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Hybrid manufacturing of metallic parts integrated additive and subtractive processes

Hybrydowe procesy kształtowania wyrobów, integrujące techniki przyrostowe i ubytkowe

WIT GRZESIK *

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 multi-axis CNC machining center. This hybrid technology is rapidly developed and has many applications in Production/Manufacturing 4.0 including the LRT (laser repair technology). In particular, some important rules and advantages as well as technological potentials of the integration of a powder metal deposition and finishing CNC milling/turning 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. Moreover, the technological strategies, CAD/CAM and CAI programs and construction designs of the hybrid manufacturing platforms are explained. Some conclusions and future trends in the implementation of hybrid processes are outlined.

KEYWORDS: hybrid machining, additive machining, CNC machining, repair technology, hybrid machine tools

The paper is a continuation of the topic of hybrid conventional and unconventional machining, initiated by the author in the previous edition of the monthly Mechanik [1]. It develops the problem of integration/combining several processes in a single manufacturing device, called a hybrid manufacturing device, which was built on the basis of multifunctional CNC machine tools for integrated/complete machining (multi-tasking machine tools), such as multi-axis milling centers or turning-milling centers [2, 3]. The first stage of the integration, dated at the turn of the 80s and 90s, consisted in installing a laser source supporting conventional processing. Currently, hybridization of manufacturing/machining processes assumes on one device an incremental or additive machining (AM), and final/finishing machining (subtractive) with automatic dimensional control [1, 3]. Additive processing is usually called 3D printing.

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The range of possible solutions is very wide - from shaping additional elements of the part using 3D printing and laser metal deposition (LMD), by applying elements from materials other than the base, to repairing damaged / worn, expensive parts.

As shown in fig. 1a, hybrid machining in this variant is a compromise between the possibility of incrementally forming products with complex construction and high productivity obtained in CNC machining. It should be emphasized that the productivity of the AM process is an order of magnitude smaller compared to CNC machining. Users often have a dilemma: choose higher efficiency (higher thickness of the deposited material layer) or better surface quality (less material layer thickness). As a result, the hybrid manufacturing process (fig. 1b) is cost-effective in the smaller and medium series, because it gives the possibility of independent control of the productivity and quality of the surface [3].

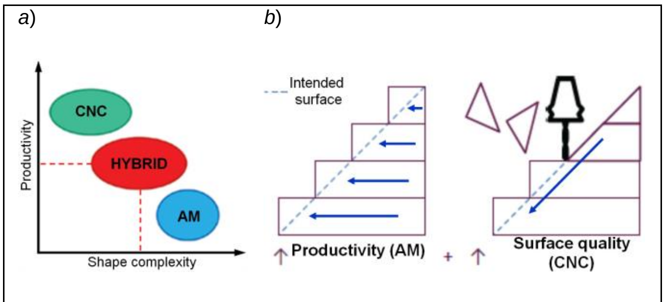

Fig. 1. Features of component processes (*a*) and their integration in the AM + CNC hybrid process (*b*) [4]

The combination of these complementary techniques is currently the standard for the majority of metal products manufactured by the AM technique, when the required quality (functionality) of the surface, narrow dimensional tolerance, elimination of the risk of excessive stress, aesthetics of the product are required. An important argument in favor of this technology is a radical reduction in the amount of waste (fig. 2) as a result of the use of foils or powders instead of monolithic blanks. This allows to minimize the allowance for finishing machining. It should be added that while shaping complex monolithic elements from aluminum and titanium in the aviation industry, up to 80÷90% of the volume of the starting material is removed [3].

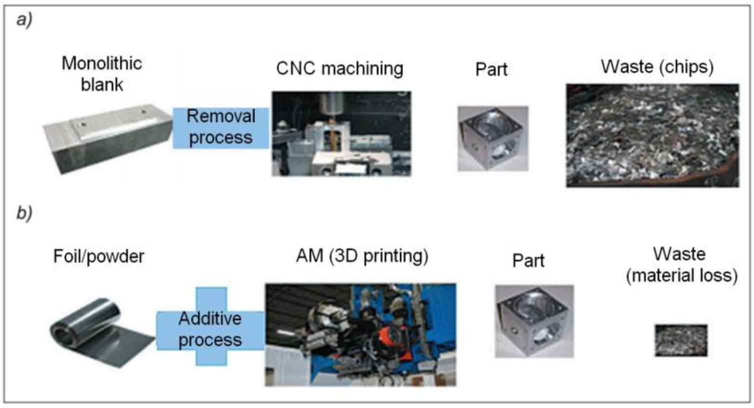

Fig. 2. Comparison of loss (*a*) and incremental treatment (*b*) [4]

Fig. 3 presents a scheme for shaping the product in the AIMS hybrid process (additive system integrated with subtractive methods), which consists in rapid EBM prototyping and subsequent high speed cutting (HSC) on a CNC machine tool, after fixing with the previously made side supporting elements (fig. 4a and fig. 4b). The AIMS process requires the use of two types of protective holders (fig. 4a and fig. 4b) to achieve overhang when depositing layers and fixing the parts in the holder on the CNC machine tool. It should be assumed that the tool change time is not included in the total machining time. For this reason, the total production time will be extended as a consequence of the shorter tool life and more tool changes (fig. 4c), which is easy to see in the case of Ti-Al6-4V titanium alloy.

