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Manufacturing powders of metals, their alloys and ceramics and the importance of conventional and additive technologies for products manufacturing in Industry 4.0 stage

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ABSTRACT

Purpose: The paper is a literature review indicating the importance of powder engineering in the modern stage of Industry 4.0 development. 47 technologies for the manufacturing and use the powders of metal and their alloys and ceramic in the manufacturing of products are indicated. All those technologies were compared in terms of their potential and attractiveness, pointing to their development trends. The focus was solely on powder production methods. Other technologies will be discussed in other papers in the powder engineering cycle.

Design/methodology/approach: The authors' considerations are based on an extensive literature study and the results of the authors' previous studies and empirical work. In order to compare the analyzed technologies, the methodology of knowledge engineering are used, including the own method of contextual matrices for comparative analysis of a large set of technologies by presenting them on a dendrological matrix.

Findings: The most interesting intellectual achievements contained in the paper include presentations of the authors' original concepts regarding the augmentation of the Industry 4.0 model. Material processing technologies occupy an important place in it, among them powder engineering technologies, both conventional and additive. The most attractive and promising development technologies in powder engineering are identified.

Originality/value: The originality of the paper is associated with the novelty of the approach to analysing powder engineering, an indication of its importance for the development of the Industry 4.0 idea, where progress does not depend only on the development of IT technologies. It is also not true that from among technologies only additive technologies play a key role. Using avant-garde analyses in the field of knowledge engineering, the most avant-garde technologies of powder engineering are pointed out.

Keywords: Powder engineering, Powders manufacturing methods, 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

In this context, among the technologies listed in the technology platform of the augmented holistic model of Industry 4.0 [1-3] there is a wide set of technologies using powders of metals and metal alloys or their mixtures with non-metallic powders to obtain semi-finished products and products from those powders in a solid-state without the need to melt the main component. Those technologies are often used to manufacture finished products or prefabricated elements with geometric features very similar to the final shape required, and for shaping their structure and physical and chemical properties. Such products can be used directly or can be subjected to finishing subtractive manufacturing. The assumption made by the authors of the paper is to break the stereotype that the issue is limited to powder metallurgy, although its essential role in this respect is absolutely irrefutable. However, as demonstrated in the content of that paper, the issue is immeasurably broader and more complex. Many times it does not only apply to metals and their alloys, but also to composite materials with the participation of metals as well as ceramic materials, which for semantic reasons is difficult to include in metallurgy. It is a much broader context of material engineering. It was noted, although the fundamental premise for all classifications and subsequent analyses was the powder form of the input materials used. The incorporation of polymer and composite materials with their participation was systematically avoided. Including this topic would probably have to extend the paper twice.

In addition, technologies developed years ago are systematically improved, as well as entirely new and unknown a few years ago or not used in industrial practice. Dynamic progress is being made in this area, which also can and certainly is important for limiting the applicability of some known technologies, which after reaching their peak capabilities are going to the decline phase of their own development. The authors tried to draw attention to such processes. On the other hand, technologies that reach the stage of full maturity should definitely be mentioned. In this regard, a very contemporary group are additive technologies that use metals and their alloys powders as well as ceramic powders. Additive technologies, in addition to being able to shape the form and properties of products, also allow the control of porosity by producing skeletal and porous products in full volume or selected areas of manufactured products. Sometimes the resulting high porosity sintered material is then saturated with molten metal or an alloy with a melting point lower than that of the main component by infiltration. Soaking of the porous structure with organic material, e.g. oil, may also occur. Methods using metal and metal alloys powders or mixtures thereof with non-metal powders can also be used to produce metal foams. Some of technologies using metal and metal alloys powders or their mixtures with non-metal powders, however, are used to produce large metal blocks weighing several hundred kilograms, which, after proper preparation can be subjected to classical plastic forming to give the required shapes and geometric form, including bars, metal sheets, billets or forgings. When analysing the discussed issue broadly, it should be noted that hybrid technologies are used, where the powder layer is applied to the substrate produced by other technologies, which have also been analysed.

