both processes is to obtain a digital model that can be used for discontinued and on-demand production, or decentralised/distributed manufacturing.

The physical workflow can be based on:

- The AM of parts (i.e., direct processes)
- The AM of tooling (i.e., indirect processes)

AM processes can be used to directly build the components to be reproduced or repaired. Alternatively, AM processes are capable of producing tools to support production through conventional manufacturing technologies (e.g., those used for the original spare parts). This AM application, which is broadly referred to as RT, does not have the geometric limitations of conventional machining, allowing tools with very complex geometries to be fabricated at a lower cost and with a shorter lead time [73]. Technologies such as injection moulding (IM) and casting/investment casting/foundry take advantage of AM for the development of polymeric moulds for small-batch production and conformal-cooling metal inserts in IM (see Section 3.1.2), and metal dies and polymeric 3D-printed foundry models and cores in casting/foundry (see Section 3.2.2). Material costs are high for metallic AM processes, and there are thermal-conductivity and material-compatibility issues when using plastic-based AM processes [74]. Furthermore, both the metal- and plastic-based AM processes have surface-finish issues; so, post-processing steps are essential for either the printed parts, the printed tooling, or the final components.

3. Automotive Spare-Part Reconstruction Based on Additive Manufacturing

Concerning the automotive field, several examples of spare-part reconstruction and production or classic-car restoration exploiting AM technologies do exist, ranging from niche workshops to automobile manufacturers. The restoration of Elvis Presley's famed BMW 507 [75] is an interesting application of the combined use of 3D scanning and 3D printing to reproduce obsolete parts such as window winders and rollers, or door handles. The case of the Pininfarina Jaguar XK120 is an excellent analogue restoration that involved AM to build the lost lights and bumpers [76]. Both cars were presented at the Concours d'Elegance in Pebble Beach, California [77,78]. There is no shortage of cases from other manufacturers, such as Volkswagen, Bentley, Bugatti, and many others [79].

From the analysis of the components' reproduction or reparation, a general framework has been depicted. The AM reconstruction of automotive components comprises several areas of a vehicle, generally classified into four main categories (Figure 2):

- Interior: the dashboard, consoles, air vents, mirror, control levers, handles, switches, trims, etc.
- Bodywork: the body panels, fenders, bumpers, mirrors, headlights/indicators, grilles, handles, trims, etc.
- Structural parts: the suspensions, wheels, subframe components, brackets, etc.
- Powertrain: the gearbox, engine, differential, carburettors, pumps, etc.

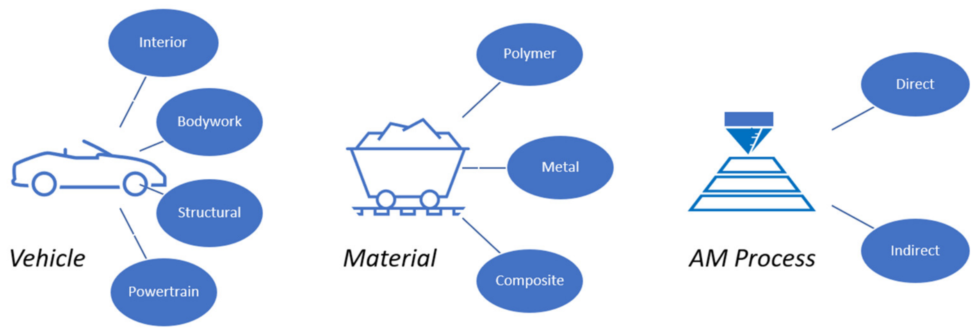

Figure 2. Automotive application classification according to: vehicle areas–materials–AM processes.

Specifically concerning automotive spare parts, the existing applications can be classified into two possible criteria (Figure 2):

- Material: polymer parts; metal parts; composite parts.
- Process: direct AM process, indirect AM process.

A complete review of the materials mainly used in AM for the automotive field is presented in [20]. The processes are analysed in the following paragraphs with a focus on the proposed case studies. Therefore, the proposed classification for this review relies on a two-level subdivision considering the aforementioned criteria.

3.1. Polymer Spare Parts

3.1.1. Direct AM Processes

The reproduction of door handles, air vents, and interior switches made of polymers commonly comprises AM processes such as ME (FDM/FFF), VP (SLA/DLP), and PBF (SLS/MJF) [80]. Most of the time, the materials adopted are acrylonitrile butadiene styrene (ABS) or acrylonitrile styrene acrylate (ASA), but depending on the applications, several industrial polymers are considered, as well as different post-processing phases. As reported by Paulic et al. [43], RE and AM integration are well suited to the production of small components, providing the full process; in this case, a set of car volume buttons, made of polyamide 2200 (PA2200), was reproduced using SLS PBF. Many interesting applications can be found comprising several components and different production requirements. Indeed, several companies base their activity on classic-car spare-part reproduction; for example, Tyr3D, a small company specialised in covering the full process, mostly focuses on plastic components and uses a wide range of 3D-printing materials [32].

The French company Gryp 3D bases its activity on spare-part reproduction of several vintage vehicles, such as the hood-release handle of the Ferrari 328 (Figure A1a) [81]. After model acquisition using an Artec Leo scanner, with an accuracy of tenths of a millimetre, the individual scans were merged through 3D modelling software, then used as a basis for 3D prints: UV-resistant ABS was adopted using an FDM ME Raise 3D printer, followed by finish treatments (i.e., sanding and filling), priming, and varnishing. Considering car manufacturers, Porsche Classic created spare parts for its classic models using 3D printing [82]. The company manufactured plastic parts, relying on SLS PBF to reproduce several components, including the crank arm of the 946 and the filler-cap seal of the 959 (Figure 3a). For all of these parts, high quality and accuracy of size and fit were ensured by performing tests to meet the specifications with respect to the original components; this included the selection of the proper polymeric materials for resistance to oils, fuels, and light. As for Porsche, Mercedes-Benz started to produce replacement parts for several classic models using 3D printing [83]: SLS PBF was adopted to reproduce polymeric parts, including the sliding sunroof rollers for the W 110, W 111, W 112, and W 123 model series (Figure A1b), made of robust polyamide 12 (PA12). Additionally, made of PA12, the spark-plug holder from the toolkit of the 300 SL Coupé and Roadster was printed (Figure A1c): In this case, the component was customised, including a magnet to ensure compatibility with all spark plug types and terminal nuts. Nissan introduced a Heritage Parts program to digitise the inventory and enable maintenance support for vintage cars [84]. For this reason, several Nissan Motorsports (NISMO) parts have been reproduced, including the reconstruction of the plastic harness protector of the R32 Nissan Skyline GT-R, digitised and printed in MJF PBF using the HP's High-Reusability PA 11 powder. Many examples can also be found for single-component reproduction. Among them, an interesting application is the reproduction of the Ferrari Dino seat-belt cover, provided by the company Blupointscan [85]. Since the original spare part was no longer available, the seat-belt buckle's top cover required a complete process of reproduction, starting from the original component, which was broken but complete. The acquisition of the reassembled part, performed through laser scanning, provided the surface data from which the component was 3D-printed in ABS through FDM ME. Finally, a textured paint was applied to reproduce the original surface finish and appearance. Similarly, Central Scanning Limited remanufactured the central console of a 1970s Mark III Ford Cortina, fully restored in the British TV show Car SOS (Renegade Pictures) [86]. Three-dimensional scanning and printing were used to make a replica of the original component, which is no longer available (Figure A1d): The Artec Space Spider scanner was used, providing high accuracy of the acquisition (up to 0.05 mm, with ultra-high resolution of up to 0.1 mm). Then, the console was reproduced using an FDM ME Stratasys Fortus 400mc 3D printer (providing accuracy below 1 mm), followed by painting to replicate the original glossy black finish. Finally, concerning custom-fit part redesign, an example is the Chevrolet Camaro front grille customisation by the V8 Speed & Resto Shop [87]. This shop made the custom grille for a 1969 Camaro starting from the original component, created using a laser scanner (after using matting spray and markers), and fully redesigned it. Then, the component was divided into several main parts, to be properly printed using FDM ME, painted, and assembled on the front of the car. Eagle produced small-batch parts such as heating air ducts (Figure 3b) for the classic Jaguar E-Type thanks to an MJ HP Jet Fusion 4200 3D printer [88]. The company only creates four or five of these parts per year, which means that 3D printing is an ideal candidate to make parts economically, without the need for a mould, starting from 3D models that can be easily stored for future jobs.

Figure 3. Polymer spare-part reconstruction based on direct AM processes: (**a**) Porsche 964 crank arm and Porsche 959 filler-cap seal (photo credits: Porsche Classic 3D printing, 2018, Porsche AG). (**b**) Jaguar E-Type heating air ducts (photo credits: Eagle/HP).

3.1.2. Indirect AM Processes

In IM polymer technologies, AM is frequently used for the development of conformal-cooling metal cores and inserts in serial productions. More recently, for discontinued or small-batch production, AM has been employed to manufacture polymeric injection moulds or polymeric masters to create silicone moulds for low-pressure moulding.

Metal-based AM technologies can produce geometries that traditional methods cannot produce, thanks to the possibility of different material structures, internal channels for heating or cooling, and embedded sensors present in parts produced in a single step [50,89–91]. Conversely, surface finish and dimensional accuracy are still two major limitations of AM in IM. The literature presents some applications of PBF technologies, namely SLM, for the production of mould cores with conformal-cooling channels in the automotive industry's plastic part production. In [89], SLM was used in overcoming fabrication complexities for the prism-shaped topology of an IM tool insert for a vehicle headlamp reflector (Figure 4a). The insert was made of stainless steel 316 L, with a particle size nominally in the range of 45–150 μm, and a build layer thickness of 50 μm. The polymer used for injection was polystyrene. The study showed that SLM technology is advantageous when dealing with complex geometries, attaining the required geometries and surface roughness and maintaining dimensional accuracy; it is proven to be an effective alternative to subtractive manufacturing for high-volume IM tools for the aftermarket automotive sector. Figure 4b shows the conformal-cooling insert designed and produced by Innomia a.s. using an EOS DMLS 3D printer for optimising the production process of an injection-moulded plastic armrest situated between the front seats [92]; this technology contributed to the extended maintenance interval and completely solved the problem of air humidity condensation and potential cavity corrosion. Thanks to conformal cooling, the cycle time was reduced by 17% and the quality of the armrest part was improved. Again, Vasco et al. [93] used SLM to produce tool inserts for the injection moulding of automotive parking-sensor housing, a plastic part typically assembled on the vehicle's front and rear bumpers, and therefore, with aesthetics concerns. Conformal-cooling channels produced by SLM enabled faster cooling in the thicker zones, reducing manufacturing costs, although it required post-processing to enhance the surface finish (e.g., drilling, grinding, and polishing). In [94], Kazmer produced aluminium tooling which showed lower yield and fatigue strength compared to steel, which typically limits aluminium injection moulds to low- or medium-volume production (<1,000,000 cycles). Conversely, the thermal conductivity of aluminium has been found to reduce the cooling time by about 30% compared to tool steel moulds.

