

Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies

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Abstract The development of additive manufacturing (AM) technology provides the possibility of producing complex parts (including internal complex features) that are difficult to manufacture by machining. However, AM technologies also have some limitations, such as low-dimensional accuracy and long production times. Recently, combining additive manufacturing technology with CNC machining is gaining significant attention. This combination not only takes advantages of individual techniques, but also minimizes their disadvantages. In this paper, taking into account consolidated benefits of such technique combination, an alternative remanufacturing strategy is proposed. The strategy allows end-of-life parts (or existing parts) to be reused directly for manufacture of new parts (or final parts) without involving the material recycling stage. In addition, the final part is intended for another product, namely the existing part has a new life and new usage in its life cycle. To achieve the geometry and quality of final part, a sequence of additive, subtractive manufacturing and inspection operations will be generated. For this purpose, additive manufacturing features and machining features are first identified and extracted from the available information of the existing and final parts. This paper particularly focuses on a feature extraction approach, which is developed using the knowledge of additive manufacturing and CNC machining processes, technological requirements, and available resources. The major

criteria and constraints have been defined and applied during the feature extraction process. The extracted features and their relationships will be used as the inputs for designing the process planning. Finally, a case study is used to illustrate the proposed approach.

Keywords Feature · Additive manufacturing · Machining · Process planning · Remanufacturing

1 Introduction

To deal with environmental impact issues and the increase of end-of-life (EoL) products, industrial manufacturers are looking for efficient strategies able to recover EoL products. Generally, EoL products are separated and recycled into raw materials, which will be used to produce new products. However, resource and energy consumptions of such recycling systems are important. Added values on EoL products and a considerable amount of energy used to produce original products are also lost during the recycling process [1]. Remanufacturing is today considered as a pertinent solution for recovery of EoL products [1, 2]. This is an industrial process allowing the conversion of worn-out products/ EoL products into products in a like-new condition (including warranty) [3, 4]. This process can potentially reduce the manufacturing costs, and minimize environmental impacts by reducing resource consumption and waste [1, 5, 6].

In the last three decades, the development of additive manufacturing (AM) can be considered as the third industrial revolution [7, 8]. AM technologies allow a complex part to be built directly from a CAD model by adding materials layer by layer [9]. In comparison with conventional manufacturing processes, such as machining, casting and forging, AM technologies have a number of advantages. The design

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freeform offered by these techniques allows producing complex geometry, including internal features that are generally difficult to achieve by machining. This capability opens new prospects for topological optimization in design of innovative products and lightweight components [8, 10]. Thus, these techniques are interesting from the point of view that they have great potential for improving material use efficiency, saving energy consumption, and reducing scrap generation and greenhouse gas emissions [11–16]. These techniques are increasingly applied in different sectors from aerospace and automobile industries to biomedical engineering [9, 17, 18]. However, AM techniques also present some limitations, such as poor surface accuracy and long production time [18–20]. On the other hand, CNC machining is usually used to manufacture components with high levels of surface and dimension accuracy. This technique also enables a relatively short production time. Nevertheless, it is still relatively difficult or impossible to achieve complex geometries (e.g. internal complex features) due to limited tool accessibility [21–23].

Recently, combining additive and subtractive manufacturing technologies is considered as a promising solution in the manufacturing field [24, 25]. This combination not only takes the advantages of independent processes, but also minimizes their limitations. Due to consolidated performance of independent processes, such process combination allows the manufacture of complex parts (including internal shapes) with a good quality. By building near-net shape of parts via AM technology, and then using CNC machining to achieve the part quality, the resource consumption and material waste, as well as environmental impacts can be significantly reduced [11, 14, 26].

Literature shows that combining additive and subtractive processes are successfully applied for manufacture of complex parts with good accuracy. For instance, Manogharan et al. [22] introduced a method to manufacture mechanical parts by combining electron beam melting (EBM) or direct metal laser sintering (DMLS) with CNC machining. In their work, the near-net shape of complex parts was achieved through EBM or DMLS process; and then, the required accuracy of parts was obtained by CNC machining. The authors showed that their approach is economically efficient in manufacturing of expensive and harder machining materials. Karunakaran et al. [23] demonstrated that combining additive gas metal arc welding (GMAW) and CNC machining processes enables the manufacture of metallic components in a cost-effective way. This combination is also adequate for most engineering applications.

Furthermore, AM and CNC machining combination has successfully been applied for remanufacturing or repair of high-value EoL components. Dutta et al. [27] stated that one of the best applications of directed energy deposition (DED) technologies, such as laser cladding and directed material deposition (DMD), is remanufacturing and repair of damaged

or worn-out parts. This is due to their ability of adding materials into selected locations on 3D surfaces. Additionally, these techniques offer the particular benefit of a minimum heat-affected zone (HAZ) that enables obtaining high quality repaired/remanufactured components. Nan et al. [28] proposed a remanufacturing system based on laser cladding and CNC machining. This system is able to extend the lifetime of aging dies and vehicle components. Jones et al. [29] used both machining and laser cladding processes to repair worn-out metallic components. In the study of Wilson et al. [30], the authors showed the efficacy of combining direct deposition (LDD) with CNC machining in remanufacturing turbine blades. The authors claimed that energy consumption and carbon footprint of using this combination to remanufacture turbine blades were significantly reduced when compared to the manufacture of new ones. Rickli et al. [31] integrated direct material deposition (DMD) and CNC machining in a remanufacturing system. This system was able to restore high-value EoL cores to original specifications and qualities. However, these mentioned works only focused on the method of remanufacturing components, namely returning EoL parts in a like-new condition, and extending their lifetime. Recently, Zhu et al. [32] proposed different possible strategies to produce new plastic parts from existing plastic parts. The strategy combines CNC machining, additive manufacturing (i.e. fused filament fabrication, or FFF) and inspection operations interchangeably. Nevertheless, these strategies were only efficient to produce prismatic plastic parts and very limited by the capability of FFF technique. In some cases, the strategies were also not time-effective because a significant amount of material is removed, subsequently added back and finished. Thus, it is necessary to extend their works for manufacture of metallic parts compatible with industrial applications.

In comparison with the DED processes, the powder bed fusion (PBF) processes, such as EBM, are limited for remanufacturing applications due to their limited manufacturing volume. However, there are many components with small or average dimensions that can be repaired or remanufactured through these processes. Navrotsky et al. [33] presented an application of selective laser melting (SLM) for repairing gas turbine burner tips. Their results also demonstrated the feasibility of SLM technique for building new features on existing components. Terrazas et al. [34] presented a method, which allows the manufacture of multi-material components using EBM technology. The authors successfully built a copper entity on the top of an existing titanium part. Their results open the perspective of using EBM for remanufacturing. Liu et al. [35] and Sing et al. [36] produced multi-material parts (e.g. 316L stainless steel and C18400 copper alloy) using SLM process. Based on the investigations on microstructures, tensile and bending properties, the authors demonstrated that a good bonding exists

at the interface between two materials. In our recent work [37], EBM technique was used to create new titanium features on existing titanium plates. The microstructures and mechanical properties of built samples were also analyzed. The results on microstructures indicated that new features added by EBM have microstructures coherent with those of the existing plate. At the interface between new EBM-built features and the existing plate, a good metallurgical bonding was also observed. This observation was also validated through the study on tensile properties. Moreover, mechanical characteristics of material base was conserved. These results have confirmed that EBM technology can be used to produce new parts from existing parts with mechanical characteristics comparable to those of parts produced by conventional processes, such as forging and machining.