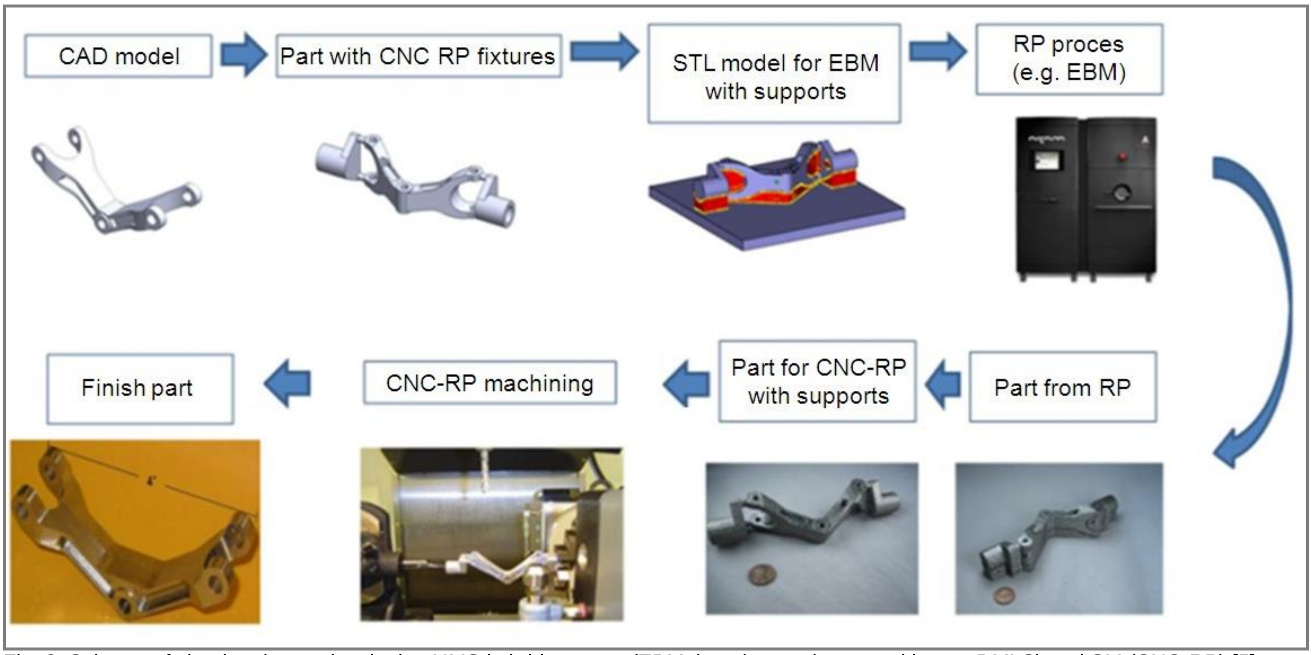

Fig. 3. Scheme of shaping the product in the AIMS hybrid process (EBM, i.e. electron beam melting, or DMLS) and SM (CNC-RP) [5]

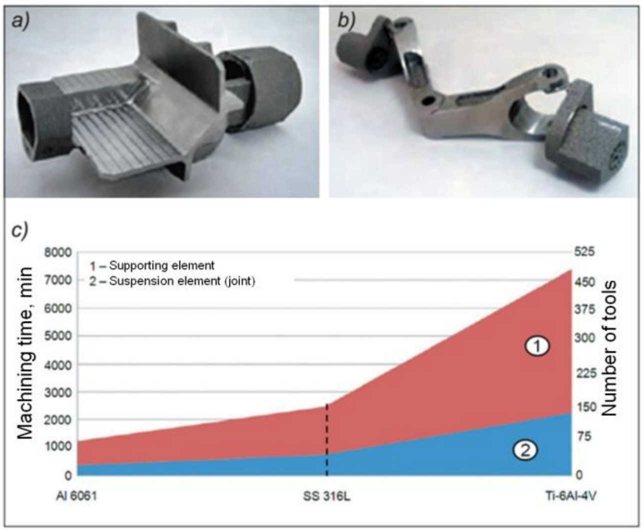

Fig. 4. Examples of parts made by the hybrid method - support (*a*), joint (*b*) - and a comparison of the cutting time for parts made by the RP method on a CNC machine tool (*c*) [5]

Basics of hybrid incremental-removal manufacturing

Previous studies on a laboratory and industrial scale were aimed at creating a modular production platform integrating various incremental techniques (AM) with machining (SM CNC), e.g. [4-7]:

- FDM/extrusion using different variants of CNC machine tools;
- SLM with vertical centers VMC, e.g. Lumex Avance-25, Matsuura, Japan;
- DMD, i.e. direct metal deposition, including laser cladding on a machining center - e.g. Hamuel HSTM 1000 (a five-axis turning and milling center), GF HPM 450U (a five-axis milling center with a tilting table), DMG MORI Lasertec 65 3D (five-axis milling center) or Mazak VC-500 AM (five-axis vertical milling center).

General concept of hybrid AM + SM CNC machining is shown in the pictorial version in Fig. 5. Simultaneously, on the basis of the 3D CAD model, the part is printed based on data transferred in STL format and a CNC control program is created in the appropriate CAM system. At the next stage, the manufactured element is subjected to finishing cutting on a CNC machine tool. An integrated programming system is available, based on the NX CAM package (fig. 4b), enabling complete hybrid processing.