Polymer-based AM technologies, such as SLA, PolyJet, and SLS are used in IM for producing tools and moulds for low-volume production. Typically, a metal die accommodates polymeric AM inserts of dies for IM that can be used to produce end components. Kalami and Urbanic [95] highlighted the contribution of such 'soft tooling' or 'temporary moulds', fabricated to produce a limited number of parts (1–200 production components), with the main advantage being that problems with the mould or design modifications can be easily rectified by re-printing the mould [96]. Conversely, the main issue is the lower thermal conductivity of polymeric RT materials, which may negatively affect the warpage, shrinkage, and mechanical properties of moulded end parts, and cause slower cooling rates, therefore resulting in longer packing and cooling times [73,97]. Generally, SLA and SLS perform much better under such temperatures and mechanical pressures, with SLA offering a superior surface finish. Volpato et al. (2016) [97] used PolyJet inserts made from digital ABS for moulding polypropylene (PP), and found that the level of surface roughness was relatively constant over 50 cycles, but that the cavities were enlarged slightly due to the forces associated with the IM process. Whlean and Sheahan [98] used both SLA and PolyJet printed inserts in a metal master die unit to mould end components. The inserts were proven to mould up to 80 components without the inserts reaching the end of their cycle life. Figure 4d shows an example of grained surface (textures) application, which can often be found in injection-moulded automotive interior parts. In conventional tooling, graining requires separate process steps, making the realisation of grained injection-moulded prototype parts very complex. Using AM, it is possible to print microstructures into the mould surface in one printing operation. In [99], a mould was manufactured using a PolyJet printer (Connex 500) with Rigur polymer as it can achieve effective results in terms of mould durability under the stresses of IM. Using a resolution of 16 µm in layer height and an infill of 100%, the printing duration for the mould was tested in 288 min. Since grain structures in the automotive industry are mainly made of polypropylene, a LyondellBasell Industries Moplen EP240P was used for the moulding of these grained parts (Figure 4c).

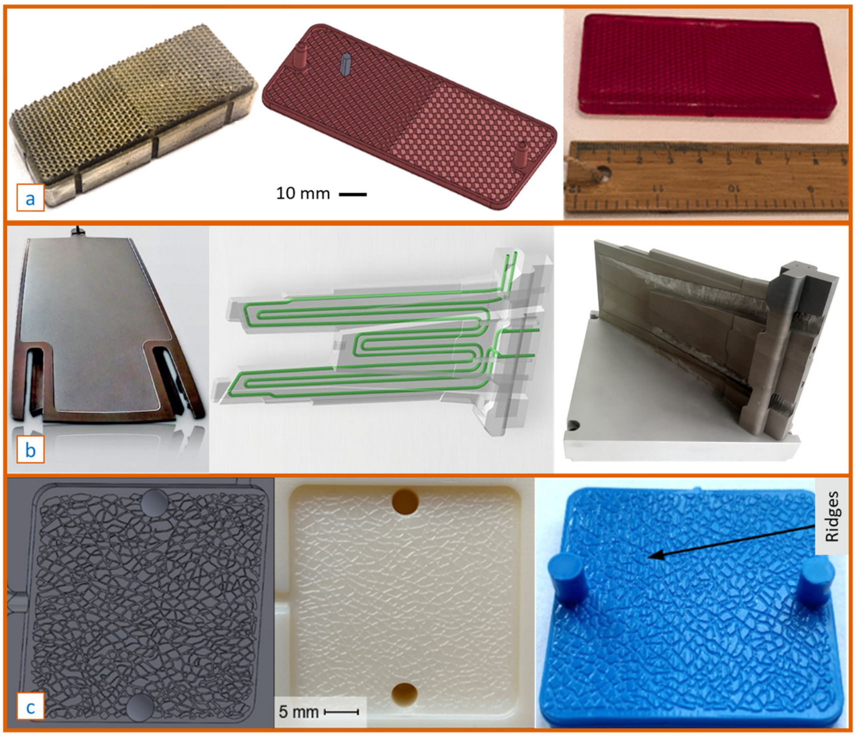

Figure 4. Polymer spare-part reconstruction based on indirect AM processes: (**a**) IM prism-shaped tool insert (reproduced under the terms of the Creative Commons Attribution 4.0 License from El Kashouty, M.F.; Rennie, A.E.; Ghazy, M.; and Aziz, A.A.E., in: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science; published by SAGE Publishing, 2021 [89]). (**b**) CAD model of the tooling insert with conformal-cooling channels, additive

manufactured tooling insert on building platform and IM component (source: Innomia, Magna, [92]). (**c**) IM polymer mould (reproduced under the terms of the Creative Commons Attribution 4.0 License from Burggräf, P.; Bergweiler, G.; Abrams, J.A.; and Dunst, A., in: J. Manuf. Mater. Process.; published by MDPI, 2022, [99]).

3.2. Metal Spare Parts

3.2.1. Direct AM processes

Direct Metal AM (MAM) processes are used to create metal end-use parts. The most widespread are laser-based PBF ones, with subsequent thermal (e.g., annealing or Hot Isostatic Pressing (HIP)) and finishing (e.g., sandblasting or machining) post-processing to, respectively, achieve the expected material and precision properties. Moreover, it has been found that SL, to which the first metal process belongs, but also ME, MJ, and BJ can be combined with specific post-processing (e.g., the debinding and sintering of "green parts") to obtain final parts. Finally, DED can be exploited either for large-part construction (e.g., Wire Arc Additive Manufacturing (WAAM)), or for component reparation [100,101] or reinforcement [102]. MAM processes (e.g., PBF and DED) are characterised by high thermal gradients during material melting and solidification, which can potentially cause many flaws [103,104]. Therefore, research still aims to overcome issues and improve process reliability by minimising the defects of parts and microstructures [105,106]. Several examples can be found of structural and interior parts, and there is no shortage of powertrain applications.

Porsche Classic [82] used to replicate rare metal spare parts, such as the cases of the release lever for the clutch of the Porsche 959 (with which only 292 vehicles were ever produced), and the bracket for the 356B and 356C (Figure A2a). The parts were made of tool steel, processed via SLM PBF. Mercedes Classic [83] provided the case of an interior part: the mirror base of the 300 SL Coupè (Figure 5a). In this case, the geometry was obtained ia 2D-to-3D conversion, which retrieved the original 2D drawings. The component was produced using aluminium alloy processed via SLM PBF, and then, finished using high-quality chrome plating.

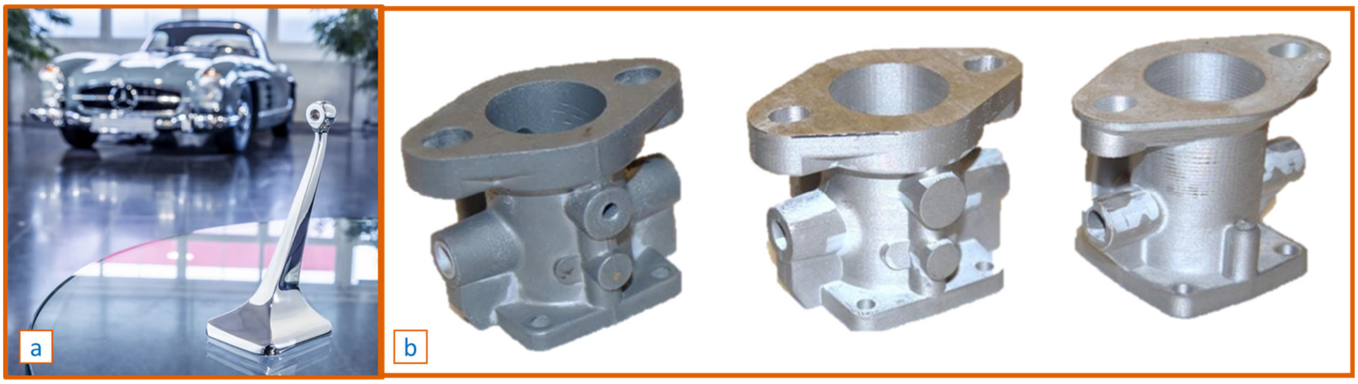

Figure 5. Metal spare-part reconstruction based on direct AM processes: (**a**) Mercedes 300 SL Coupè mirror base (photo credits: Mercedes-Benz Group AG). (**b**) Steyr 220 carburettor body (**left**), 3D-printed original design (**centre**), 3D-printed DfAM design (**right**) (photo credits: Tecron s.r.o.).

Many examples even concern engines and transmissions. A diesel engine valve cover reconstruction process based on RE and AM is described by Montero et al. [34]. The RE, modelling, construction, and testing of lightweight valves is described by Cooper et al. [107]. Mercedes also reproduced rare spare parts for Unimog models (Figure A2b), such as in the case of thermostat covers for installation in truck engines [108]. In this case, the digital model was retrieved from a data inventory, and the components were made of AlSi10Mg aluminium alloy, processed via SLM PBF. Jay Leno's Garage often makes use of AM technologies to reproduce rare or lost components for classic-car restoration. An interesting engine case is that of the pilot burner of a vintage steam engine (Figure A2c) for a 1907

White Steamer [109]. The component was produced using Inconel 718 (a nickel-based superalloy), and processed ia DMLS PBF, in collaboration with Stratasys. Another engine application is from Tecron, which restored the carburettor of a 1930s Steyr 220 Roadster (Figure 5b) [110]. They performed RE of the parts via 3D scanning and produced them in 17-4 PH stainless steel using a Metal Fused-Filament Fabrication ME process described by Markforged [111]. Interestingly, they also demonstrated how manufacturing time and costs can be reduced by 30%, by applying DfAM guidelines (Figure A2d). The famous motorsport company Sauber currently has stakes in the historic-vehicle sector reproducing classic cars components [112]. A case from a powertrain is the gearbox housing of a 1950s Ferrari 350 America Barchetta. They performed RE of the housing via 3D scanning, and they built the component in aluminium alloy using the laser-based PBF process of Additive Industries. Finally, if components can be repaired rather than reproduced, DED or Cold Spray AM processes can be exploited, such as in the cases of engine crankshafts [113], oil pumps [114], and cylinder heads [115]. Furthermore, since repairing engine blocks through AM can cost 40% less than a new engine with spare parts priced at 40% of the original cost, economic advantages are also possible [116].

3.2.2. Indirect AM Processes

Metal-casting technologies take advantage of AM for the development of tooling, where two main approaches can be distinguished, according to [116,117]: direct tooling and indirect tooling. The first group includes 3D-printed sand moulds and cores for casting processes. The second group comprises the production of 3D-printed master models (patterns) to form the sand mould in sand casting, to produce sacrificial patterns for fabricating ceramic disposable moulds for investment (lost-wax) casting, or—also indirectly—to fabricate silicone or rubber moulds for producing the wax patterns.

The direct tooling group, belonging to the rapid tooling processes, mainly focuses on sand-casting processes for the production of sand-cast moulds and cores according to the techniques currently commercially available [118], e.g., Direct Laser Sand Sintering (DLSS) and 3D Sand Printing (3DSP). DLSS, similarly to SLS and DMLM, uses a low-power laser to sinter the silica sand directly, without any binder. It has a relatively low deposition rate (2500 cm^3/h) and it requires no tools to produce the mould [119], providing design freedom for the engineer. It leads to accurate casting capable of fitting the mass customisation model, but due to the low relative speed and high machine price, can only be viable for high-value, highly complex, small, one-off castings [120].