From the survey studies above, it is clearly possible to develop a strategy that allows achieving metallic parts from existing components using combined metal-based AM techniques (e.g. DMD, SLM and EBM) and CNC machining. The obtained parts also have a good “material health” (i.e. good mechanical characteristics) that are compatible with actual industrial applications.

In this work, an *alternative remanufacturing strategy*, which can give a new life to EoL parts (or existing parts) by transforming them into new parts intended for another product. The final part is achieved from the existing parts by an adequate manufacturing sequence combining subtractive, additive and inspection operations. The scope of this work focuses on a feature extraction approach, which allows achieving AM features and machining features from the

available information of the existing and final parts. These features will be used as input data for designing the process planning compatible with the proposed strategy.

This paper is organized as follows: Sect. 2 presents the proposed strategy. Section 3 particularly focuses on a feature extraction approach. The approach is developed using the knowledge of metal-based AM and CNC machining processes, technological requirements of EoL and final parts and available resources. In Sect. 4, a case study is used to demonstrate the major steps of the approach. Conclusions and future work are finally presented in Sect. 5.

2 Proposition of alternative remanufacturing strategy

The objective of alternative remanufacturing strategy is to give a new life to an EoL part (or an existing part) by transforming it into a new part intended for another product. The strategy consists of combining CNC machining, metal-based AM, inspection processes, and heat treatment [38]. This combination takes advantage and performance of AM and CNC machining processes, while minimizing the disadvantage of these processes. In comparison with the approaches presented in [32,39], the strategy is extended to manufacture metallic parts. Hence, the metal-based AM techniques and CNC machining are focused in this study.

The generation of a process adequate for the proposed strategy contains three major steps (Fig. 1), namely the pre-processing, the processing and the post-processing.

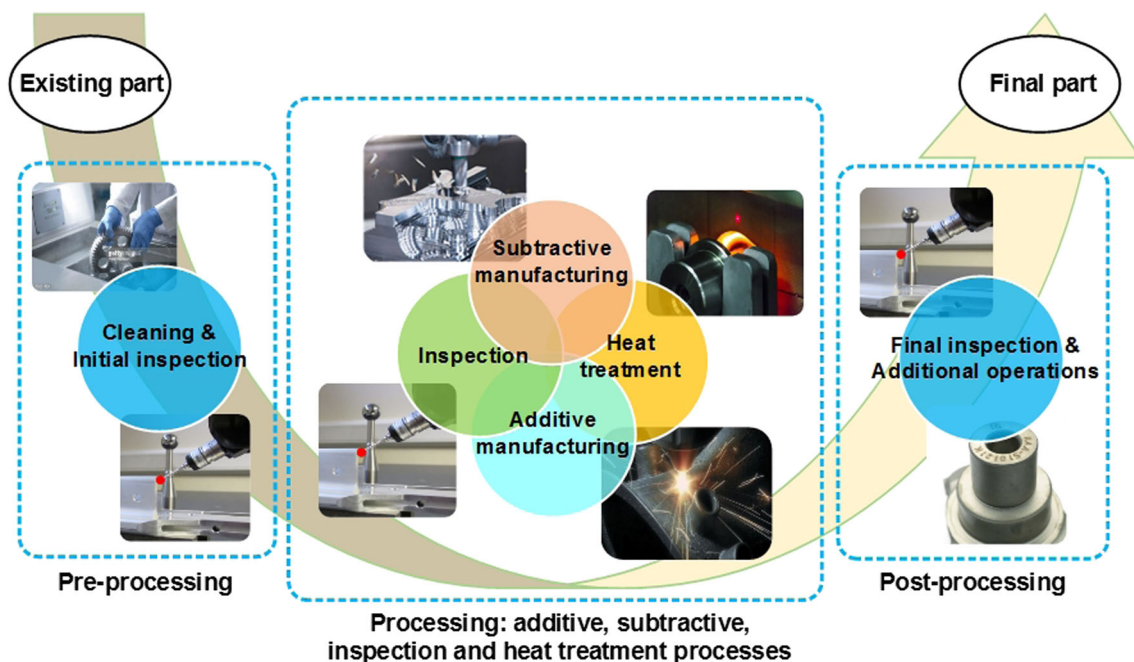


Fig. 1 Major stages of the proposed strategy

- (i) *The pre-processing stage* Firstly, the existing part is cleaned and evaluated in terms of material quality and geometry. If the existing part is suited for manufacture of the final part, its actual shape and dimensions are achieved by a system of measurement and scanning to generate the CAD model.
- (ii) *The processing stage* This stage refers to define a manufacturing sequence containing subtractive, additive manufacturing operations, and inspection operations, even the heat treatment. The heat treatment may be required after AM operations to obtain expected mechanical characteristics (e.g. good microstructures and fully dense part) or to reduce residual stresses and thermal deformation of the part. The inspection operations are placed in the way to rehabilitate the sequence and to avoid waste.
- (iii) *The post-processing stage* Once the actual final part achieved through manufacturing activities (i.e. subtractive, additive and inspection operations, as well as heat treatment), final inspections are performed to verify technological requirements of the final part. Some additional operations (e.g. labeling) are executed to complete the part manufacture.

The major question that should be solved is: “How the manufacturing sequence that combines additive, subtractive and inspection operations is designed?” To deal with this question, an approach to extract both machining and AM features is proposed in the next section. The approach allows identifying and extracting machining features and AM features, which will be used as input data to generate the manufacturing sequence.

In this study, it is assumed that the existing part has been identified in terms of material quality, size and shape that are suitable to produce the final part. This allows existing part material to be reused effectively, and avoiding a number of subtractive and additive operations have to be performed to achieve the final part. This assumption means that the information of both the existing and final parts are available for the feature extraction process.

3 Feature extraction approach development

Many studies published in the literature focus on automatic machining feature extraction methods in the context of CAPP (computer-aided process planning), as shown in [40,41]. These methods are based on the information of design parts and the knowledge of machining processes (e.g. milling and turning). The extracted features are then used for designing process planning [42,43]. However, these methods are only

efficient in the machining field. In our work, an existing part will be transformed into the final part using a sequence of additive and subtractive manufacturing operations, as well as inspection operations. This process is totally different from the machining process, which generally removes materials from a cylindrical or rectangular workpiece to achieve the geometry and quality of final part. Consequently, the previous methods are not effective in this case. Hence, in this study, an extended feature extraction approach is proposed using the knowledge of AM processes and machining process, geometric specifications of final parts, and available resources (i.e. AM machines and CNC machine-tools). The available technological information and the CAD models of existing and final parts are the input data of the approach.

3.1 Definition of manufacturing features

In this paper, manufacturing features refer to machining features and additive manufacturing features.

3.1.1 Machining features

In this study, the definition of machining features presented in [43] was adopted. A machining feature (MF) is defined by a geometrical shape and a set of specifications for which at least a machining process is known; and this process is quasi-independent from processes of other MFs. A machining process of a MF is an ordered sequence of machining operations. This machining process is defined from MF attributes (such as feature type, tool approach directions or TADs, intrinsic tolerances, estimated material volume to remove, and rough state of features) [43].

