

Received: 06 February 2018 / Accepted: 16 November 2018 / Published online: 20 December 2018

*hybrid manufacturing, CNC machining,  
additive machining, laser cladding,  
repair technology*

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## **HYBRID ADDITIVE AND SUBTRACTIVE MANUFACTURING PROCESSES AND SYSTEMS: A REVIEW**

This review paper highlights the hybrid manufacturing processes which integrate the additive and subtractive processes performing on one hybrid platform consisting of the LMD (laser metal deposition) unit and CNC machine tools. In particular, some important rules and advantages as well as technological potentials of the integration of different AM technique and finishing CNC machining operations are discussed and overviewed. Some representative examples such as formation of difficult features around the part periphery, deposition of functional layers and coatings and repair of high-value parts in aerospace industry are provided. Some conclusions and future trends in the implementation of hybrid processes are outlined.

### **1. INTRODUCTION**

Hybridization of is one of the leading strategies in developing more flexible and efficient manufacturing processes and implementing them into Production/Manufacturing 4.0 environment. In general, hybridization includes conventional and unconventional manufacturing/ machining processes using two rules, i.e. combination of different energy sources/tools or controlled applications of process mechanisms [1]. On the other hand, the concept of hybrid machining/manufacturing systems in which two or more individual machining/manufacturing processes are combined into one system is developed. In particular, hybrid machine tools (e.g. mill-turn centers) integrate different machining operations within one machining platform. Accordingly, the multi-tasking or complete machining is also defined [2]. Recently, a new trend in developing hybrid manufacturing processes combining additive (AM) and subtractive (SM) processes, which are performed on one hybrid manufacturing platform consisting of a multi-functional (multi-tasking) CNC machine tool and AM module along with automatic 3D scanning and dimensional control abilities, is observed [2, 3]. It should be noticed that additive manufacturing is commonly

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<https://doi.org/10.5604/01.3001.0012.7629>

termed 3D printing. As a result, additive fabrication and finish machining of a part is carried out on one machine without any additional fixing and transportation.

The main reasons for the use of hybrid additive systems in low volume production, high construction variability of parts include [4–6]:

1. Repair – Hybrid machines allow to use either additive or subtractive process and the main application for hybrid systems is repair of currently existing components
2. Surface finish–By coupling the additive technique seamlessly with CNC milling, all internal and external surfaces can be milled to traditional CNC surface finish.
3. Precision – Hybrid additive manufacturing allows every surface to be printed and milled in the same reference coordinate system, allowing tighter tolerances.
4. Adding difficult features– In traditional manufacturing, multiple parts are bolted, welded, and brazed into a final product. On the other hand, hybrid additive manufacturing design reduces complicated, multiple-part into one single part and difficult features are added around the periphery. A single part building reduces time, labour and cost to one part.
5. Multi-metal 3D printing – Parts consisting of multiple metals are difficult to produce even with additive manufacturing. A hybrid system architecture allows for a part to start with a preform of material A, add material B using additive manufacturing, and then switch to material C for further additive manufacturing.

In general, additive manufacturing uses the powder and wire technology [7] and two deposition methods are mainly utilize, i.e. laser cladding and arc welding in order to fabricate the near-net shaped parts directly from CAD models. Usually, the powder technology is adapted for fine components and small parts, whereas wire technology is recommended for large structural components. However, a CNC finish machining is implemented to ensure desired accuracy by eliminating the stars effects resulting from deposition of certain layers (Fig. 1b).

The spectrum of possible solutions is very broad including the fabrication of additional complex features using 3D printing and blown-powder melting (LMD-laser metal deposition), deposition of additional elements made of materials different than the base (substrate) material, as well as remanufacturing/regeneration of damaged/worn high-value parts. In production practice, several equivalent names for directed energy deposition by laser or electron beam are used including:

- Laser powder fusion welding,
- Directed metal deposition,
- Reverse machining laser cast,
- Laser cladding.

It is well known that laser-sintered additive manufacturing is at least one order of magnitude slower than traditional CNC metal removal (subtractive) process. The technological dilemma is to select higher productivity and thicker deposition layer (but lower surface finish due to the “stairs effect” shown in Fig. 1a) or improve surface finish by performing a slower deposition of thinner layers. In other words, the productivity of an AM process can be increased with much higher energy input, yielding thicker layers of powder and much faster builds, but the surface finish deteriorates (see Fig. 1b).

In contrast, the slow process, producing smaller layers, creating a better surface finish can be accepted. Even with the slower process – producing thinner layers for better surface finish – further post-deposition processing on some type of CNC machine platform is needed. This is where the struggle has always been between additive and subtractive manufacturing. This is an argument that these processes have been seen as competing technologies instead of being complementary to one another (Fig. 1a). On the other hand, hybrid process is the bridge allowing to print material, add metal to existing components, grow parts from zero volume, and then to machine them in that same envelope (see Fig. 1b). As a result, hybrid machining process integrating the AM and SM CNC operations becomes a profitable process for small and medium batches due to the fact that the productivity and surface finish can be controlled independently [3].

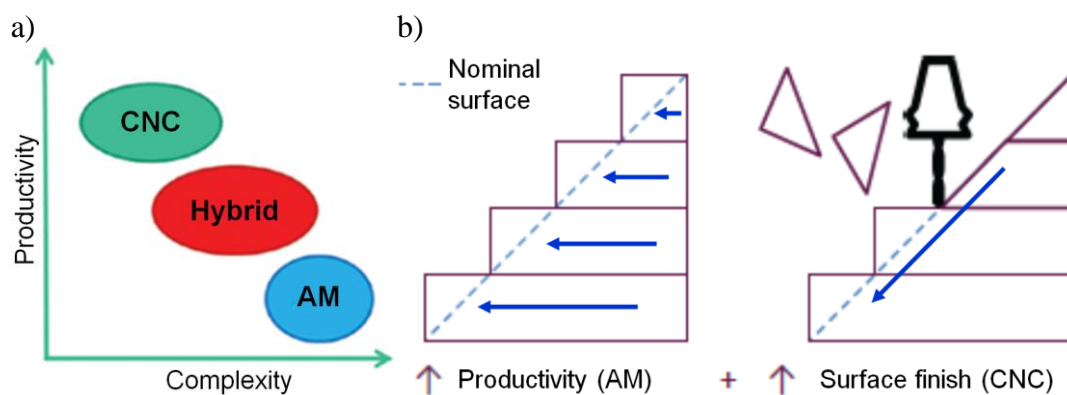


Fig. 1. Comparison of pure additive and subtractive processes and hybrid process (a), effects of integration of AM and SM CNC processes [8]

Hybridizing between additive and subtractive processes is currently almost standard practice for the vast majority of metallic parts produced by AM which additionally require machining in order to obtain a suitable surface finish (see Fig. 1b), narrower dimensional tolerances and functional properties, and avoid excessive residual stresses or even improve cosmetics, etc. It also results in substantial reducing scraps due to the fact that powder or foil are used instead solid blanks made of aluminium or titanium for which in aerospace industry 80÷90% material volume is removed when machining complex monolithic parts [2].

As mentioned above the need for integrating additive and subtractive processes is to produce complex part geometries directly from a CAD model (Fig. 3) with minimal machining to achieve precision part-feature accuracy and fine surface finish. A unique integration between direct metal deposition (DMD) which is used for additive manufacturing and subtractive machining in CNC-RP is shown in Fig. 2.

This system termed AIMS (Additive system Integrated with subtractive MethodS) integrates process capabilities of two different manufacturing approaches, i.e. EBM (electron beam melting) or DMLS (direct metal laser sintering) and rapid CNC (CNC-RP) machining to create near-net shaped complex parts. Fig. 2 illustrates the basic concept of the AIMS system which creates a metal linkage via AM (EBM) and SM (CNC-RP)

processes. In particular, a direct metal process creates not only a near-net shape of the desired part but also fixture elements are attached for a subsequent rapid machining process.