The 3DSP process belongs to BJ technologies. A deposition head uses a multi-jet print head to deposit micro-droplets of the foundry-grade resin binder into a fine, thin layer of permeable casting sand premixed with an activator. It is a cold process requiring only post-production off-machine de-powdering. The components produced are extremely accurate, and the machines have high build rates. The 3DSP can produce the size of moulds required by many automotive manufacturers. In this process, casting is performed in the same way as the conventional process as only the mould is produced differently, with the advantages of AM.

As for classic cars, an early example of RC application is the development of the engine block of the last-surviving 1914 Delage Type-S [121]; this was possible thanks to a digital workflow based on 3D scanning of the cracked block, 3D modelling of the mould of the engine, and 3D printing of the mould using a Voxeljet VX1000 printer. Finally, the metal was poured into the 3D-printed moulds to recreate the entire engine block (Figure A3a). Another example from the field of car restoration is the reproduction of a 1912 one-cylinder car engine, which was damaged [122]. The 3D-scanned model required the addition of contraction allowance, machining allowance, a gating system, risers, chills, vents, and a hoisting system, creating partitions in the moulds and cores. The mould parts were fabricated using an ExOne S-Max 3D sand printer. The cores and moulds were coated as used in the conventional process. Figure 6a shows the cores, the mould, and the final casting.

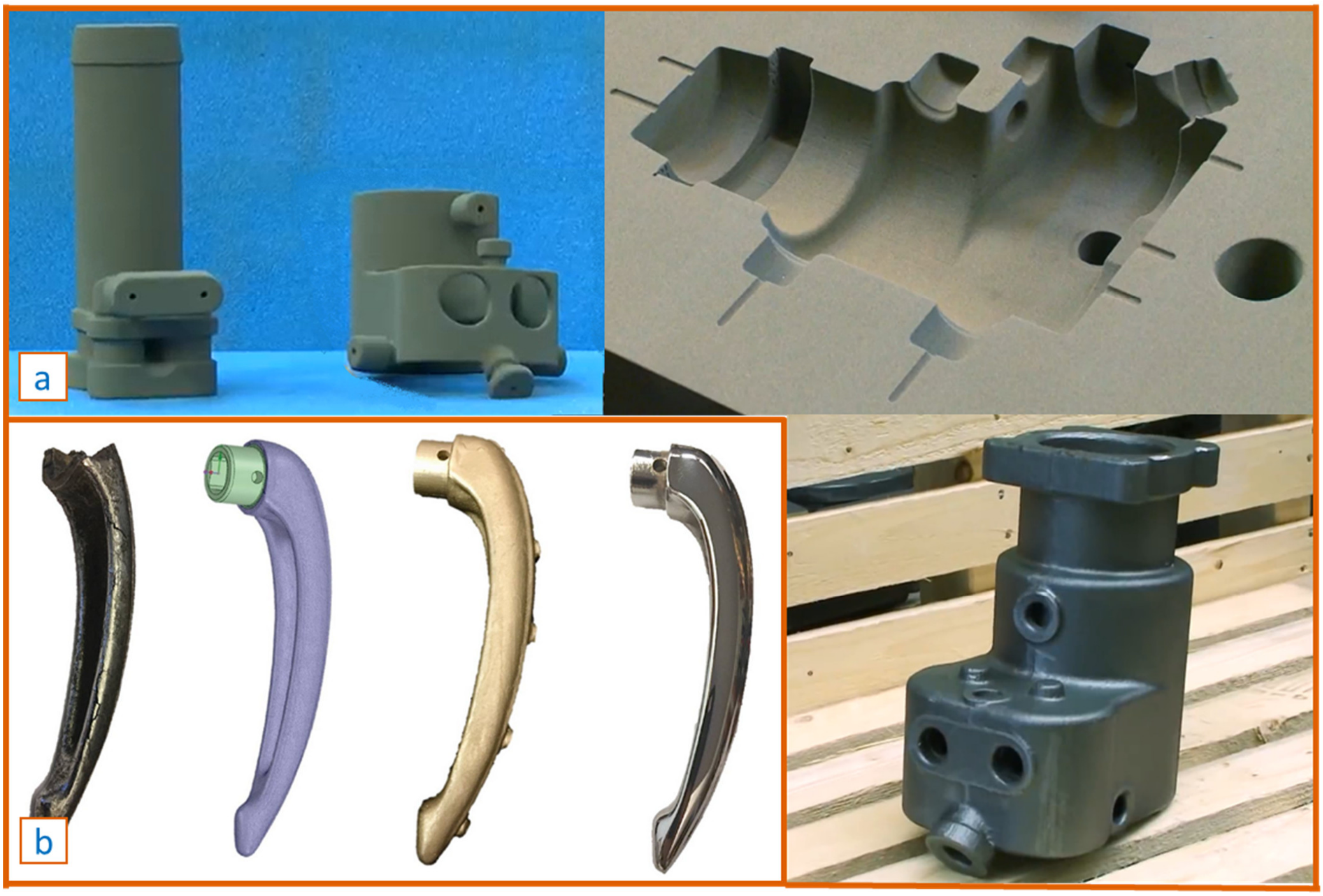

Figure 6. Polymer spare-part reconstruction based on indirect AM processes: (**a**) Sand mould and cores for casting a 1912 one-cylinder car engine (photo credits: 3Dealise). (**b**) Investment cast door handle (photo credits: Rare Parts Club, a division of Freshmade 3D).

The indirect tooling group, also called rapid casting (RC), produces patterns—used for forming moulds—that are created using 3D-printing techniques such as FDM, SLA, SLS, or any other 3D-printing technique. According to Chhabra [117], we distinguish indirect tooling applications in sand casting and investment casting.

As for the indirect tooling applications in sand casting, the patterns, cores, and gating systems are fabricated sing AM processes in a relatively short period of time, proving to be cost-effective and time-efficient [123]. AM helps to fabricate patterns with added cores by disregarding internal cavities and designing core prints. Starting from the first application using Laminated Object Manufacturing (LOM) for fabricating paper master patterns, Pereira et al. (2008) [124] reported the advantages gained with the application of FDM patterns in sand moulding, and are open to other AM techniques (SLA, PolyJet, and SLS).

Other examples of indirect tooling applications are in investment (lost-wax) casting (IC), which employs a wax or polymer pattern as a sacrificial pattern to produce solid-metal parts. These sacrificial patterns are used to create a ceramic mould by investing refractory ceramic coatings on patterns, which are then removed via heating. Chhabra [117] distinguishes IC processes into direct wax patterns (made using the SLS, FDM, SLA, and DOD techniques) and direct non-wax patterns (made using thermoplastic polymers such as ABS and PLA, from which the name "lost-PLA casting" originates).

Gray and Depcik [116], and Chhabra [117] reported the use of rapid-casting (RC) techniques for the production of internal combustion engine components by printing master models using PolyJet, SLA, or FDM processes, for the investment casting of crankcases, cylinder blocks, air-intake manifolds, exhaust manifolds, and gearboxes.

As for classic cars, the reproduction of the broken door handle of a 1959 Lancia Aurelia B24S (Figure 6b) was 3D-scanned; then, it was reverse-engineered before wax models were 3D-printed (SLA) to cast an exact replica in solid brass, which was then chrome-plated [125]. Similarly, a 1937 Voisin C30 fan (Figure A3b) was reverse-engineered, raw-cast in aluminium, and then, machined to create the mounting holes [125]. Finally, the original door and trunk key of a 1955 Mercedes Gullwing 300 SL was 3D-scanned, the 3D model was cleaned up, and then, a wax pattern of the key was 3D-printed to be used in an investment-casting process (Figure A3c). The key was cast in solid brass, post-processed, and slotted [125].

3.3. Composite Spare Parts

3.3.1. Direct AM Processes

AM of fibre/polymer composites is a turning point in AM technology. The enhanced mechanical properties provided by the addition of reinforced materials into plastic materials have widened the application field, improving AM potential [126]. Several AM processes using fibre-reinforced polymers have been developed, comprising ME (FDM/FFF), PBF (SLS), VP (SLA), and SL (LOM) [127,128]. Concerning direct AM, the most common automotive applications of polymer composites comprise exterior panels and trims, and interiors and seating, but also electrical sensors, suspension, and engine components [9]. Moreover, it is worth mentioning the increasing interest in vehicle restoration, in part reproduction, redesign, and customisation.

An interesting example is the Oak Ridge National Laboratory (ORNL), which made a full-sized replica of the Shelby Cobra for the 50th anniversary of the car [129]. This replica was conceived as a complete and functional vehicle; therefore, the company planned to 3D-print all of its components, except for the engine and electrical components. The components were 3D-printed using an ME Big Area Additive Manufacturing (BAAM) machine, adopted for producing full-sized car models (e.g., the Local Motors 3D-printed Strati Car). By using an advanced composite material, consisting of ABS plastic and carbon fibre, the defined layers made up the body of the vehicle, starting from the 3D print of the main chassis. Once provided with the base structure on which to assemble all the other bodywork parts, the rest of the vehicle was printed in several pieces, which were bonded together to form the main body (Figure 7a). Finally, the components were smoothened, finished, and painted (Figure 7b).

Figure 7. Composite spare-part reconstruction based on direct AM processes: the Shelby Cobra's (**a**) rough and (**b**) finished bodywork (photo credits: Oak Ridge National Laboratory (ORNL)).

3.3.2. Indirect AM Processes

Indirect AM processes of fibre-reinforced components mainly include the construction of moulds and cores. AM of large moulds and dies is widespread, to provide tooling for low productions or unique prototypes. Over the years, AM technology has further improved to cover the main typologies of composite moulding (prepreg and wet moulding), reducing tooling costs for better productivity. Among these, BAAM has been implemented with interesting results, and there have been recent developments in metal additives for the compression moulding of composite parts [130]. Moreover, AM of sacrificial tooling, such as cores and mandrels, combined with filament winding, prepreg, and wet layup, can be used to automatise the production of ducts, pipes, manifolds, tanks, or tubular/hollow structures. The material used to build cores must be made either soluble or breakable to facilitate the removal phase, but it also requires compatibility with the temperature and pressure required by composites processes. Conventional methods make use of eutectic salts, soluble ceramics, and flexible urethanes, which, in turn, do require metal moulds, or the direct application of clamshells. FDM cores made of materials such as soluble SR100/ST-130 or break-away ULTEM® Support, which bear autoclave processing (up to 110–130 °C and 2–5 bars), provide many advantages such as the elimination of bonding and seams and improved internal and external surface finishes. The parts, produced, therefore, in one layup operation, also allow for reduced manufacturing time and cost (up to 85%), as demonstrated by the case of carbon fibre inlet ducts (Figure 8a) for the Porsche 997 Turbo, provided by Champion Motorsport in collaboration with Stratasys [131].

Figure 8. Composite spare-part reconstruction based on indirect AM processes: (**a**) the FDM sacrificial core and the carbon fibre inlet ducts (photo credits: Stratasys/Champion Motorsport; the Maserati MV 3200 GTC (**b**) body components and (**c**) related tooling (photo credits: Bercella Srl).

Among several applications, it is worth mentioning the restomod Maserati MV 3200 GTC created by the Italian companies Bercella Srl and CMS Spa [132]. An innovative composite layup process for custom and restored vehicles was introduced, consisting of an AM hybrid system. This system combines an ME large-format 3D printer (LFAM) with multi-axis milling-print composite components to shorten the supply chain, specifically for automotive composite part reproduction. Each component of the car bodywork was built from carbon fibre prepreg (Figure 8b), manufactured via hand layup on a 3D-printed mould, then, cured via autoclave; 20 total carbon fibre moulds were printed from 40% carbon fibre-filled polyamide 6 (PA6) and immediately finished within the same machining centre (Figure 8c). In this way, a total of 26 body components were redesigned, including the door, roof, hood, and front and rear bumpers.