During the past decade, the authors have carried out very extensive and multi-faceted own research on issues covered by the content of this paper or even at least partly related to it, published in numerous detailed papers, monographic studies [4-20] and books [21-29]. Due to the framework of this paper, it is impossible to present even a synthesis of detailed results obtained as part of those studies. However, it was decided to illustrate the information provided in individual sections of this paper with the results of metallographic investigations taken from those studies. The authors remain deeply convinced that it will facilitate the perception of the presented content and justify the desirability of such a large variety of developed technologies referenced in the review of the subject literature.

Other hybrid technologies are also used, consisting in the production of products using metals and their alloys powders and applying to the surface layers by physical/chemical vapour deposition PVD/CVD or atomic layers deposition ALD methods. It is the content of the authors' research over the past fifteen years, which includes numerous published papers, projects, monographs and books [30-38] from among those previously cited. Although the topic is closely related to the matters discussed here, the limitations on the volume of this paper, it was decided not to develop it in that elaboration.

The study contains an extensive, richly illustrated literature study, including a significant contribution of theoretical studies and practical work, as well as our own original achievements regarding the current development trends of these technologies using metal powders and ceramics. Powder production is the basis for all the considerations in the article. It is part of a series of extensive literature reviews, which are presented in subsequent publications [39-41]. The article makes a general classification of the various technologies that use metal powders and their alloys produced by one of the methods of the technologies discussed in this paper. In many cases, those operations are autonomous, although in many cases they are only a fragment of a complex technological process. Over the past decades, the scope of technologies using metals and their alloys powders or their mixtures with non-metallic powders, including ceramic powders, which have generally been subject to the rigours of the concept of cyber-physical Industry 4.0 systems has significantly developed. The factor determines their wide practical application, and the paper presents the scope, purpose and use areas of the technologies listed.

2. The augmented holistic Industry 4.0 model

The progress of civilisation depends on many factors, including successively appearing inventions and implemented new technologies. Contemporary requirements imposed by the development of civilisation have been included in several introduced strategic programmes, including in the SDG 17 Sustainable Development Goals [1,42], in the Society 5.0 programme on general well-being of society [1, 42-49] implemented in Japan and Industry 4.0 announced in Germany, widespread in many countries, especially in the European Union [1,2, 50-78]. As the first stage of Industry 1.0 initiating the industrial revolution, the invention and distribution of the steam engine were considered (Fig. 1).