The AIMS process utilizes two kinds of sacrificial supports, first to support overhangs in AM process and second to support the part in a CNC machine fixture. Figs. 3a and 3b show two parts, a hinge component from an airframe (a) and a suspension part from a bicycle (b), with sacrificial fixtures (prior to removing them after machining). Fig. 3c presents the machining time and number of tools used for different materials including Al 6061 aluminium alloy, SS 316L stainless steel and Ti6-4 titanium alloy. In this analysis the cutting tool change time was not considered in the total machining time. It can be reasoned that machining duration of CNC-RP production is significantly longer that AIMS because only the finishing stage of CNC-RP is taken into account in the hybrid process (1590 min and 3432 min for a suspension part and the airframe hinge made of Ti6-4 alloy respectively).

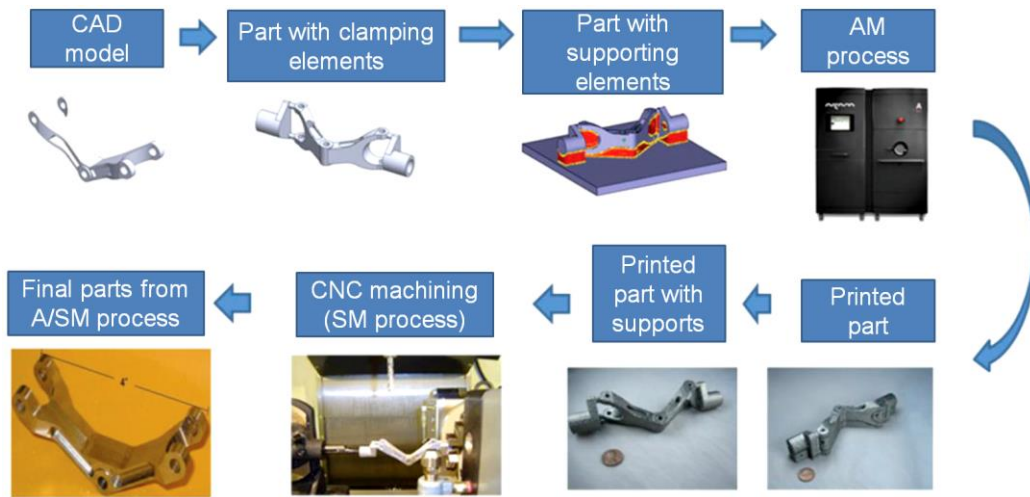


Fig. 2. Flow of the AIMS process including AM (EBM- electron beam melting or DMLS- direct metal laser sintering) and SM (CNC-RP) [9]

a) Suspender part



b) Hinge part



c) total machining time

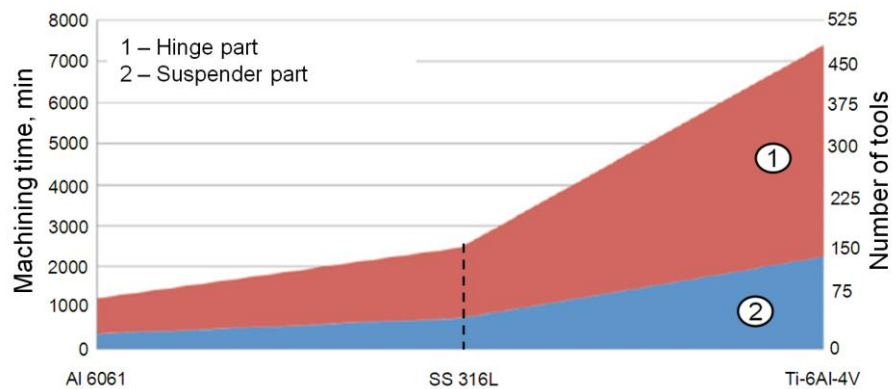


Fig. 3. Examples of machined parts: hinge (a) and suspender (b) parts after machining and prior to removing sacrificial fixtures, (c) influence of material selection on total machining time for RP using CNC machine tool [9]

## 2. FUNDAMENTALS OF HYBRID ADDITIVE-SUBTRACTIVE MANUFACTURING

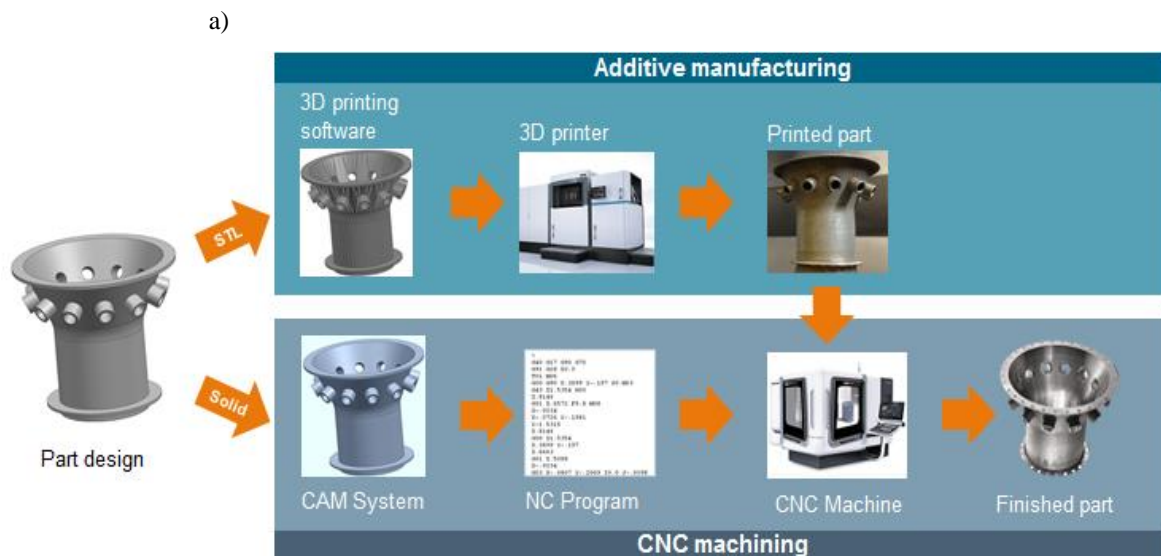
### 2.1. INTEGRATION RULES OF ADDITIVE AND SUBTRACTIVE PROCESSES

As reported in many literature and industrial sources, as for instance [8–11] appropriate research efforts are focused on the design of a modular hybrid manufacturing platform which integrates various additive techniques (AM) with finish machining (subtractive processes (SM CNC), including:

- FDM/extruding on different types of CNC machine tools,
- SLM on the vertical machining center (VMC), for example Lumex Advance-25, Matsuura, Japan.
- Direct metal deposition (DMD), as for instance laser cladding on the multi-functional/multi-axis machining centers, for example Hamuel HSTM 1000 (5-axis turning –milling center), GF HPM 450U (5-axis milling center equipped with a rotating-tilting table), DMG Mori Lasertec 65 3D (5-axis milling center), Mazak VC-500 AM (5-axis vertical milling center).

As can be noted multi-axis milling centers are the basic machine tools utilized for the platform for installation of an AM module. The second variant, more rarely used, is based on a turning-milling center which allows performing both turning and milling operations using the same workpiece alignment.

A general concept of the hybrid (AM+SM CNC) process is schematically shown in Fig. 4a. Simultaneously, based on the 3D CAD model the part is printing using transferred STL data and CNC control program is generated using the selected CAM system. In the next step, the rough part fabricated in the first step by AM process is finished by CNC milling or polished using special polishing tools. At present, an integrated programming system based on NX CAM system by Siemens, which allows efficient performing the complete hybrid process, is offered as depicted in Fig. 4b.