4. Automotive Spare-Part Reconstruction Based on Additive Manufacturing

The analysis carried out in the previous sections highlights the potentialities and widespread applications of AM technologies in the automotive spare-part field, with a particular focus on the restoration of classic or historic vehicles.

The selected works share—and so, implicitly define—a common framework for component reconstruction. Figure 9 highlights the digital workflow for the development of the 3D model, which is the required input for the following AM process. In the field of the reconstruction of lost automotive spare parts, we highlight some trends and sum them up using workflows, diagrams, and tables.

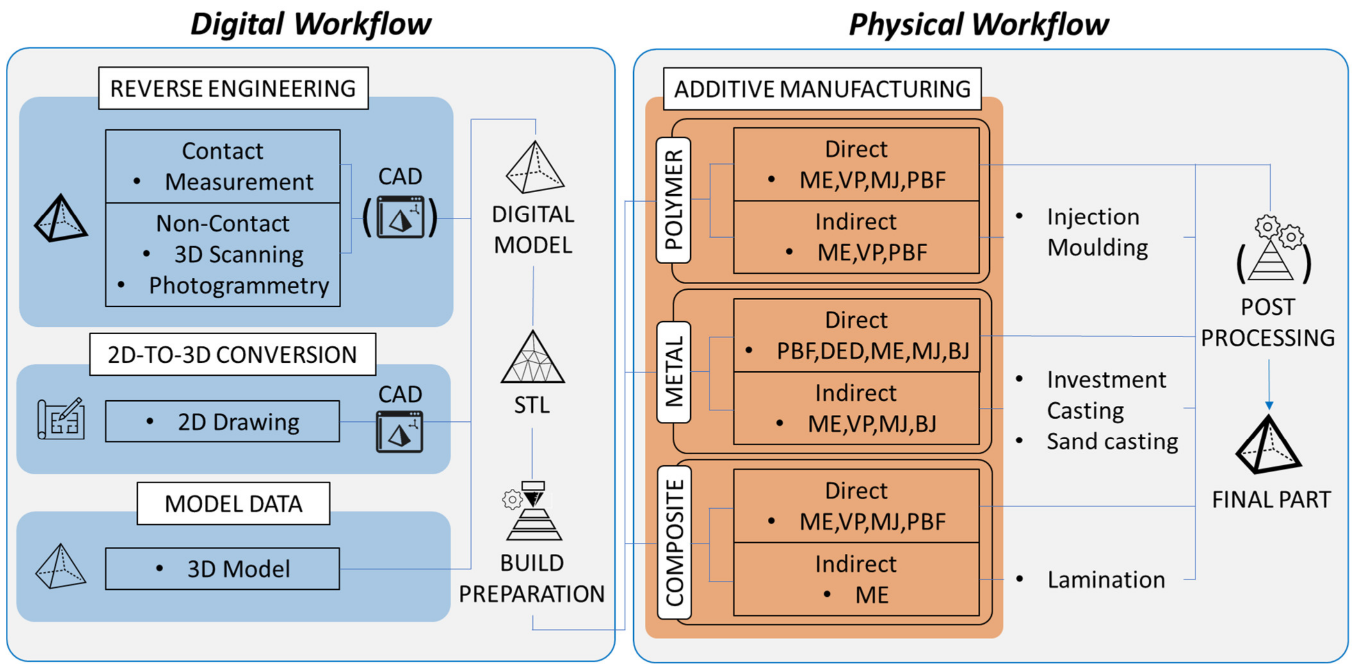

Figure 9. The framework of component reconstruction based on AM.

The pie diagram of Figure 10 shows a homogeneous distribution of cases in all the vehicle areas, with a slight predominance of structural parts. The detail of this analysis is summed up in Table 1, which correlates parts, materials, and AM technologies, and which we discuss in the following section.

Polymeric parts are mainly related to interior vehicle components (e.g., buttons, handles, arms, holders, etc.) made through direct processes using PBF and ME technologies. The most used materials are polyamide (PA12, PA2200) powder with PBF and ABS filaments (sometimes with additives such as UV stabiliser) with ME. Due to the specific functions of the components made with these materials, both PA and ABS share high impact strength, high thermal stability, and good chemical resistance, which make them suitable for applications in vehicle cabins (with high summer temperatures and exposure to sunlight).

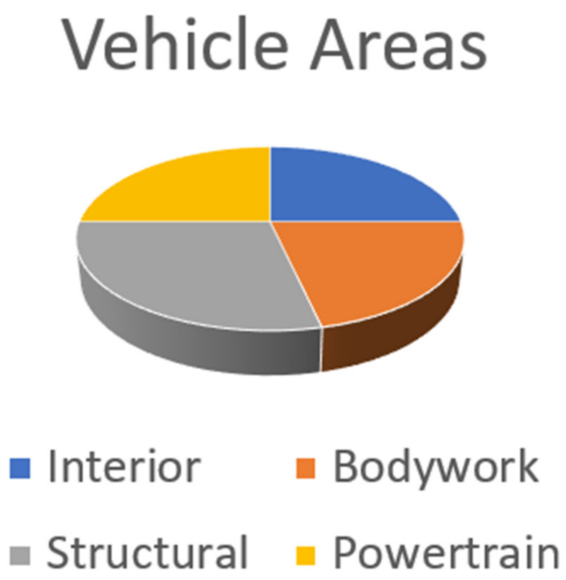

Figure 10. Spare-part reconstruction cases according to vehicle areas (source: authors' elaboration based on the literature review).

As for indirect processes, the production of polymeric final parts is mainly based on IM, in which AM is used to produce equipment, and processes and materials are selected for their enhanced performance with respect to the traditional processes/materials or, conversely, for their affordability (low cost). In the first category, AM is therefore widely used to produce complex-shaped inserts and thermally efficient cores (i.e., conformal-cooling channels) in stainless steel and maraging steel using PBF (specifically, SLM). Conversely, in the second category, AM is used to produce high-resolution resin moulds, to reduce the equipment cost in small-batch production.

Most of the powertrain, bodywork, and structural components are metal parts. Aluminium alloys (e.g., AlSi10Mg), as well as stainless and tool steels, are used to produce housing, bodies, brackets, and covers, mainly using PBF (SLM) and, in some cases, ME. The materials used in the reconstruction process are very close to the original part materials, due to the conservative approach that usually guides the restoration process of historic and classic vehicles.

As for indirect processes, metal-casting technologies employ AM to produce sand moulds and cores, as well as patterns (master models). Moulds and cores for sand casting can be additively manufactured in sintered silica sand (DLSS) or using a mixture of casting sand and an activator, together with a resin-base binder (3DSP). In the conventional sand-casting process, the patterns can be made using various AM technologies and materials: paper in LOM, and various polymers in FFF/FDM, SLA, PolyJet, and SLS. Finally, in investment casting (lost-wax casting), sacrificial patterns—which can be removed from the casting mould via heating—can be made using wax with VP and MJ technologies, or wax-like filaments in ME, e.g., a thermoplastic polymer as PLA.

Carbon fibre composite components mainly relate to bodywork panels, but also the some complex-shaped parts, as in the case of inlet ducts. Examples of direct processes are limited to bodywork panels, and are only related to the ME process thanks to BAAM technologies. Conversely, the indirect process consists of the development of large moulds and dies, or cores. A polymeric mould can be produced in ME, and is generally used as direct support for wet lay-up laminating or for the production of a carbon moulds to be used in autoclave curing. Conversely, FDM cores are made of soluble materials (e.g., SR100/ST-1309) or break-away materials (e.g., ULTEM® Support) that bear autoclave processing.

Table 1. Automotive spare-part reconstruction: reproduced parts–materials–processes.

Spare Part	Material	AM Process
Car volume buttons [43]	Polyamide 2200 (PA2200)	PBF—Direct (SLS)
Hood-release handle [81]	UV-resistant ABS	ME—Direct (FDM)
Crank arm [82]	Polymer	PBF—Direct (SLS)
Filler-cap seal [82]	Polymer	PBF—Direct (SLS)
Sliding sunroof rollers [83]	Polyamide 12	PBF—Direct (SLS)
Spark-plug holder [83]	Polyamide 12	PBF—Direct (SLS)
Plastic harness protector [84]	Polyamide 11 powder	PBF—Direct (MJF)
Seat-belt cover [85]	ABS	ME—Direct (FDM)
Central console [86]	Polymer	ME—Direct (FDM)
Custom front grille [87]	Polymer	ME—Direct (FDM)
Heating air ducts [88]	Polyamide	PBF—Direct (MJF)
IM prism-shaped tool insert [89] > (headlamp reflector)	Stainless steel 316 L > (polystyrene)	PBF—Indirect (SLM) > (injection moulding)
IM conformal-cooling insert [92] > (armrest)	Maraging steel 1.2709 > (polymer)	PBF—Indirect (SLM) > (injection moulding)
IM tool inserts [93] > (parking sensor housing)	Maraging steel CL 50WS > (polybutylene terephthalate (PBT))	PBF—Indirect (SLM) > (injection moulding)
IM polymer mould [99] > (grain textured surfaces)	Simulated polypropylene material (Rigur) > (polypropylene)	MJ—Indirect (PolyJet) > (injection moulding)
Bracket [82]	Tool steel	PBF—Direct (SLM)
Mirror base [83]	Aluminium alloy	PBF—Direct (SLM)
Thermostat cover [108]	AlSi10Mg	PBF—Direct (SLM)
Pilot burner [109]	Inconel 718	PBF—Direct (DMLS)
Carburettor body [110]	17-4 PH stainless steel	ME—Direct (Metal X)
Gearbox housing [112]	AlSi10Mg	PBF—Direct (MetalFAB1)
Sand mould and cores [121] > (engine block)	Quartz sand > (cast iron)	BJ—Indirect (3DSP) > (metal casting)
Sand mould and cores [122] > (one-cylinder car engine)	Sand + foundry-grade resin > (cast iron)	BJ—Indirect (3DSP) > (metal casting)
Wax master model [125] > (door handle)	Wax > (solid brass)	VP—Indirect (wax SLA) > (investment casting)
Wax master model [125] > (fan)	Wax > (aluminium)	VP—Indirect (wax SLA) > (investment casting)
Wax master model [125] > (door and trunk key)	Wax > (solid brass)	VP—Indirect (wax SLA) > (investment casting)
Shelby Cobra replica [129]	ABS plastic and carbon fibre	ME—Direct (BAAM)
Core for composite lamination [131] > (Porsche 997 turbo inlet ducts)	Stratasys ST-130 (sacrificial-tooling material) > (carbon fibre prepreg)	ME—Indirect (FDM) > (lamination)
3D-printed mould [132] > (composite body of a Maserati 3200 GT restomod)	40% carbon fibre-filled polyamide 6 > (carbon fibre prepreg)	ME—Indirect (LFAM) > (lamination)

As for AM technologies in the field of automotive spare-part reproductions, Figure 11a shows that most of the applications deal with the Material Extrusion (ME) of polymeric materials (e.g., FDM/FFF). This result could have been expected due to the spread and accessibility of this technology in terms of the cost-effectiveness of machines and materials, and the related ease of use. Although most of the sources that we have selected are commercial, most are small-sized companies such as start-ups that occupy a small, highly specialised market niche in the restoration field. However, Figure 11a shows that the second most used technology is metal-based PBF. The depicted scenario confirms a trend similar to other application fields of AM.