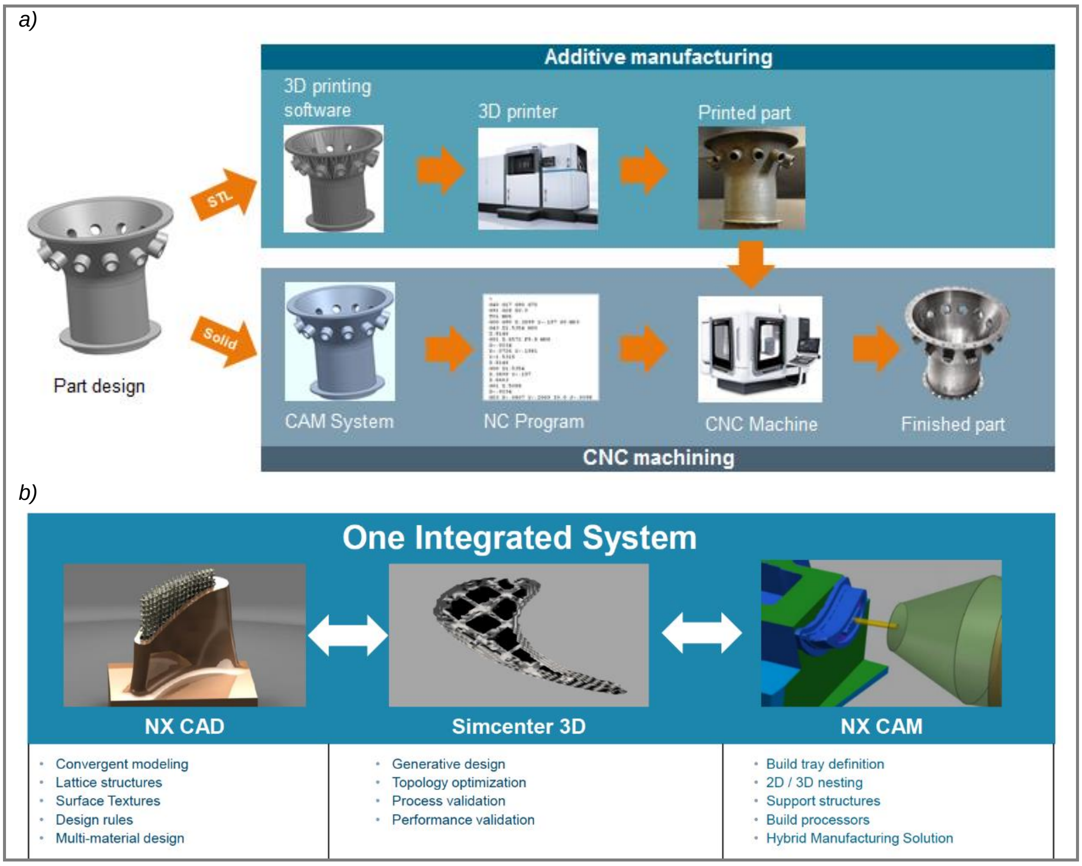

Fig. 5. General concept of integration (*a*) and complete programming (*b*) incremental and CNC machining (AM + CNC) according to Siemens [4]

The basic design problem in the synergistic integration of AM and CNC techniques is to add the system to virtually any CNC machine (new or used, regardless of the control system used) without special modification or after appropriate retrofitting. The pioneer research project, completed in 2008, was RECLAIM (*Remanufacture of high value products using a combined laser cladding, inspection and machining system*) [4, 8], which recommended cost-effective modernization of new CNC machines by installing laser cladding module (fig. 7). It should be mentioned that one of the first Aero-Met Corp. hybrid machine tools, integrating laser welding/application of layers on a CNC milling machine, was already used in 2004 for the manufacture of materials / products for the aviation industry for F-15 fighter aircraft .

An important design problem faced by the originator of the directed metal deposition (DMD) system in the CNC machine tool was the use of standard tool holders, e.g. HSK 63 cone, for mounting the head in the machine spindle (fig. 6b). However, an additional distributor is necessary, which: feeds the head - when mounted in the spindle, cuts off the power supply - when the LMD head is replaced by a milling cutter.

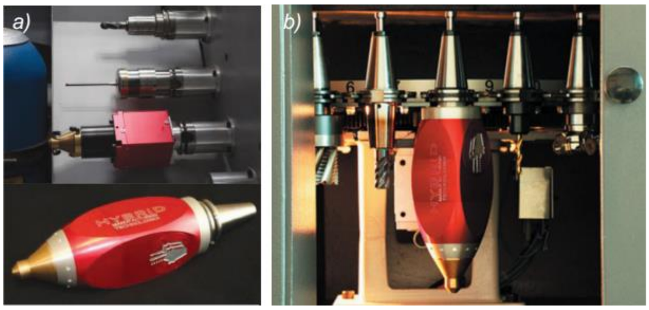

Fig. 6. Example of placing in the tool magazine of the laser head, ball-end mill and measuring probe (*a*) (below the view of the powder cladding head) and the vertical tool magazine of the HSC hybrid turning and milling center (*b*) [4, 9]

The scheme of the construction and operation of a five-axis prototype hybrid machine tool, which was designed in the Laser Laboratory of Assisted Production Processes (LAMP) at the University of Missouri in the late 90s, is shown in fig. 7. The additive process (LMD) and subtractive process (milling) were integrated in the machine tool to allow the creation of thin-walled prototypes with complex external elements that are not obtainable separately in AM (LMD) and SM CNC processes. Other applications of this machine are: repair of damaged elements, creation of gradient functional materials, production of elements with a long overhangs without additional supports, embedding sensors and making special internal channels. The machine is equipped with: Mikron's real-time control NI RT, an IR fiber optic sensor for measuring the temperature in the powder melting zone, the Omron laser displacement sensor for positioning the head and the Fastcom vision system [10].