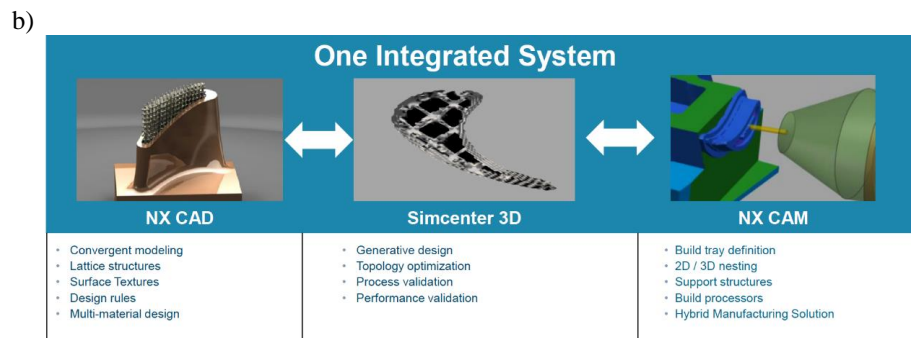


Fig. 4. General concept of technological (a) and programming integration (b) of additive and subtractive processes (AM+SM CNC) according to Siemens [8]

The basic design problem which appears in the synergetic integration AM and SM techniques is the installation of an AM module on a new or partly exploited CNC machine tool without its fundamental modifying or after retrofitting. The first concept was proposed within the pioneered research project RECLAIM (REmanufacture of high value products using a Combined LASER cladding, Inspection and Machining system) which was finished in 2009 [8, 12]. It was recommended there a profitable retrofitting of new CNC machine tools by adding a laser cladding module as shown in Fig. 7. It should be noted that one of the first hybrid machine tools manufactured by AeroMet Corp., which integrated laser cladding/laser deposition on a CNC milling machine was applied in 2004 for production of materials/products in the aerospace industry for a F-15 fighter. This system was not so efficient as demanded due to technical problems with the CO<sub>2</sub> laser and powder supplying (additionally the manifold is attached to the laser head in order to dock the powder during deposition phase).

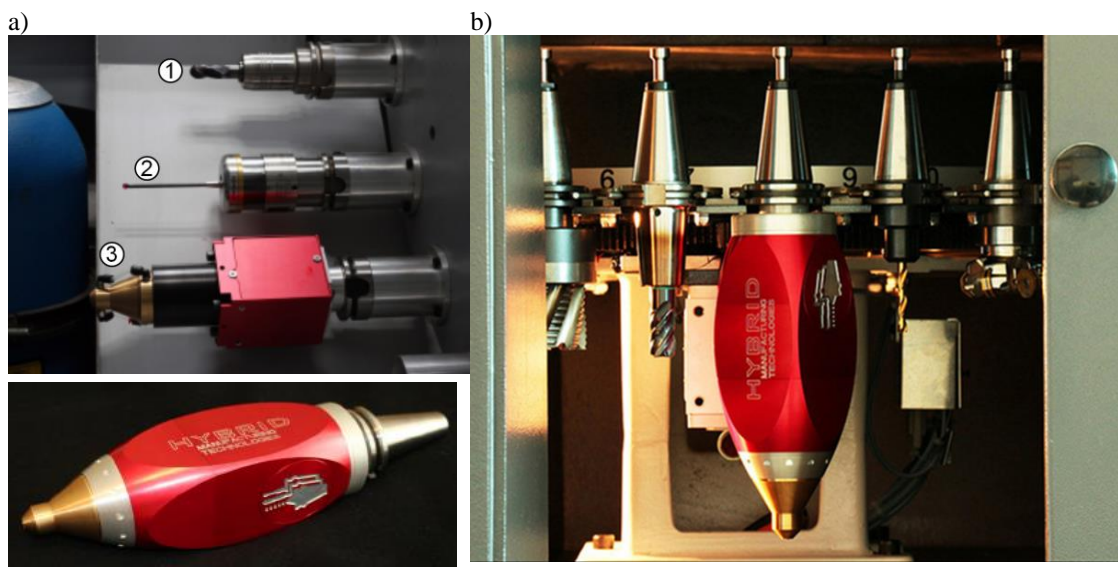


Fig. 5. Storage of cladding head (3), ball end-mill cutter (1) and touch probe (2) in the automated tool changer (below typical changeable laser cladding head- versions A and B in Fig. 6) (a), tool magazine in hybrid vertical manufacturing platform equipped with several milling cutters and laser cladding head (b) [8, 13]

## 2.2. DESIGN OF HYBRID MACHINES AND TOOLING

Next important innovative design problem for the machine tool builder, which naturally follows the adding of a AM module (DED – directed metal deposition module) to the basic machine structure, is to use the standard tool holders, as for instance HSK 63 taper, for mounting the head into the spindle (see Fig. 5b). Moreover, the laser head should be stored out of the working area of the CNC machine and the manifold undocked after deposition operations (i.e. when the LMD head is replaced by the milling cutter). Of course, the workpiece should be electrically grounded when arc-based welding approach is alternatively used in order to avoid the catastrophic consequences of the high arc voltage through the CNC machine itself.

Hybrid Manufacturing's Ambit system (Fig. 5) offers seven different laser deposition heads, each of which is fully compatible with a standard tool changer and any standard machine spindle (CAT 40, HSK63, etc). The heads automatically link up with a supply unit to deliver the laser energy, shield gas, and powder supply. The use of a standard tool changer allows the expanded capability of the laser-based hybrid system by application of a set of laser processing heads for specific tasks, as shown in Fig. 6. For instance, it is possible to use the head C to re-open holes covered over during cladding. Moreover, the head of D type can be used for cleaning, pre-heating, annealing, heat treatment, etc. In general, laser processing heads can have different geometries, laser profiles, powder supply configurations and unfocussed beams.

The integration of additive and subtractive processes within a single machine footprint causes that the laser aided manufacturing process (LAMP) system creates fully dense, metallic parts and provides all the advantages of the commercial LMD systems. Capabilities beyond complex geometries and good surface finish include: (1) functional gradient material metallic parts where different materials are added from one layer to the next or even from one section to another, (2) seamlessly embedded sensors, (3) part repair to reduce scrap and extend product service life, and (4) thin-walled parts due to the extremely low processing forces. This hybrid system is a very competitive and economical approach to fabricating metallic structures.

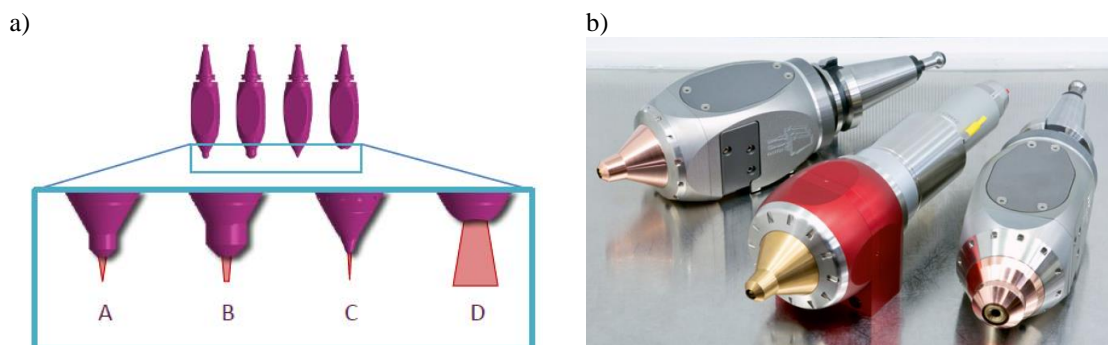
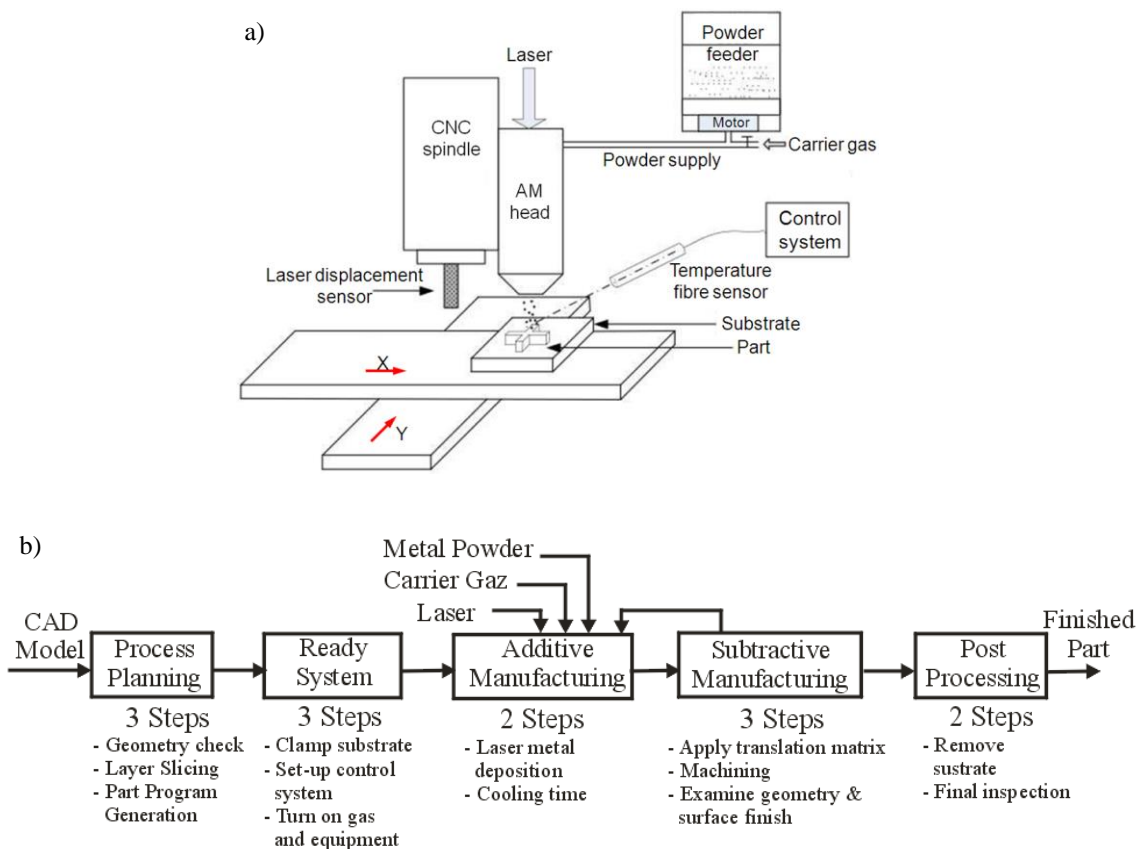