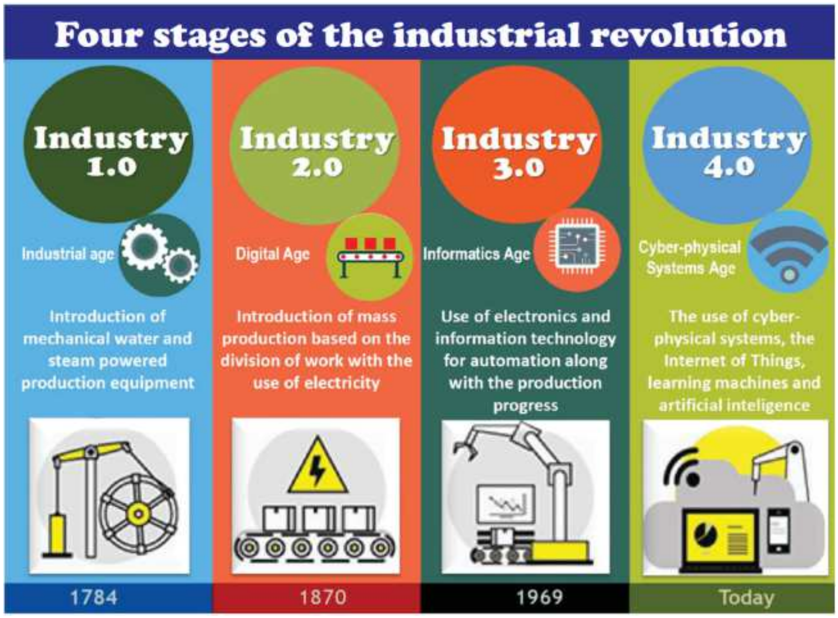

Fig. 1. Diagram of the four stages of the industrial revolution

The current stage of Industry 4.0 [1,2, 50-78] marks the beginning of a new era of digital industrial technology. Systems, sensors, machines, details and information technologies are used, with the necessary participation of people who support manufacturing automation. Participants in the value chain are connected by internal and inter-organisational networks, integrating the Internet of people, things (IoT) and services [1,59,60,62, 64-68, 72,75]. The Industry 4.0 stage in the technological aspect applies mainly to cyber-physical systems, including high-computing cyberspace, communication infrastructure and numerous algorithms for the development and processing of big data. Cyber-physical systems (CPS) [1,2,61, 69-71, 73,74] contain various elements required to perform tasks using the Internet of Things, including radiofrequency, identification methods, sensors, actuators, cell phones [1,2,59,60,62, 64-68, 72]. The divisions between the Internet of People, Internet of Services and the Internet of Things are blurring because it connects employees and stakeholders, technological and organizational processes as well as production data.The Internet of Things enables visualization of processes carried out throughout the factory. As a result, data collection efficiency, scalability and time have improved, which indirectly has a beneficial effect on savings in industrial organisations. Costs and energy were also saved, predictive maintenance improved, safety increased and operational efficiency improved. Thanks to the unique addressing schemes, information from the physical and virtual world are used to communicate and interact between various elements, which allows cyber-physical CPS systems to cooperate with neighbouring intelligent components. As a result of using the Industry 4.0 concept, the competitiveness of companies and regions, which is manifested in increased productivity, improved production economics, and accelerated industrial growth and favourable changes in the workforce profile is improved [63]. The high level of production automation ensures a significant reduction in the scope of human work input. The use of the Industry 4.0 system provides real benefits, enables faster response to customer needs and improves flexibility, speed, efficiency and quality of production. That approach improves smoothness of the production process, savings in the order management system, material handling, inventory storage, increased availability and operational flexibility, as well as improved supply chain efficiency. Thanks to advanced sensor technology, analysis of big data sets and determination of significant regularities, the production needs for each manufactured product or element are automatically recognised, and a sustainable increase in productivity is ensured.

In the opinion of the authors of this paper [1,2,56,57,76], the current Industry 4.0 model focuses only on cyber-physical systems and the development of IT support for manufacturing. It is only an IT element of industrial development, therefore really does not apply to all aspects of the current state of industrial development. The current model is therefore incomplete and needs to be supplemented [1,2,56,76], because it does not include engineering materials from which every product is produced, without exception, processes and manufacturing technologies and technological machines. Skipping the progress in real machines and production technologies as well as materials used to manufacture any product in the Industry 4.0 model is an apparent oversight [1,78]. Without materials, it is impossible to produce any product and the existence of any industrial activity at any stage of development. In addition to including in the Industry 4.0 model the share of the only technology group so far, i.e. additive technologies [43-72, 79-93], it is necessary to take into account other technology groups [1,2,57,76,77]. Only additive technologies, which from an extensive perspective, include whole powder metallurgy are considered. However, in many cases, additive technologies cannot be used as competitive, let alone unrivalled, as they are often only complementary. It is impossible to ignore most of the very often avant-garde manufacturing technologies, which nowadays have reached almost universally advanced level and almost always require computer aid to a very advanced level. It proves that they meet the requirements of Industry 4.0. It is highly desirable to include in this model living and bioengineering machines promoted in the book [94]. For those reasons, Authors own augmented holistic model of Industry 4.0, which takes into account all required aspects, i.e. materials, processes and technological machines as well as their development and cyber-physical systems, combined in the technological platform (Fig. 2) was developed and presented. That model is universal, both for large industrial organisations and for micro, small and medium enterprises.

