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Additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics

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ABSTRACT

Purpose: The paper is a comprehensive review of the literature on additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics.

Design/methodology/approach: Extensive literature studies on conventional powder engineering technologies have been carried out. By using knowledge engineering methods, development perspectives of individual technologies were indicated.

Findings: The additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics as the advanced digital production (ADP) technologies are located in the two-quarters of the dendrological matrix of technologies "wide-stretching oak" and "rooted dwarf mountain pine" respectively. It proves their highest possible potential and attractiveness, as well as their fully exploited attractiveness or substantial development opportunities in this respect.

Originality/value: According to augmented holistic Industry 4.0 model, many materials processing technologies and among them additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics are becoming very important among product manufacturing technologies. They are an essential part not only of powder engineering but also of the manufacturing development according to the concept of Industry 4.0.

Keywords: Powder engineering, Manufacturing of powder products, Hybrid technologies using powders, Additive manufacturing technologies using powders, Dendrological matrix of the technologies potential and attractiveness, Holistic augmented Industry 4.0 model

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

This paper is the third in a series of papers [1-3] containing a comprehensive review of the literature on powder engineering. These papers describe comprehensively the methods of manufacturing powders of metals and their alloys and ceramic powders as well as the technological processes of using these powders for manufacturing finished products. It should be noted that materials processing technologies, which include powder engineering, are essential components of material engineering. The material engineering paradigm boils down to six "E" and can be represented as an octahedron. The expected material is subjected to the expected technological process, consisting in giving the expected shape, shaping the expected structure, which guarantees the expected physicochemical properties ensuring the expected functionality and functional properties of the product [4-7]. When dealing with material engineering, it is impossible to ignore the technological processes of shaping the structure and shape, and it is impossible not to abstract from the requirements that ensure the utility functions of a particular product. It seems quite evident that different demands are placed, for example, on dental implants, and other on elements of a supersonic aircraft, although in both cases the same alloys can be used, e.g. titanium alloys.

Each time the basis for launched production is engineering design inseparably composed of structural design (including the development of the form and geometric shape of the product or its elements), material (related to shaping the structure and properties of materials that meet the requirements) and technological (related to the methods of processing engineering materials to make a product) [4-19]. Structural design methods have been significantly computerised by using widely available computer-aided design CAD software and methodology. The use of computed materials science (CMS) methods and increasingly advanced material design methods is also indispensable [9, 20-32]. Otherwise, it is impossible to properly select engineering material for a specific application from over 100,000 currently known and used engineering materials. Initially, the method of trial and error in material selection was used to replace it approximately 100 years ago with systematic laboratory testing of materials by prototyping subsequent solutions and assessing them in working conditions. Currently, this still applies to about 80% of cases [9,28,32, 33-35]. For the most advanced Materials 4.0 approach, cyber-physical systems and IT tools are used, including material data, artificial intelligence tools, and intelligent machine learning algorithms to calculate the design of materials with assumed functionality.

Currently, production is a complex activity connecting people working in different professions and performing various tasks using many machines, equipment and tools, increasingly automated and using computers, computer networks and robots [4-6, 8-10]. The issues of technological processes are closely related to the current stage of development of the Industrial Revolution Industry 4.0 [13-18, 27-32, 36-43]. The production process is integrated with the Internet of People, Things (IoT) and services [43-52] as part of networks connecting participants in the value chain. Industry 4.0 is the beginning of a new era of digital industrial technology, which uses systems, sensors, machines, details and information technologies, with the necessary participation of people, supporting production automation. The Industry 4.0 concept combines modern production processes composed of various components, such as digital production technology, nanotechnology, biotechnology and new materials [53]. New technologies as part of inclusive and sustainable industrial development (ISID) decide on the introduction of new goods on the market and improvement of production efficiency. Progress is made through the evolutionary transition to advanced digital production (ADP) technologies of the fourth industrial revolution and the combination of equipment, including cobots (robots that collaborate with employees to accomplish tasks), software and communications. Currently, only ten countries in the world have introduced (ADP) technologies, possessing 90% of patents and carrying out as much as 70% of exports in this area. However, it has been estimated that another 40 countries can join this group thanks to intensive, inclusive and sustainable industrial development (ISID) shortly [53].

According to the authors' concept [13-17, 27-31, 33-35, 42,54], the full, extended holistic model of Industry 4.0 in the form of an octahedron contains, among others a technological plane with four mutually complementary components taking into account the development of engineering materials, product manufacturing processes, technological machines, as well as information technology with a defined cyber-physical systems model. One of the main differences is that in addition to cyber-physical systems (CPS) [43, 55-62], which are cyber-IT systems in the current model, there are the remaining components of the technological plane. However, to the addition of the only technology group to date in the Industry 4.0 model, i.e. additive technologies [36-42, 44-52, 54-60, 63-142], other technology groups should be taken into account [13-17, 27-32, 43,122,123]. Many products or their components cannot be made using only additive technologies.

In this context, powder engineering technologies (PET) described in this paper and other papers from the said cycle [1-3] become particularly important. This paper focuses exclusively on powders of metals and their alloys as well as ceramics. The paper deals with characterisation based on a comprehensive review of the literature. Additive technologies for manufacturing products using powders of metals and their alloys. However, manufacturing technologies thick-layer coatings on various substrates and manufacturing gradient materials using powders of metals, their alloys and ceramics, which were described in a separate paper [3], were excluded from the analysis. In turn, this paper incorporates hybrid powder metallurgy technology and conventional plastic deformation to obtain large-sized blocks, billets or bars of tool steels, including high-speed ones. Despite substantial differences, these technologies combine these hybrid technologies, gas atomised spray forming (GASF) technology, which also allows the production of large blocks, including high-speed steels. For this reason, both these technology groups are discussed in the same paper.

2. General characteristics of additive technologies for manufacturing products using metals and their alloys powders

Additive manufacturing (AM) is a process of producing three-dimensional objects based on their 3D computer models, which usually involves combining successive layers of material one after the other [34]. Often this technology is called 3D print, although it is an imprecise term and sometimes even inadequate to the essence of the process. Additive manufacturing technologies have many advantages compared to subtractive manufacturing methods, in which material is removed, for example, by machining or electro-erosion, It is possible to include to them primarily providing less material losses, greater production flexibility and ease of making items with complex shapes. It occurs a clearly noticeable successive and significant improvement in the accuracy and quality of products and an increase in the profitability of production.

Regardless of the method, in all cases, the additive manufacturing process consists of four main stages. The first of them concerns 3D modelling using Computer-Aided Design (CAD) methods, 3D scanning as part of Reverse Engineering and creation of STL-Data (triangulation). The second stage includes data preparation of files, close holes or open surfaces, part orientation and support structures and creates slices from the model and slicing. The third stage covers manufacturing on (AM) machine covering the generation of control data and productions of the parts. Finally, post-processes are used along with the removal of powder, support structures and platform, heat treatment, surface finish, polishing and possibly other operations.

Figures 1b,c gives the proportions between the costs of selected technologies used in Additive Manufacturing related to the volume unit or mass of products made of titanium, respectively. Figure 1d schematically shows the positioning of additive manufacturing in comparison with powder metallurgy technologies. Additive manufacturing (AM) technologies, analogous to hot isostatic pressing (HIP), are suitable for the production of small or medium series of small metal components of a complex shape and weighting a few kilograms at the most. On the other hand, Metal Injection Molding (MIM) and pressing and sintering (P&S) technologies are recommended for the production of small components, but in large series.