Fig. 6. Several variants of laser cladding head with the following functions (a): A – fine cladding, B – high rate cladding, C – laser hole drilling, D – divergent laser beam focus for pre-heating, annealing or heat treatment [8, 13], (b) a range of processing heads with different functions [14]

Beam-directed technologies, such as laser cladding, are very easy to integrate with other processes and computer numerically controlled (CNC) milling machines by simply mounting the cladding head to the z-axis of the milling machine. For instance, retrofitted 5-axis milling machine with a Nd:YAG laser cladding head and powder feeding unit are all controlled by extended CNC-control. Similarly, a Direct Laser Deposition (DLD) process utilizing an Nd:YAG laser, coaxial powder nozzle and digitizing system was integrated into a 3-axis milling machine [15]. The hybrid machine which entails additive-subtractive integration, is shown in Fig. 7a. It was designed to build a rapid prototyping/manufacturing infrastructure for producing thin wall structures with good surface finish, and complex internal features, which are not possible by a LMD or machining system alone. Applications of the system include repairing damaged parts, creating functionally gradient materials, fabrication of overhang parts without support structures, and embedding sensors, and cooling channels into specialty parts.



Five-axis hybrid manufacturing process shown in Fig. 7a is comprised of five subsystems or integration elements: process planning, control system, motion system, manufacturing process, and a finishing system. The process planning system is an in-house layered manufacturing or slicing software that imports STL models from a commercial CAD package to generate a description that specifies melt pool length (mm), melt pool peak



temperature, clad height (mm) and sequences of operations. The objective of the process planning software is to integrate the five-axis motion and deposition-machining hybrid processes (Fig. 7b). Control of the hybrid manufacturing subsystems require a versatile industrial controller (the National Instruments Real Time Control System (NI RT System) and a range of sensors to acquire feedback. System feedback is acquired through temperature and laser displacement sensors (Fig. 7a). An Omron Z4M-W100 laser displacement sensor is used to digitally determine the cladding head height above the substrate. There are danger zones and safe zones that the nozzle can be with respect to the substrate. Output of the displacement sensor is converted into a minimum and maximum distance value, respectively. The temperature sensor is a non-contact, fiber-optic, infrared temperature sensor. It was installed onto the Z-axis of the VMC. There is also a machine vision system, an image sensor, to watch the melt pool in real-time.

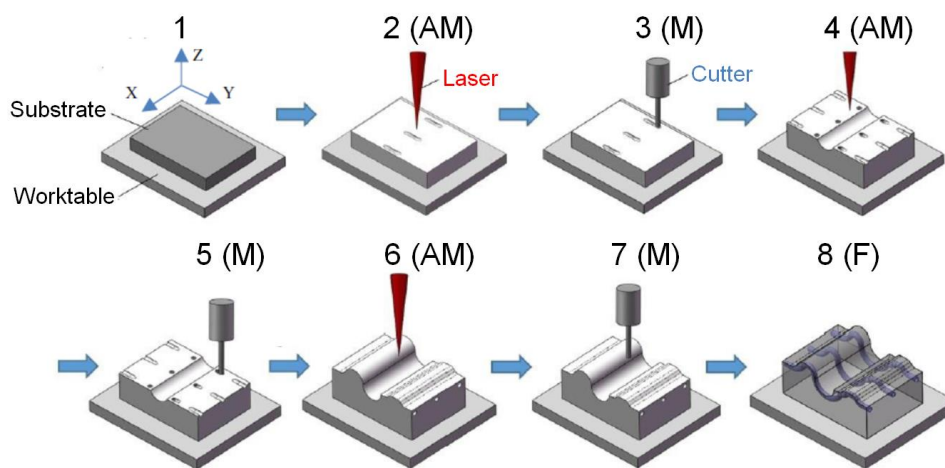


Fig. 8. Schematic layout of the hybrid A/SM process [16]. Symbols: AM – additive machining, M – milling, F – finishing (mainly polishing)

A schematic description of the A/SM hybrid process combining a SLM (selective laser melting) system with a CNC milling for producing a metallic part with curved cooling channels is shown in Fig. 8. First, a digital CAD part model is divided into a number of thin layers which are then deposited by selective laser melting layer by layer. A substrate is clamped onto the worktable (position 1). The part is created from metallic powder bed which is melted when the laser beam scans the surface. After the layer is deposited, the build platform lowers by the distance of the layer thickness and a new layer of powders is melted. The process is repeated for several times and some features of the created part are milled (position 3). The cycle consisting of additive and subtractive processes (positions 4 and 5, and 6 and 7 respectively) occur until the part is finished. In the example shown in Fig. 8 both external free-form and internal complex structures can be formed and machined. A set of waved cooling channels parallel to the external surface can be seen in position 8. Moreover, the dimensional and shape errors can be corrected by the CNC milling operations. Finally, the part surface is polished (position 8) using special polishing tools.

## 2.3. PRACTICAL EXAMPLES OF APPLICATIONS OF HYBRID (A/SM) PROCESSES

A novel additive/subtractive hybrid manufacturing (A/SM) method is rapidly developed in last years for many applications such as [4, 8, 17–19]: producing complex parts with high accuracy and good surface finish, producing parts with overhang elements, flanges and fins (Figs. 9c and 11a), repairs of worn elements in one clamping and producing multi-material parts using 3D printing (e.g. local deposition of Inconel 718 on the hollow shaft in Fig. 9c). This method is particularly suited to small-lot production of difficult-to-machine materials, such as aerospace alloys, high-hardness materials used in the energy, die and mould, tooling and medical device sectors.

Injection mold presented in Fig. 9a was made of the 18Ni (C300) maraging steel powders of the 35  $\mu\text{m}$  particle size using the additive SLM and high speed milling processes. A stainless steel plate was used as a substrate and the deposited layer thickness was equal to 40  $\mu\text{m}$ . A special laser scanning strategy was applied in order to avoid excessive residual stresses and, as a result, to minimize distortions and cracks [8]. The laser beam was travelled at the speed of 1400 mm/s with a 0.2 m spot diameter. The workpiece temperature during high speed milling operations was relatively high because the molten pool in the previous AM process. In general, the part is heat treated after the A/SM hybrid process.