3. Importance and general classification of manufacturing methods of metal and metal alloys powders

In the development of the current state of Industry 4.0 of the industrial revolution, issues of technology in which metal powders, their alloys and ceramics are used, play a significant role. The basis of those technological activities is the possibility of using powders on which this article focuses.The basis of all the listed technologies using metals and metals alloys powders or their mixtures with non-metal powders is manufacturing of powders of those materials. Powders are produced as a result of mechanical or physicochemical comminution of solid material or chemical or physicochemical reactions – from other materials or chemical compounds. The properties of the powders obtained and their prices depend on the costs of raw materials, small or large scale production, the shape and size of powder particles, the level of their contamination, including mainly oxygen sensitivity [95-98]. Powder production ensures the expected powder graininess, particles shape, chemical composition and structure. All of the listed elements of characterised powder properties depend on the method and conditions of powder manufacturing. The methods for powders manufacturing were divided in the 1960s [99], while today, there are many more such methods. Some of them have exceptional significance and are, therefore of relatively small use. Atomisation and chemical reduction are most commonly used for high-volume powder production, while mechanical crushing and electrolysis are used for special materials manufactured in relatively small quantities. The general classification of the currently used methods for the production of powders, in which mechanical, physical and chemical processes were specificated, is presented in Figure 3.