3.1.2 Additive manufacturing features

Recently, Zhang et al. [44] proposed a definition of AM features that is based on shape features and consistent with the characteristics of AM processes. The definition in their work has an important role in optimization of build directions in AM process. Particularly, in PBF processes, the build direction has a significant influence on surface roughness and mechanical properties, as well as support volumes. However, the build direction selection for AM operations in the current study depends on the starting surface on the existing part (the build direction is the normal vector of the starting surface). All entities to be added into the part will be considered as AM features. In the similar way to define MFs, *an AM feature is defined as a geometrical shape and associated technological attributes for which at least an AM process is known; this AM process is also independent from processes of all*

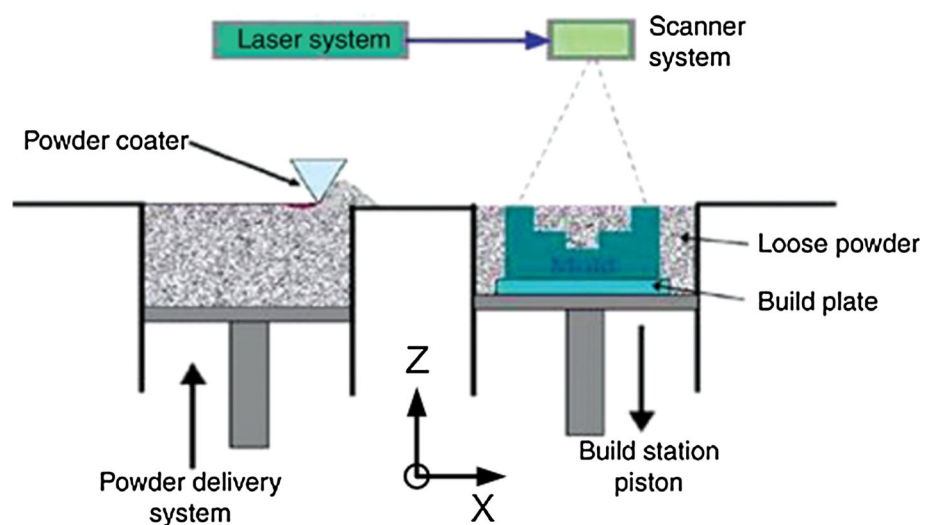
other features. The attributes of AM features are outlined as follows:

- *The geometrical form and dimensions* The shape and dimensions of an AM feature are defined from an entity that is added into the existing part to achieve the final shape or near-net shape of a final feature.
- *The build directions* In PBF processes, each AM feature has only one build direction. It is the normal vector of a planar surface, on which materials will be deposited. This planar surface is achieved from the existing part by machining. On the other hand, in DED processes, the build direction of AM features can be the normal vector of planar surfaces or a local normal vector of 3D surfaces of the existing part.
- *The starting surface* To build an AM feature on the existing part, material deposition process will be started from a surface of the existing part. This surface is called “starting surface” of the AM feature.
- *The estimated material to add* This volume refers to the material volume inside an envelope made of the form and the starting surface of an AM feature.
- *The quality* This attribute allows identifying whether an AM feature becomes a final feature or the rough state of other machining features.

3.2 Knowledge of manufacturing processes

As mentioned previously, the powder bed fusion (PBF) processes (e.g. EBM and SLM) and the directed energy deposition (DED) processes (e.g. DMD), as well as CNC machining are investigated to develop the strategy. The knowledge of these processes necessary for the feature extraction is outlined as follows:

Fig. 2 Manufacturing principle of PBF processes (adapted from [27])



3.2.1 The capacities of AM processes

In PBF processes (Fig. 2), metal powder is distributed on a bed in flat layers, and subsequently melted by a heat source (laser or electron beam) to produce the geometry [45]. Thus, one of the major advantages of PBF processes is the outstanding ability to build components with high-complex geometries. These processes also provide the feasibility of manufacturing overhanging features. However, the build of parts must be started from a flat surface. The existing part should be machined to obtain such a surface for material deposition stages. Moreover, these processes are limited by their build envelope; and only one material is added into the part in a single manufacturing setup.

On the other hand, in DED processes, the powder is applied to the substrate using a nozzle, which sprays the powder into the focal point of heat sources, such as laser beam (Fig. 3). The metal powder is melted in a melting pool on the previous layer within an inert atmosphere; and the parts are then built layer by layer [46]. In contrast to PBF processes, DED processes offer a larger build volume, high build rate and flexible build directions due to a 3- or 5-axis CNC machine configuration. This technique can also deposit multiple materials in a single build. However, they are limited in building internal structures and overhanging structures [45,47].

3.2.2 The accuracy of parts built by AM processes

The surface roughness of AM-built parts are not always compatible with final quality of parts; thus, a post-processing step is often necessary [20,38]. There are different factors that influence part precision, such as mean powder diameter, process parameters, shrinking and distortion due to thermal phenomena and residual stresses. The surface roughness of

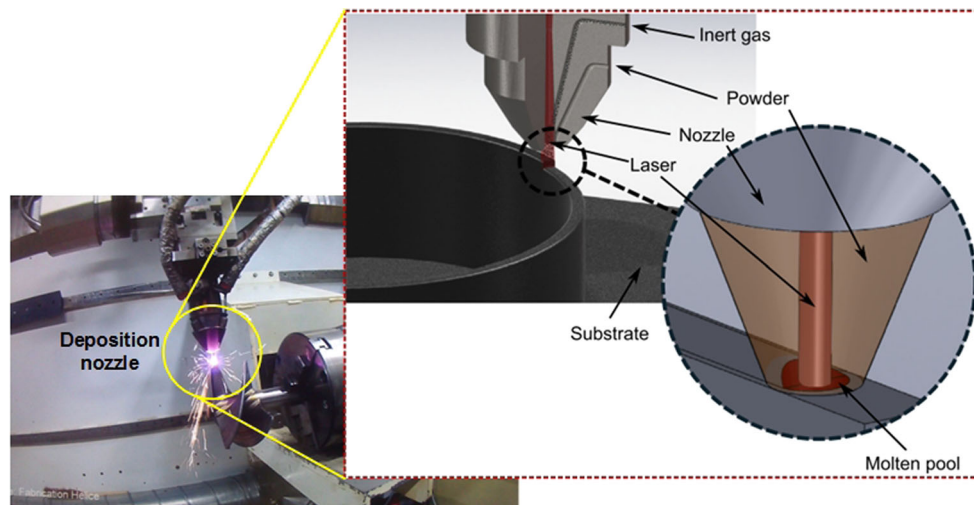


Fig. 3 Manufacturing principle of DED processes. Adapted from [48]

SLM-built parts is better than that of the parts built by EBM or DMD. A reason is that the powder layer thickness and mean powder diameter applied in SLM are generally smaller than those in EBM and DMD. The arithmetic roughness surface of SLM-built parts can reach 9–26 μm [49], whereas a typical value of surface roughness of EBM-built parts is 25–35 μm [18, 27, 50]. The arithmetic roughness of DMD-built surfaces is also important, between 20 and 50 μm , that depends on beam size [51]. Furthermore, geometric errors due to thermal distortion and residual stresses should be taken into account.

3.2.3 The tool accessibility constraints

The tools mentioned in this study refer to material deposition nozzles in DED processes (Fig. 3), or powder distributors in PBF processes (Fig. 2), or cutting tools in machining. The tools may have collisions with parts during manufacturing processes. Thus, to avoid the collisions and the quality of parts, these constraints should be taken into consideration.