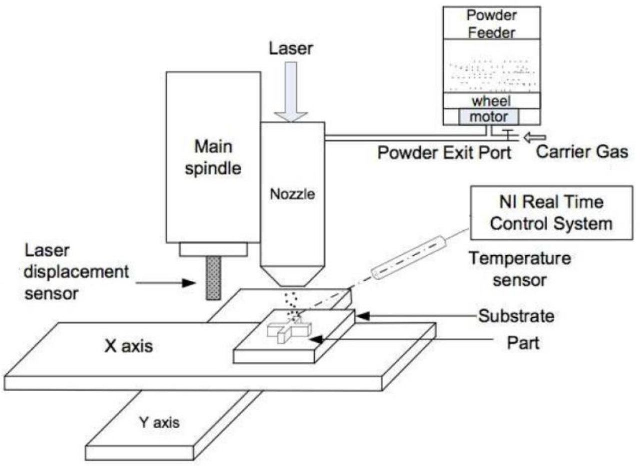

Fig. 7. Construction of a 5-axis hybrid machine tool with a milling spindle and a laser powder cladding head [10]

Fig. 8 shows the structure of the hybrid manufacturing process (A/SM) composed of selective laser melting SLM and CNC milling. The digital CAD model is divided into thin layers, which are then virtually applied by STM, layer by layer. The substrate is attached to the machine table. The part is made of a powder that is fused when the laser scans the surface. The process is repeated and proceeds when the platform is successively reduced by the thickness of the layer, and the deposited powder layers are successively melted and form a fragment of sintered part (2), which then is milled (3). The complete configuration of the part follows two successive stages of alternate incremental and removal (subtractive) machining - respectively (4) and (5) and (6) and (7). It should be emphasized that milling usually eliminates dimensional and shape errors introduced in the previous AM operation. It is possible to make complex internal contours, e.g. miniature cooling channels.

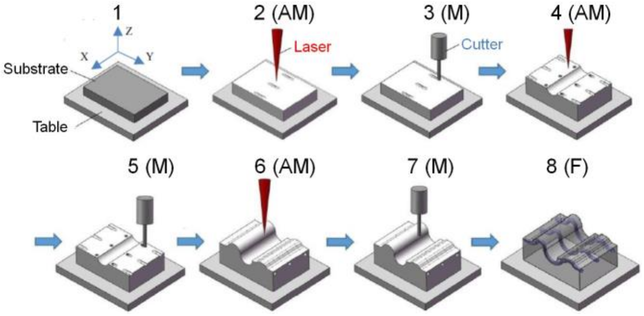

Fig. 8. Structure of the hybrid A/SM process [11]. Marking: AM - additive machining, M - milling, F - finishing (usually polishing)

Examples of the use of AM + SM CNC hybrid processes

In recent years, there has been a significant increase in interest in hybrid additive and removal processes in various applications. This results for at least several reasons [4, 12-15], including the possibility of: producing elements with the desired accuracy and surface quality; extension of complex fragments (e.g. connectors and flange – fig. 9c and fig. 11a), which reduces costs; performing repairs in one fixing; manufacture of multi-materials elements in 3D printing technology (e.g. depositing layers of Inconel 718 - fig. 9c).

The injection mold shown in fig. 9a was made of dispersion-hardening steel 18Ni powder (C300) with a grain size of 35 μm on a corrosion resistant steel substrate by SLM sintering and high speed milling (HSM). A constant thickness of the deposited layer (40 μm) and a special laser scanning strategy were used to avoid distortions or cracks [4]. The speed of the laser beam was equal to 1400 mm/s, and the diameter of the laser spot - approx. 0.2 mm. Milling was performed in a heated state and therefore the cutting temperature was higher than in the conventional process. The part after the machining is still subjected to heat treatment.

The injection mold shown in fig. 9b was made entirely on the Matsuura Lumex Avance-25 hybrid machine tool, the first stage being laser sintering of the metal powder (3-D SLS) and the second - high-speed milling [19]. The machine tool is equipped with a two-bladed compaction system for molten powder - the guide vane cleans the path under the new layer, and the auxiliary layer smoothes and compacts the freshly applied layer. The hybrid process used results in significant cost savings and basically eliminates EDM as a method of making molds and matrices.

The hollow shaft, shown in fig. 9c, was made on an INTEGREX i-400 AM hybrid machine by Mazak by incremental method - in two stages. Two laser heads were used, operating at different capacities - HS LMD and F LMD (fig. 10b). The principle of laser cladding in the AM process is shown in fig. 10a. In incremental machining (fig. 9c), the flange (1), six segments of the spiral coating (2), 12 fins (3) and six stubs (4) from the Inconel 718 alloy are applied (powder with a grain size of 50 ÷ 100 μm). Operations 1, 2 and 3 are carried out using the LMD HS head (high speed LMD), and the nozzles are formed with the LMD head F (fine LMD). The total manufacturing time of the part was 634 min and - interestingly - it was not shorter than the time of the monolithic part of Inconel 718. However, the decisive factors were much lower material and tooling costs and maintenance of the required operational properties (thermal and corrosion resistance, on oxidation and creeping).