As for the direct/indirect AM processes, Figure 11b shows that the direct process quite exclusively employs ME and PBF technologies; conversely, all the other AM technologies are used in the indirect process (i.e., tooling).

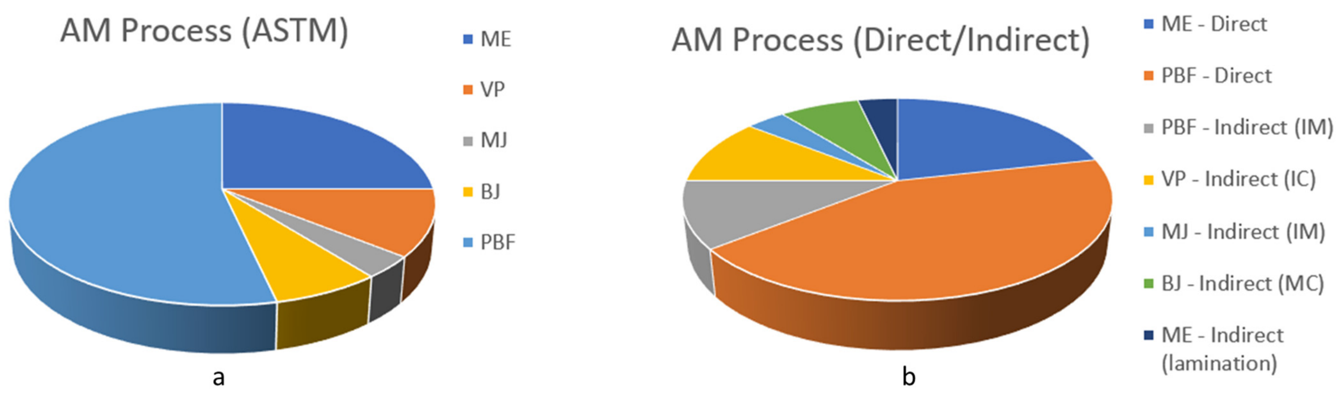

Figure 11. Use of AM in spare-part reconstruction cases, respectively, in accordance with (**a**) the ASTM categories and (**b**) the direct/indirect processes (source: authors' elaboration based on the literature review).

5. Conclusions

This paper proposes a review and analysis of the best practices in AM processes in the field of automotive spare parts that are no longer available on the market. A digital production workflow for part reproduction is shared by car manufacturers, restorers, OEMs, and similar companies, starting from original components, even if they are broken. From a technological point of view, the additive process allows on-demand production, in one-off or small batches, without the need for dedicated tools.

This review focused on the reproduction of automotive spare parts, and the findings are as follows:

- All types of AM technologies are used to produce automotive spare parts, although some technologies predominate (such as so-called polymeric Material Extrusion processes) for their ease-of-use, and cost-effectiveness in terms of both equipment and materials. In other cases, AM is used as an intermediate process in conventional primary technologies, such as sand casting and investment casting, contributing to the digital transformation of traditional manufacturing processes.
- The users of AM technologies range from car manufacturers, OEMs, and restoration body shops, to small-sized companies such as start-ups dedicated to this market niche. Moreover, in many of the selected case studies, a provider of AM equipment was involved in the development of a specific solution in terms of processes or materials.
- On the one hand, the technology providers, car manufacturers, and technology scholars aim to improve the finish and performance of AM as a primary process; on the other hand, post-processing for additively manufactured parts has been developed to be capable of limiting the main criticalities of layer-by-layer processes.
- The framework that emerges from the case studies presented in this review leads to the abstraction of a complete methodology for the reproduction of components based on a digital and physical workflow, which uses AM for both part production and tooling.

In conclusion, thanks to this ever-growing development of technologies and materials, this study states the consolidated role of AM in the production of classic-car spare parts, but also highlights its potential implications in the current automotive supply chain.

Author Contributions: Conceptualisation, E.D., A.P., and F.G.; methodology, E.D., A.P., and F.G.; formal analysis, E.D., A.P., and F.G.; investigation, E.D., A.P., and F.G.; resources, E.D., A.P., and F.G.; data curation, E.D., A.P., and F.G.; writing—original draft preparation, E.D., A.P., and F.G.; writing—review and editing, E.D., A.P., and F.G.; visualisation, E.D., A.P., and F.G.; supervision, E.D., A.P., F.G., and F.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Figure A1. Polymer spare-part reconstruction based on direct AM processes: (**a**) Ferrari 328 hood-release handle (photo credits: SAS Gryp 3D). (**b**) Sliding sunroof rollers for Mercedes-Benz W 110, W 111, W 112, and W 123 model series (photo credits: Mercedes-Benz Group AG). (**c**) Spark-plug holder for Mercedes-Benz 198 model series (Coupé and Roadster) (photo credits: Mercedes-Benz Group AG). (**d**) Central console of a 1970s Mark III Ford Cortina (photo credits: Car SOS, Renegade Pictures).

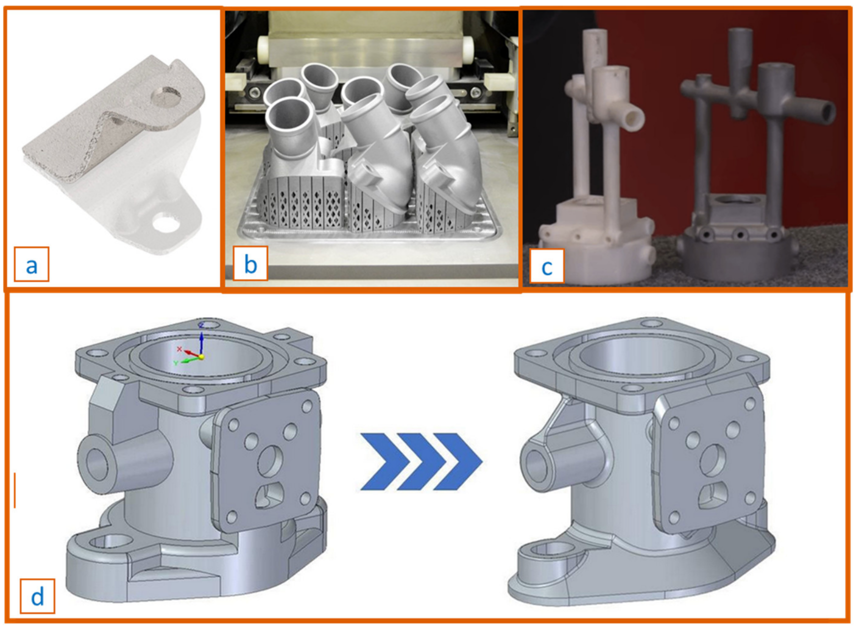

Figure A2. Metal spare-part reconstruction based on direct AM processes: (**a**) Porsche 356 B/C bracket (photo credits: Porsche Classic 3D printing, 2018, Porsche AG). (**b**) Mercedes Unimog thermostat cover (photo credits: Mercedes-Benz Group AG). (**c**) White Steamer pilot burner (photo credits: Stratasys/Jay Leno's Garage). (**d**) CAD models of the original carburettor body (**left**) and the DfAM version (**right**) (photo credits: Tecron s.r.o.).

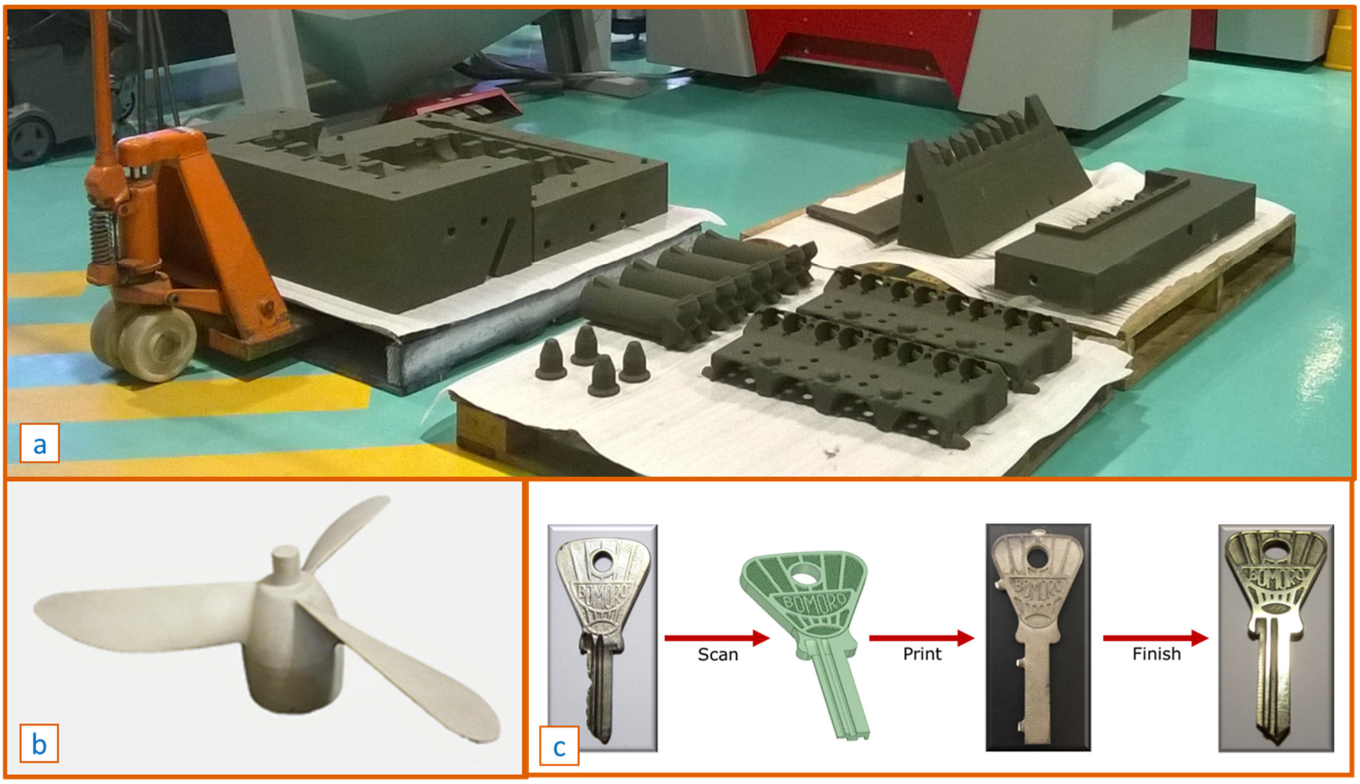

Figure A3. Polymer spare-part reconstruction based on indirect AM processes: (**a**) Sand moulds for casting the engine block of the 1914 Delage Type-S (photo credits: Voxeljet). (**b**) Investment-cast fan. (**c**) Investment-cast key for door and trunk (photo credits for (**b**,**c**): Rare Parts Club, a division of Freshmade 3D).