3.3 Feature extraction procedure

As mentioned above, the feature extraction process is performed using the knowledge of additive and subtractive manufacturing processes, the technological requirements, and the available resources. The proposed procedure for feature extraction contains five major steps (A01 to A05), as shown in Fig. 4. In this study, this process is manually performed using Boolean functions of the CAD software and considering the following criteria:

- (i) The existing part material is preserved as much as possible.

- (ii) The features are independent. This allows defining a process for each feature that is independent from processes of all other features.
- (iii) The attribute volume of features should be compatible with required qualities. If an AM feature must be machined to obtain final part surfaces, its volume attribute should provide the rough state of corresponding MFs.

3.3.1 Local coordinate system definition and part positioning (A01)

In the first step, a local coordinate system is defined for each CAD model of the existing part and the final part. Thereafter, two local coordinate systems (i.e. two parts) are positioned so that the common volume between existing part and final part is as big as possible. This aims to respect the criterion (i) on reusing the existing part material efficiently. However, considering the criterion (iii), a sufficient over-thickness for finishing operations is left on functional surfaces of the final part, if possible.

3.3.2 Extraction of the common volume, the removed volume and the added volume (A02)

Once the existing part and the final part were positioned, the common volume is extracted using the intersection function of the CAD software:

$$\begin{aligned} \{Common\ volume\} \\ = \{Existing\ part\ volume\} \text{ INTERSECT } \{Final\ part\ volume\} \end{aligned} \quad (1)$$

Afterward, the removed volumes (or the added volumes) are obtained from the existing part volume (or the final part

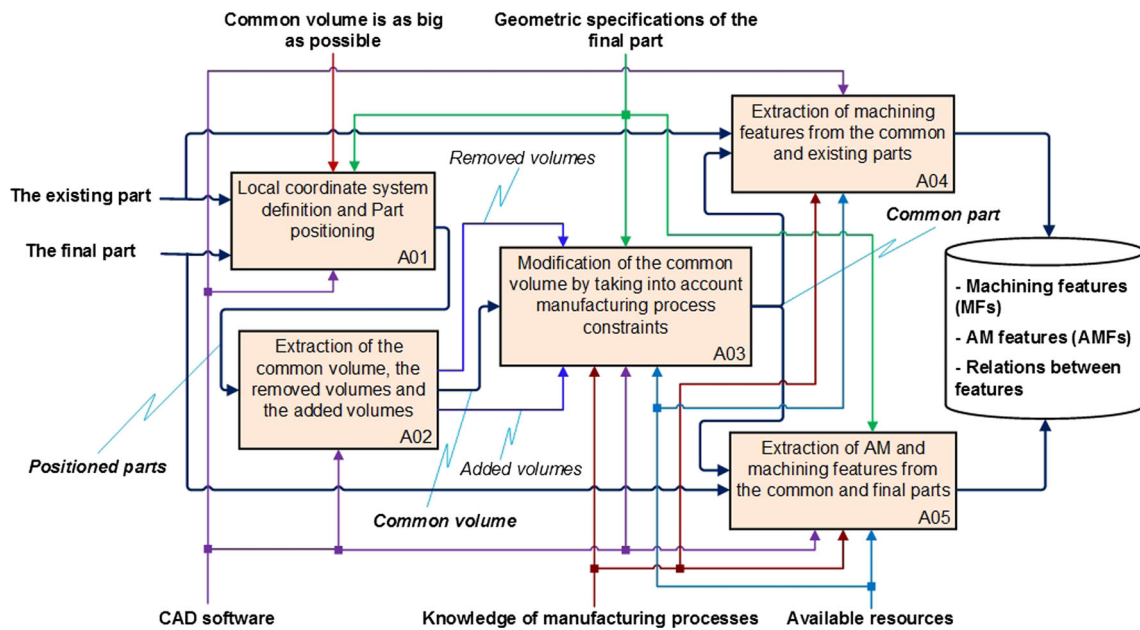


Fig. 4 Procedure for extracting machining and additive manufacturing features

volume) and the common volume using the subtraction function.

$$\begin{aligned} &\{Removed\ volumes\} \\ &= \{Existing\ part\ volume\} \text{ SUBTRACT } \{Common\ volume\} \end{aligned} \quad (2)$$

$$\begin{aligned} &\{Added\ volumes\} \\ &= \{Final\ part\ volume\} \text{ SUBTRACT } \{common\ volume\} \end{aligned} \quad (3)$$

3.3.3 Extraction of the common volume, the removed volumes and the added volumes (A03)

The obtained common volume is generally not adequate for AM processes. In the PBF processes (e.g. EBM and SLM), the build surface must be flat to avoid collisions between the powder distributors and the part (Fig. 2). In the DED processes (e.g. DMD and LDD), the material deposition nozzles may have collision with the part (Fig. 3). Hence, to respect the tool accessibility constraints in these AM processes, it is necessary to modify the common part geometry. The new geometry of the common volume after modifying is called the common part.

3.3.4 Extraction of machining features and AM features (A04 and A05)

In the steps A04 and A05, AMFs and MFs are extracted from the common part, the existing part and the final part. In addition, the precedence relations between these features are created to respect the tool accessibility constraints and the accuracy constraints.

Considering the tool accessibility constraints, these features must be extracted independently; and precedence relations between these features are also created. For instance, if the machining feature (MF1) provides the planar surface for building the AM feature (AMF1) by PBF processes, MF1 is the precedence of AMF1. In the case where the rough state of MF1 is the actual state of existing part, MF1 is extracted from the existing part and the common part; and MF1 should first be machined. Moreover, if the AM feature (AMF2) is built on the AM feature (AMF1) that causes an inaccessibility of cutting tools to machine the MF1, then AMF1 and AMF2 must be decomposed independently even though they can be built in a single AM phase. In this case, the precedence relations between these features are assigned: AMF1 → MF1 → AMF2.

Additionally, the accuracy constraints should also be taken into account in the feature extraction process. To obtain required qualities of the final part, AM-built features must be machined. They become the rough state of other MFs. Therefore, a sufficient over thickness should be added into the CAD model of AM features. This over thickness is estimated in a function of technological specifications of final part, roughness of surfaces built by AM, errors due to thermal distortion or residual stresses, and cutting conditions. The AM feature which provides the rough state of corresponding MFs is also the precedence of its corresponding MFs.

In addition to the precedence relations, the topological relations and the geometrical relations are also assigned to extracted features. The topological relations present the associativity of a feature with its neighbor features. For MFs,

these relations are classically defined in terms of “opens into” or “opens onto” when a MF opens into (or onto) another MF, or “intersects with” when two features intersect each other [43]. For AM features, an AM feature may “start onto” a MF; or an AM feature provides the rough state to other MFs. The geometrical relations are directly defined from technological specifications of the final part (i.e. dimensional or position tolerances).

4 Case study

The feature extraction process is demonstrated using the case study presented in Fig. 5. The final part has the pocket (P), the hole (H), the surfaces (fS1, fS2, fS5 and fS7), and the step surfaces (fS4 and fS6) which require a high surface precision (Fig. 5a). The position of the pocket (P) is defined by the dimensions X1 and X2 with a tight tolerance (IT = 0.06 mm). The hole (H) is also constrained with the surface (fS5 and fS7) by the dimensions X3 and X4 (with IT = 0.06 mm), and so on (Fig. 5c). It is assumed that the quality of surfaces (eS1, eS2, and eS3) of the existing

part satisfies the quality of the final surfaces (fS1, fS2 and fS3).