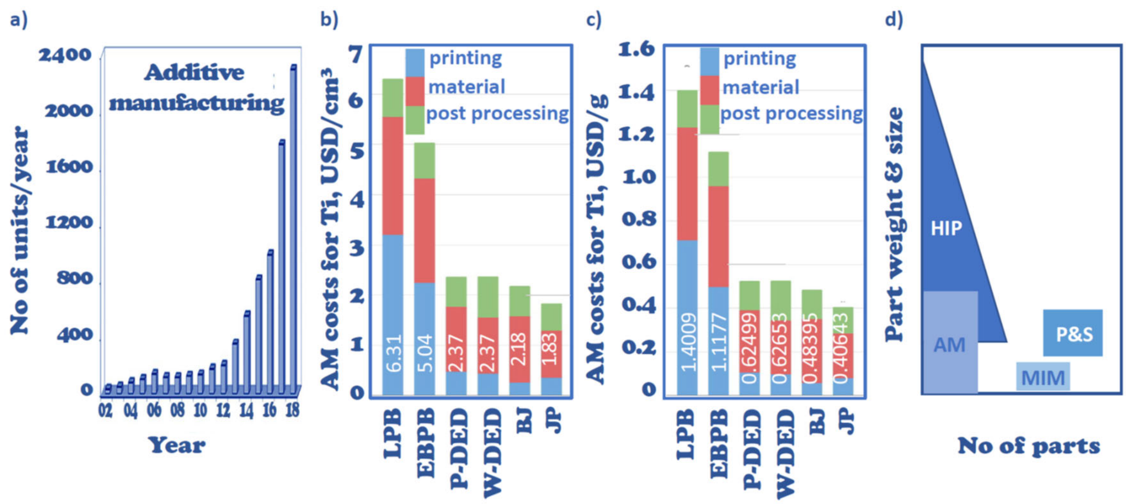

Fig. 1. General characteristics of selected manufacturing additive manufacturing technologies for metal components (according to Woehlers Report 2019 in EPMA information materials); a) increase in sales of industrial installations for additive manufacturing in the years 2000-2018; b, c) forecasting the specific cost in USD/cm^3 (b) and USD/g (c) of a product produced by various additive manufacturing methods: LPB – Laser Powder Bed, EBPB – Electron Beam Powder Bed, DED – Directed Energy Deposition, P – powder, W – wire, BJ – Binder Jetting, JP – Jet Printing; d) the suitability of individual technologies, depending on the mass of a single product and the scale of production: HIP – hot isostatic pressure, HP – hot pressing, AM – additive manufacturing, MIM – metal injection moulding

The rapid development of additive manufacturing observed in recent years [34, 92-95, 97, 101-112, 143-145] results from the apparent benefits of using these technologies. These technologies create increased possibilities and freedom in the design of manufactured elements, usually with a reduced mass with the participation of porous and skeletal areas, while reducing the need for the subtractive manufacturing application. For example, it is possible to make internal channels, e.g. in manufactured tools for shaping polymeric materials. Consumption of input materials is significantly less than in any case of each subtractive manufacturing technology, up to 25 times. It also simplifies the final assembly processes, as it is repeatedly possible to manufacture one-stage without the need for moulds and other metal forming or removal tools. Usually, the production time of these methods is much shorter compared to conventional technologies. The analysis of the cost-effectiveness of additive production is, at the same time, an essential issue for all producers using these technologies [146]. Significant restrictions on the application of these technologies relate to the maximum dimensions of manufactured elements. The standard bed sizes of powders usually do not exceed 250 x 250 x 250 mm. In the case of directed energy deposition (DED), the manufactured elements may be larger in size, but this requires unprofitably long production time. Economically and organisationally unjustified is the use of additive manufacturing (AM) technology for long production series and mass production. Hard-to-weld metal materials can also create difficulties in additive manufacturing processes. Due to the risk of microporosity and due to the isotropy of properties depending on the spatial orientation of manufactured products, it is generally impossible to obtain mechanical properties comparable to elements conventionally produced with the use of plastic deformation technology. In general, these properties are better than in the case of parts manufactured by casting methods.

Initially, additive manufacturing methods were mainly used as rapid prototyping (RP). Over time their strong development was associated with the manufacturing of products, including many metal ones, which is associated with a strong increase in sales of these products since 2012. Increasing demand for purchases of industrial installations for the production of products with these technologies is illustrated in Figure 1a.

Currently, there is a wide set of additive manufacturing (AM) technologies used for metals (Fig. 2). Of all the additive manufacturing methods, only some use metal and their alloys powders as well as powders of ceramic materials and due to the subject of this paper, only these technologies have been analysed in it. For example, a wide range of technologies using polymer materials has been completely omitted, as well as a wide group of technologies that do not provide the industrially required tight dimensional tolerances, and which use very cheap so-called 3D printers widespread on the market and possible to use only for hobby purposes, not for professional purposes, as well as avant-garde technical solutions useful only in the research sphere. Additive manufacturing is strongly associated with the idea of Industry 4.0, because of the essence of this technology, significant commitment in the field of (ICT) is necessary. The development of these technologies is significantly associated with progress in various industrial sectors, including in the aviation industry, energy, automotive industry, medical supply, especially in surgical implants and dental applications, in the tool industry and in the production of many consumer goods. For example, additive technologies are often used to produce matrices with high geometric complexity, for example, with internal channels and those that cannot be produced by conventional subtractive manufacturing methods. They often need to be used as finishing in places requiring appropriate dimensional tolerances or roughness [147]. This paper characterizes the main of additive manufacturing technologies and methods in which metal and their alloy

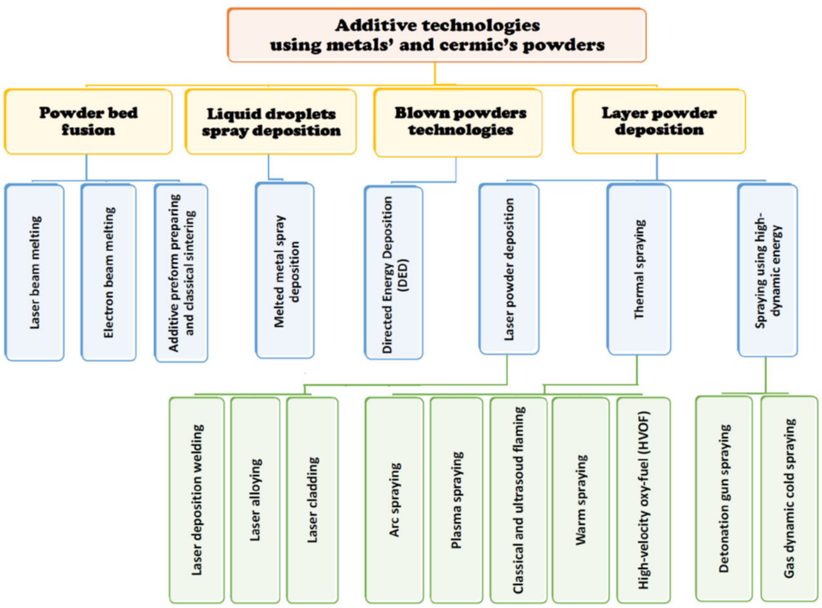

Fig. 2. The general classification of additive manufacturing technologies and methods in which metal and their alloys powders and engineering ceramics powders are used

powders and engineering ceramics are used. It is described the vast application field of technologies using metal and their alloys powders, much more comprehensive than traditional powder metallurgy.

Since this paper is one of four parts of the series of papers on the use of powders of metals and their alloys and ceramics, the only part on the additive technology is described. All technologies in this group are discussed, with the exception of layers powder deposition, which is the subject of another paper.

3. Selective Laser Sintering

Selective Laser Sintering (SLS) is currently one of the most popular and fastest-growing additive manufacturing technologies [148] in the laser additive manufacturing (LAM) group, classified in Figure 2 as Laser Beam Melting (LBM). Selective laser sintering (SLS) technology was first developed in the mid-1980s at the University of Texas in Austin, USA [149]. In commercial terms, it was the first Powder Bed Fusion (PBF) technology [148]. In Germany, the Selective Laser Melting (SLM) technology was developed, which resulted in the creation of two companies: SLM Solutions GmbH and Realizer GmbH. The other two CONCEPTLASER laser bonding technologies and direct laser metal sintering (DMLS) implemented by the company by EOS are similar [150]. Due to the almost simultaneous development of this method in various research and industrial centres, multiple names have also been introduced, including Selective Laser Melting (SLM), which could suggest a different mechanism for joining powder particles than sintering. Even if it is assumed that each subsequent layer of powder is melting, or slightly melting, it is still sintering but with the participation of the liquid phase. Phenomena occurring at that time are similar to those described during the heating of supersolidus and shown in [2]. Therefore, the method known as selective laser melting (SLM) is actually identical to the discussed (SLS) method, when sintering takes place with the participation of the liquid phase as Liquid Phase Sintering (LPS). Other names of this technology are also known, most often even in practice not differing from the (SLS) method, called direct metal laser sintering (DMLS) or high-temperature laser sintering (HTLS). All of the above technologies are similar in terms of basic operating principles and are presented together as one, using the name (SLS).