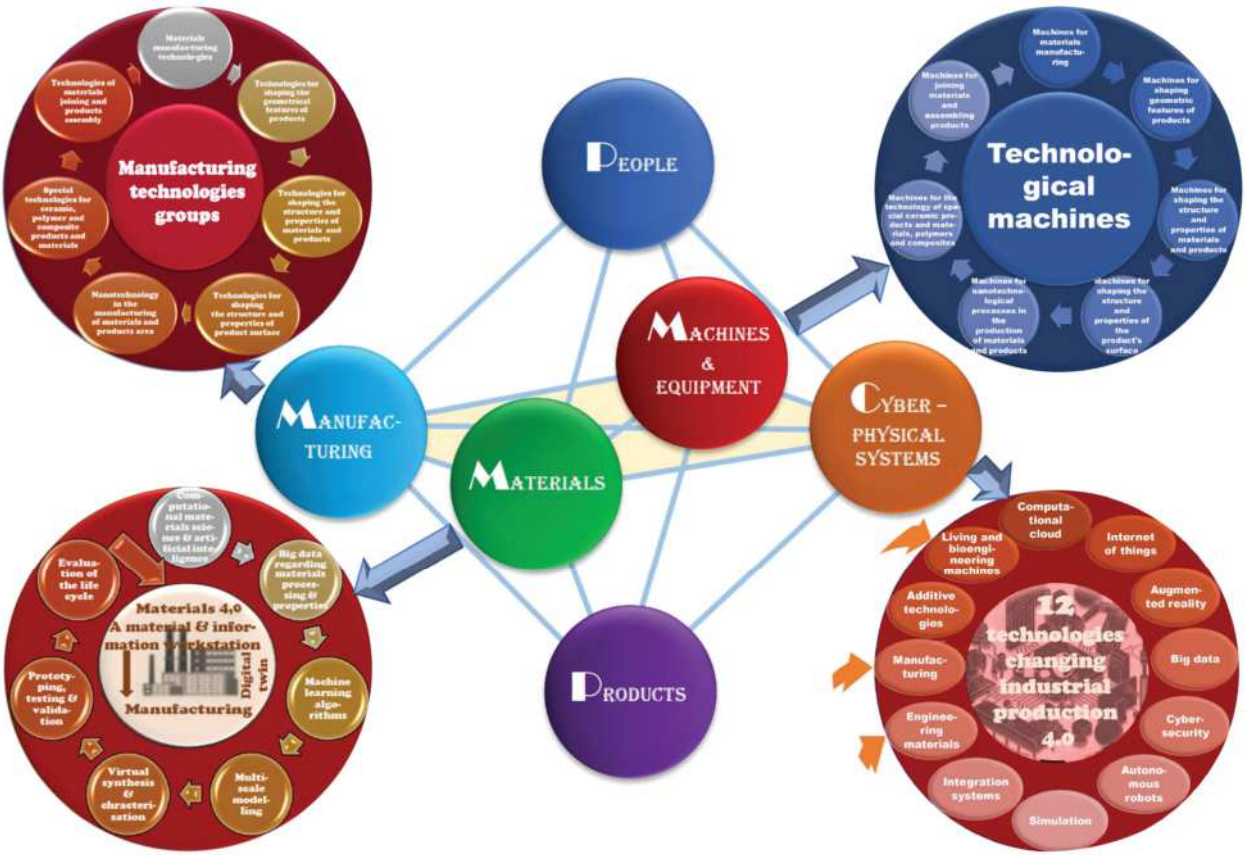

Fig. 2. Diagram of the augmented holistic Industry 4.0 model

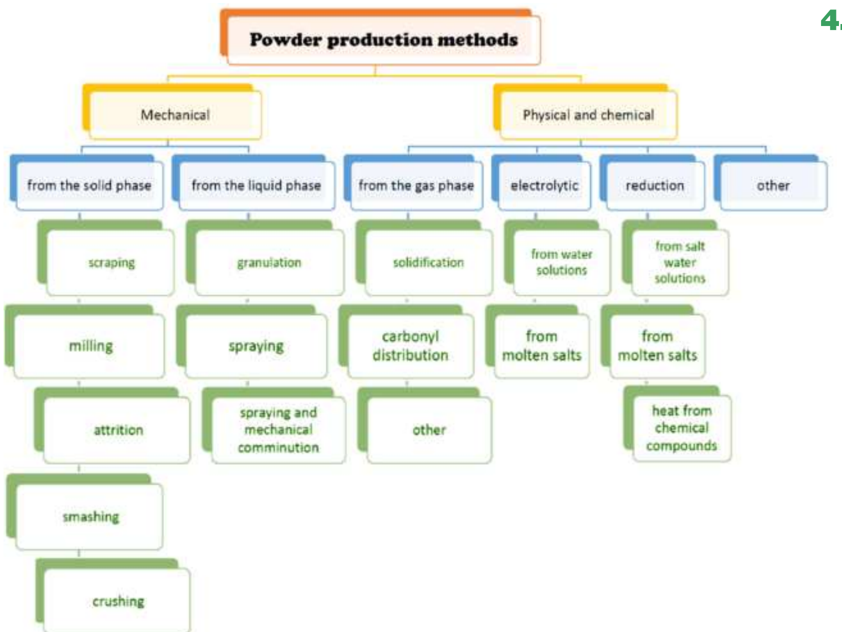

Fig. 3. The general classification of currently used powders manufacturing methods

4. Overview of mechanical methods of manufacturing of metal and metal alloys powders

The mechanical methods of producing metal powders are associated with the disintegration of solids when there is no phase change or liquid disintegration during phase changes.

Mechanical methods through the disintegration of solids as a result of grinding in the ball, vibration or vortex-impact mills, powders in the form of a plate, multi-wall blocks or splinter fragments are obtained. Such mechanical methods are inefficient and can be used in principle to crush brittle metals and non-metals. Powders crushed in the ball or vibration mills are usually contaminated with mill liner and ball material, which requires subsequent chemical cleaning. During high-energy milling, including the use of attritor grinding mills, repeated cracking and re-welding of powders occurs.