Figure 6 describes the first three steps (A01 to A03) in the feature extraction process. From the assumption mentioned above, the coordinate systems have been assigned to the CAD models of the existing and final parts; and then the parts are positioned by aligning the surfaces eS1, eS2 and eS3 to the surfaces fS1, fS2 and fS3, respectively. There are sufficient over thicknesses that exist on the functional surfaces (fS5 and fS7) of the final part (Fig. 6a). Thereafter, the common volume, the removed volumes and the added volumes are extracted using Boolean functions of the CAD software, as shown in Fig. 6b.

In the step A03, the common volume is modified to adapt with the configuration for depositing materials in AM processes and the accuracy constraints (Fig. 6c). Firstly, the volume located on the plane (S1) should be removed to obtain a flat surface, on which the materials will be deposited by PBF or DED processes. This allows avoiding the collisions between the powder distributors or the material deposition nozzles and the part during these processes. Moreover, the hole (H) that does not exist on the existing part will be

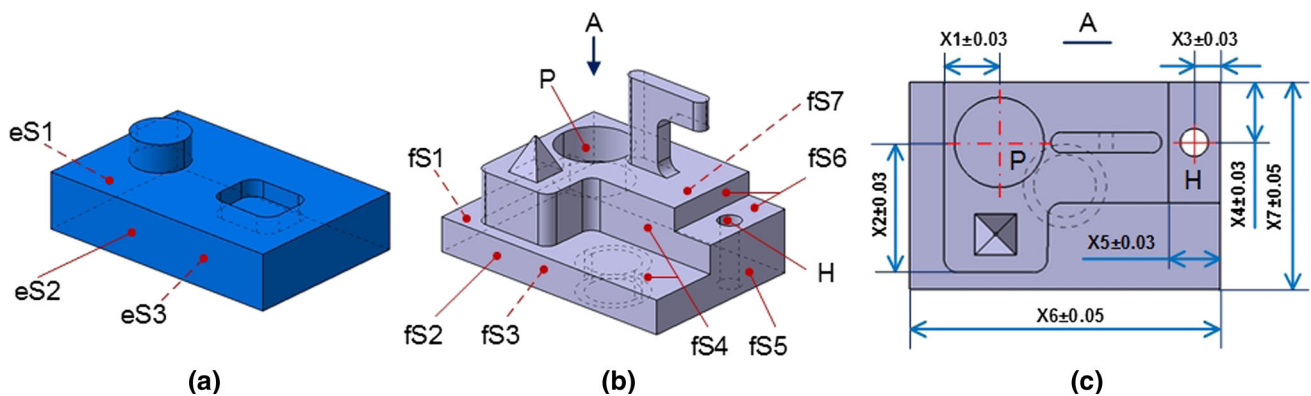


Fig. 5 Test parts: **a** the existing part, **b** the final part and **c** the top view of final part with some important dimensions

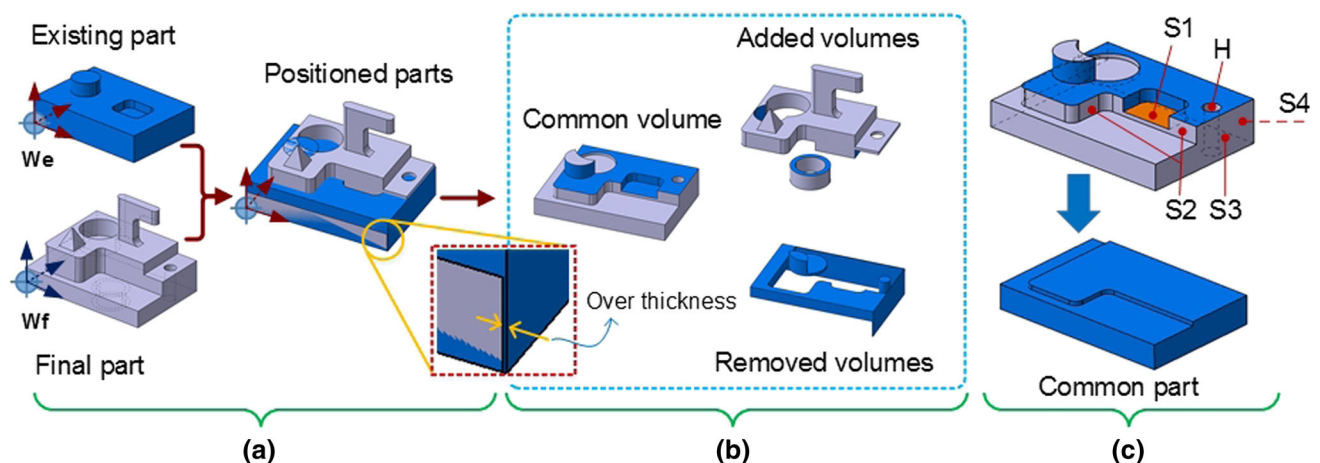


Fig. 6 Illustration of **a** the step A01, **b** the step A02 and **c** the step A03

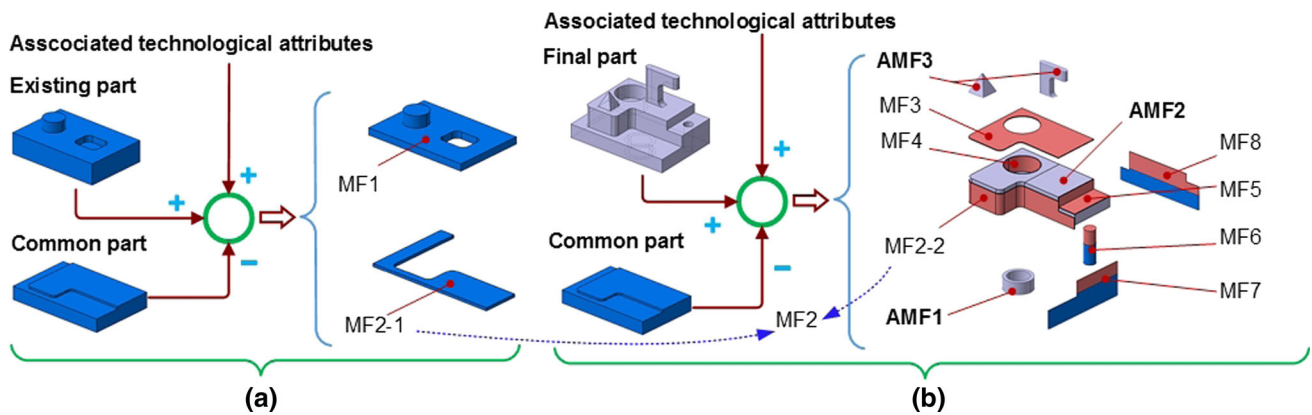


Fig. 7 Extraction of machining and AM features in **a** the step A04 and **b** the step A05

machined after AM phases to avoid the loss of powder during AM processes. Lastly, the over thicknesses on the surfaces (S3 and S4), which respectively correspond to the surfaces (fS5 and fS7), is sufficient for machining operations. This over thickness is a portion of the existing part material (Fig. 6b).