This process uses a bed of metal or alloy powder (Fig. 3), which is broken down into thin layers for precise sintering using a laser beam [151]. Usually, a laser beam of infrared

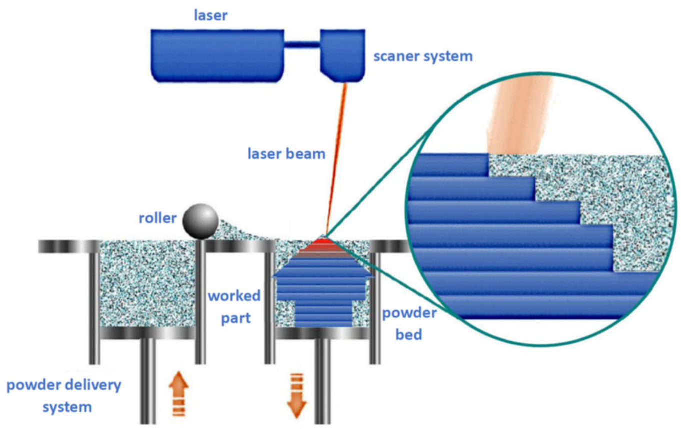

Fig. 3. Scheme of selective laser sintering

radiation is used, which source is a CO_2 or Nd:YAG laser. The process is applied to melt metals or metal alloys powder particles, and even a mixture of one or several metals or alloys, ceramic powders, as well as glass or polymeric materials powders not included in the analysis under of this paper. The (SLS) method is used, among others for sintering a wide range of metal powders, including but not limited to light alloys, titanium alloys, steel, cobalt and chromium alloys, as well as superalloys and mixtures thereof, or ceramics and composite materials [152-155], as well as polymer materials powders not covered by this paper such as nylon, polystyrene and polyamide. For some (SLS) devices, use one-component powder, usually made in a ball mill, but in most cases, two-component powders, usually in the form of coated powders or a mix of powders, are used.

The product manufacturing process is computer-controlled after designing and modelling using appropriate computer-aided design (CAD) software [152,156]. During the technological process, the powder layers are first combined with the working plate of the device, most often by manufacturing appropriate technological brackets or supports, removed from the product mechanically after the process. Then subsequent layers of the manufactured element are created with a computer-designed 3D shape. The table with the next layer of powder is lowered to a fixed height corresponding to one layer thickness resulting from the automatic virtual spatial division of the object's model into layers of fixed thickness. After each cycle corresponding to one section of the powder bed, a new powder layer is applied on top [152,154,157,158]. In order to produce any product using (SLS) technology, successive layers of powder or a powder mix with computer-designed thickness are automatically spread on the working surface of the base plate with automatic position control, and then on the surface of previously bonded layers (Fig. 3). Each layer of powder is levelled with a scraper each time.

The laser beam is guided over the surface of the next layer of powder under the design assumptions made with the use of (CAD) software based on reverse engineering (RE) scanning data. The sintering of powder particles is progressing in a strictly defined manner and selectively selected places on the powder surface. Subsequently, local sintering takes place with the participation of the liquid phase or in the solid-state of two or several powder particles located in the same layer currently affected by the laser beam, with part of the element previously manufactured by this method, pre-consolidated in previous laser beam transitions [154,157,159]. The (SLS) device heats loose powder material in the bed just below its melting point to facilitate local temperature rise with a laser beam. Under the influence of the laser beam, the material passes from a solid-state, in the form of a powder, through a liquid state to a solid-state, in the form of a consolidated manufactured item. Alternatively, it is possible to partially melt the powder at the boundaries of particles or only diffusive transfer of matter according to the mechanisms given in [2]. Laser in single-component powders melts only the outer surface of the powder particles, as a result of which the unmelted solid cores of such particles are combined with a previously sintered layer [155,158,160]. The powder distribution process and cyclic laser sintering are repeated several times layer by layer until the completed design obtains a completely consolidated element. The produced part can be recovered after cooling and cleaning, remove excess powder. If the sintered powder surrounding such an element during the process cannot be mechanically removed using a scraper, it can be disposed of through small windows or drainage holes specially designed for the given part.

The quality of components manufactured by SLS can be affected by the quality of the powder and laser power, which affect the density of the manufactured item. Because the density depends on the peak power of the laser, therefore the time of laser impact is not very important, most often the pulse laser is used. It is possible to use also a double or even multiple laser system. The quality of manufactured elements is influenced by many factors, including the operator's design and experience as well as the proper level of device maintenance. The sintering process depends significantly on the selection of sintering conditions, mainly the type and size of powder, laser power, laser spot diameter, laser beam overlap at subsequent passes, the thickness of a single layer and the orientation of the manufactured part concerning the base plate [161]. Some elements are most preferably produced in a plane oriented at an angle of 45° [152,153] relative to the base plate. The particle size range of the powder is 20 to 70 μm, and the thickness of a single layer corresponds less as 0.1 mm. The system ensures monitoring of the manufactured item temperature and laser sintering conditions with repeatable mechanical properties throughout the volume. Depending on the powdered material after laser sintering, it is possible to achieve up to 100% density and properties of materials with identical chemical composition but produced by conventional methods. Exemplary structures of solid sintered metal alloys from powders of these alloys by the selective laser sintering method are shown in Figure 4.

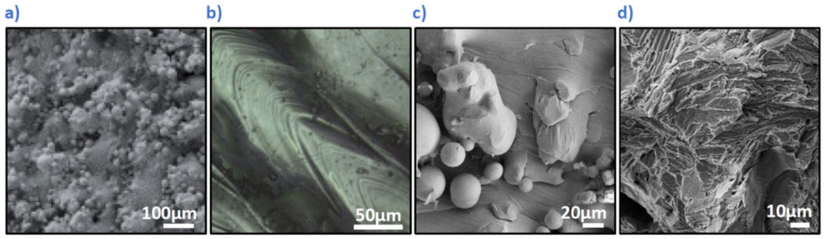

Fig. 4. The structure of solid sintered metal alloys from powders of these alloys by the selective laser sintering method: a) austenitic 316L steel according to ASTM (SEM); b) CoCr25W5Mo5Si alloy – visible adjacent laser paths (LM); c) as figure b (SEM); d) breakthrough as in figure a) after static tensile (SEM)

(SLS) technologies are widely used all over the world because it is easy to produce parts with very complex shapes directly from digital data in (CAD) systems, without having to create any tools (Fig. 5). One of the reasons for the popularity of this technology is the ability to design and manufacture elements with innovative structures, e.g. multi-material, with complex geometric features, including cellular structure [148]. (SLS) technologies allow the

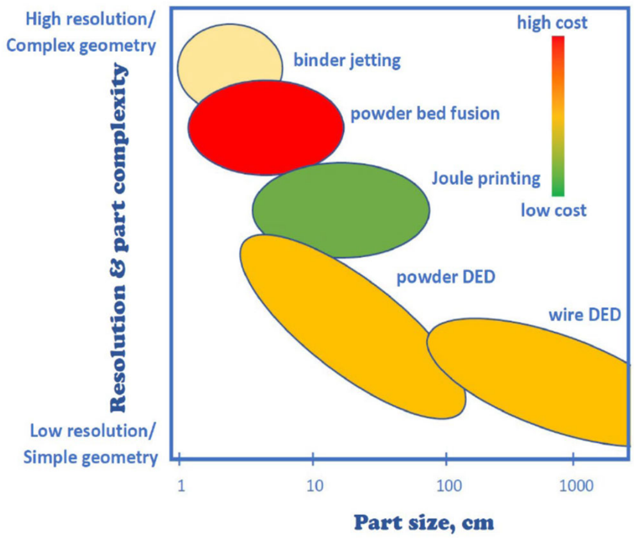

Fig. 5. Areas of potential applications of selected additive technologies

production of individual parts or elements in small series, in accordance with the individual requirements of the market, providing recesses, cuts and internal channels that are difficult or even impossible to achieve in a conventional manner [152-158, 160].

A significant increase in process efficiency can be achieved by simultaneously loading several or even smaller elements into the working chamber of the device. (SLS) methods are used, among others for Rapid Tooling (RT) steel moulds for injection moulding or pressure casting, for metal stamping, dies, as well as for machine parts, and now less often for Rapid Prototyping (RP) and for the production of metal prototypes end products. Currently, these technologies have also found application in art, exhibitions, industrial design, and even in jewellery making. These methods are also used for applications in medicine, implantology, regenerative medicine and regenerative dentistry, for various endoprostheses, e.g. in maxillofacial surgery and for the production of highly specialized tools used in medicine [61,162]. Another example is own research [152,153] regarding the development of metallic microporous materials with average micropores of 100-600 nm, microporous composite materials and microscopic composite materials made using hybrid technologies of rapid production with selective laser sintering (SLS) alloys titanium and TiAl6V4 (Fig. 6). This technology is combined with chemical treatment, by etching the surface of porous skeletons, and then covering the inner surface of the micropores with biocompatible materials by means of depositing (ALD) atomic layers or by dipping, pressing, sol-gel method and by infiltration [161].

