Does Metal Additive Manufacturing in Industry 4.0 Reinforce the Role of Substractive Machining?

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Abstract. The article describes in a review and debatable way a trend that can be seen in modern industry, also known as the fourth industrial revolution or Industry 4.0. After years of dynamic development of additive techniques from polymeric, composite, ceramic and metal materials, it can be noticed that these techniques have penetrated into the modern production reality. In particular, it is used by such industries as space, air, automotive, precision, power, electronics and the medical industry. The article focuses on the answer to the question contained in the title. In almost all applications of metal additive manufacturing, further processing is necessary in order to obtain the correct shape and/or geometry accuracy. So there is a phenomenon of repeated interest in an accurate, often multi-axis, substractive machining. The more problematic machining, the more it is used in machining of elements with the so-called free forms resulting even from optimizing the topology of additively manufactured metal elements. The methods of metal additive manufacturing allow to obtain a geometry that until now was impossible to achieve using conventional methods, and generates additional technological problems in substractive machining. The answer to the somewhat rhetorical question contained in the title of the article is self-evident, and it is confirmed by observations from industry events and literature reports related to classical and hybrid additive-substractive machining methods.

Keywords: Additive manufacturing · Industry 4.0 · Hybrid machining · Additive - substractive machining

1 Introduction – Industry 4.0

The fourth industrial revolution, called Industry 4.0, aims to increase economic competitiveness by integrating modern production techniques with new information technologies [1, 2]. The key factors that enable the fourth industrial revolution include, among others Internet of Things (IoT), Cloud Computing with response dynamics at the level of milliseconds, Big Data - analysis of large data sets on all aspects of product

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development and production, advanced human-machine interfaces, additive manufacturing techniques used both for prototyping and for the execution of individual orders (Fig. 1) [1, 3].

Industry 4.0 is based on the paradigm of serial, personalized production, as a result of which non-traditional methods of obtaining products complying with individual customer requirements should be developed. Therefore, AM can become a key technology for the production of non-standard products due to the ability to create advanced objects with advanced attributes (new materials, shapes) [1]. Thanks to the increased product quality, additive manufacturing is currently used in various industries, such as aviation, biomedicine and production [2, 4]. As a rapidly developing technology for creating accurate and complex objects, it can offer a way to replace conventional production techniques in the near future.

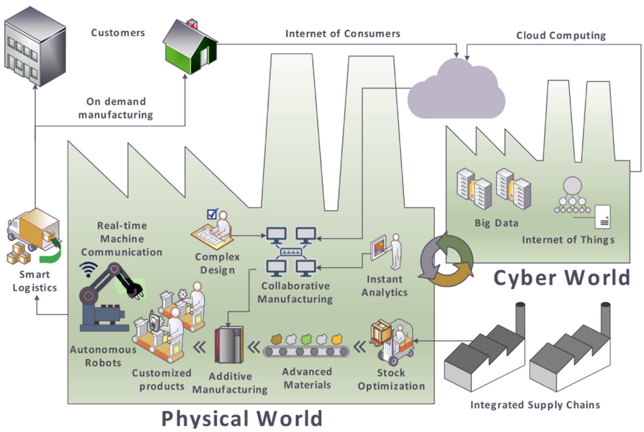

Fig. 1. Scheme of intelligent factories divided into areas and main issues [1]

According to the Wohlers report from 2017 [5], at the moment over 60% of devices for additive manufacturing are used to create functional parts, spare parts and for education purposes. He predicts that with the development of technology, in the next years AM techniques participation will increase in the production of final parts and even finished products. He assumes two scenarios according to which the level of production performed using traditional methods and additive methods will be equal in 2040 or at the latest in 2060. In the first case, he assumes that in 5 years, investment outlays for 3D printers will increase twice, and in 10 years investment outlays on traditional production machines will decrease by 33%, while in the second case, investment outlays for 3D printers and traditional manufacturing machines will remain the same as today. And although on the one hand the above predictions are promising for both the devices manufacturers and for industries that already use AM techniques (i.e. aviation, automotive or medical industry), they also carry a negative impact. If the above predictions prove reliable, due to the savings generated by additive technologies, by 2060 the value of global trade will decrease depending on the scenario by 20% in 2040, or by nearly 25% in 2060. The reason for this is primarily the reduction of import of mass-produced goods in favour of local, low-volume production on demand (this will lead to a significant reduction in production costs, logistics, forwarding, etc.).