Once the common part is obtained, the machining features and AM features are extracted in the steps A04 and A05, as shown in Fig. 7. In this case study, there are three AM features (AMF1, AMF2 and AMF3) which are extracted from the common part, the final part and the associated technological attributes (Fig. 7b). The AM features (AMF2 and AMF3) are decomposed independently to respect the tool accessibility constraints. If these AM features are built together in an AM phase, the cutting tool that machines the pocket (P), corresponding to MF4, will have collision with the AMF3. Once AMF2 is built, its top surface (corresponding to the feature MF3) must be machined to achieve a flat surface for the build of AMF3. Thus, the precedence relations of these features are also created: $AMF2 \rightarrow \{MF3, MF4\} \rightarrow AMF3$.

The feature MF1 is corresponding to the top surface of the common part, on which the AM feature AMF2 will be built. Thus, MF1 is also the precedence of AMF2: $MF1 \rightarrow AMF2$. MF1 has the rough state of the existing part and it is extracted from the common part and the existing part (Fig. 7a).

AMF1 will be built on the bottom surface of the common part. AMF1 and AMF3 become final features that do not require finishing machining operations. On the other hand, AMF2 provides the rough state for machining features (MF2 to MF8). The geometry of MF5 is the step (fS6) of the final part; and its rough state comes from the build of AMF2. The geometry of MF2 is the “irregular” step (fS4) of the final part. Its volume attribute includes a material portion of the common part (MF2-1) and a material portion of AMF2 (MF2-2). The features MF6, MF7

and MF8 also have the volume attribute and the rough state, which comprise a part of the common part and a part of AMF2. In this case, AMF2 is also the precedence of the feature MF2 to MF8: $AMF2 \rightarrow \{MF2 \text{ to } MF8\}$.

Note that the volume attribute of AMF2 includes the volume of corresponding final feature and the volume attributes of MF2 to MF8. The volume attribute of MFs 2, 3, 4, 5, 7 and 8 are the over thicknesses that are estimated in function of the surface roughness of AM-built surfaces, the required quality of final surface, and cutting conditions.

The hole (H) of the final part (i.e. MF6) has a small diameter (e.g. $D < 8$ mm) and the ratio of height on diameter is superior to 3. Thus, its rough state is a plain material state after the build of AMF2. This allows avoiding the issue on removing non-melted powder after AM processes [52]. In the case the diameter of the hole (H) is bigger (e.g. $D > 8$ mm), it is preferable to create a hole on AMF2 to reduce the amount of powder to build AMF2 and reduce the volume of chips in drilling of the hole.

Finally, machining features, AM features and their precedence relations (blue links) achieved during the feature extraction process are shown in Fig. 8. The geometrical relations (orange links) between the features are also created using the available technological of the final part. The position of the pocket (P) (i.e. MF4) is defined by the tolerance of dimensions X1 and X2 (Fig. 5); thus, there is a geometrical relation between MF2 and MF4. The position of the hole (H) (i.e. MF6) is constrained with the surfaces fS5 and fS7 (corresponding to MF7 and MF8 respectively) by a tight tolerance of dimensions X3 and X4. There is also a geometrical relation between MF5 and MF7. These extracted features and their relationships will be used for designing the process planning, which allows achieving the geometry and quality of the final part.

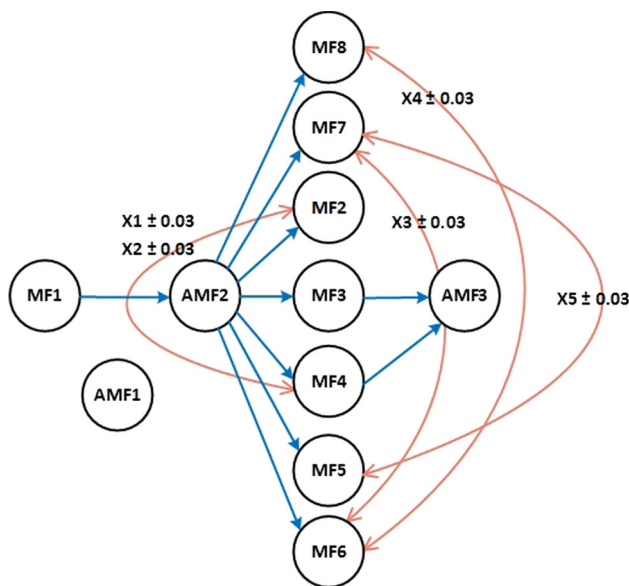


Fig. 8 Extracted features and their relationships

5 Conclusions and future work

Taking into account benefits of combining additive and subtractive manufacturing processes, this paper proposes an alternative remanufacturing strategy, which allows the manufacture of metallic parts directly from EoL parts/existing parts without stepping into the material recycling stage. The final part is achieved from the existing part using an adequate process planning, which combines additive, subtractive and inspection operations. The new parts are intended for another product, namely EoL parts have new life and new uses in their life cycle.

To design the process planning, the study focused on developing a methodology that enables defining and extracting machining and AM features from the available information of the existing and final parts, the knowledge of manufacturing processes and the available resources. For this purpose, the models of manufacturing features and the knowledge of manufacturing processes were first exploited. Afterward, all steps of the methodology were deeply presented. The major constraints and criteria were defined and applied during the feature extraction process. The proposed approach was finally demonstrated through the case study.

Our future work will focus on designing a manufacturing sequence compatible with the proposed strategy using the extracted features and their relationships. The proposed strategy has potential to reduce energy and resource consumptions, as well as environmental impacts during the manufacturing process. However, it is essential to develop the models for assessment of the strategy in terms of environmental impacts in future work. Furthermore, in the scope of this study, we have assumed that the information of existing

and final parts are available. Thus, the procedure and criteria for identification of EoL product types, which would give suitable components for manufacture of final parts, should be defined. Lastly, the feature extraction process was manually performed using the functions of CAD software. It is also interesting to develop a numeric tool that enables users to select the initial part, analyze and perform the feature extraction process in an interactive way.