In the attritor mill, particles suspended in a liquid as a result of displacement through blades, colliding with each other or with the milling agent are ground. Due to the need to counteract temperature increase, it is necessary to use liquids, e.g. 2-propanol. That process is also used for mechanical alloying, by grinding mixtures of various metal powders, even with the participation of hard particles, e.g. Y_2O_3, ZrO_2, Al_2O_3. Grinding strengthens the powder particles by increasing the dislocation density, which has an adverse effect on the subsequent compacting of the powder. Therefore, it requires powder softening annealing before following stages of product manufacturing. The milling process with the need to perform heat treatment is expensive, which determines its limited use, almost exclusively in cases where other methods fail and/or as a secondary process to break up agglomerates and to ensure the required distribution of the particle size of the powder. The classic method for powders manufacturing is to grind the brittle material in a ball and vibration mills [100]. The solid material is subjected to impact, compression and shear by hard balls, which leads to its fragmentation into increasingly finer powder grains> 100 μm, and for brittle metals or ceramics up to <1 μm. Brittle materials are disintegrated during cold plastic welding. A frequently used device for mechanical powder grinding is the Hametag vortex-impact mill. In the mill drum, two steel propellers rotating in opposite directions at high speed cause the formation of vortices of air, which entrain the particles of metal charge in the form of cut wire, chips and other metal particles. Particle crushing occurs as a result of hitting them against the propellers and drum walls and each other. The gas blown into the drum by the fan lifts the powder, directing it through the binder to the settler. The powder is periodically collected into hermetic containers. In the case of jet mills, a circular chamber rotates with particles colliding at high speed under the influence of a gas stream, which leads to their fragmentation and removal of small particles in the centre of the chamber. Due to lack of crutches, there are no impurities associated with the crumbling of those crutches, which is beneficial. The easiest way used to produce special materials, though costly, is machining, including turning and milling, for making fine chips. However, it is one of the most expensive ways to produce powders, with low efficiency, with a significant level and risk of contamination.

Liquid disintegration occurs with phase change, using gases, water, oil or a mechanical dispersion to atomize the liquid metal stream.

Atomisation [100-106] is the primary method of liquid disintegration. It is the most flexible process, ensuring the most favourable shaping of the properties of obtained metal powders and alloys. All atomisation processes consist of three main integrated stages: melting, atomisation and solidification. Melting can be achieved by such techniques as vacuum induction melting, plasma arc melting, induction drip melting or direct plasma heating. As a result of melting solid metal fragments, liquid metal droplets form and at the same time, they solidify into powder particles as a result of cooling. The energy required for the disintegration of molten metal during spraying can be transferred in several ways. It could be made by fluid atomisation, centrifugal atomisation, subsonic, supersonic gas atomisation and other high-energy atomisation [107]. However, gas atomisation remains the most popular approach to efficiently producing a wide range of metal alloys. The high-speed fluid jet striking the molten liquid metal stream may be water or various gases. Spraying with water is more uncomplicated than spraying with gas, and installation requires less money. Water also has a higher viscosity, density and cooling capacity than gases, but tends to oxidize reactive metals during atomisation. Atomisation with water involves the disintegration of a free-falling stream of liquid metal or alloy, supplied from the nozzle in the tundish through water jets (Fig. 4). Depending on the type of device, the dismemberment of the pool or liquid