2 Techniques of Metal Additive Manufacturing (MAM)

Additive manufacturing techniques use a wide range of materials - from liquid crystal and photocurable polymeric resins, polymer powders through thermoplastics in various forms to metals. And the latter ones have the greatest opportunities in mass production [1, 2, 6, 7]. Metal Additive Manufacturing (MAM) is already the most frequently chosen technique for obtaining complex metal elements in industry [8] in almost all engineering areas [1, 2, 6, 7]. Among the MAM techniques, the most common are Selective Laser Melting and Direct Laser Metal Sintering (SLM/DLMS) implemented in the automotive industry and Electron Beam Melting (EBM). These methods use metal powders on the basis of powder bed. Figure 2 shows an example of the optimal arrangement of small elements in the working space of the SLM device for serial production. Figure 3 shows elements with a larger height after completing the process.

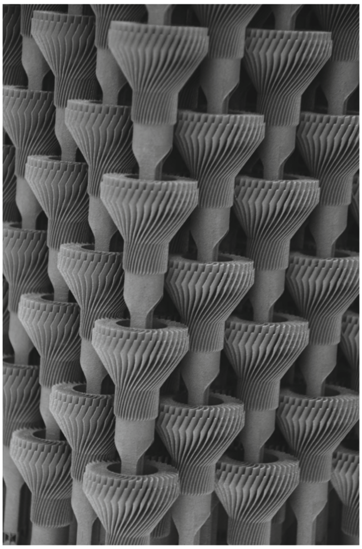

Fig. 2. A series of elements arranged in the working space for the purpose of the largest packing. SLM method. Renishaw brand. [own source - FORMNEXT 2018]

Fig. 3. Elements on the production platform. Not cut off. [own source - FORMNEXT 2018]

The SLM/DLMS methods allow the production of metal elements with virtually unlimited geometry on a unit or production scale. An integral process of additive manufacturing is the removal of obtained elements from work platforms. The most often used for this are electrical discharge machining methods. At trade fairs, more and more companies are offering comprehensive solutions in the field of powder recycling and removal of components from work platforms after MAM, including the recovery of work platforms.

Methods using metal powders are characterized by the complexity of the process, the high cost of equipment and material. In addition, they also require a very expensive infrastructure due to the strong carcinogenic effects of powders. This aspect is finally being revealed even at official trade fairs. This applies not only to the process itself but also to pre- and post-processing, i.e. preparation and drying of the material, and then machining. In each of these processes it is necessary to comply with strict safety regulations (including the risk of ignition). EOS uses costly closed systems based on cassette modules, where the workspace is a cassette placed in the device and picked up by robots. However, this system requires additional, significant expenditure on pre-processing and postprocessing of cassettes, transport and placement by robots. In order to gain the trust of industrial customers, the company has built even a demonstration factory fully serviced by robots. This factory is primarily intended to show that MAM processes using powders can be carried out maintenance-free, and therefore safely.

Therefore, it causes a trend to create and promote alternative methods. Since it is already known that it is not true, as it was originally announced that MAM methods will completely or almost completely remove the classical substractive machining, there appeared methods for which material removal is simply the next stage of the technological process of shaping parts. One of the innovative methods with high volumetric efficiency is WAAM [9]/SMD [10] (Wire + Arc Additive Manufacturing/ Shaped Metal Deposition) or commercial AMLTEC™ (Additive Metal Layering Technologies), reserved for AML Technologies from the USA [11], which rely on multi-layer, precisely controlled arc welding [9, 12–14]. Among the WAAM techniques we can distinguish gas metal arc welding (GMAW) based, gas tungsten arc welding (GTAW) based, and plasma arc welding (PAW) based processes [9]. PAW technology is characterized by a higher energy density than GTAW causing less deformation of the weld and also generating smaller welds at higher welding speeds [15]. WAAM methods are the subject of many studies due to their complexity. For example, Williams et al. [16] studied the effect of dealing with residual stress strategies on mechanical properties and elimination of defects (porosity) in girders made of Ti-6Al-4V, aluminum wing ribs or steel wind tunnels. Ding et al. [17] investigated the influence of different wire feeding strategies on the quality and accuracy of the parts produced. Zhan et al. [18] noted that the WAAM methods should examine many different aspects affecting the final result of manufacturing, among others quality and efficiency of used materials, designing production strategies, modeling and monitoring of processes as well as their development. These methods have recently been implemented in the aviation industry due to the ability to produce very large components and the ability to shape all weldable metals [9, 12]. In particular, the aviation industry has accepted additive methods based on hardfacing, not accepting any (besides bonding and composites) methods of joining metals either by soldering or by welding. For these methods, material removal is a shaping process as for semi-finished products made by plastic forming or foundry methods. However, this is also a MAM method characterized by great freedom of shaping and high volumetric productivity. Figure 4 shows the raw part (a) and the machined element (b) after the WAAM method.