Fig. 9. Injection mold with internal cooling channels made in hybrid process A/SM (additive/subtractive manufacturing) (*a*), pressure form made in a hybrid SLM + process CNC milling (*b*) and hollow shaft, made on the needs of the oil industry with locally deposited layers of Inconel 718 (*c*) [4, 11, 13, 16, 17]. Marking: AM/T - additive machining plus turning, AM/F - additive machining plus milling, Z - laser marking

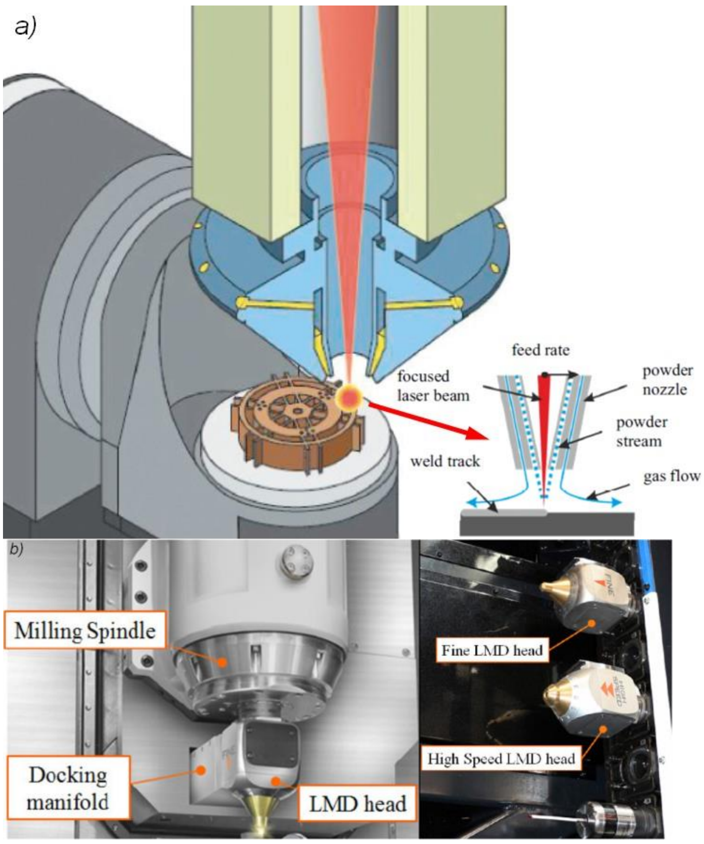

Fig. 10. Principle of LMD (laser metal deposition) process (*a*) and view of heads for deposition layers with different efficiency, mounted in a milling spindle (*b*) [14, 17]

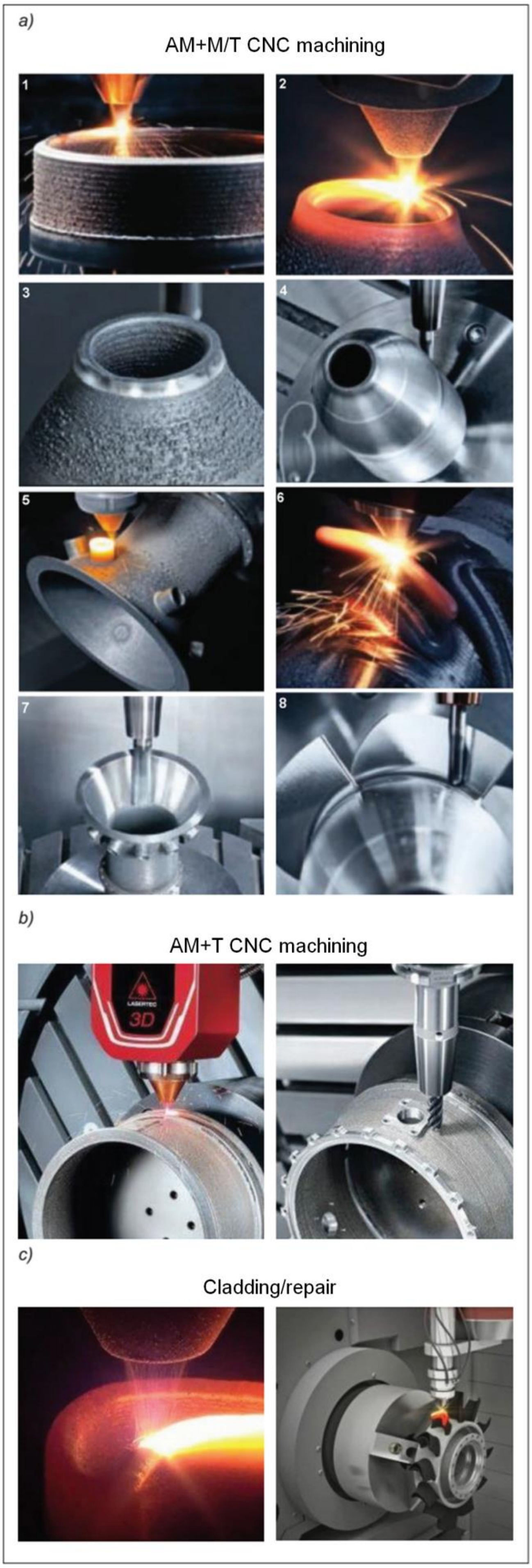

Fig. 11. Examples of powder laser deposition and milling/CNC turning (*a*, *b*) and repair of blades (*c*) [7, 18]

The DMG MORI company has achieved a high level of development in the field of hybrid shaping, coating deposition and repairs [7]. Its standard hybrid machine tool with a high versatility is the Lasertec 65 3D machining center, which uses the powder deposition welding technique which is blown into the zone of the laser beam. This technique is more efficient than laser sintering, e.g. making parts with a mass of approx. 3.5 kg is 20 times faster, and finishing milling is used only in justified cases. The machine tool was created on the basis of a five-axis center for precise milling with the possibility of a five-axis simultaneous machining. The AM unit was equipped with a 2.5 kW diode laser. Examples of technological possibilities and practical application of this machine are presented in fig. 11.