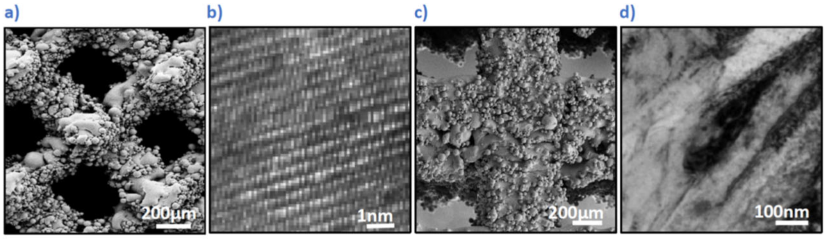

Fig. 6. Structure; a) a porous skeleton of pure titanium sintered from powder by selective laser sintering (SEM); b) as in fig. a) – distribution of titanium atoms in a spatial network (HRTEM thin foil); c) Ti6Al4V sintered from powder using the method of selective laser sintering (SEM); d) as fig. c) (TEM thin foil)

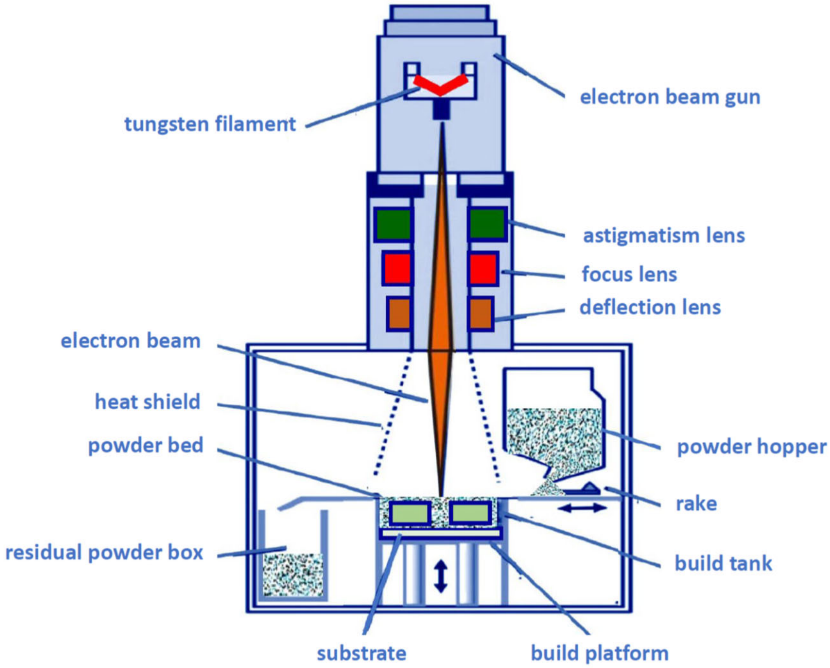

Fig. 7. Diagram of the electron beam melting (EBM) method

4. Electron Beam Selective Melting

Electron beam selective melting (EBSM) [163], more often and shortly called electron beam melting (EBM), is an additive technology that is part of the powder bed fusion group and is similar to (SLS). Still, an electron beam is used to melt metal powders instead of a laser beam (Fig. 7) [158, 164-170]. An alternative variation of this technology, not analysed in this paper, uses metal wire as the raw material melted by an electron beam. The process was launched around 1997 by Arcam AB Corporation in Sweden, acquired in 2016 by GE Additive, which is the only leading company currently selling machines using this technology. (EBM) technology differs from selective laser sintering because the raw material melts completely. In (EBM) technology, the accelerated electron beam emitted by a tungsten electron gun after passing through the electromagnetic coil interaction zone with a frequency of up to thousands of hertz focusing the beam and providing the required beam diameter is specially deflected and directed according to the design in the (CAD) system to the right place on the surface of the powder bed (Fig. 7).

The process requires electrical charges, so only conductive materials can be used because without this, the interaction between the electron beam and the powder cannot occur. The electron gun has no moving mechanical parts for deflecting the beam, which ensures a very high scanning speed, even up to 1000 m/s and allows the constitution of the manufactured item with high efficiency up to 3300 cm^3/h, which in the case of a light alloy, such as titanium gives deposition rates 18 kg/h. Metal powders are supplied in a thin layer, up to 100 µm thick, forming a powder bed. Constant scanning of the powder bed with a precisely focused electron beam in high vacuum, 1.333 x 10^{-2} Pa or more, causes the powder to melt and attach another layer to previously created layers of the manufactured element. The manufactured part is made of powders layer by layer, each of which melts in places where the electron beam hits, and after it solidifies, the process is repeated for subsequent layers until the finished element is formed. As a result of running the metal powder, its kinetic energy is transformed into thermal energy [165].

If the temperature rises above the melting point of the powder, then the surface layer of the powder is melted and the material is sintered with the previously formed layers. Due to the high cooling rates, in the heat-affected zone grains usually grow through several layers along the (EBSM) growth direction, with scanning directions being changed. If this process occurs at a higher temperature (up to 1000°C) during solidification, and mainly in a solid-state, phase changes occurring in the equilibrium system for the alloys produced. There is electrostatic repulsion between metal powder particles, and when ceramic powders or mixtures with them are used, the electrical conductivity is poor, which causes the powder to blow and hinders melting. Powder blowing can be prevented by preheating the substrate, resulting in slight sintering of the powder bed. The (EBM) process takes place in a vacuum, which is why the elements can be made of reactive metals, e.g. titanium, with high affinity for oxygen with high energy efficiency, even 5-10 times higher than in the case of open processes in laser technology. At the same time, the electron spot is wider than the laser one, which results in a relative reduction in the accuracy of manufacturing elements using this method. The presence of a vacuum ensures no pollution, unlike laser and arc processes when it is necessary to use inert gases. The (EBM) method is much faster and cheaper compared to conventional machining methods, including products and components made of titanium and its alloys. In addition, its application can simultaneously reduce manufacturing costs, reduce the weight of the element and reduce manufacturing time. The (EBM) method has 3-5 times higher efficiency than other additive metal fabrication technologies, which places this technology among the most efficient additive technologies. Parts made using the (EBM) method are filled in the whole volume, therefore infiltration is not used. Machining operations including grinding may be required to ensure required dimensional tolerances and roughness [169]. The dimensions of the manufactured parts are limited to a diameter of 350 mm and a height of 380 mm when selective laser sintering machines can produce larger parts up to twice. The advantages of this technology include the fact that after the process, a large part of the unalloyed powder can be reused almost directly. It is of particular importance, because e.g. in the aviation sector it often happens that only 20% of the purchased material is actually used to manufacture the designed elements when almost 80% is removed in subtractive manufacturing processes as waste to be recycled.

Table 1.
A set of metal alloys for which electron beam melting technology is used on an industrial or laboratory scale

No.	Alloy groups	Used alloys
1	Co–Cr–Mo	Co-26Cr-6Mo-0.2C
		Co-28Cr-6Mo-0.23C-0.17N
2	Cu	Pure Cu
3	Fe	Pure Fe
		316L
		H13
4	Nb	Nb
5	Ni	IN625
		IN718
		CMSX-4
		Rene142
6	Ti	Pure Ti
		Ti-6Al-4V
		Ti-48Al-2Cr-2Nb
		Ti-45Al-7Nb-0,3W
7	Open-cellular materials	Fe/stainless stel
		TiAl/IN625
		Co-Cr
		Cu

(EBM) technology has found wide application in machining various materials. In work [171], based on numerous sources, metal alloys for which electron beam melting technology is used on an industrial or laboratory scale are listed (Tab. 1). These materials include Inconel, copper, niobium, aluminium, loose metallic glass, stainless steel, pure titanium and titanium alloys, Vitalium Co-Cr alloys and intermetallic phases γ-TiAl used for turbine blades in gas turbine engines.