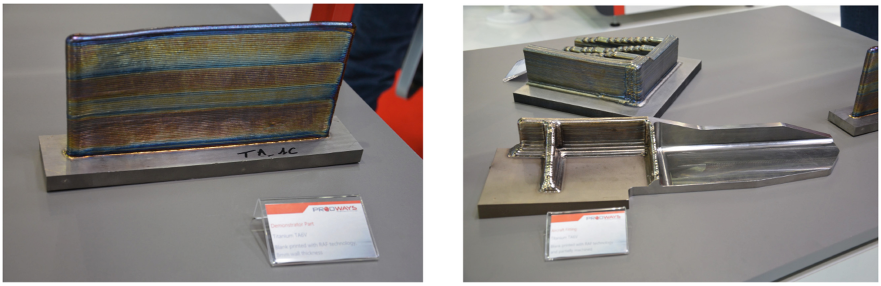

Fig. 4. (a) an unprocessed element produced by the WAAM method; (b) element after milling [own source - FORMNEXT 2018]

In comparison to substractive machining, the WAAM method can reduce the production time by 40–60% and the material removal time by 15–20% depending on the size of the part produced [19]. For example, the use of WAAM technology for the production of aircraft chassis rib saved about 78% of raw material compared to traditional substractive machining [16].

One of the MAM methods also used in the process of combined technologies, as Wang et al. [20] write in a review on the production of titanium alloys, is a Laser Cladding Method (CLAD) also called LMD (Laser Metal Deposition). This method allows to apply layers to already existing objects creating multimaterial hybrids or coated elements. It also allows to regenerate worn parts and, in the case of complex and expensive parts of machine elements, to modify existing geometry.

Szost et al. [21] compared the microstructure and residual stresses generated in components made of Ti-6Al-4V produced by WAAM and CLAD techniques. They noticed that these methods allow to obtain fully dense structures with few porosities in the vicinity of the motherboard, differing in microstructure (CLAD - narrow wavy columnar grains and large columnar grain spreading on almost all the wall height in the WAAM specimen), characterized by occurring stresses (the occurrence of maximum residual stresses in the wall-baseplate transition in both samples with the higher value in WAAM sample was observed).

Another method of increasing popularity is the MFDM (Metal Fused Deposition Modeling) method, referring to the well-known FDM method. It is applicable to small dimensions but it belongs to methods that do not require any industrial infrastructure (desktop devices). The company with the characteristic name Desktop Metal has developed a solution in which the entire process takes place in the office premises. This is a breakthrough in the metal additive manufacturing which until now required laboratory conditions or industrial infrastructure. At least during the final forming of metal parts in the process of e.g. sintering. Elements created on MFDM devices from Desktop Metal are shown in Fig. 5a, and the complete set is shown in Fig. 5b.

Fig. 5. (a) elements made with MFDM; (b) a complete station of the company Desktop Metal. [own source - FORMNEXT 2018]

There is a trend to incorporate the classic FDM method into MAM (and its derivatives). The company BASF (Fig. 6) has implemented, on an industrial scale, high-filled thermoplastic materials in the form of monofilaments with diameters of 1.75 or 3 mm intended for classic, also low-budget, FDM devices.