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References

- King, A.M., Burgess, S.C., Ijomah, W., McMahon, C.A.: Reducing waste: repair, recondition, remanufacture or recycle? *Sustain. Dev.* **14**, 257–267 (2006). doi:[10.1002/sd.271](https://doi.org/10.1002/sd.271)
- Bashkite, V., Karaulova, T., Starodubtseva, O.: Framework for innovation-oriented product end-of-life strategies development. *Procedia Eng.* **69**, 526–535 (2014). doi:[10.1016/j.proeng.2014.03.022](https://doi.org/10.1016/j.proeng.2014.03.022)
- Gehin, A., Zwolinski, P., Brissaud, D.: A tool to implement sustainable end-of-life strategies in the product development phase. *J. Clean. Prod.* **16**, 566–576 (2008). doi:[10.1016/j.jclepro.2007.02.012](https://doi.org/10.1016/j.jclepro.2007.02.012)
- Aksoy, H.K., Gupta, S.M.: Buffer allocation plan for a remanufacturing cell. *Comput. Ind. Eng.* **48**, 657–677 (2005). doi:[10.1016/j.cie.2003.03.007](https://doi.org/10.1016/j.cie.2003.03.007)
- Goodall, P., Rosamond, E., Harding, J.: A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility. *J. Clean. Prod.* **81**, 1–15 (2014). doi:[10.1016/j.jclepro.2014.06.014](https://doi.org/10.1016/j.jclepro.2014.06.014)
- Östlin, J., Sundin, E., Björkman, M.: Product life-cycle implications for remanufacturing strategies. *J. Clean. Prod.* **17**, 999–1009 (2009). doi:[10.1016/j.jclepro.2009.02.021](https://doi.org/10.1016/j.jclepro.2009.02.021)
- Kruth, J.-P., Leu, M.C., Nakagawa, T.: Progress in additive manufacturing and rapid prototyping. *CIRP Ann. Manuf. Technol.* **47**, 525–540 (1998). doi:[10.1016/S0007-8506\(07\)63240-5](https://doi.org/10.1016/S0007-8506(07)63240-5)
- Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R.I., Gibson, I., et al.: Design for additive manufacturing: trends, opportunities, considerations, and constraints. *CIRP Ann. Manuf. Technol.* **65**, 737–760 (2016). doi:[10.1016/j.cirp.2016.05.004](https://doi.org/10.1016/j.cirp.2016.05.004)
- Guo, N., Leu, M.: Additive manufacturing: technology, applications and research needs. *Front. Mech. Eng.* **8**, 215–243 (2013). doi:[10.1007/s11465-013-0248-8](https://doi.org/10.1007/s11465-013-0248-8)
- Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., et al.: Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *J. Clean. Prod.* (2015). doi:[10.1016/j.jclepro.2015.04.109](https://doi.org/10.1016/j.jclepro.2015.04.109)
- Huang, R., Riddle, M., Graziano, D., Warren, J., Das, S., Nimbalkar, S., et al.: Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *J. Clean. Prod.* **135**, 1559–1570 (2016). doi:[10.1016/j.jclepro.2015.04.109](https://doi.org/10.1016/j.jclepro.2015.04.109)
- Gebler, M., Schoot Uiterkamp, A.J.M., Visser, C.A.: Global sustainability perspective on 3D printing technologies. *Energy Policy* **74**, 158–167 (2014). doi:[10.1016/j.enpol.2014.08.033](https://doi.org/10.1016/j.enpol.2014.08.033)
- Ford, S., Despeisse, M.: Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J. Clean. Prod.* **137**, 1573–1587 (2016). doi:[10.1016/j.jclepro.2016.04.150](https://doi.org/10.1016/j.jclepro.2016.04.150)
- Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M., Ituarte, I.F.: Comparative environmental impacts of additive and subtractive