5. Directed Energy Deposition

Directed Energy Deposition (DED) [172-177] has gained many names, including Electron Beam Additive Manufacturing (EBAM), Laser melted deposition (LMD), Laser Engineered Net Shaping (LENS), 3D Laser Cladding (LC) and Directed Light Fabrication (DLF). The process involves applying the melted powder stream layer by layer. However, the material can also be fed in the form of wire, and melting it with a laser beam, electron beam or plasma arc in an inert gas shield. A typical device for directed energy deposition consists of a head for feeding the deposited material (Fig. 8) and an aggregated or autonomous radiation beam projector, which melts the supplied wire by directing high-power radiation. The nozzle head that embeds the material is usually mounted on a five-axis robot-controlled arm.

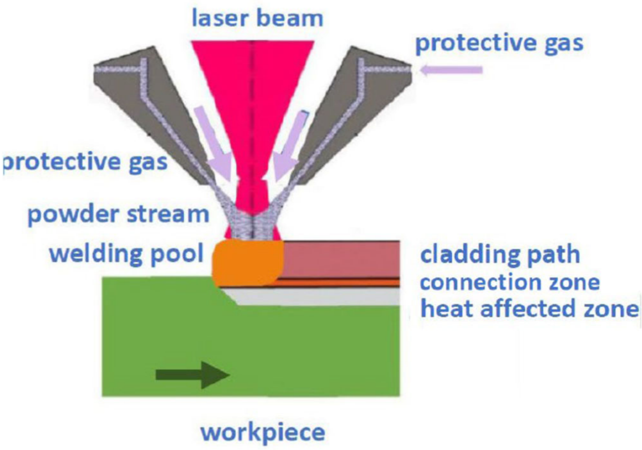

Fig. 8. Diagram of the head and the laser melted deposition process

(DED) technology is very useful for depositing materials and producing finished products from scratch by the additive method. However, it may apply to the application of layers, which is discussed elsewhere in this paper. This technology could be used to repair defects in various elements, arising, among others as a result of manufacturing errors or resulting from exploitation. It is possible to manufacture parts larger than 1 meter, and in some cases larger than 5 meters. In terms of size, this technology is second to none. Because this technology, primarily when used for the production of large and huge components, does not guarantee a sufficiently high smoothness, devices for their production are often combined with (CNC) numerically controlled machines. With the use of the (DED) machine, a ready-made element is produced, and then, using a (CNC) machine tool, it is milled to give it the right size and smoothness. (DED) machines are also often mounted directly on existing (CNC) equipment. In the production of small-size components, the feedstock almost exclusively powders, when in the production of larger-sized components it is one of the possible forms of input material.

These technologies in various forms have existed for decades. Laser welding and electron beam welding were technologies enabling the joining of metals and alloys. They were and still are widely used in the aerospace industry. For some time, actions have been taken to apply them to additive manufacturing. These activities have been undertaken in many industrial sectors and hence their numerous applications today. Typical applications include the repair and maintenance of structural components.

The main advantage of (DED) technology for the production and repair of three-dimensional elements is the accuracy and the ability to control the production of the structure to a large extent, which allows the manufacturing of small three-dimensional parts. However, the process is usually long and the speed of product constitution is low. The use of materials is also limited. This technology is mainly used for the production of titanium, tantalum and cobalt components. It is the reason why the use of (DED) technology is usually limited to the aviation, automotive and space sectors. Due to limited development opportunities, this process is not considered as an applicable technology in major industrial sectors.

In many cases, these technologies known as (LENS) have been used to manufacture or repair military equipment, including satellites and military aircraft. It, among other things, caused the development restrictions of this technology, because for years it was kept secret, which became a direct reason for the development of other substitution technologies that have developed much more. (DED) technology was then widely used to repair engine turbine blades and other high-class equipment. The possibilities of using this technology for commercial aircraft components in the automotive and shipbuilding industries are being considered.

6. Gas Atomized Spray Forming

The gas atomized spray forming (GASF) process, most often referred to as Spray Forming (SF) or Controlled Spray Deposition (CSD) is also known as spray deposition, in-situ compaction and even spray casting. In the classification (Fig. 2) it is specified as liquid droplets spray deposition [178-187]. It is a hybrid process that combines in one operation the gas atomisation phase of the powder with the formation of large integrated blocks, of a similar size as in the methods of the (ASP) group or individual elements, but differently as in other technologies discussed so far.

Therefore, this technology can be treated as a hybrid, because large-size blocks and even billets produced in this way undergo further plastic processing by forging and rolling, and the atomisation and deposition phase itself on a properly shaped substrate can be considered a casting operation. The method involves the preparation of liquid metal or alloy by conventional metallurgical methods usually in an induction furnace and after pouring it into a ladle, bringing it to atomisation with an inert gas in a sealed chamber with simultaneous merging of individual droplets, striking a suitably shaped substrate in a semi-solid state, containing the liquid fraction sufficient for consolidation with the previously applied layer (Fig. 9).

The molten metal is poured into the tundish to lower it slowly in the form of a narrow free-falling stream through a small diameter ceramic nozzle. This stream of liquid metal is disintegrated into droplets by an annular system of gas streams to hit the substrate. Subsequent layers are solidified with those previously applied until the entire element is made. Usually, the flow rate of the molten alloy is 1-20 kg/min, but it can be increased by using a double atomizer. This technology can produce steel blocks or billets with a mass of even more than 1 ton, in the case of nickel superalloys up to 500 kg and billets of Al alloys up to a mass of approx. 400 kg. Spray moulding has found application in a wide area of for the production of high-speed steels, for the lining of stainless steel pipes in incinerators, nickel superalloys, for discs and rings for the airspace of jet engines, for aluminium-titanium, aluminium-neodymium and aluminium-silicon alloys for cylinder liners and aluminium-silver sputtering discs.

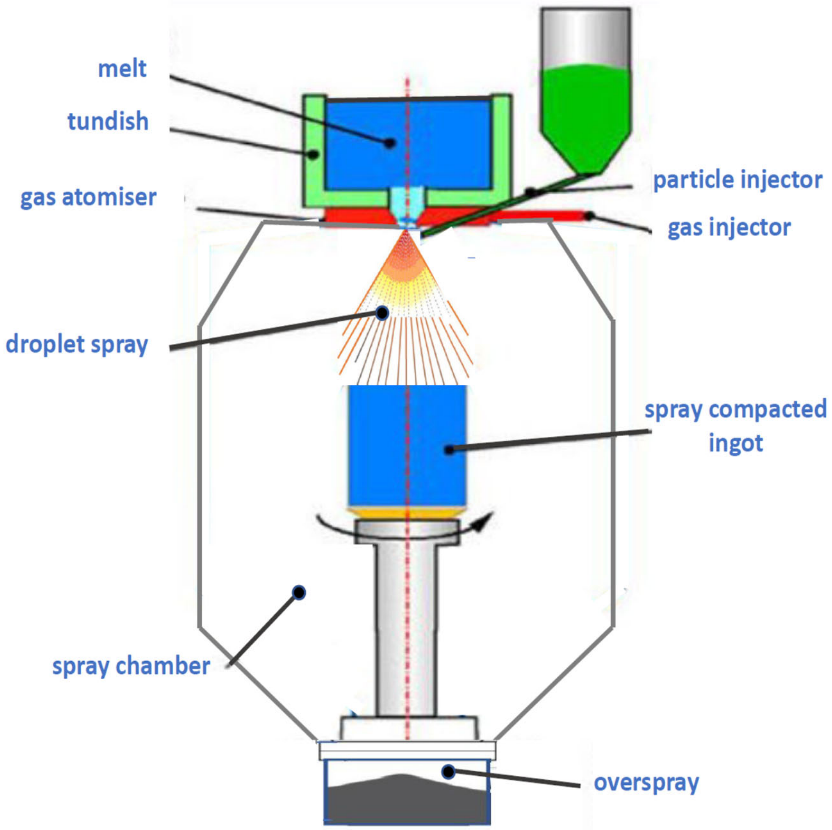

Fig. 9. Diagram of gas atomised spray forming technology used for the formation of large integrated blocks of aluminium and its alloys