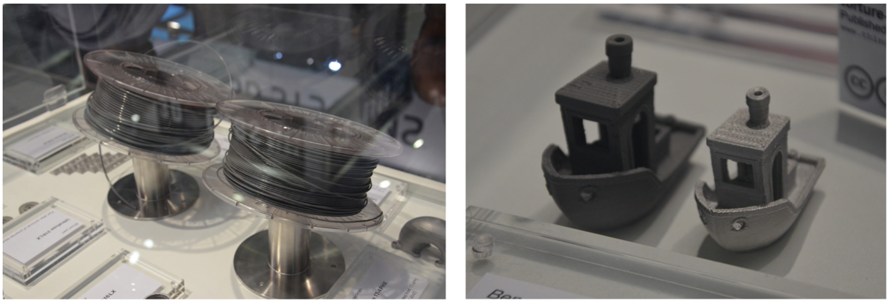

Fig. 6. (a) high-filled with steel filament 316L; (b) standard FDM test model after FDM and after sintering - element made of steel 316L. BASF company. [own source - FORMNEXT 2018]

The elements are then sintered under controlled conditions, as a result of which a metal object is obtained (Fig. 6b). And the matrix is melted/burned out. However, one observes here a volume loss and a significant change in the dimensions of the final object. Although it is becoming a viable alternative to expensive MAM powder methods in some applications [22]. The disadvantage of this method is the need to master the process of post-processing by sintering. And this makes the process more complicated than just "printing" using the FDM method.

3 Substractive Machining as the Next Stage of the Technological Process of Metal Parts After AM

As a rule, machining of the right part is also necessary to correct the inaccuracy of additive methods [23, 24]. This treatment is treated as finishing (postprocessing), especially for elements of cooperating parts (Fig. 7).

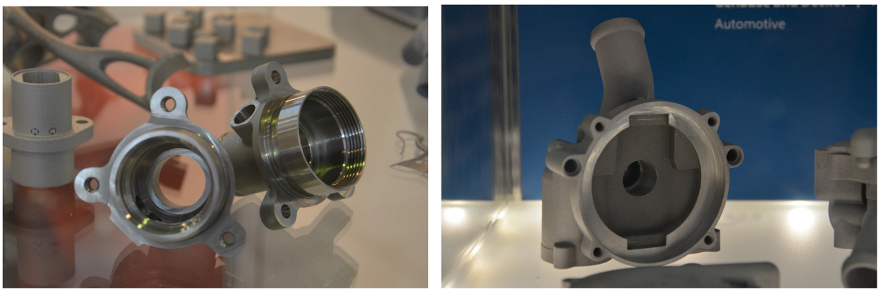

Fig. 7. Examples of exact elements produced MAM and machined with conventional material removal methods. [own source - FORMNEXT 2018]

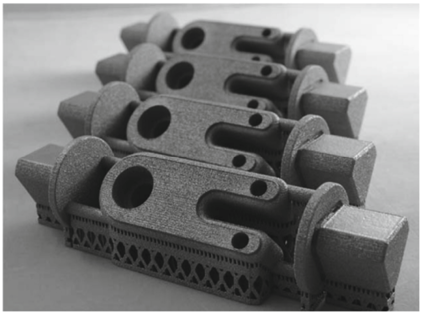

Fig. 8. Elements generated by MAM methods with prepared gripping elements for processing on a double-spindle milling and turning center [24].

It is worth noting that under Industry 4.0, a creation of hybrid methods is expected, which will combine various additive techniques with each other or lead to different combinations of production processes going beyond the conventional MAM processes to produce better products with increased surface quality, endurance strength, etc. [1]. Hybrid machining processes, in particular the combination of additive and substractive processing, require an individual approach to part modeling already at the stage of 3D design in CAD programs. Since one of the biggest problems is just homing and fixing of elements, it is necessary to predict the technology of substractive machining. Here specially designed machining bases are used, which are later removed [24, 25] (Fig. 8).

This approach to hybrid machining not only provides "any" mounting but also, depending on the functions and construction bases, enables to achieve the assumed dimensional and shape accuracy. In special cases, it is possible to use as base elements the production boards, which in this approach during the machining processes act as pallets. Of course, the possibility of machining the lower fragments is then limited. Figure 9 shows the hybrid additive-substractive machining cycle carried out on a series of elements using technological bases generated together with the element during MAM.

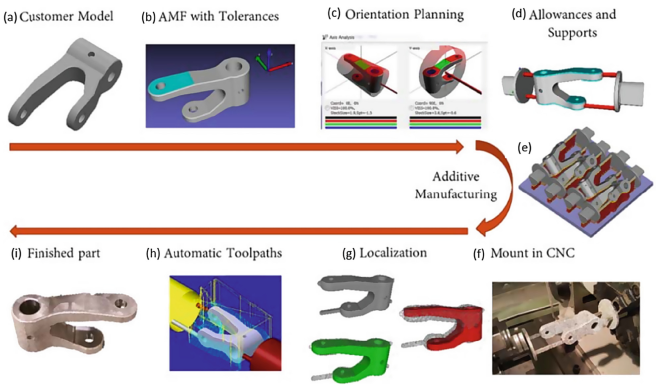

Fig. 9. (a) CAD model; (b) surpluses imposed; (c) orientation in the machining space; (d) ensuring the access and exit of the tool and the design of the gripping elements; (e) MAM; (f) fastening in a machine tool; (g) determination; (h) generating tool paths; (i) finished element [24].