The technological process of gradual part formation is similar to the A/SM process shown in fig. 8. After welding the cylindrical part (1) and the conical part (2), the CNC (3) and finishing (4) are machined. It is possible to build connectors (5) or coils (6), and then finish milling the entire profile (7, 8). The possibilities of the hybrid machine tool are extended by turning, which allows machining of rotational-symmetrical elements with subsequent milling of the risers (fig. 11b). The rotary table is the solution used in welding or repair (fig. 11c), e.g. compressor rotor blades.

Fig. 12a presents a vertical milling center equipped with a laser additive module LENS (Laser Engineered Net Shaping) printing machine by OPTOMEC, which has numerous applications in milling machines, lathes and robots - as a complement to the machining process. An example of a part produced in one setting is shown in fig. 12b.

A new idea is the integration of popular FDM (fused deposition modeling) and CNC milling (fig. 13). This applies to elements made of polymer materials, printed without additional supports or reinforced with metal fillings [20]. CNC machining is used for finishing, trimming or shaping free-form surfaces (fig. 14). It allows to eliminate the unfavorable influence of the FDM process on the shape of the element due to high material shrinkage and the introduction of excessive residual stresses. The construction of a prototype hybrid machine tool equipped with a head for extruding a liquid material is shown in figs. 13a and fig. 13b, and the principle of operation of the head - in fig. 13c.

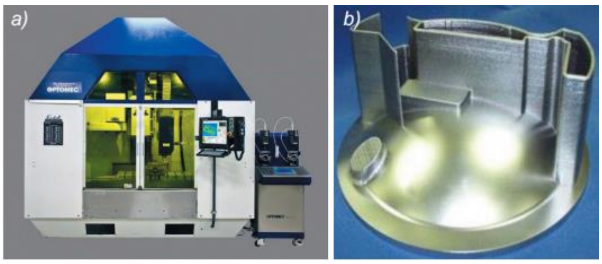

Fig. 12. Vertical milling center equipped with a OPTOMEC LENS AM module (*a*) and an example of a housing made by a hybrid method (*b*) [9]

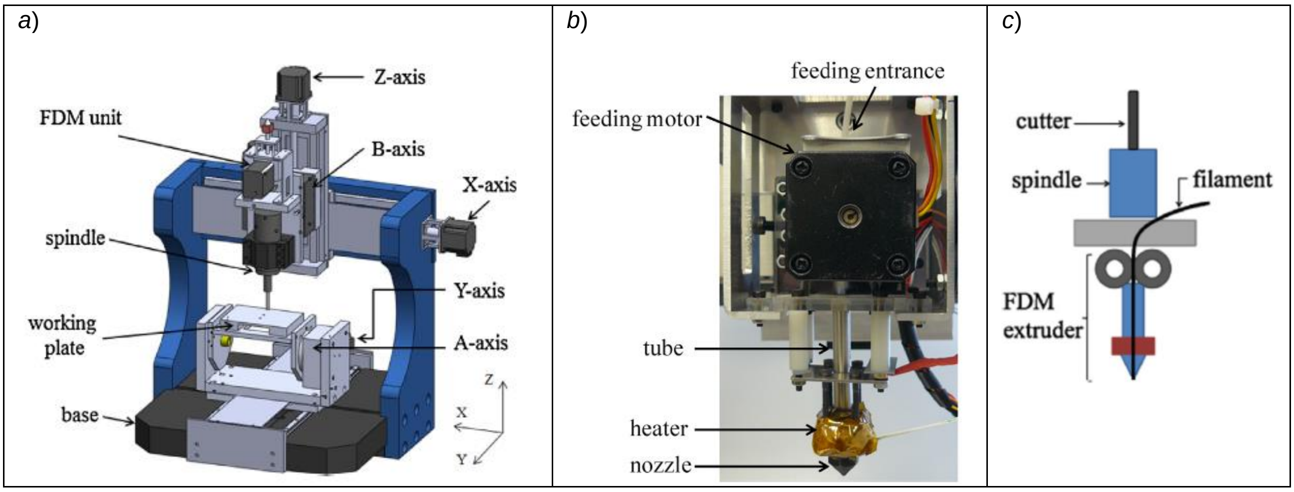

Fig. 13. Construction of the FDM + 5-axis CNC hybrid machine tool: *a*) construction scheme, *b*) construction of the FDM extruder, *c*) the principle of the extrusion head operation [20]

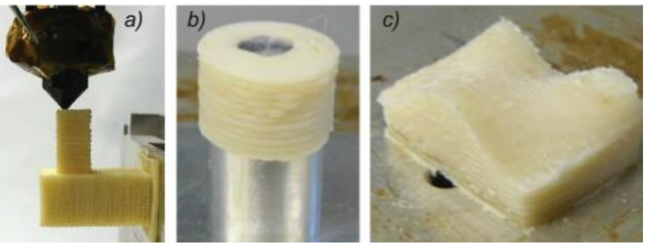

Fig. 14. Examples of parts made on the FDM + CNC hybrid machine tool: *a*) part with overhang (type Γ), *b*) stepped aluminum element with plastic filling, *c*) element with free-form surface after milling [20]

Product repair using the integrated AM + CNC technique

A separate area of research and applications for the hybrid treatment is regeneration/renovation (remanufacturing) of expensive parts for the aviation industry, in which heat-resistant and heat-resistant materials (HRSA alloys) are used on a large scale, e.g. Ti6-4 titanium alloy or Inconel 718. In the initial phase of development, the focus was on repairing turbine blades with Ti-6Al-4V alloy with damaged edges and visible wear scars. Currently, the laser repair technology (LRT) technology - covering several similar techniques of applying layers, such as: direct metal deposition (DMD), LAM (laser additive manufacturing) or laser LMD (laser metal deposition) - it is dynamically developed and finds many applications in practice. In short, this method consists in: removing the material in the vicinity of the damage zone, applying new material filling the cavity and finishing the cutting and polishing, restoring the original geometry and functional properties of the surface.