References

1. Deloitte Insights. Industry 4.0 in Automotive. Digitizing the End-to-End Automotive Value Chain. Deloitte Development LLC. 2020. Available online: https://www2.deloitte.com/content/dam/insights/us/articles/automotive-news_industry-4-0-in-automotive/DI_Automotive-News-Supplement.pdf (accessed on 12 August 2022).
2. Rüßmann, M.; Lorenz, M.; Gerbert, P.; Waldner, M.; Justus, J.; Engel, P.; Harnisch, M. Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consult. Group* **2015**, *9*, 54–89. Available online: https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries (accessed on 12 August 2022).
3. Butt, J. Exploring the Interrelationship between Additive Manufacturing and Industry 4.0. *Designs* **2020**, *4*, 13. [CrossRef]
4. Plocher, J.; Panesar, A. Review on Design and Structural Optimisation in Additive Manufacturing: Towards next-Generation Lightweight Structures. *Mater. Des.* **2019**, *183*, 108164. [CrossRef]
5. Dalpadulo, E.; Pini, F.; Leali, F. Integrated CAD Platform Approach for Design for Additive Manufacturing of High Performance Automotive Components. *Int. J. Interact. Des. Manuf.* **2020**, *14*, 899–909. [CrossRef]
6. Dalpadulo, E.; Pini, F.; Leali, F. Systematic integration of topology optimization techniques in design for additive manufacturing methodologies applied to automotive settings. In Proceedings of the ASME 2020 International Mechanical Engineering Congress and Exposition, Virtual, Online, 16–19 November 2020; Volume 6, p. V006T06A016. [CrossRef]
7. Bubna, P.; Humbert, M.P.; Wiseman, M.; Manes, E. Barriers to Entry in Automotive Production and Opportunities with Emerging Additive Manufacturing Techniques. *SAE Tech. Pap.* **2016**, 2016-01-0329. [CrossRef]
8. Leal, R.; Barreiros, F.M.; Alves, L.; Romeiro, F.; Vasco, J.C.; Santos, M.; Marto, C. Additive manufacturing tooling for the automotive industry. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 1671–1676. [CrossRef]
9. Salifu, S.; Desai, D.; Ogunbiyi, O.; Mwale, K. Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review. *Int. J. Adv. Manuf. Technol.* **2022**, *119*, 6877–6891. [CrossRef]

10. Khajavi, S.H.; Salmi, M.; Holmström, J. Additive manufacturing as an enabler of digital spare parts. In *Managing 3D Printing*; Eyers, D., Ed.; Palgrave Macmillan: Cham, Switzerland, 2020; pp. 45–60. [CrossRef]
11. Isasi-Sanchez, L.; Morcillo-Bellido, J.; Ortiz-Gonzalez, J.I.; Duran-Heras, A. Synergic sustainability implications of additive manufacturing in automotive spare parts: A case analysis. *Sustainability* **2020**, *12*, 8461. [CrossRef]
12. Wiese, M.; Leiden, A.; Rogall, C.; Thiede, S.; Herrmann, C. Modeling energy and resource use in additive manufacturing of automotive series parts with multi-jet fusion and selective laser sintering. *Procedia CIRP* **2021**, *98*, 358–363. [CrossRef]
13. Thomas, D. Costs, benefits, and adoption of additive manufacturing: A supply chain perspective. *Int. J. Adv. Manuf. Technol.* **2016**, *85*, 1857–1876. [CrossRef]
14. Koller, J.; Häfner, R.; Döpper, F. Decentralized Spare Parts Production for the Aftermarket using Additive Manufacturing-A Literature Review. *Procedia CIRP* **2022**, *107*, 894–901. [CrossRef]
15. Mecheter, A.; Pokharel, S.; Tarlochan, F. Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management. *Appl. Sci.* **2022**, *12*, 4160. [CrossRef]
16. Lim, J.; Le, K.Q.; Lu, Q.; Wong, C. An Overview of 3-D Printing in Manufacturing, Aerospace, and Automotive Industries. *IEEE Potentials* **2016**, *35*, 18–22. [CrossRef]
17. Delic, M.; Eyers, D.R. The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. *Int. J. Prod. Econ.* **2020**, *228*, 107689. [CrossRef]
18. Giffi, C.A.; Gangula, B.; Illinda, P. 3D Opportunity in the Automotive Industry: Additive Manufacturing Hits the Road. A Deloitte Series on Additive Manufacturing. Deloitte University press. 2014. Available online: https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-3d-opportunity-in-automotive/DUP_707-3D-Opportunity-Auto-Industry_MASTER.pdf (accessed on 12 August 2022).
19. Wohlers, T.T. Wohlers Report 2019. Analysis. Trends. Forecasts. In *3D Printing and Additive Manufacturing State of the Industry*; Wohlers Associates Inc.: Fort Collins, CO, USA, 2019; p. 369.
20. Tuazon, B.J.; Custodio, N.A.V.; Basuel, R.B.; Delos Reyes, L.A.; Dizon, J.R.C. 3D Printing Technology and Materials for Automotive Application: A Mini-Review. *Key Eng. Mater.* **2022**, *913*, 3–16. [CrossRef]
21. Hawken, R. Classic Cars Make Great Investment Vehicles. Modern Trader. 2018. Available online: http://www.futuresmag.com/2018/03/16/classic-cars-make-great-investment-vehicles (accessed on 12 August 2022).
22. Johnson, S. Classic cars: Keep motoring heritage alive. *Eng. Technol.* **2021**, *16*, 1–6. [CrossRef]
23. Valerga, A.P.; Batista, M.; Bienvenido, R.; Fernández-Vidal, S.R.; Wendt, C.; Marcos, M. Reverse Engineering Based Methodology for Modelling Cutting Tools. *Procedia Eng.* **2015**, *132*, 1144–1151. [CrossRef]
24. Zhang, X.; Cui, W.; Li, W.; Liou, F. A Hybrid Process Integrating Reverse Engineering, Pre-Repair Processing, Additive Manufacturing, and Material Testing for Component Remanufacturing. *Materials* **2019**, *12*, 1961. [CrossRef]
25. Strong, D.; Kay, M.; Wakefield, T.; Sirichakwal, I.; Conner, B.; Manogharan, G. Rethinking reverse logistics: Role of additive manufacturing technology in metal remanufacturing. *J. Manuf. Technol. Manag.* **2019**, *31*, 124–144. [CrossRef]
26. Dúbravčík, M.; Kender, Š. Application of reverse engineering techniques in mechanics system services. *Procedia Eng.* **2012**, *48*, 96–104. [CrossRef]
27. Buican, G.R.; Oancea, G.; Manolescu, A. Remanufacturing of damaged parts using selective laser melting technology. *Appl. Mech. Mater.* **2014**, *693*, 285–290. [CrossRef]
28. Palka, D. Use of reverse engineering and additive printing in the reconstruction of gears. *Multidiscip. Asp. Prod. Eng.* **2020**, *3*, 274–284. [CrossRef]
29. Edinbarough, I.; Akundi, A. Rapid manufacturing of critical industrial parts: A method based on reverse engineering, rapid prototyping, and coordinate metrology. In Proceedings of the ASEE Annual Conference and Exposition, Online, 21–24 June 2020; p. 1162. [CrossRef]
30. Sasson, A.; Johnson, J.C. The 3D printing order: Variability, supercenters and supply chain reconfigurations. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 82–94. [CrossRef]
31. Taylor, E.; Cremer, A. Daimler Trucks to Use 3D Printing in Spare Parts Production. Reuters, Frankfurt, 13 July 2016. Available online: www.reuters.com/article/us-daimler-3dprintingidUSKCN0ZT201 (accessed on 12 August 2022).
32. 3D Printed Car Parts. 3DPrint.com. Available online: https://3dprint.com/tag/3d-printed-car-parts/ (accessed on 12 August 2022).
33. Savastano, M.; Amendola, C.; D'Ascenzo, F.; Massaroni, E. 3-D Printing in the Spare Parts Supply Chain: An Explorative Study in the Automotive Industry. In *Digitally Supported Innovation. Lecture Notes in Information Systems and Organisation*; Caporarello, L., Cesaroni, F., Giesecke, R., Missikoff, M., Eds.; Springer: Cham, Switzerland, 2016; Volume 18. [CrossRef]
34. Montero, J.; Paetzold, K.; Bleckmann, M.; Holtmannspoetter, J. Re-design and re-manufacturing of discontinued spare parts implementing additive manufacturing in the military field. In Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, 21–24 May 2018; pp. 1269–1278. [CrossRef]
35. Subeshan, B.; Abdulaziz, A.; Khan, Z.; Uddin, M.N.; Rahman, M.M.; Asmatulu, E. Reverse Engineering of Aerospace Components Utilizing Additive Manufacturing Technology. In *TMS 2022 151st Annual Meeting & Exhibition Supplemental Proceedings, The Minerals, Metals & Materials Series*; Springer: Cham, Switzerland, 2022; pp. 238–246. [CrossRef]
36. Dwivedi, G.; Srivastava, S.K.; Srivastava, R.K. Analysis of barriers to implement additive manufacturing technology in the Indian automotive sector. *Int. J. Phys. Distrib. Logist. Manag.* **2017**, *47*, 972–991. [CrossRef]