MAM methods using metal powders are used on an industrial scale, especially where surfaces are curved or channels are to be, for example, conformal, as in aircraft constructions. The obtained machining accuracy, treated as postprocessing, depends on its proper preparation already at the design stage of AM parts and processes. This was confirmed by Flynn et al., who in his work [26] noted that the synergistic combination of additive manufacturing processes and substractive machining within a single workstation allows to take advantage of each of them, facilitates the production of elements with high shape factor with the desired geometrical accuracy and surface characteristics. Also Manogharan et al. [25] noted that it is possible to improve the efficiency of the process through a hybrid process consisting of EBM and rapid CNC machining. It is worth adding here that Simons [27] in his article considered the possibility of elimination of substractive methods in favour of additive manufacturing in the production of metal parts. As a result of the analysis of costs, benefits and changes that must be introduced to improve the competitiveness of AM, he noticed that in order to achieve cost competitiveness of the AM technique it would have to have a performance of at least 500 cm^3 per hour. He also stated that material costs are a significant limitation in AM techniques, which, however, will decrease over time as a result of the increasing use of AM techniques not only in special production. A separate problem in the introduction of MAM methods to the industrial everyday life is the need for subcontractors and cooperators to adapt. They need to adapt to new realities and technological barriers related to additive manufacturing methods as elements of a typical technological process [28].

4 Hybrid Techniques; Additive-Subtractive Hybrid Manufacturing (DASH) [29]

The main recipients of additive techniques - the automotive and aviation industries mainly use metal AM processes [30]. However, additively manufactured metal parts usually have large residual stresses caused by the heat due to the nature of the process itself. Therefore, currently manufactured parts are subjected to heat treatment and normalized before further processing. In addition, a finishing treatment is normally required to achieve the surface quality required for certain types and areas of products (bearing seats, cooperating flanges, threaded holes, etc.). The machining is also required to remove the base plates and/or support elements. However, the above operations create additional difficulties, because in order to be able to effectively process an additively manufactured part, you need to know its exact shape, and this part should be properly positioned and fixed in the machining space, which is crucial for the accuracy of the dimensionally shaped part. The most promising way to solve the above problems and even wider industrialization of AM solutions is their combination with subtractive manufacturing (SM) processes [31]. The combination of both techniques gives the opportunity to eliminate weaknesses and strengthen the stronger of each methods. It enables the production of complicated parts in a shorter time ensuring the appropriate quality. Kapil et al. [31] using Hybrid Layered Manufacturing (HLM) investigated the impact of process parameters such as cladding current, stepover and torch speed have been optimized to achieve the desired thickness of the layers and spatter free cladding.

They found that producing a turbine blade as part of a hybrid process is 68.29% more efficient compared to conventional techniques. Stavropoulos et al. in their article [30] they proposed solutions for additive manufacturing aimed at solving existing problems by: complete personalization of machines in all aspects (work space, efficiency, quality of parts, monitoring and control system, etc.), use of existing equipment (laser source, positioning systems, sensors, SM head, etc.) to create a hybrid AM-SM machine and the possibility to re-design and change the machine or its components to meet new needs and even the re-use of machine components in various applications (modular approach). Kendrick et al. [32] considered the use of hybrid systems in local factories - Just-in-Time production (JIT), in specialized stores, using Fab Lab and at home. They note that the use of the proposed solutions will reduce transport costs and the costs of storing various stocks also reducing production lines with JIT. Jones et al. [33] described the use of hybrid techniques (Laser Cladding and CNC) for regeneration of used turbine blades. They emphasized that a fully integrated approach to the regeneration process may eliminate the need to configure a single operation on each machine at all stages of manufacturing, which are not only laborious, but above all generate a series of errors resulting from setting the machine tool to a specific machining operation and mounting. This approach is used on the one hand to increase dimensional accuracy, and on the other hand to accelerate the entire production process. Also the problem of manufacturing complicated parts, where a single production process (substractive or additive) is insufficient, can be increased by means of hybrid techniques [34]. The combination of selective laser melting and precise milling to achieve the desired surface finish was also introduced by Du et al. [35].