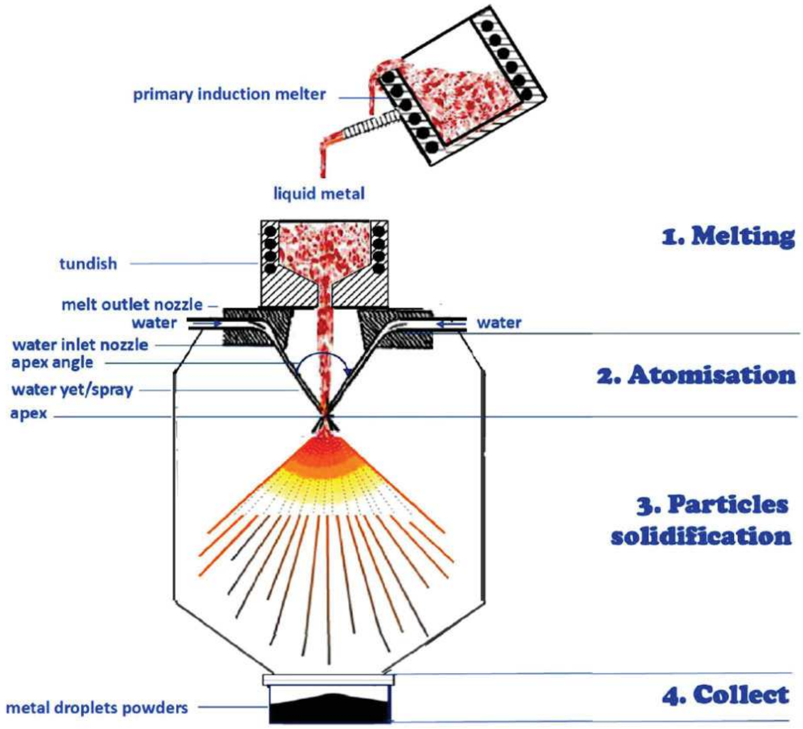

Fig. 4. Scheme of atomisation of liquid metal using a water stream as a disintegrating agent

stream of molten metal into droplets occurs. Its occurrence is connected withThe high-speed impact of another fluid stream (by the way: gas is also considered a liquid) or using rotating discs or spindles, and the resulting drops cooled in an inert gas stream. Rotating pressure discs and nozzles require the controlled flow of only one liquid, i.e. molten metal. Drops formed as a result of disk spin, centrifugal accelerate and solidify during flight. Two-component atomisation of two fluids also requires flow control of the second fluid in addition to the molten metal. Quench atomisation, therefore, consists of the controlled flow of two liquids, i.e. molten metal and most often water (Fig. 4).

The disintegrated alloy solidifies immediately, as the water cooling rate reaches 10,000 K/s, while the surface of the powder oxidizes. The powder-water suspension is collected, dried and then reduced with hydrogen. The freshly reduced powder is slightly sintered and then subjected to gentle grinding and undergo final treatment of the powders, possibly with the help of magnetic separation, sieving and levelling. Such a method can be used for the production of iron powders and alloy steels containing Mo, Ni or Cr, stainless steel powders, copper and copper alloys. Therefore, atomisation with water is mainly used to produce high-tonnage powders from these irregularly shaped alloys. Water atomisation is the most common and most productive way to produce powders up to 50 tons per production batch. Most of the world's supply of iron and steel powders are produced by water atomisation. At ordinary pressures of water jets <15 MPa, powder particles with a size of 30-100 μm are obtained.

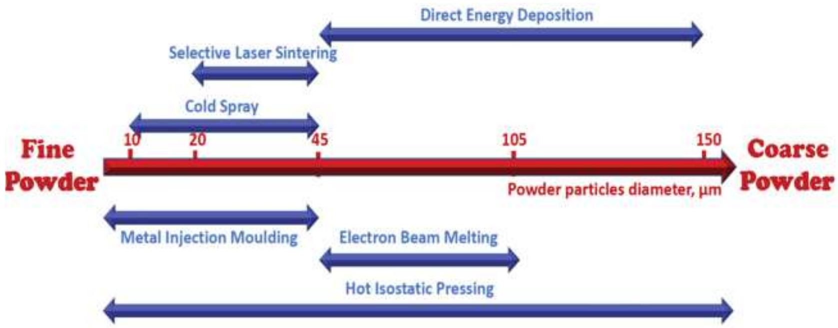

Fig. 5. Requirement regarding the particle size distribution of the spherical powder on the example of titanium for various modern technologies for the production of products using metal powders and their alloys