Initially, 6 m x 0.5 m x 5 mm aluminium alloy strips were cast [178]. Many other products have also been made, including full and empty billets, rings, pipes, laminates and coatings. The technology has all the advantages of the Near Net Shape (NNS) approach [178] and provides high solidification rates, typically 10^1-10^4 K/s. The deposition rate per square millimetre is controlled according to the rate of heat recovery from the bed by the substrate or radiation and convection into the gas, striking it. Then, depending on the process and alloy, it is possible to obtain conditions in which only a very thin layer of liquid or partially liquid metal with a thickness of 20 μm to 1 mm remains on the surface at any time. Drops of liquid or semi-liquid particles reach the surface and meet with a thin layer of liquid on the surface and combine to prevent the formation of a splat border and/or burst. The speed of solidification is high, and as a result, after solidification, a fine-grained and cellular structure with low porosity (usually less than 2%) is formed. The decrease in the spraying density drops of liquid fall on the already solidified layer and the solidification rate is higher. The splats borders will appear, and at the same time, the porosity will increase. In turn, a significant increase in atomisation density causes the liquid to accumulate on the surface, leading to a reduction in solidification rate, a substantial increase in grain size, and removal of the liquid layer from the solidified surface by the gas stream. In this way, the conditions are very similar to traditional casting, with all the disadvantages, i.e. segregation and uncontrolled grain growth. This method also produced metal matrix composites with introduced powders, whiskers and chopped ceramic fibres, e.g. SiC in an aluminium alloy matrix to provide high strength aircraft materials and friction materials with introduced SiC powders and graphite for aluminium matrix for use in brake linings and clutches in the production of cars [183]. The method consisted of the injection of ceramic strengthening particles entrained by the atomizing gas and aggregated with the stream of atomized liquid particles [183].

The method was developed in the years 1970. by A.R.E. Singer from Swansea University [178-185]. The first pilot installation was built in cooperation with Davy Ashmore (later Davy McKee). After consolidation to full density, spray-moulded materials consistently show better properties than conventionally cast materials and comparable to powder metallurgy equivalents. Shortening the processing steps for spray moulding compared to powder metallurgy and conventional casting/forging methods provides potential economic benefits. However, it was pointed out [184] that there were serious economic barriers to widespread commercialization of spray moulding. These include the high cost of inert gases for atomisation, significant losses due to excessive spraying, reflection and machining, poor process reproducibility and problems with implementing robust online control for metallurgical quality. A few years later, work on (OSD) was implemented at Osprey Metals Ltd., Neath, South Wales, from which the name of the process became Osprey [186], the number of processing operations was reduced, structure and properties were improved, and rapid solidification was introduced [187], and this process was used to produce high-alloy tool steels and high-speed steels [188], improving structure and properties with increased production efficiency [186, 188-193]. The Osprey process has become an alternative to the existing methods of producing this group of steel, although it has proved impractical because of too high levels of oxide pollution [187]. In 1980, Aurora Steels Ltd. applied spray deposition principles to the high-alloy tool and high-speed steels, but unfortunately, production was discontinued in 1983 due to the economic crisis [193].

High-speed steel PM HS 6-5-2 (successively given the average concentration of W-Mo-V-Co in %) produced by the Osprey spray forming technology known as controlled spray deposition (CSD) and then forged and heat-treated it achieves a slightly higher hardness than the same steel produced conventionally, and PM HS 6-4-5-5 steel showed up to 60% better susceptibility to grinding [187, 194]. The mechanical properties of steels manufactured by the Osprey spray forming method and then forged are comparable to those produced conventionally, as demonstrated in the case of stainless steel containing 12% chromium with better plastic properties [195] and steel for work in creep conditions containing 9% chromium and molybdenum additives [196]. Similar results were also obtained for aluminium alloys [197], and this technology was also applied to aluminium-lithium alloys with other micro-additives [187,198]. It could be considered a success if not for the uncontrolled increase in the share of oxide impurities [187]. This technology has also proved to be an attractive alternative to magnesium alloys Mg-Al-Zr and Mg-Zn-Zr [199]. This technology was also applied to superalloys based on nickel alloys containing high concentrations of alloying elements such as aluminium, titanium, zirconium, chromium and hafnium [187,200], and the tensile strength was higher than in the case of casting alloys with the same chemical composition and without loss of ductility. Isostatically hot spray deposited properties of these alloys at room temperature as well as elevated have significantly improved [201,202]. The properties of Fe-Nd-B magnetic alloys have also been improved [203,204].

Currently, this process is mainly used for titanium, chromium and cobalt alloys used in the aviation industry and for medical purposes, especially for the production of implants. For example, items made of titanium and its alloys can be mentioned, including TiAl6V4 commonly used for joint and bone implants and dental implants [154,205]. Parts made using this technology of titanium alloys exhibit mechanical properties corresponding to forged materials but have much better properties than cast materials. Porous structure implants can also be made by this technology [206].

A typical hybrid technology belonging to the powder bed fusion group is additive preform preparing one of the possible methods, including those in this group as (SLS) and (EBM) but under conditions that do not ensure complete sintering and subsequent sintering with each of the possible classical sintering methods mainly used in forming methods hot and cold with compaction and sintering. By its nature, this hybrid technology is used for special purposes.

7. Hybrid powder metallurgy technology and conventional plastic deformation to obtain large-sized blocks, billets or bars of tool steels, including high-speed ones

Powder metallurgy methods have found wide application in the manufacturing of alloyed tool steels, mainly sintered high-speed steels, but also alloyed tool steels for cold work and some die steels for processing polymer materials [5, 207-225]. By the end of 1960, the only technology for producing high-speed steels and other alloy tool steels with ledeburitic structure was the conventional metallurgy method. After melting steel in the steelmaking process and possible ladle processing, often in a vacuum, ingots were cast. Electroslag remelting was also used to clean the chemical composition. The ingots were then forged, and the resulting billets and flat slabs, if it was necessary to obtain them, were then rolled into bars from which tools could be made. Steels manufactured by powder metallurgy technologies, mainly sintered high-speed steels, are characterized by a much more even structure than conventional grades. In sintered high-speed steels, carbide segregation is not revealed because they do not contain large carbides, which in conventional steels come from primary dendritic carbides found in ingots after casting, Requiring breakage during plastic processing with a significant degree of throughput and changes in the direction of plastic deformation, preferably by forging, and only at the final stage by rolling.

Sintered high-speed steels, in comparison with conventional steels, show many desirable technological properties:

- good plasticity,
- good machinability,
- excellent grinding ability,
- high dimensional stability after hardening and tempering,
- in most cases, better performance.

Sintered tool alloy steels also show more desirable technological and operational properties than analogous steels manufactured conventionally.

Tools made of sintered high-speed steels have better machining properties than those made of conventional steels with comparable chemical composition, especially in the case of machining difficult-to-machine steels and at higher cutting speeds. The indicators of increasing the utility properties are different depending on the type of tool, test conditions, and mainly on the strength of the workpiece.

The even structure facilitates the heat treatment of sintered tool steels, including high-speed ones, and provides significant isotropic structure and properties of these steels in a heat-treated state. Sintered high-speed steels are subjected to heat treatment, consisting of quenching and at least twice tempering, analogous to conventional steels. During heat treatment, sintered steels undergo comparable phase transformations as in conventional steels with identical chemical composition. The austenitizing temperature of individual sintered steel grades is 30-40°C lower than the corresponding temperature for conventional steels with similar chemical composition. It is generally due to the higher concentration of carbon in sintered steels and their manufacturing technology. The melting temperature of sintered high-speed steels is lower than conventional steels with comparable chemical composition, which also affects the need to reduce the austenitizing temperature during heat treatment. Sintered high-speed steels are also subjected to thermo-chemical treatment, mainly nitriding, carbonitriding and related operations, in the same way as conventional steels. These treatments provide an improvement in the operational properties of tools made of sintered high-speed steels.

The properties of tools made of sintered high-speed steels are increased by several dozen to several hundred per cents as the cutting conditions increase. At the same time, tools made of sintered high-speed steels show more even machinability compared to tools made of conventional steels.

Technological methods for the production of alloy tool steels, including high-speed ones from powders, can be divided into two groups:

- specialized or classic methods of powder metallurgy, allowing the production of finished tools or semi-finished products and products with a shape similar to the final one; these methods do not differ from those commonly used in powder metallurgy and therefore will not be discussed in detail;
- hybrid technologies of powder metallurgy and conventional plastic deformation, as a result of which large blocks obtain billets or rods and other metallurgical semi-finished products from which machining methods manufacture ready-made tools.