37. Grunewald, S.J. 3D Printing Will Help Mercedes-Benz Trucks Deliver Thousands of Replacement Parts on Demand. 3Dprint.com. 14 July 2016. Available online: https://3dprint.com/142207/mercedes-benz-trucks-parts (accessed on 12 August 2022).
38. Lee, K.H.; Woo, H. Direct integration of reverse engineering and rapid prototyping. *Comput. Ind. Eng.* **2000**, *38*, 21–38. [CrossRef]
39. Otto, K.N.; Wood, K.L. *Product Design: Techniques in Reverse Engineering and New Product Development*; Prentice Hall: Upper Saddle River, NJ, USA, 2006.
40. Otto, K.N.; Wood, K.L. Product evolution: A reverse engineering and redesign methodology. *Res. Eng. Des.* **1998**, *10*, 226–243. [CrossRef]
41. Geng, Z.; Bidanda, B. Review of reverse engineering systems–current state of the art. *Virtual Phys. Prototyp.* **2017**, *12*, 161–172. [CrossRef]
42. Buonamici, F.; Carfagni, M.; Furferi, R.; Governi, L.; Lapini, A.; Volpe, Y. Reverse engineering modeling methods and tools: A survey. *Comput.-Aided Des. Appl.* **2018**, *15*, 443–464. [CrossRef]
43. Paulic, M.; Irgolic, T.; Balic, J.; Cus, F.; Cupar, A.; Brajlih, T.; Drstvensek, I. Reverse engineering of parts with optical scanning and additive manufacturing. *Procedia Eng.* **2014**, *69*, 795–803. [CrossRef]
44. Bacciaglia, A.; Ceruti, A.; Liverani, A. Photogrammetry and additive manufacturing based methodology for decentralized spare Part Production in automotive industry. In *Intelligent Human Systems Integration 2020. IHSI 2020. Advances in Intelligent Systems and Computing*; Ahram, T., Karwowski, W., Vergnano, A., Leali, F., Taiar, R., Eds.; Springer: Cham, Switzerland, 2020; Volume 1131, pp. 796–802. [CrossRef]
45. Petruccioli, A.; Gherardini, F.; Leali, F. Assessment of close-range photogrammetry for the low cost development of 3D models of car bodywork components. *Int. J. Interact. Des. Manuf.* **2022**, *16*, 703–713. [CrossRef]
46. Chang, M.; Park, S.C. Reverse engineering of a symmetric object. *Comput. Ind. Eng.* **2008**, *55*, 311–320. [CrossRef]
47. Rathore, N.; Jain, P.K. Reverse Engineering Applications in Manufacturing Industries: An Overview. In *DAAAM International Scientific Book 2014*; DAAAM International: Vienna, Austria, 2014; pp. 567–576. [CrossRef]
48. Wang, J.; Gu, D.; Yu, Z.; Tan, C.; Zhou, L. A framework for 3D model reconstruction in reverse engineering. *Comput. Ind. Eng.* **2012**, *63*, 1189–1200. [CrossRef]
49. *ISO/ASTM 52900:2021*; Additive Manufacturing-General Principles–Fundamentals and Vocabulary. International Organization for Standardization: Geneva, Switzerland, 2021. Available online: https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-2:v1:en (accessed on 24 October 2022).
50. Gibson, I.; Rosen, D.; Stucker, B. *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*; Springer: New York, NY, USA, 2015. [CrossRef]
51. Ngo, T.D.; Kashani, A.; Imbalzano, G.; Nguyen, K.T.; Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
52. Gao, W.; Zhang, Y.; Ramanujan, D.; Ramani, K.; Chen, Y.; Williams, C.; Wang, C.; Shin, Y.; Zhang, S.; Zavattieri, P. The status, challenges, and future of additive manufacturing in engineering. *CAD Comput. Aided Des.* **2015**, *66*, 65–89. [CrossRef]
53. Thompson, M.; Moroni, G.; Vaneker, T.; Fadel, G.; Campbell, R.; Gibson, I.; Bernard, A.; Schulz, J.; Graf, P.; Ahuja, B.; et al. Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP Ann. Manuf. Technol.* **2016**, *65*, 737–760. [CrossRef]
54. Mehrpouya, M.; Dehghanghadikolaei, A.; Fotovvati, B.; Vosooghnia, A.; Emamian, S.S.; Gisario, A. The potential of additive manufacturing in the smart factory industrial 4.0: A review. *Appl. Sci.* **2019**, *9*, 3865. [CrossRef]
55. Barbieri, L.; Calzone, F.; Muzzupappa, M. Form and function: Functional optimization and additive manufacturing. In *Advances on Mechanics, Design Engineering and Manufacturing II. Lecture Notes in Mechanical Engineering*; Cavas-Martínez, F., Eynard, B., Fernández Cañavate, F., Fernández-Pacheco, D., Morer, P., Nigrelli, V., Eds.; Springer: Cham, Switzerland, 2019; pp. 649–658. [CrossRef]
56. Dilberoglu, U.M.; Gharehpapagh, B.; Yaman, U.; Dolen, M. The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manuf.* **2017**, *11*, 545–554. [CrossRef]
57. McKnight, M. Generative Design: What it is? How is it being used? Why it's a game changer. *KnE Eng.* **2017**, *2*, 176–181. [CrossRef]
58. McCormack, J.P.; Dorin, A.; Innocent, T.C. Generative design: A paradigm for design research. In *Future Ground*; Redmond, J., Durling, D., de Bono, A., Eds.; Monash University: Melbourne, Australia, 2005; Volume 2.
59. Taborda, L.L.L.; Maury, H.; Pacheco, J. Design for additive manufacturing: A comprehensive review of the tendencies and limitations of methodologies. *Rapid Prototyp. J.* **2021**, *27*, 918–966. [CrossRef]
60. Wiberg, A.; Persson, J.; Ölvander, J. Design for additive manufacturing–a review of available design methods and software. *Rapid Prototyp. J.* **2019**, *25*. [CrossRef]
61. Vaneker, T.; Bernard, A.; Moroni, G.; Gibson, I.; Zhang, Y. Design for additive manufacturing: Framework and methodology. *CIRP Ann.* **2020**, *69*, 578–599. [CrossRef]
62. *ISO/ASTM 52911-1:2019(E)*; Additive Manufacturing—Design—Part 1: Laser-Based Powder Bed Fusion of Metals, ISO, the International Organization for Standardization. ASTM International: West Conshohocken, PA, USA, 2019. Available online: https://standards.iteh.ai/catalog/standards/cen/dfc92d06-505b-4f52-9800-ac3b026a9318/en-iso-astm-52911-1-2019 (accessed on 24 October 2022).

63. Briard, T.; Segonds, F.; Zamariola, N. G-DfAM: A methodological proposal of generative design for additive manufacturing in the automotive industry. *Int. J. Interact. Des. Manuf.* **2020**, *14*, 875–886. [CrossRef]
64. *ASTM F2792-12a*; Standard Terminology for Additive Manufacturing Technologies. ASTM International: West Conshohocken, PA, USA, 2012.
65. *ISO/ASTM 52900:2015*; Additive Manufacturing–General Principles–Terminology, ISO, the INTERNATIONAL Organization for Standardization. ASTM International: West Conshohocken, PA, USA, 2015.
66. Shanmugam, R.; Ramoni, M.; Chandran, J.; Mohanavel, V.; Pugazhendhi, L. A Review on Significant Classification of Additive Manufacturing. *J. Phys. Conf. Ser. IOP Publ.* **2021**, *2027*, 012026. [CrossRef]
67. Martínez-García, A.; Monzón, M.; Paz, R. Chapter 12-Standards for additive manufacturing technologies: Structure and impact. In *Handbooks in Advanced Manufacturing, Additive Manufacturing*; Juan, P., Antonio, R.J., Paulo, D., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 395–408. ISBN 9780128184110. [CrossRef]
68. Pérez, M.; Carou, D.; Rubio, E.M.; Teti, R. *Current Advances in Additive Manufacturing, Procedia CIRP*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 88, pp. 439–444. ISSN 2212-8271. [CrossRef]
69. Holmström, J.; Holweg, M.; Khajavi, S.; Partanen, J. The direct digital manufacturing (r)evolution: Definition of a research agenda. *Oper. Manag. Res.* **2016**, *9*, 1–10. [CrossRef]
70. Tofail, S.A.M.; Koumoulos, E.P.; Bandyopadhyay, A.; Bose, S.; O'Donoghue, L.; Charitidis, C. Additive manufacturing: Scientific and technological challenges, market uptake and opportunities. *Mater. Today* **2018**, *21*, 22–37. [CrossRef]
71. Calignano, F.; Manfredi, D.; Ambrosio, E.P.; Biamino, S.; Lombardi, M.; Atzeni, E.; Salmi, A.; Minetola, P.; Iuliano, L.; Fino, P. Overview on Additive Manufacturing Technologies. *IEEE* **2017**, *105*, 593–612. [CrossRef]
72. Razavykia, A.; Brusa, E.; Delprete, C.; Yavari, R. An Overview of Additive Manufacturing Technologies-A Review to Technical Synthesis in Numerical Study of Selective Laser Melting. *Materials* **2020**, *13*, 3895. [CrossRef]
73. Mendible, G.A.; Saleh, N.; Barry, C.; Johnston, S.P. Mechanical properties and crystallinity of polypropylene injection molded in polyjet and aluminum tooling. *Rapid Prototyp. J.* **2022**, *28*, 686–694. [CrossRef]
74. Morar, D.; Kemper, H.; Lasi, H. Challenges in Processing Digital and Physical Parts in Additive Manufacturing: An Exploration. In Proceedings of the 2017 Portland International Conference on Management of Engineering and Technology (PICMET), IEEE, Portland, OR, USA, 9–13 July 2017; pp. 1–9. [CrossRef]
75. Bridget O'Neal, B. 3D Printing Plays a Role as Elvis Presley's Long-Lost BMW 507 Is Returned to Original Condition–And to the USA. 3DPrint.com. 5 August 2016. Available online: https://3dprint.com/145105/3d-printing-elvis-bmw-507/ (accessed on 12 August 2022).
76. Watkin, H. Unique Pininfarina Jaguar XK120 Rejuvenated with 3D Printing. All3DP.com. 23 August 2017. Available online: https://all3dp.com/unique-pininfarina-bodied-xk120-jaguar-rejuvenated-3d-printing/ (accessed on 12 August 2022).
77. BMW, Elvis' BMW 507–A Legend Revived. Available online: https://www.bmw.com/en/automotive-life/bmw507-elvis.html (accessed on 12 August 2022).
78. Pebble Beach Concours d'Elegance, Celebrating 70 Years with Cars at Pebble Beach. Available online: https://pebblebeachconcours.net/wp-content/uploads/2021/04/Corrected_-Pebble-Beach-Concours-Honors-Its-Historic-Ties-to-Racing.pdf (accessed on 12 August 2022).
79. Hamill, S. 3D Printed Car Parts: The Savior of Classic Cars. 3Dsourced.com 26 June 2021. Available online: https://www.3dsourced.com/feature-stories/3d-printed-car-parts-classic-car-restoration/ (accessed on 12 August 2022).
80. Wiese, M.; Thiede, S.; Herrmann, C. Rapid manufacturing of automotive polymer series parts: A systematic review of processes, materials and challenges. *Addit. Manuf.* **2020**, *36*, 101582. [CrossRef]
81. Gryp Youngtimers Parts, Ferrari-328-Hood Release Control-Raw Finish. Available online: https://www.gryp-3d.com/gb/ferrari-328/85-commande-d-ouverture-de-capot.html (accessed on 12 August 2022).
82. Porsche. Porsche Classic Supplies Classic Parts from a 3D Printer. 12 February 2018. Available online: https://newsroom.porsche.com/en/company/porsche-classic-3d-printer-spare-parts-sls-printer-production-cars-innovative-14816.html (accessed on 12 August 2022).
83. Mercedes. "Future Meets Classic": Next Generation of Genuine Mercedes-Benz Replacement Parts from the 3D Printer. Mercedes-Benz Group Media. 22 November 2018. Available online: https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/Future-meets-Classic-Next-generation-of-genuine-Mercedes-Benz-replacement-parts-from-the-3D-printer.xhtml?oid=41898228 (accessed on 12 August 2022).
84. SOLIZE corporation. SOLIZE and HP Enable Sustainable 3D Production of Replacement NISMO Heritage Parts. 16 March 2021. Available online: https://www.solize.com/en/news/2021/0316/ (accessed on 12 August 2022).
85. Blupointscan. Dino Seatbelt Cover. Available online: https://www.blupointscan.com/ferrari-dino (accessed on 12 August 2022).
86. Everett, H. Car SOS TV Show Uses 3D Printing and Scanning to Restore Classic Car. 3DPrintingIndustry.com. 28 August 2021. Available online: https://3dprintingindustry.com/news/car-sos-tv-show-uses-3d-printing-and-scanning-to-restore-classic-car-195222/ (accessed on 12 August 2022).
87. 3D Printing. 3D Printed Car Parts Bring Back the Classics. 3DPrinting.com. 7 August 2019. Available online: https://3dprinting.com/automotive/3d-printed-car-parts-bring-back-the-classics/ (accessed on 12 August 2022).