Fig.9. Injection mold with internal cooling channels produced by hybrid A/SM (Additive/Subtractive Manufacturing) process (a), injection mold for the head of electric driver produced by hybrid process including SLM and CNC milling (b) and cylinder shaft for oil industry with locally deposited layers of Inconel 718 alloy (c) [5–6, 8, 16–18]. Symbols: AM/T – additive process plus turning (1), AM/M – additive process plus milling (2, 3, 4), LM – laser marking (5)

The mold made of a maraging steel shown in Fig. 9b was produced on a hybrid Matsuura Lumex Avance-25 machine using a special AM process, which combines powder bed fusion with selective laser melting (3D-SLS), and high speed milling [20]. The process begins when the laser melts a specified thickness of powder. This layer thickness can vary based on the material that is being sintered. The machine is equipped with a two-blade

squeezing system which works in such a way that the leading blade clears the path for the new powder layer, and the trailing blade smooths and compacts the new powder layer. A machining pass typically follows after every 10 sintering passes, but this is a variable that can be set by the user. The hybrid process reduces substantially costs and practically eliminates EDM from the die and mould making technology.

The cylinder shaft presented in Fig. 9c was produced on a multi-tasking hybrid machine “INTEGREX i-400 AM” in two steps using LMD (Laser Metal Deposition technique is presented in Fig. 10a) heads. The hybrid platform consists of 3 linear axes (X, Y and Z) and two rotary C and B axes. As shown in Fig. 10b the high-speed LMD and the fine LMD (denoted as LMD (2) and LMD (1)) heads perform laser cladding with more efficient or lower deposition rating respectively. As a result the fine LMD head (1) is used for intricate feature generation and a more accurate powder deposition process. The substrate is made of 316S31 stainless steel and the metal powder for deposition is Inconel 718 nickel-based alloy with the particle diameter of 50–100  $\mu\text{m}$ .

As shown in Fig. 9c the hybrid A/SM process makes 6 parts of spiral coating (2), 12 fins (3) and a flange (1) using the more productive LMD (2) head and CNC machining and 6 pins (bosses) (4) using the LMD (1) head and CNC machining. The total cycle time is equal to 634 minutes (AM: 454 min, CNC machining: 180 min) and it is not decisively lower than in the machining from a solid material. However, the material and tool costs are lower and functional properties such as high-temperature, corrosion, oxidation and creep resistance is substantially improved.

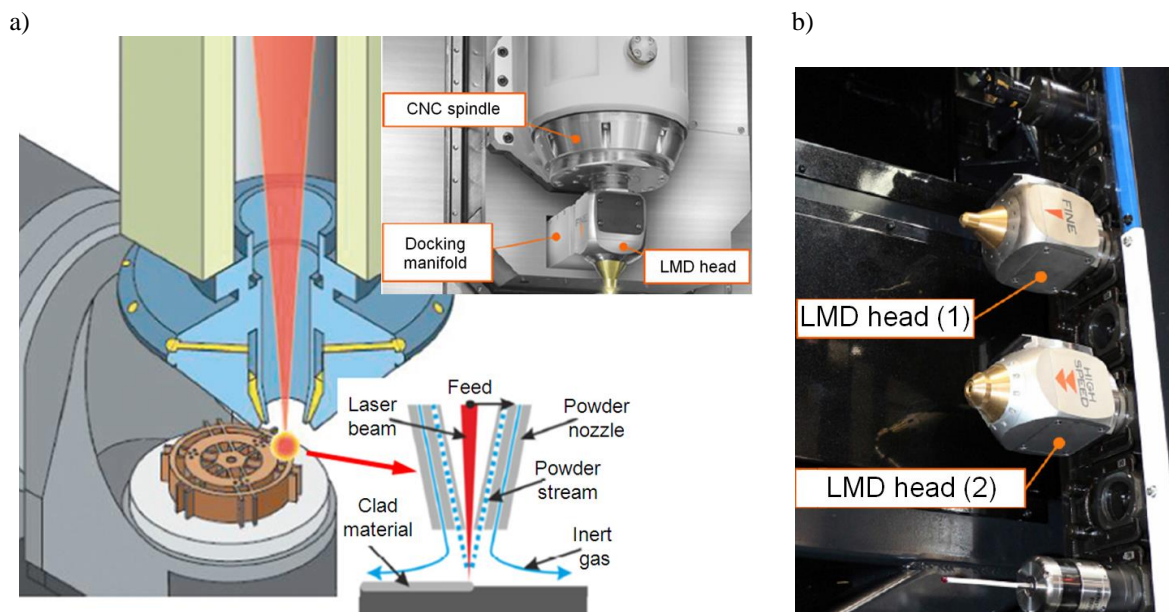


Fig. 10. Scheme of LMD (Laser Metal Deposition) process (a) and deposition heads mounted in the milling spindle (b)  
Symbols: LMD (1) – fine head, LMD (2) – high speed head [6, 19]

One of the leading world machine tools’ manufacturers DMG Mori is also the leader in developing hybrid A/SM platforms for hybrid fabrication, coating deposition and



remanufacturing/repair [11]. Standard universal hybrid machine is a machining center Lasertec 65 3D (see Fig. 18a) which uses the blown-powder deposition welding process (the metallic powder stream is sprayed to the melt pool (Fig. 11c1) and fused to the substrate). This AM technique is more efficient than laser sintering (STL) and for instance the part of 3.5 kg mass is build 20 times faster, and due to the high accuracy high speed milling operations can be employed wherever fine precision is needed or some critical features should be machined. A hybrid machine tool combining laser metal deposition for additive manufacturing with five-axis CNC simultaneous machining is equipped with the 2 kW diode laser head located in the machine's spindle with an HSK interface. For the shift to machining mode, this head swivels to a protected parking area. By using laser deposition to build up the part, while employing milling throughout the process to machine critical features as the part is taking shape, the machine can produce a component through additive manufacturing while also producing it to its completed tolerances within the same cycle.