A certain reversal of the issue is the use of a head using LMD/DMD technology (Laser Metal Deposition/Direct Metal Deposition) as one of the tools used on metal cutting machine tools. An integral part of the machining process is the additive manufacturing and then machining (material removal) as postprocessing. It can be used as a production process or a process of part regeneration or correction of errors at a construction or technological level.

In April 2018 a report on the development of hybrid techniques was published [36]. According to the report, the development of the hybrid additive manufacturing (HAM) machinery market is related to their wider use in heavy, automotive, aviation, medical, energy and electronic industries. It distinguishes three branches of the use of hybrid additive manufacturing techniques: repairs, production and prototyping. It has been observed that the production of complex components is leaving the conventional production methods in favor of additive techniques. This is caused by the specificity of the processes themselves - the material is added layer by layer, instead of selecting material from the blank for the purpose of mapping geometry as it is in conventional techniques - e.g. milling. This results in shorter production times and significant savings in material consumption and leads to a reduction in component production costs. It is assumed that the aviation segment will have the main market participation due to the increasing speed of using hybrid techniques. He used HAM to produce critical parts that are both light and durable. Fulfillment of these requirements at the highest level is guaranteed by HAM machines. In Europe Airbus, the leading aerospace manufacturer, works with the Swiss Oerlikon group for the production of structural titanium components. According to [30], the car industry has 21% of the total number of additive manufacturing devices. It is anticipated [36] that the European market will grow in a significant CAGR over the forecast period. In February 2018, CECIMO, a Europe-based association of the machine tool industry signed an agreement with EPMA, European Powder Metallurgy Association for the promotion of additive manufacturing and to support the industry in Europe from one application of 3D printing to the other. The report also details the main players involved in the development of HAM: DMG MORI Co., Ltd., Mazak Corporation, Stratasys Ltd, voxeljet AG, Optomec, SLM SOLUTIONS GROUP AG, Matsuura Machinery Corporation and Renishaw Plc. For example, Matsuura Machinery Corporation introduced the Matsuura LUMEX Avance-60 (Fig. 10) to the market using Metal Laser Sintering, which in standard mode can build parts in 3D at a speed of 36 cubic centimeters per hour.

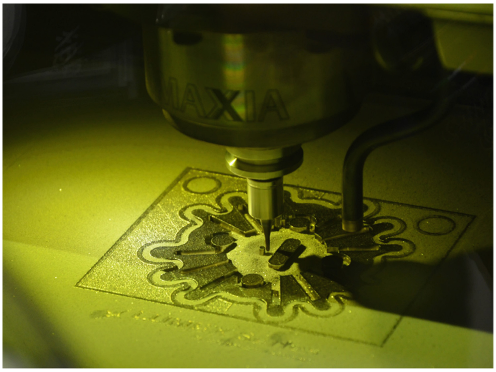

Fig. 10. View of the workspace of the LUMEX device during the milling process of the element without liquid cooling directly after the additive manufacturing process [own source - FORMNEXT 2018]

Figure 11 shows the element produced and processed on the LUMEX device.

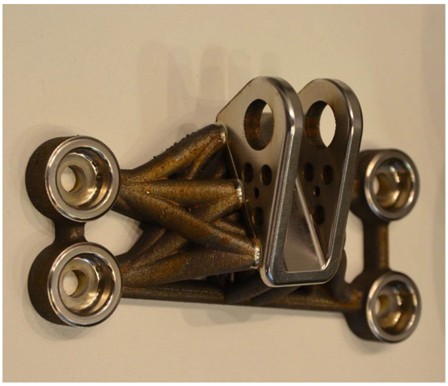

Fig. 11. Element produced and processed in the HAM process on the LUMEX device [own source - FORMNEXT 2018]

DMG MORI introduced LASERTEC 65 3D hybrid using Laser Deposition Welding and 5-axis simultaneous milling in one mount and LASERTEC 30 SLM based on Selective Laser Melting technique. Figure 12 shows a bi-material element with interesting geometry manufactures and processed on a device using Laser Cladding technology, made by DMG MORI.