- manufacturing technologies. *CIRP Ann. Manuf. Technol.* **65**, 29–32 (2016). doi:[10.1016/j.cirp.2016.04.036](https://doi.org/10.1016/j.cirp.2016.04.036)
15. Serres, N., Tidu, D., Sankare, S., Hlawka, F.: Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. *J. Clean. Prod.* **19**, 1117–1124 (2011). doi:[10.1016/j.jclepro.2010.12.010](https://doi.org/10.1016/j.jclepro.2010.12.010)
 16. Huang, S., Liu, P., Mokasdar, A., Hou, L.: Additive manufacturing and its societal impact: a literature review. *Int. J. Adv. Manuf. Technol.* **67**, 1191–1203 (2013). doi:[10.1007/s00170-012-4558-5](https://doi.org/10.1007/s00170-012-4558-5)
 17. Song, B., Zhao, X., Li, S., Han, C., Wei, Q., Wen, S., et al.: Differences in microstructure and properties between selective laser melting and traditional manufacturing for fabrication of metal parts: a review. *Front. Mech. Eng.* **10**, 111–125 (2015). doi:[10.1007/s11465-015-0341-2](https://doi.org/10.1007/s11465-015-0341-2)
 18. Vayre, B., Vignat, F., Villeneuve, F.: Metallic additive manufacturing: state-of-the-art review and prospects. *Mech. Ind.* **13**, 89–96 (2012). doi:[10.1051/meca/2012003](https://doi.org/10.1051/meca/2012003)
 19. Zhu, Z., Dhokia, V., Newman, S.T., Nassehi, A.: Application of a hybrid process for high precision manufacture of difficult to machine prismatic parts. *Int. J. Adv. Manuf. Technol.* **74**, 1115–1132 (2014). doi:[10.1007/s00170-014-6053-7](https://doi.org/10.1007/s00170-014-6053-7)
 20. Vayre, B., Vignat, F., Villeneuve, F.: Designing for additive manufacturing. *Procedia CIRP* **3**, 632–637 (2012). doi:[10.1016/j.procir.2012.07.108](https://doi.org/10.1016/j.procir.2012.07.108)
 21. Zhu, Z., Dhokia, V., Newman, S.T.: The development of a novel process planning algorithm for an unconstrained hybrid manufacturing process. *J. Manuf. Process.* **15**, 404–413 (2013). doi:[10.1016/j.jmapro.2013.06.006](https://doi.org/10.1016/j.jmapro.2013.06.006)
 22. Manogharan, G., Wysk, R.A., Harrysson, O.L.A.: Additive manufacturing-integrated hybrid manufacturing and subtractive processes: economic model and analysis. *Int. J. Comput. Integr. Manuf.* **29**, 473–488 (2016). doi:[10.1080/0951192X.2015.1067920](https://doi.org/10.1080/0951192X.2015.1067920)
 23. Karunakaran, K.P., Suryakumar, S., Pushpa, V., Akula, S.: Low cost integration of additive and subtractive processes for hybrid layered manufacturing. *Robot. Comput. Integr. Manuf.* **26**, 490–499 (2010). doi:[10.1016/j.rcim.2010.03.008](https://doi.org/10.1016/j.rcim.2010.03.008)
 24. Lauwers, B., Klocke, F., Klink, A., Tekkaya, A.E., Neugebauer, R., McIntosh, D.: Hybrid processes in manufacturing. *CIRP Ann. Manuf. Technol.* **63**, 561–583 (2014). doi:[10.1016/j.cirp.2014.05.003](https://doi.org/10.1016/j.cirp.2014.05.003)
 25. Flynn, J.M., Shokrani, A., Newman, S.T., Dhokia, V.: Hybrid additive and subtractive machine tools—research and industrial developments. *Int. J. Mach. Tools Manuf.* **101**, 79–101 (2016). doi:[10.1016/j.ijmactools.2015.11.007](https://doi.org/10.1016/j.ijmactools.2015.11.007)
 26. Tang, Y., Mak, K., Zhao, Y.F.: A framework to reduce product environmental impact through design optimization for additive manufacturing. *J. Clean. Prod.* **137**, 1560–1572 (2016). doi:[10.1016/j.jclepro.2016.06.037](https://doi.org/10.1016/j.jclepro.2016.06.037)
 27. Dutta, B., Froes, F.H.: *The Additive Manufacturing (AM) of Titanium Alloys*. Elsevier Inc., Amsterdam (2015). doi:[10.1016/B978-0-12-800054-0.00024-1](https://doi.org/10.1016/B978-0-12-800054-0.00024-1)
 28. Nan, L., Liu, W., Zhang, K.: Laser remanufacturing based on the integration of reverse engineering and laser cladding. *Int. J. Comput. Appl. Technol.* **40**, 254–262 (2010). doi:[10.1504/IJCAT.2010.032200](https://doi.org/10.1504/IJCAT.2010.032200)
 29. Jones, J., McNutt, P., Tosi, R., Perry, C., Wimpenny, D.: Remanufacture of turbine blades by laser cladding, machining and in-process scanning in a single machine. In: 23rd Annual International Solid Freeform Fabrication Symposium, Austin, TX, pp. 821–827 (2012)
 30. Wilson, J.M., Piya, C., Shin, Y.C., Zhao, F., Ramani, K.: Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis. *J. Clean. Prod.* **80**, 170–178 (2014). doi:[10.1016/j.jclepro.2014.05.084](https://doi.org/10.1016/j.jclepro.2014.05.084)
 31. Rickli, J.L., Dasgupta, A.K., Dinda, G.P.: A descriptive framework for additive remanufacturing systems. *Int. J. Rapid Manuf.* **4**, 199–218 (2014). doi:[10.1504/IJRAPIDM.2014.066043](https://doi.org/10.1504/IJRAPIDM.2014.066043)
 32. Zhu, Z., Dhokia, V., Newman, S.T.: A novel decision-making logic for hybrid manufacture of prismatic components based on existing parts. *J. Intell. Manuf.* **28**, 131–148 (2017). doi:[10.1007/s10845-014-0966-8](https://doi.org/10.1007/s10845-014-0966-8)
 33. Navrotsky, V., Graichen, A., Brodin, H.: Industrialisation of 3D printing (additive manufacturing) for gas turbine components repair and manufacturing. *VGB PowerTech* **12**, 48–52 (2015)
 34. Terrazas, C.A., Gaytan, S.M., Rodriguez, E., Espalin, D., Murr, L.E., Medina, F., et al.: Multi-material metallic structure fabrication using electron beam melting. *Int. J. Adv. Manuf. Technol.* **71**, 33–45 (2014). doi:[10.1007/s00170-013-5449-0](https://doi.org/10.1007/s00170-013-5449-0)
 35. Liu, Z.H., Zhang, D.Q., Sing, S.L., Chua, C.K., Loh, L.E.: Interfacial characterization of SLM parts in multi-material processing: metallurgical diffusion between 316L stainless steel and C18400 copper alloy. *Mater. Charact.* **94**, 116–125 (2014). doi:[10.1016/j.matchar.2014.05.001](https://doi.org/10.1016/j.matchar.2014.05.001)
 36. Sing, S.L., Lam, L.P., Zhang, D.Q., Liu, Z.H., Chua, C.K.: Interfacial characterization of SLM parts in multi-material processing: Intermetallic phase formation between AlSi10Mg and C18400 copper alloy. *Mater. Charact.* **107**, 220–227 (2015). doi:[10.1016/j.matchar.2015.07.007](https://doi.org/10.1016/j.matchar.2015.07.007)
 37. Mandil, G., Le, V.T., Paris, H., Suard, M.: Building new entities from existing titanium part by electron beam melting: microstructures and mechanical properties. *Int. J. Adv. Manuf. Technol.* **85**, 1835–1846 (2016). doi:[10.1007/s00170-015-8049-3](https://doi.org/10.1007/s00170-015-8049-3)
 38. Le, V.T., Paris, H., Mandil, G.: Using additive and subtractive manufacturing technologies in a new remanufacturing strategy to produce new parts from End-of-Life parts. In: 22nd Conference of French Mechanics (CFM2015), 24th–28th August, Lyon (2015)
 39. Newman, S.T., Zhu, Z., Dhokia, V., Shokrani, A.: Process planning for additive and subtractive manufacturing technologies. *CIRP Ann. Manuf. Technol.* **64**, 467–470 (2015). doi:[10.1016/j.cirp.2015.04.109](https://doi.org/10.1016/j.cirp.2015.04.109)
 40. Harik, R.F., Derigent, W.J.E., Ris, G.: Computer aided process planning in aircraft manufacturing. *Comput. Aided Des. Appl.* **5**, 953–962 (2008). doi:[10.3722/cadaps.2008.953-962](https://doi.org/10.3722/cadaps.2008.953-962)
 41. Harik, R., Capponi, V., Derigent, W.: Enhanced B-Rep graph-based feature sequences recognition using manufacturing constraints. In: Krause, F.-L. (ed.) *The Future of Product Development: Proceedings of the 17th CIRP Design Conference*, pp. 617–628. Springer, Berlin (2007). doi:[10.1007/978-3-540-69820-3_60](https://doi.org/10.1007/978-3-540-69820-3_60)
 42. Liu, Z., Wang, L.: Sequencing of interacting prismatic machining features for process planning. *Comput. Ind.* **58**, 295–303 (2007). doi:[10.1016/j.compind.2006.07.003](https://doi.org/10.1016/j.compind.2006.07.003)
 43. Paris, H., Brissaud, D.: Modelling for process planning: the links between process planning entities. *Robot. Comput. Integr. Manuf.* **16**, 259–266 (2000). doi:[10.1016/S0736-5845\(99\)00056-3](https://doi.org/10.1016/S0736-5845(99)00056-3)
 44. Zhang, Y., Bernard, A., Gupta, R.K., Harik, R.: Feature based building orientation optimization for additive manufacturing. *Rapid Prototyp. J.* (2016). doi:[10.1108/RPJ-03-2014-0037](https://doi.org/10.1108/RPJ-03-2014-0037)
 45. Herzog, D., Seyda, V., Wycisk, E., Emmelmann, C.: Additive manufacturing of metals. *Acta Mater.* **117**, 371–392 (2016). doi:[10.1016/j.actamat.2016.07.019](https://doi.org/10.1016/j.actamat.2016.07.019)
 46. Shamsaei, N., Yadollahi, A., Bian, L., Thompson, S.M.: An overview of direct laser deposition for additive manufacturing; part II: mechanical behavior, process parameter optimization and control. *Add. Manuf.* **8**, 12–35 (2015). doi:[10.1016/j.addma.2015.07.002](https://doi.org/10.1016/j.addma.2015.07.002)
 47. Smith, J., Xiong, W., Yan, W., Lin, S., Cheng, P., Kafka, O.L., et al.: Linking process, structure, property, and performance for metal-based additive manufacturing: computational approaches with experimental support. *Comput. Mech.* (2016). doi:[10.1007/s00466-015-1240-4](https://doi.org/10.1007/s00466-015-1240-4)

48. Ponche, R., Kerbrat, O., Mognol, P., Hascoet, J.Y.: A novel methodology of design for additive manufacturing applied to additive laser manufacturing process. *Robot. Comput. Integr. Manuf.* **30**, 389–398 (2014). doi:[10.1016/j.rcim.2013.12.001](https://doi.org/10.1016/j.rcim.2013.12.001)
49. Yap, C.Y., Chua, C.K., Dong, Z.L., Liu, Z.H., Zhang, D.Q., Loh, L.E., et al.: Review of selective laser melting: Materials and applications. *Appl. Phys. Rev.* (2015). doi:[10.1063/1.4935926](https://doi.org/10.1063/1.4935926)
50. Suard, M., Martin, G., Lhuissier, P., Dendievel, R., Vignat, F., Blandin, J.-J., et al.: Mechanical equivalent diameter of single struts for the stiffness prediction of lattice structures produced by Electron Beam Melting. *Add. Manuf.* **8**, 124–131 (2015). doi:[10.1016/j.addma.2015.10.002](https://doi.org/10.1016/j.addma.2015.10.002)
51. Dutta, B., Froes, F.H.: Additive manufacturing of titanium alloys. *Adv. Mater. Process.* **172**, 18–23 (2014)
52. Vayre, B., Vignat, F., Villeneuve, F.: Identification on some design key parameters for additive manufacturing: application on electron beam melting. *Procedia CIRP* **7**, 264–269 (2013). doi:[10.1016/j.procir.2013.05.045](https://doi.org/10.1016/j.procir.2013.05.045)