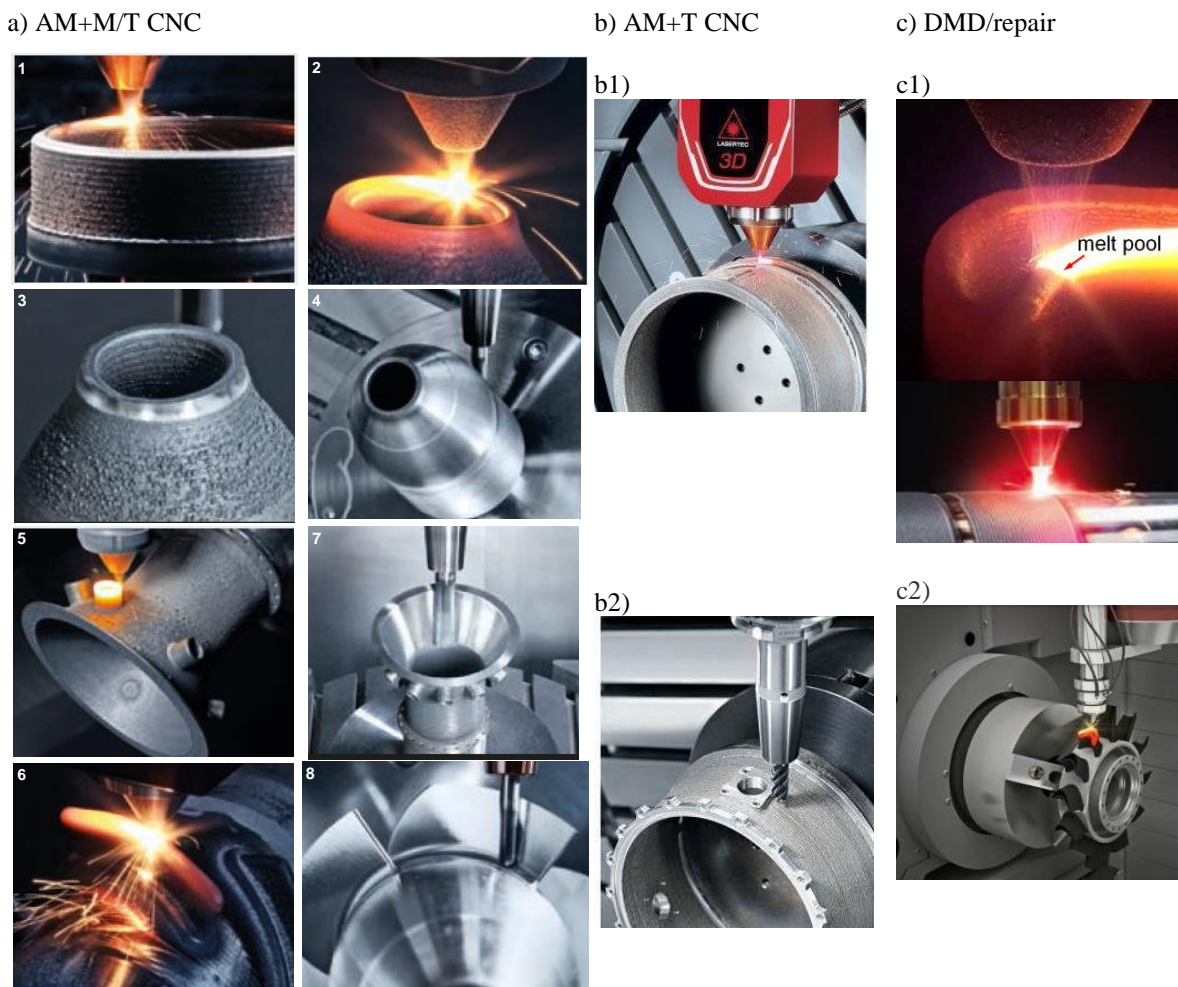


Fig. 11. Examples of laser cladding and finish CNC milling and turning (a, b) and regeneration of blades (c) [11, 21]

Some examples of technological capabilities of this hybrid manufacturing platform is shown in Fig. 11. In general, the hybrid technological process is similar to that shown in

Fig. 8. After deposition of the cylindrical (1) and conical (2) elements the part is milled (3) and finished (4). Another construction variant of the part include additional deposition of a number of bosses (5) or helical flanges (6) and finish milling (7, 8) of the blank. Recently, the second hybrid machine which adds the possibility of turning operations (b1) to laser deposition welding and 5-axis CNC milling (b2). As a result, rotational-symmetric components can be produced with the hybrid A/SM process, as shown in Fig. 11b. The machine is equipped with a mirrored C axis and workpieces can be machined on the rear side with the counter-spindle enabling six-sided machining of the finished part. Moreover, the rotational table is employed in the laser cladding for deposition or repair of blades of rotors as shown in Fig. 11c.

In ref. [7] a multi-AM process platform including Wire Arc Additive Manufacturing (WAAM), High Speed Machining (HSM) and Laser Metal Deposition (LMD) is used in the laboratory scale to manufacture complex large parts made of aluminium alloys. In general, five axis toolpaths are recommended to obtain an acceptable accuracy.

The approach known as laser metal deposition (LMD) is also termed Laser-Engineered Net Shape (LENS, a Sandia National Labs trademark licensed by Optomec), and direct metal deposition (DMD, a Precision Optical Manufacturing trademark). Fig. 12a shows a VMC equipped with a AM LENS module which features a high-power fiber laser. The VMC enables to print and finish machine parts to a 4-micron tolerance. It has found a number of practical applications including milling, lathes and robots. A monolithic housing build-up in one set-up is shown in Fig. 12b.

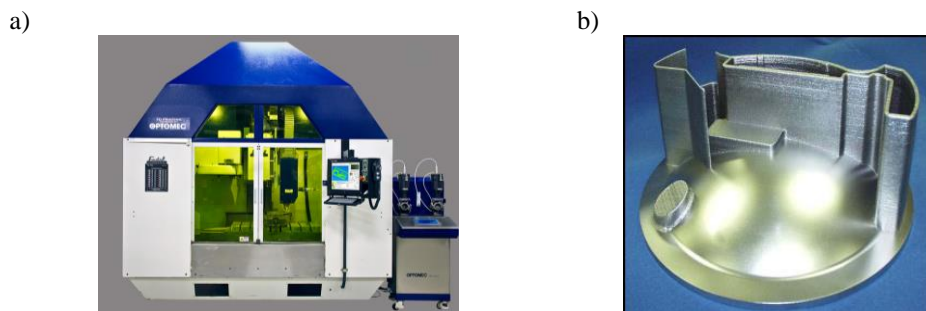


Fig. 12. Vertical milling center equipped with AM module LENS by OPTOMEK (a) and example of monolithic housing produced by hybrid process (b) [13]

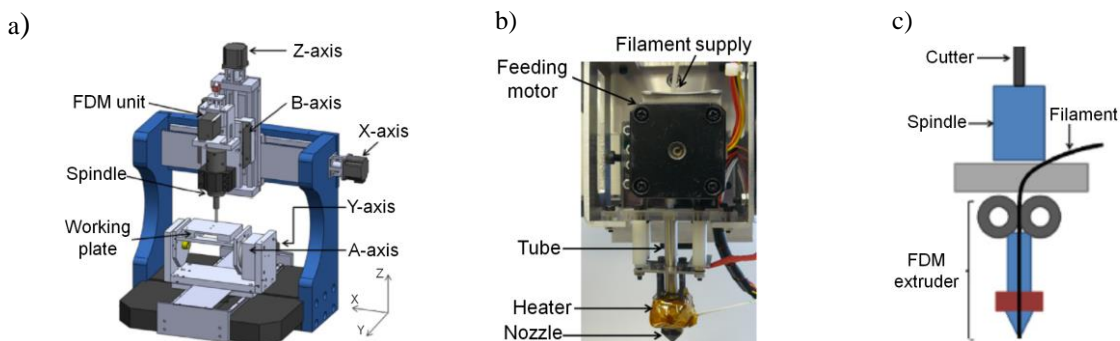


Fig. 13. Design of the hybrid FDM and 5-axis machine tool: a) scheme showing the localization of FDM head, b) FDM extruder, c) milling mode [22]



A relatively new idea is to integrate the FDM (fused deposition modelling) rapid prototyping technique with CNC milling, as illustrated in Fig. 13a. It is the case of mechanical design where the FDM extruder (Fig. 13b) and the cutting spindle are integrated and controlled in the frame of 5-axis machine tool. Its main application area concerns printing of polymer parts with overhang features ( $\Gamma$ -shape object in Fig. 14a) without additional support materials or producing FDM parts with metal embedded to increase the stiffness (Fig. 14b) [13, 22]. The applications of CNC milling include finishing, trimming and shaping free-form surfaces (Fig. 14c). It is also can reduce the shrinkage effect and deformations resulting from excessive residual stresses induced during the FDM process. Some typical examples of above-mentioned parts producing by hybrid FDM and 5-axis machining are presented in Fig. 14.

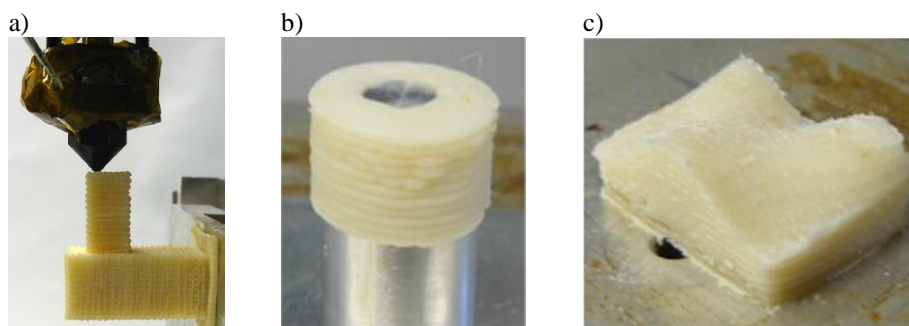


Fig. 14. Examples of polymer/metal parts producing on FDM+CNC hybrid machine: a) fabrication of the horizontal portion of the  $\Gamma$ -shaped polymer component, b) stepped aluminium part embedded in polymer before trimming, c) free-form polymer part after finish milling [22]

### 3. REPAIR TECHNOLOGY USING HYBRID A/SM CNC PROCESSES

Nowadays, a new specific field of research and applications of hybrid A/SM processes is repair/remanufacturing high-value metal parts made of HRSA materials such as Ti6-4 and Inconel 718 alloys produced mainly for the aerospace industry. The initial focus of this research activities was to repair turbine blades made of Ti6-4 titanium alloy with tip damage and wear [17, 23].