88. HP Press Center. Eagle Uses HP Jet Fusion 3D Printer for Premium Quality Jaguar Car Parts. 10 August 2020. Available online: https://press.hp.com/us/en/blogs/2020/eagle-uses-hp-jet-fusion-3d-printer-for-premium-quality-jaguar-c.html (accessed on 12 August 2022).
89. El Kashouty, M.F.; Rennie, A.E.; Ghazy, M.; Aziz, A.A.E. Selective laser melting for improving quality characteristics of a prism shaped topology injection mould tool insert for the automotive industry. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2021**, *235*, 7021–7032. [CrossRef]
90. Çalışkan, C.İ.; Özer, G.; Koç, E.; Sarıtaş, U.S.; Yıldız, C.F.; Çiçek, Ö.Y. Efficiency Research of Conformal Channel Geometries Produced by Additive Manufacturing in Plastic Injection Mold Cores (Inserts) Used in Automotive Industry. In *3D Printing and Additive Manufacturing*; Mary Ann Liebert: Larchmont, NY, USA, 2021. [CrossRef]
91. Cicconi, P.; Mandolini, M.; Santucci, F.; Germani, M. Designing die inserts by additive approach: A test case. *Procedia CIRP* **2021**, *100*, 702–707. [CrossRef]
92. EOS GmbH and Innovia, a.s. Accelerate Production and Reduce Maintenance: Czech Tool Manufacturer Relies on Additive Manufacturing for Complex Customer Projects. Available online: https://www.eos.info/01_parts-and-applications/case_studies_applications_parts/_case_studies_pdf/en_cases/cs_m_tooling_innomia_en.pdf (accessed on 12 August 2022).
93. Vasco, J.; Barreiros, F.M.; Nabais, A.; Reis, N. Additive manufacturing applied to injection moulding: Technical and economic impact. *Rapid Prototyp. J.* **2019**, *25*, 1241–1249. [CrossRef]
94. Kazmer, D.O. *Injection Mold Design Engineering*; Hanser-Gardner Publications: Munich, Germany, 2007.
95. Kalami, H.; Urbanic, R.J. Design and fabrication of a low-volume, high-temperature injection mould leveraging a 'rapid tooling' approach. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 3797–3813. [CrossRef]
96. ACO Mold. Rapid Injection Moulding. InjectionMoulding.org. Available online: http://www.injectionmoulding.org/rapid-injection-moulding.html (accessed on 12 August 2022).
97. Volpato, N.; Solis, D.; Costa, C.A. An analysis of Digital ABS as a rapid tooling material for polymer injection moulding. *Int. J. Mater. Prod. Technol.* **2016**, *52*, 3–16. [CrossRef]
98. Whlean, C.; Sheahan, C. Using Additive Manufacturing to Produce Injection Moulds Suitable for Short Series Production. *Procedia Manuf.* **2019**, *38*, 60–68. [CrossRef]
99. Burggräf, P.; Bergweiler, G.; Abrams, J.A.; Dunst, A. Additive Surface Graining in Prototype Tooling for Injection Molding. *J. Manuf. Mater. Process.* **2022**, *6*, 54. [CrossRef]
100. Saboori, A.; Aversa, A.; Marchese, G.; Biamino, S.; Lombardi, M.; Fino, P. Application of Directed Energy Deposition-Based Additive Manufacturing in Repair. *Appl. Sci.* **2019**, *9*, 3316. [CrossRef]
101. Rahito, W.D.A.; Azman, A.H. Additive manufacturing for repair and restoration in remanufacturing: An overview from object design and systems perspectives. *Processes* **2019**, *7*, 802. [CrossRef]
102. Josten, A.; Höfemann, M. Arc-welding based additive manufacturing for body reinforcement in automotive engineering. *Weld World* **2020**, *64*, 1449–1458. [CrossRef]
103. Taheri, H.; Shoaib, M.R.B.M.; Koester, L.W.; Bigelow, T.A.; Collins, P.C.; Bond, L.J. Powder based additive manufacturing—A review of types of defects, generation mechanisms, detection, property evaluation and metrology. *Int. J. Addit. Subtract. Mater. Manuf.* **2017**, *1*, 172–209. [CrossRef]
104. Zhang, J.; Song, B.; Wei, Q.; Bourell, D.; Shi, Y. A review of selective laser melting of aluminum alloys: Processing. *J. Mater. Sci. Technol.* **2019**, *35*, 270–284. [CrossRef]
105. Ramoni, M.; Shanmugam, R.; Thangapandian, N.; Vishnuvarthanan, M. Challenges in Additive Manufacturing for Metals and Alloys. In *Innovations in Additive Manufacturing*; Springer International Publishing: Berlin/Heidelberg, Germany, 2022.
106. Dalpadulo, E.; Pini, F.; Leali, F. Components residual stress and deformation reduction: An integrated process design for additive manufacturing. In Proceedings of the ASME 2021 International Mechanical Engineering Congress and Exposition, New York, NY, USA, 1–5 November 2021. [CrossRef]
107. Cooper, D.; Thornby, J.; Blundell, N.; Henrys, R.; Williams, M.A.; Gibbons, G. Design and manufacture of high performance hollow engine valves by Additive Layer Manufacturing. *Mater. Des.* **2015**, *69*, 44–55. [CrossRef]
108. Metal-AM. First Metal Additively Manufactured Spare Parts Produced at Mercedes-Benz Trucks, metal-am.com. 4 August 2017. Available online: https://www.metal-am.com/first-metal-additively-manufactured-spare-part-produced-mercedes-benz-trucks/ (accessed on 12 August 2022).
109. Stratasys. DMLS for Auto Parts: Jay Leno's Take. 13 November 2018. Available online: https://www.stratasys.com/en/stratasysdirect/resources/articles/3d-printed-car-parts-dmls-jay-leno/ (accessed on 12 August 2022).
110. Keane, P. Classic Car Carburetor Replica by Tecron & Markforged. 3dprinting.com. 24 July 2020. Available online: https://3dprinting.com/automotive/classic-car-carburetor-replica-by-tecron-markforged/ (accessed on 12 August 2022).
111. Markforged. How 3D Printing Drives Change in the Automotive Industry. Available online: https://markforged.com/it/resources/blog/how-3d-printing-drives-change-in-the-automotive-industry (accessed on 12 August 2022).
112. Metal-AM, Sauber's F1 Technology Used in Production of Additively Manufactured Classic Car Parts, metal-am.com. 9 June 2021. Available online: https://www.metal-am.com/saubers-f1-technology-used-in-production-of-additively-manufactured-classic-car-parts/ (accessed on 12 August 2022).
113. Koehler, H.; Partes, K.; Seefeld, T.; Vollertsen, F. Laser reconditioning of crankshafts: From lab to application. *Phys. Procedia* **2010**, *5*, 387–397. [CrossRef]

114. Lyalyakin, V.P.; Kostukov, A.; Denisov, V.A. Special features of reconditioning the housing of a Caterpillar diesel oil pump by gas-dynamic spraying. *Weld. Int.* **2016**, *30*, 68–70. [CrossRef]
115. Liu, Z.; Jiang, Q.; Li, T.; Dong, S.; Yan, S.; Zhang, H.; Xu, B. Environmental benefits of remanufacturing: A case study of cylinder heads remanufactured through laser cladding. *J. Clean. Prod.* **2016**, *133*, 1027–1033. [CrossRef]
116. Gray, J.; Depcik, C. Review of additive manufacturing for internal combustion engine components. *SAE Int. J. Engines* **2020**, *13*, 617–632. [CrossRef]
117. Chhabra, M.; Singh, R. Rapid casting solutions: A review. *Rapid Prototyp. J.* **2011**, *17*, 328–350. [CrossRef]
118. Hackney, P.; Wooldridge, R. Optimisation of Additive Manufactured Sand Printed Mould Material for Aluminium Castings. *Procedia Manuf.* **2017**, *11*, 457–465. [CrossRef]
119. Mognol, P.; Rivette, M.; Jégou, L.; Lesprier, T. A first approach to choose between HSM, EDM and DMLS processes in hybrid rapid tooling. *Rapid Prototyp. J.* **2007**, *13*, 7–16. [CrossRef]
120. Hackney, P.; Wooldridge, R. Characterisation of direct 3D sand printing process for the production of sand cast mould tools. *Rapid Prototyp. J.* **2017**, *23*, 7–15. [CrossRef]
121. Clarke, C. 103 Year Old Delage Type-S Grand Prix Car Brought Back to Life with 3D Scanning and Printing. 3DPrintingIndustry.com, 28 March 2017. Available online: https://3dprintingindustry.com/news/103-year-old-delage-type-s-grand-prix-car-brought-back-life-3d-scanning-printing-109314/ (accessed on 12 August 2022).
122. 3Ders. World's Largest 3D Sand Printer Gives 1912 Brush Car a New Lease of Life. Available online: https://www.3ders.org/articles/20141112-world-largest-3d-sand-printer-gives-1912-brush-car-a-new-lease-of-life.html (accessed on 12 August 2022).
123. Wang, W.; Conley, J.G.; Stoll, H.W. Rapid tooling for sand casting using laminated object manufacturing process. *Rapid Prototyp. J.* **1999**, *5*, 134–141. [CrossRef]
124. Pereira, A.; Perez, J.A.; Dieguez, J.L.; Pelaez, G.; Ares, J.E. Design and manufacture of casting pattern plates by rapid tooling. *Arch. Mater. Sci.* **2008**, *29*, 63–67.
125. Rare Parts, Catalogue. Available online: http://www.rarepartsclub.com/parts-catalog.html (accessed on 12 August 2022).
126. Parandoush, P.; Lin, D. A review on additive manufacturing of polymer-fiber composites. *Compos. Struct.* **2017**, *182*, 36–53. [CrossRef]
127. Ning, F.; Cong, W.; Qiu, J.; Wei, J.; Wang, S. Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. *Compos. Part B Eng.* **2015**, *80*, 369–378. [CrossRef]
128. Valino, A.D.; Dizon, J.R.C.; Espera, A.H., Jr.; Chen, Q.; Messman, J.; Advincula, R.C. Advances in 3D printing of thermoplastic polymer composites and nanocomposites. *Prog. Polym. Sci.* **2019**, *98*, 101162. [CrossRef]
129. Krassenstein, B. ORNL 3D Prints Working Shelby Cobra Replica—President Obama Approves. 3dprint.com. 10 January 2015. Available online: https://3dprint.com/36433/3d-printed-shelby-cobra/ (accessed on 12 August 2022).
130. Hassen, A.A.; Noakes, M.; Nandwana, P.; Kim, S.; Kunc, V.; Vaidya, U.; Love, L.; Nycz, A. Scaling Up metal additive manufacturing process to fabricate molds for composite manufacturing. *Addit. Manuf.* **2020**, *32*, 101093. [CrossRef]
131. Stratasys, Application Customer Story: Champion Motorsports. Available online: https://stratasysstorage01.file.core.windows.net/ssys-websites-files-prod/Public1/Resources/Case%20Studies/FDM/Applications/Champion%20Motorsports%20-%20EN%20FDM%20Case%20Study.pdf?sv=2017-04-17&sr=f&sig=mXC0nVV1DiZCp1kaDujck8UFVRDBD7eQuqPL%2FbAq224%3D&st=2022-08-18T10%3A45%3A30Z&se=2023-08-19T10%3A45%3A30Z&sp=rwl (accessed on 12 August 2022).
132. Mason, H. Hybrid 3D printing/Machining Center Enables Custom Vehicle Restoration Project. 6 September 2021. Available online: https://www.compositesworld.com/articles/hybrid-3d-printingmachining-center-enables-custom-vehicle-restoration-project (accessed on 12 August 2022).