Powder metallurgy is the foundation of this technology, used to manufacture cutting tools, cold work tools, saws and knives, and wear-resistant elements. Powder metallurgy makes it possible to produce high-speed steels with higher strength than conventional steels, and for this reason, the conventional technology of these steels has lost its importance today. This technology also offers the possibility of producing materials with a higher concentration of alloying elements and carbon than conventional steels, which at the same time ensures higher hardness after heat treatment and better wear resistance. Steel with a suitable chemical composition is usually melted in a medium frequency induction furnace. The liquid metal from the furnace is poured into a ladle, in which it is transported and poured into a crucible, currently, after electro slag treatment in a ladle, placed on top of a chamber several meters long (Fig. 10). Although in some methods it can be horizontally located (Fig. 11) when smaller industrial halls can be built.

The basis of the technology is gas atomisation of high-speed molten steel with a stream of nitrogen. Through the centric opening in the upper part of the chamber, molten metal flows into the chamber, into which at the same time an inert gas, usually nitrogen, is introduced under pressure. The primary method of obtaining powder is to atomize molten tool steel, including high-speed steels by inert gases, mainly nitrogen. However, argon or helium which were also sometimes used, and even water in an initial state of idea application (Fig. 12). As a result, tiny drops of steel are formed, which solidify when falling in a high column of atomisation tower in nitrogen protection. Increasing the height of the atomisation column is conducive to extending

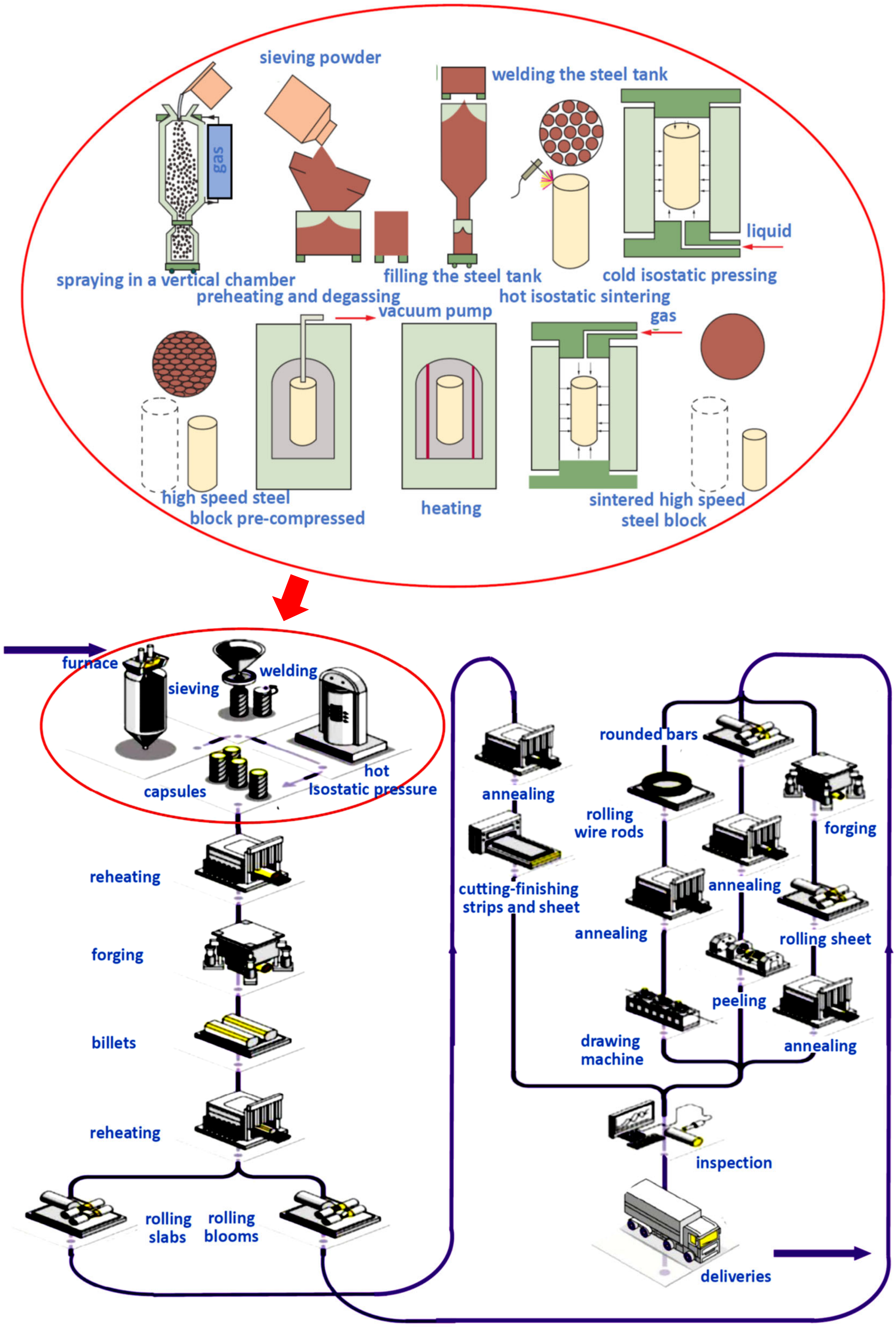

Fig. 10. Diagram of the ASEA-Stora process for producing high-speed steels; sequence of technological operations a) in the initial process; b) full currently implemented

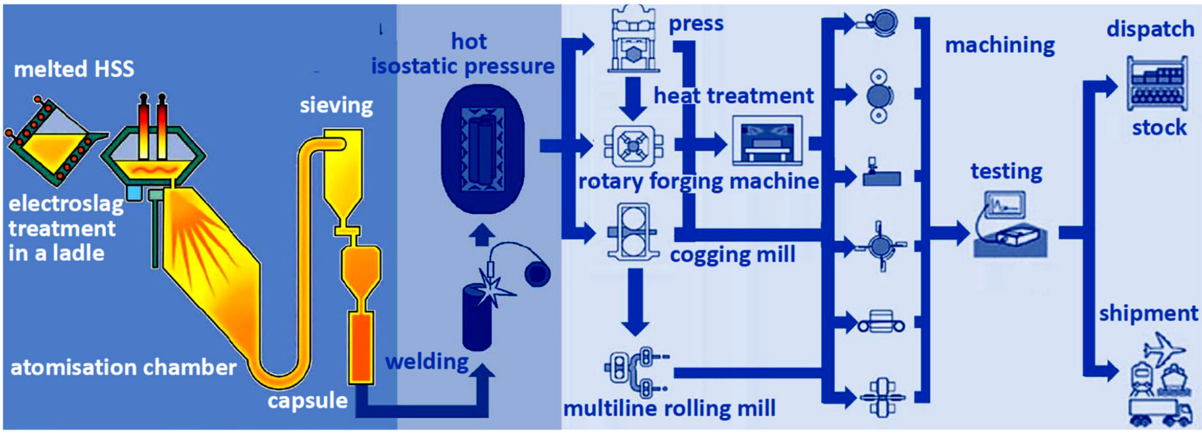

Fig. 11. MICROCLEAN Process Diagram

the solidification time of liquid droplets by lengthening their path of fall in the column, which ensures their spherical shape and no agglomeration before complete solidification of the particles. At the same time, these conditions allow the pressure of the atomizing gas to be reduced, which reduces the risk of its excessive concentration in the obtained powder particles and the absence of gas bubbles in them.

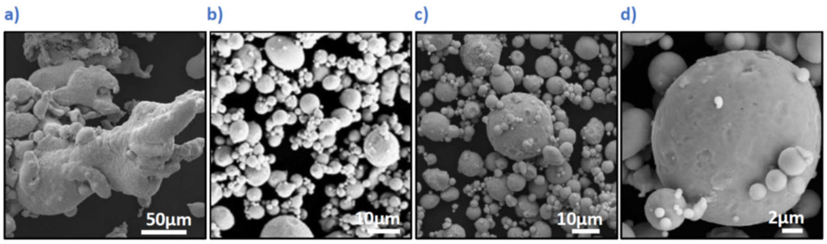

Fig. 12. Powder structure of high-speed steel a) water-atomized HS6-5-2 steel particles; b) gas-atomized HS12-0-5-5 steel particles; c) gas-atomized HS6-5-2 steel particles; d) single spherical particle of HS12-1-5-5 gas atomized steel powder (SEM)

The resulting powder with a chemical composition corresponding to the finished tool steel, including high-speed steel is an intermediate for the production of sintered steel. Steel powders have a spherical shape combined with a high level of purity. Each atomised particle of powder has the composition of high-speed steel, such as a full-sized ingot, and the segregation problem does not occur at all. The weight of each particle is 100 million times smaller than the weight of the ingot. The same is the reduction in the segregation scale. After atomisation and sieving, the powders are collected in a cylindrical carbon sheet capsule, which after degassing is welded tightly and then pressed isostatically cold and hot (HIP) successively. A significant technical achievement was the design and implementation of the Quintus press used for hot isostatic pressing (Fig. 13).