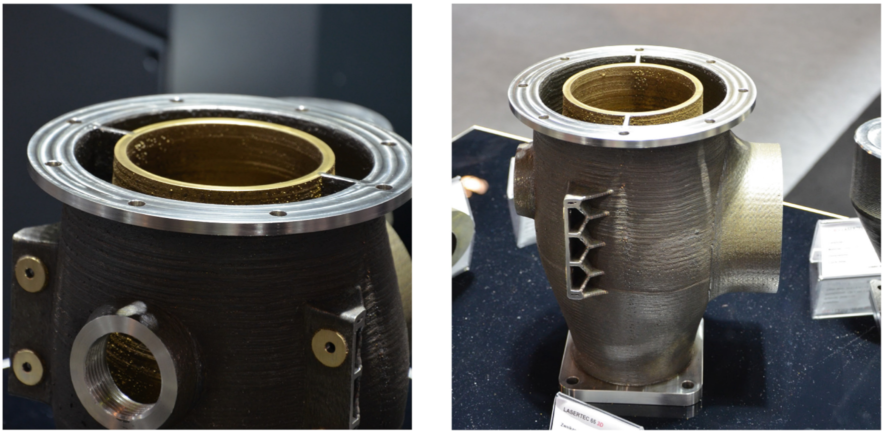

Fig. 12. Bi-material elements produced on DMG MORI LASERTEC 65 3D devices in the hybrid manufacturing process [own source - FORMNEXT 2018]

Mazak Corporation has created an INTEGREX i-400AM machine that using Laser Deposition Welding and 5-axis machining can combine different types of metals, allowing efficient repair of existing worn or damaged components such as air turbine blades. All the above-mentioned devices are used to produce complex components that can not be produced using conventional production methods. Considering the ever wider applications of hybrid techniques and the faster development of devices used in them, according to the report, it is estimated that the global hybrid additive-manufacturing machines market is expected to reach US$ 6,757.1 Mn by 2026. The market is projected to expand at a CAGR of 21.69% during the forecast period. It should be added that device manufacturers are currently investing in software that allows integration of machining processes in integrated CAD/CAM systems, as has been the case with subtractive machining processes for years. CAD/CAM software creators already commercially offer design of technological processes using this type of machining, calling it a hybrid machining (e.g. Siemens NX).

Summary

To conclude the discussion and review that were carried out earlier, the answer to the question contained in the title should be affirmative. With the increase of the importance of industrial metal additive machining, the complexity of machining processes increases considerably both as a separate element of the technological process of manufactured parts as well as in the case of combined, additive - subtractive machining. The most important machining tool makers have already adapted their products to the changing market and not only does the hybrid machining begin to be noticed, but above all the formation of hybrid machining tools. This is caused by considerably lower machining costs, if it is carried out in one mounting on one machine. What's more, virtually all major producers of computer aided manufacturing software already present products that support additive manufacturing or hybrid machining. The increase in the importance of machining (material removal), in particular multiaxial machining, is dictated by the greater possibilities of producing geometrically complex elements from hard-to-machine materials. Particularly SLS, SLM, DLMS and LMD or Laser Cladding methods allow to manufacture elements of special alloys and super alloys. While the progress in the design and manufacture of modern tool materials and coatings allows for effective machining, the bar increases the geometrical complexity that makes the cutting process run in difficult conditions. It is also worth mentioning the growing popularity of WAAM methods generating with high volumetric capacity objects at low level of shape reproduction. In this case, the increase in the importance of cutting machining consists in the necessity of using high-performance methods of multi-axis shaping and even multi-axis roughing. Interestingly, the aviation industry, which does not accept joining metals by welding, very quickly accepted the WAAM method, which is a method of arc welding. This generates further challenges for high-performance machining processes.

Additive manufacturing processes are included as components of typical manufacturing processes and start to be operated by computer-aided manufacturing (CAM) systems as typical technological processes combined with manufacturing processes by subtractive machining methods. Similarly, they begin to be elements of PPC (Production Planning and Control) and ERP (Enterprise Resource Planning) systems. Slowly combining additive and subtractive machining will cease to be a hybrid machining and will become a classic in the fourth industrial revolution that is already taking place. The progress in the field of adaptation of the market of devices, tools and infrastructure to the requirements of Industry 4.0 allows to conclude that it is actually no longer a revolution. In industrialized regions - it is everyday life.

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