Currently, manufacturers offer specialized, multi-axial hybrid machine tools (integrating the process of incremental, direct layering with removal process), which are equipped with 3D laser scanners and control devices (3D measurement probes). The complete hybrid process includes: high-speed milling (HSM), 3D surface scanning, model creation and separation of material losses, laser deposition, 3D inspection, deburring / polishing and laser marking [12, 21, 22]. A detailed description of the repair cycle, proposed as part of the RECLAIM project [8, 12], is shown in fig. 15.

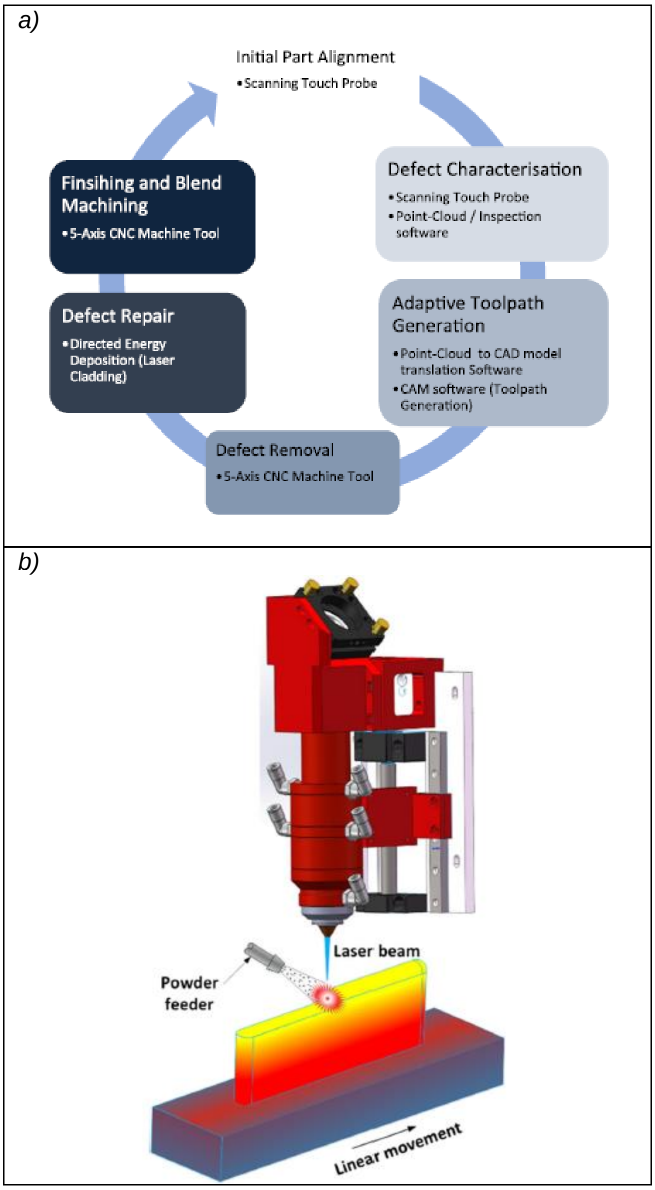

Fig. 15. Concept of hybrid repair technology on a multi-tasking machine (turn-milling machine) (*a*) [12] and the principle of the process of laser-assisted direct metal deposition (*b*) [18]

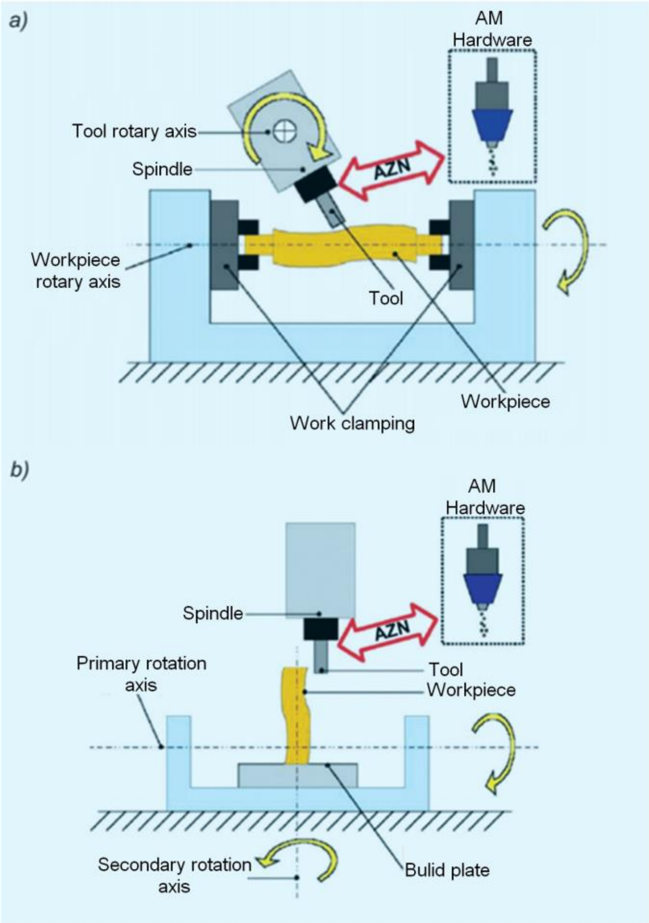

Fig. 16. Configurations of hybrid manufacturing platforms: *a*) on the basis of a turning and milling center, *b*) on the basis of a five-axis machining center (AZN - automatic tool changer) [20]

Fig. 17. Edge deposition (*a*) and milling of the turbine blade after deposition (*b*) [21]

It is believed that a hybrid machine tool with such equipment is the most flexible system for renewing worn parts and absorbs only part of the energy, time and costs required to manufacture a new part.