The vast majority of additive machines for remanufacturing use one of two approaches: directed energy deposition (DED) or powder bed fusion (PBF). Whereas the PBF approach is probably the market leader for additive-only machines in metalworking, the DED approach is used far more often in hybrid machines. An excellent application for directed energy deposition (DED) is the addition of super-hard materials to existing parts in order to improve their durability. In general, the LRT (laser repair technology) covers a family of similar deposition techniques including DMD (direct metal deposition), LAM (laser additive manufacturing) and LMD (laser metal deposition) which are dynamically developed by machine tool's manufacturers due to numerous advantages. First of all, the hybrid system is capable of remanufacturing components in order to recover the second life along with demanded functionality.

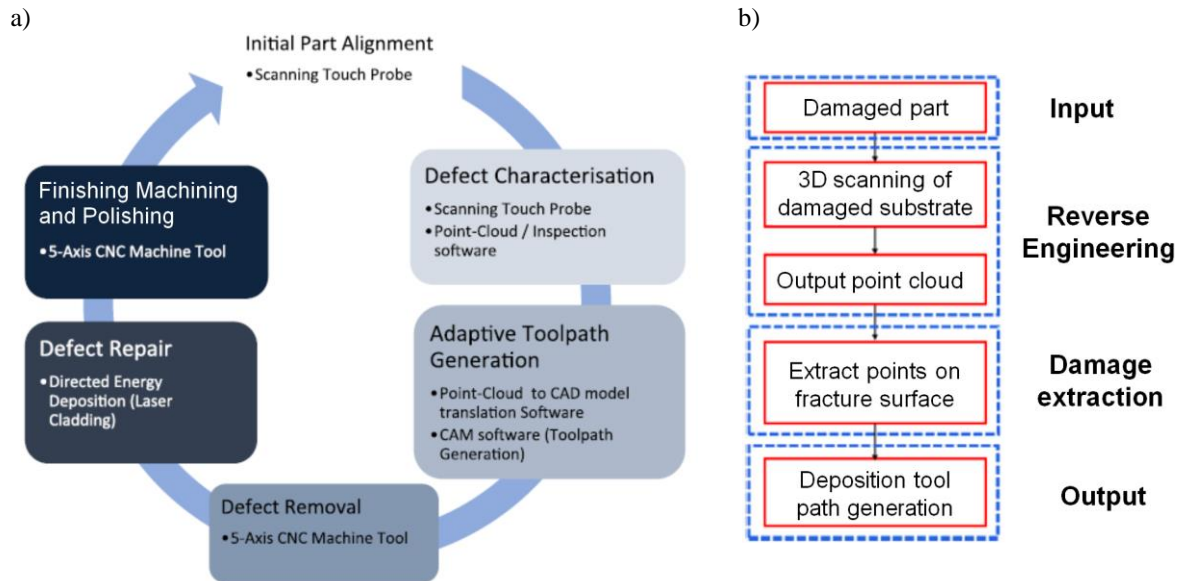


Fig. 15. Concept of hybrid repair technology on multifunctional (turn-milling) machine tool (a) and flowchart of the repair process (b) [22, 24]

This result in a decisive cost reduction, in particular where high value and intricate components are concerned [23, 24]. In a big shortcut, the LRT includes removing a certain material volume in the vicinity of the damage, then refilling the missing material volume, for instance by laser cladding, and finish machining and/or polishing of the surrounding surface. In addition to restoring worn or damaged material to apart, laser cladding can combine different materials together to enhance component performance. With appropriate processing parameters, the clad and parent materials achieve a very strong bonding to the substrate material, which ultimately determines the part properties and microstructure.

In total, the hybrid process includes the following machining and non-machining (metrological, inspection) operations: High Speed Milling+3D Scanning+3D Laser Cladding +3D Inspection+Deburring / Polishing+Laser Marking [17, 23, 24].

Figure 15a presents the structure of the RECLAIM remanufacturing process cycle mentioned in Section 2.1 which include all these stages (Ref 11, 16). The process is performed on multi-purpose machine tools via the combination of additive, subtractive and inspection processes.

It is commonly concluded [24] that *the hybrid manufacturing machine is the most flexible system for remanufacturing worn parts and consumes only a fraction of the energy, time and cost required to manufacture new parts.*

One of the important operations included into remanufacturing cycle is reconstructing repair volume of worn components which is the key to provide laser scanning tool path for further material deposition. In refs. [23, 24] hemispherical-shaped defects were modelled and machined. In particular, some indexing points are marked on the surface to define the relative position of the substrate with the tool path. Therefore, the repair volume is obtained by scanning the damaged area and then processed using the point-cloud technique. The flowchart of the procedure of the tool path generation based on the scanned data is shown in Fig. 15b.

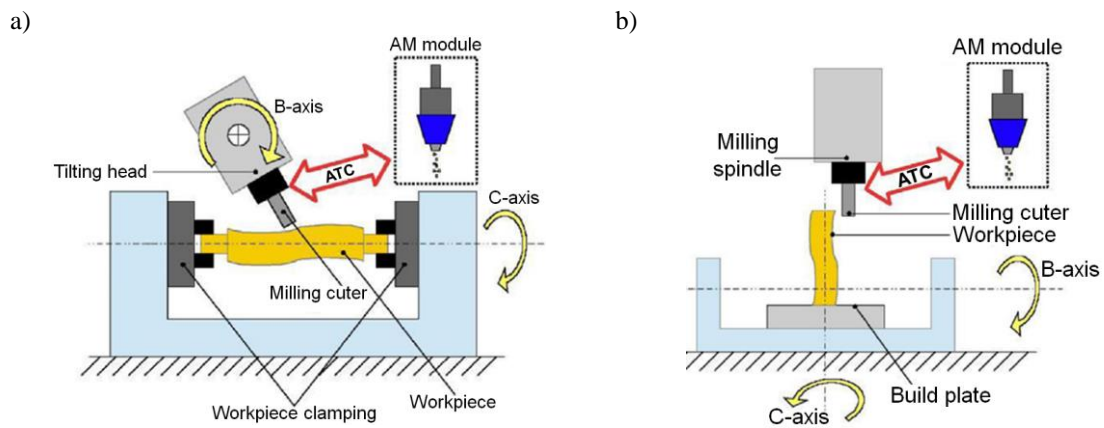


Fig. 16. Examples of configurations of hybrid machining platforms: a) based on turn-milling machine tool, b) based on 5-axis machining center, ATC- automatic tool changer [22]



Fig. 17. Remanufacturing of turbine blade: laser deposition of the worn blade edge (a) and subsequent milling of turbine blade after cladding (b) [23]