Currently, isostatic pressing is limited to one hot technological operation. After the skinning the sintered capsule, the plastic deformation is processed by forging, hot rolling and drawing or cold rolling into various product forms, such as round and flat rods or profiled wire, sheets and strips. The process has been systematically improved over the past half-century. The authors have personal scientific experience from a visit to this steel plant and to prepare an extensive series of multi-faceted studies of

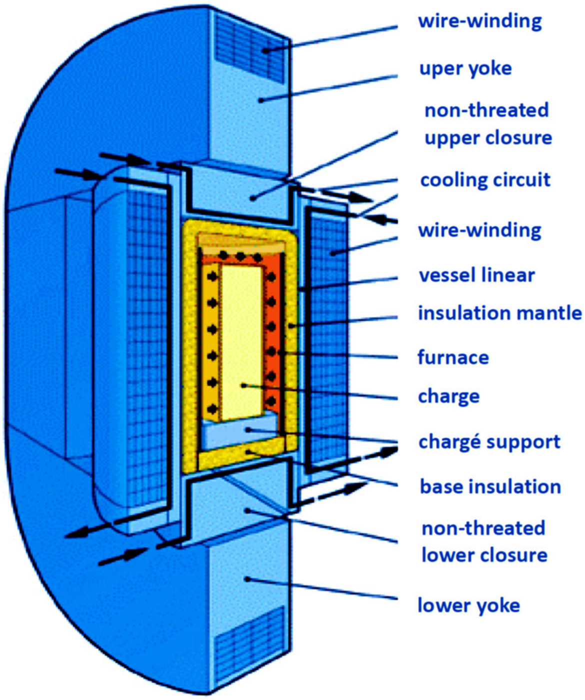

Fig. 13. Diagram of Quintus press design

sintered high-speed steels of various grades produced with these technologies.

The history of this technology dates back to 1969, when for the first time the efforts of a consortium of Swedish companies, the electricity and transport group concern Allemana Svenska Elektriska Aktienbolaget (ASEA), founded in 1883 in Stockholm by Ludvig Fredholm and from 1890 after the merger with Wenströms & Ganströms Elektriska Kraftbolag as (ASEA) and the steelworks in Söderfors by Stora Kopparbergs Bergslags AB, probably the oldest since 1288, but still, active joint-stock company in the world, although currently without an iron and steel smelter, industrial production of sintered high-speed steels according to the original ASEA-Stora Process abbreviated (ASP), used until today. The steel mill in Söderfors, Sweden has a tradition since 1676, when the production of anchors began there and in 1966 it was taken over by Stora Kopparbergs Bergslags AB, and from 1976 to become part of the Uddeholms AB concern, an international producer of high-alloy tool steels with production in Hagfors in Sweden. Since 1991, the company has been part of the Austrian Böhler-Uddeholm group, which in turn has been part of the Voestalpine AG group since 2007. The company is also a producer of sintered high-speed steels in the MICROCLEAN process (Fig. 11), which also used the experience of joint activity in Söderfors, Sweden within the Uddeholms AB concern. After several subsequent ownership changes, the smelter in Erasteel Kloster AB, Söderfors, Sweden has been part of the Erasteel group based in Paris, France since 1992.

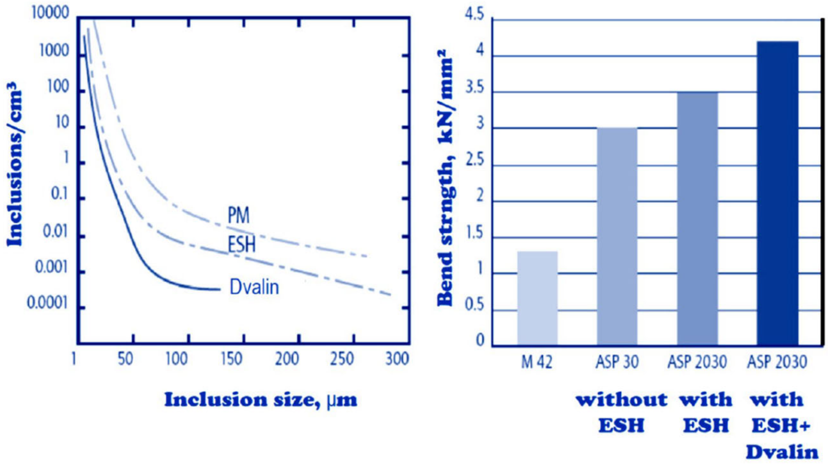

Fig. 14. Scheme a) density distribution of non-metallic inclusions b) Bend strength of high-speed (ASP) steels manufactured in different historical periods

In Söderfors, Sweden in 1969, the world's first high-speed steel powder atomisation installation with a high vertical chamber was implemented. (ASP) steels are produced by blowing molten steel with high-pressure nitrogen jets. At that time, several new high-speed steel grades ASP23, ASP30 and ASP60 were implemented, some of which could not be produced conventionally. Since 1995, a new electro slag heating (ESH) process for electro slag remelting (ESR) of steel prior to atomisation in the tundish has been implemented, while analogous grades of high-speed steels ASP2023, ASP2030 and ASP2060 have been implemented, with a significantly reduced by 90% of oxide inclusions (Fig. 14). In 2011, the DvalinTM (PM HSS ASP) process was launched with the highest atomisation tower in the world and with the (ESH) plant with a heating size of 14 ton, are ensuring that the steels are the cleanest on the global market (Fig. 14). The name was taken symbolically from Norse mythology, where Dvalin is a dwarf producing the invincible Turfing sword. The introduction of this process reduced the overall number of non-metallic inclusions by a further 90% compared to the (ESH) process and virtually eliminated significant inclusions. This process ensures a homogeneous distribution of alloying elements and causes even distribution of carbides in the form of very small particles. Historical details are presented here due to the extraordinary technical achievements of several generations of Swedish engineers who, despite the fact that their company has repeatedly changed owners and name, implemented a technical design ensuring their complete dominance in this area in the world.

Currently, hybrid technologies of powder metallurgy and conventional plastic deformation are implemented, among others by two entities, by the Erasteel group based in Paris, France as the DvalinTM PM HSS ASP process and the Böhler-Uddeholm group as part of the Voestalpine AG group based in Austria in the MICROCLEAN process. Years ago, the (STAMP) process was introduced, in which in a horizontal chamber high-speed molten steel, was atomized. It required an increase in the pressure of the atomizing gas and the implementation of plastic deformation of the produced capsules using a forging press with very high pressure. From the own research and business experience of the authors of this paper, it is also known that ASP technology was widespread not only in relation to tool steels but also others, including heat-resistant ones. For example, around a quarter of a century ago in Beijing, China, a medium-efficient installation was used working on the needs of the aviation and defence industries. It should be assumed that various elements of this technology or even other technological varieties are used by other manufacturers.

8. Summary

This paper presents additive and hybrid technologies for products manufacturing using powders of metals, their alloys and ceramics. The general characteristics of powder engineering technologies (PET) are indicated in [1], which also presents a dendrological matrix comparing the attractiveness and potential of individual technologies for manufacturing as well as use powders of metals and their alloys and ceramic. Despite the general remark that additive technologies cannot be treated as the only advanced digital production (ADP) technologies, they are located in the two-quarters of this matrix "wide-stretching oak" and "rooted dwarf mountain pine" respectively. It proves their highest possible potential and attractiveness, as well as their fully exploited attractiveness or substantial development opportunities in this respect. Additive manufacturing (AM) technologies are becoming very important among product manufacturing technologies. They are consisting in joining together layer by layer of individual layers of metals and alloys, ceramic and polymeric materials that can be produced in the form of powder or liquid, as well as in the type of curled material or thin fibres. Hybrid powder metallurgy technology and conventional plastic deformation to obtain large-sized blocks, billets or bars of tool steels, including high-speed ones are also very promising. In general, the industry uses many additive technologies, and for this reason, they are an essential part not only of powder engineering but also of the manufacturing development according to the concept of Industry 4.0.

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