Configurations of the two most commonly used hybrid platforms in the industry for repairs of worn / damaged parts are shown in fig. 16. The solution from fig. 16a was created on the basis of a turning-milling center. The part is mounted in the spindle axis, which provides a different orientation in relation to the tools (the tool cluster is shown in fig. 6a and special polishing tools are used [21]). An example of hybrid manufacturing on the HSTM 1000 (Hamuel Reichenbacher) manufacturing platform, built according to the concept in fig. 16a, is shown in fig. 17.

In turn, an example of the implementation of hybrid manufacturing on the LASERTEC 65 3D manufacturing platform (made by DMG MORI), built according to the concept from fig. 16b, is shown in fig. 18. In the additive process, the above-mentioned LDT technique is used. In this case, integration includes laser deposition and five-axis machining, which enables the performance of technological tasks such as hybrid manufacturing, deposition of powder coating or repair. It should be noted that the production may consist in the creation of parts from many materials (e.g., copper/brass protrusions applied around the periphery of an Inconel 718 enclosure): corrosion resistant steels, nickel-based superalloys (Inconel 625, Inconel 718), bronze and brass, Cr-Co-Mo alloys, stellite and weldable steel [21, 23].

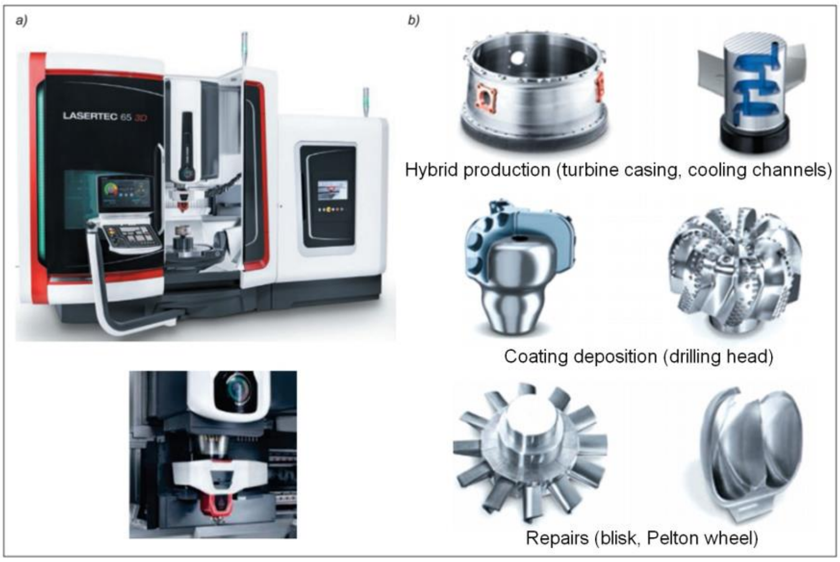

Fig. 18. Integration of a five-axis milling machine with laser cladding (*a*) and examples of application (*b*) [7]

Examples of other large and expensive parts - e.g. compressor casing from Inconel 718 alloy, shaft and planetary gear connector - on which a 420 SS stainless steel layer was applied, as well as a missing titanium alloy forging Ti6-4 is shown in fig. 19.

Fig. 19. Examples of repairing various products using the LDT technique [18]: *a*) repair of the gas compressor housing (material: Inconel 718), *b*) repair of the steel shaft 4340 (welded material: corrosion resistant steel 420 LC), *c*) repair of the planetary gear connector (welded material: 420 LC corrosion resistant steel), *d*) repair of undersized forgings (welded material:Ti6-4 titanium alloy

Conclusions

Implementation of the Production/Generation 4.0 strategy is closely related to the hybridization of manufacturing processes. Its range includes hybrid processes and devices that combine additive shaping with CNC machining (LM/SM CNC) and are not included in the basic classification of hybrid machining processes [1]. Three typical applications are: manufacture of parts (or only some of the complex fragments) of powder materials, application of coatings from non-base materials, repairs.

Additive processing modules, which are installed on various multi-axis CNC machines, use such layer deposition techniques as: FDM, SLM, EBM, DED or LBDW (laser beam deposition welding). The generally accepted principle is the laser metal deposition process (LMD). It is possible to meet with various names of laser techniques used by manufacturers of hybrid machine tools, e.g. LENS, DMD, DED, PBF (powder bed fusion) or POM (precision optical manufacturing) [24].

An important area of application of AM/SM CNC processes are repairs and restoring of functional features to defective parts (e.g. undersized forgings) of large dimensions, made of expensive materials. For this purpose, a special repair technology (LRT) is used.

Currently, manufacturers offer specialized multi-axis hybrid machine tools that integrate the process of incremental, direct layering with finish material removal. These machines are equipped with 3D laser scanners and control devices (3D measurement probes). The integration also includes CAD/CAM and CAI (Computer Aided Inspection) packages.

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