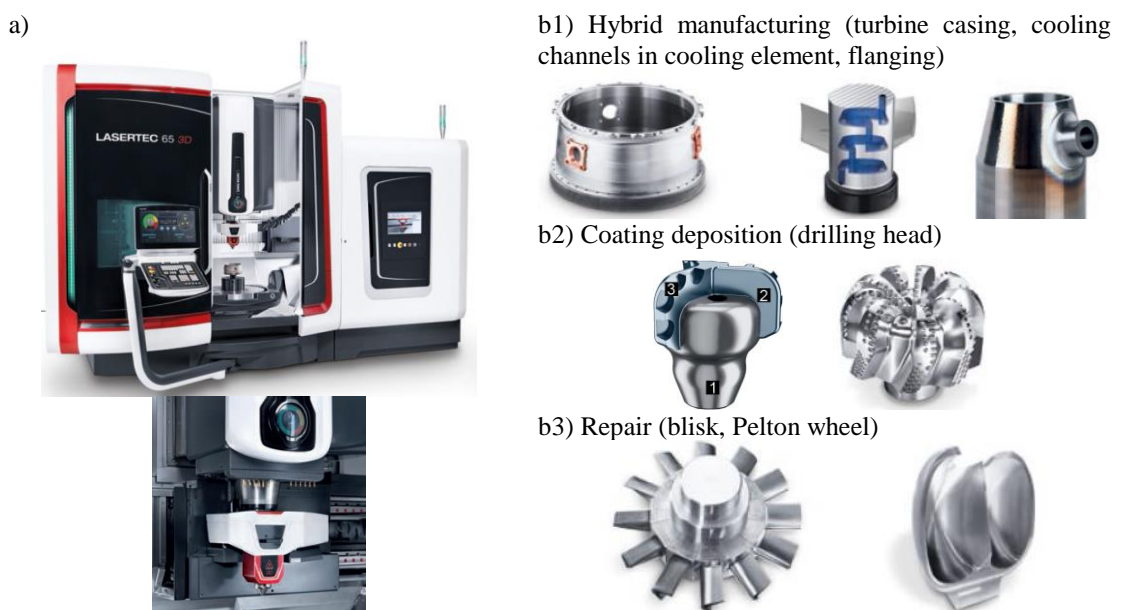


Fig. 18. Integration of 5-axis milling machine with laser deposition welding (below laser head coupled with the HSK milling taper) (a) and application examples for manufacturing (b1), coating deposition 1 – SS, 2 – IN718, 3 – HW (b2) and repairing (b3) [11]

Configurations of the two most frequently applied in industry hybrid manufacturing platforms with hybrid manufacturing process capabilities for repair of worn/damaged parts are presented in Fig. 16. The configurations shown in Fig. 16a is based on the modification of a commercial turning-milling center, where the workpiece is clamped in the spindle (rotary axis) and by its revolving different part orientations are achieved. The tool has also a rotary degree of freedom which allows its contact to the machined surface. This configuration is used in the case when the workpiece during repair is clamped at its ends to reduce unwanted deflection.

The practical solutions of this configuration, which was built on the hybrid platform HSTM 1000, Hamuel Reichenbacher is presented in Fig. 17. In general, this machine combines high speed milling, direct energy deposition via laser cladding, inspection, deburring/polishing and laser marking.

The second configuration presented in Fig. 16b is based on the adaptation of a five-axis machining center with additive capability in both manual or automatic manner via automatic tool changer (ATC). An accessible build-plate causes that this machine can be applied to the hybrid machining of new parts. This concept was practically utilized by DMG Mori in the LASERTEC 65 3D hybrid platform which combines laser cladding (LDT – Laser Deposition Technology) with 5-axis CNC machining. The laser head is equipped with a coaxial nozzle (see Fig. 10a), so the metal powder is welded to and melted onto the base material in layers. Hence, the metal powder is joined to the base material with a high-strength bond. Coaxially supplied shielding gas protect the melted metal against oxidation during the build-up process. After cooling, the deposited metallic layers can be finished by machining. As a result, some important technological tasks such as hybrid manufacturing (b1), deposition of powder beds (b2) and repairs (b3) are performed. List of potential deposited materials includes: stainless steels, nickel based alloys (Inconel 625, 718), tungsten carbide matrix materials, bronze and brass alloys, chrome-cobalt-molybdenum alloys, stellite and weldable tool steels [23, 25].

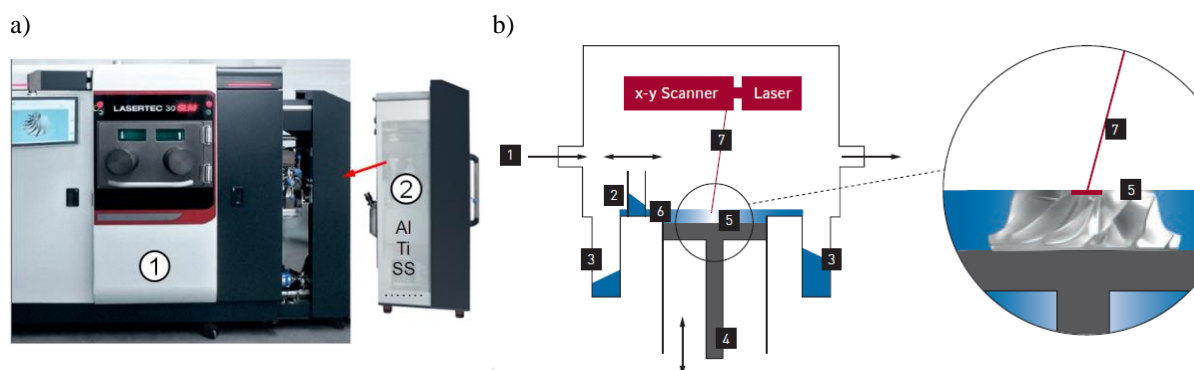


Fig. 19. LASER 30 SLM hybrid machine (1) with moveable powder tank (2) (a) and scheme of SLM (selective laser melting) additive process (b). 1 – inert gas (argon), 2 – coater, 3 – powder container, 4 – lowerable working platform, 5 – SLM component, 6 – powder bed, 7 – laser beam

DMG Mori offers also LASERTEC 4300 3D hybrid machine based on laser deposition welding via powder nozzle with integrated turning/milling in finished part quality.



Its technological capability includes 6-sided machining performed by turning and milling operations. The flexibility of additive manufacturing is combined with the precision of CNC machining. DMG MORI LASER 30 SLM hybrid machine utilizes additive manufacturing with powder bed process shown in Fig. 19. A wide range of different areas of application, in particular creation of the filigree parts with lattice structures, internal cooling channels and lightweight structures is possible. It allows high-precision generation of 3D parts with layer thickness of 20  $\mu\text{m}$  to 100  $\mu\text{m}$  (in general from 20  $\mu\text{m}$  to 150  $\mu\text{m}$  [26]. The powder module can be simply inserted into the machine, docked and used immediately. Fiber laser sources of 400 W or up to 1kW are installed. As reported in ref. [26] the monitoring of the energy consumption is also developed in order to achieve the energy saving by 15%. For this purpose special machine learning algorithms are used to optimize individual toolpaths.

a) regeneration of the seal of gas compressor made of Inconel 718



b) regeneration of the atomizer shaft made of 4340 steel, clad material- stainless steel 420 LC



c) material deposition on the undersized forging (atomizer wheel) made of Ti6-4 titanium alloy



Fig. 20. Examples of repairs of different parts using LDT technique (Laser Deposition Technology) [21], 1 – worn part, 2 – part after cladding, 3 – part after machining of deposited layer

Fig. 20 presents some typical examples of remanufacturing of large, high-value parts such as housing of a gas compressor (Inconel 718), shaft (420 SS steel) and rejected forging with unacceptable dimensions (Ti6-4 alloy).



## 4. CONCLUSIONS

1. Implementation of the strategy of Production/Manufacturing 4.0 covers the hybridization of manufacturing processes. The most important are hybrid processes which integrate additive and subtractive (CNC machining) processes (A/SM CNC). They are not specified in the CIRP classification of hybrid manufacturing processes [1]. They are used to produce solid part from metallic powders or/and add some complex features, deposition of special layers to produce multi-metal parts and repair/re-manufacturing of worn or damaged high-value parts.
2. Hybrid manufacturing platforms consist of multi-axis CNC machine tools and AM modules which utilize different deposition techniques, i.e. FDM, SLM, EBM, DED (laser cladding), or LBDW (laser beam deposition welding). In practice, difference names of laser techniques are used by machine tools' manufacturers, as for instance LENS, DMD, DED, PBF (powder bed fusion) or POM (precision optical manufacturing) [27].
3. One of the most practical applications of AM/SM CNC processes is repair of large and complex parts mainly from aerospace industry. For this purpose a special LRT (laser repair technique) based on laser cladding or selective laser melting is employed.
4. Nowadays specialized hybrid manufacturing platforms consisting of multi-axis and multi-functional machine tools equipped with special laser heads, 3D laser scanners, 3D inspection tools (touch probes) are used intensively in industry. Moreover, highly integrated CAD/CAM and CAI (Computer Aided Inspection) are available.

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