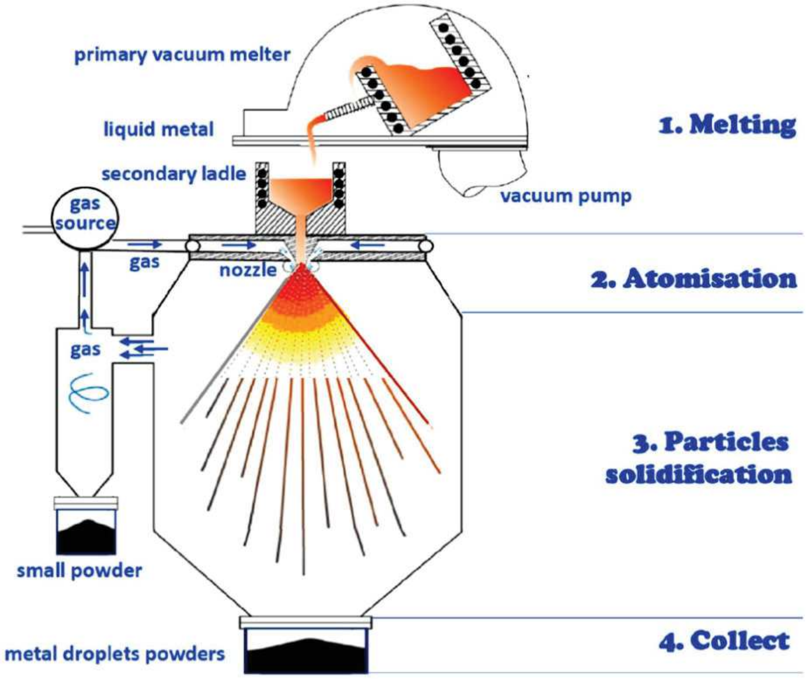

Fig. 6. Scheme of gas atomisation of metal powder production

High water pressure up to 60 MPa or special powder production methods is required to produce a powder with a particle size of 3 to 30 μm.The importance of those methods became particularly important after 2000, due to the growing interest in additive technologies as well as metal injection moulding and other NNS near net shape methods, requiring the use of very fine powders (Fig. 5) produced with low financial outlays [108-110].

The use of inert gases avoids oxidation, and the shape of the powder particles is similar to spherical. Therefore, inert gas atomisation is used for powders of reactive and special alloys, and when a spherical form of the powder is required. It is used when high bulk density and high flow velocity are necessary, e.g. in hot isostatic pressing technologies, metal injection moulding, additive manufacturing. The cooling rate, which allows the droplets to form balls before solidification is about 1000 K/s. Since the gas energy input for cooling liquid droplets is much smaller than that of water, special nozzles are used to ensure very high gas flow rates [111] (Fig. 6).

Nitrogen [112] is the most commonly used gas, although only argon can be wholly neutral. Argon, on the other hand, can dissolve in liquid metals, which increases undesirable porosity. Helium, or even petroleum or kerosene and oil, can also be used as atomizing gas, while maintaining extraordinary safety measures, which prevents oxidation of the powder surface, may cause slight carburization.

Air is rarely used as atomizing gas, while the majority of aluminium powders are air-atomized [113,114]. During the flight phase, the particles undergo a a spherical shape under the action of surface tension forces. The Vacuum Induction Melting (VIM) atomisers are used to obtain fine powders d = 10-40 μm, most often used in additive technologies. The melting chamber is evacuated to minimize melt contact with oxygen and nitrogen. The technology for obtaining powders using vacuum melting machines is called VIGA-Vacuum Induction Melt Inert Gas [115].

The development of modern technologies for the production of products using metal powders and their alloys extends them beyond the classical canon of materials. There where only powder metallurgy, including concerning reactive metals such as titanium and even magnesium is used. It sets specific requirements regarding special atomisation techniques. For titanium and its alloys, as well as other materials, the molten metal must not interact with the crucibles.

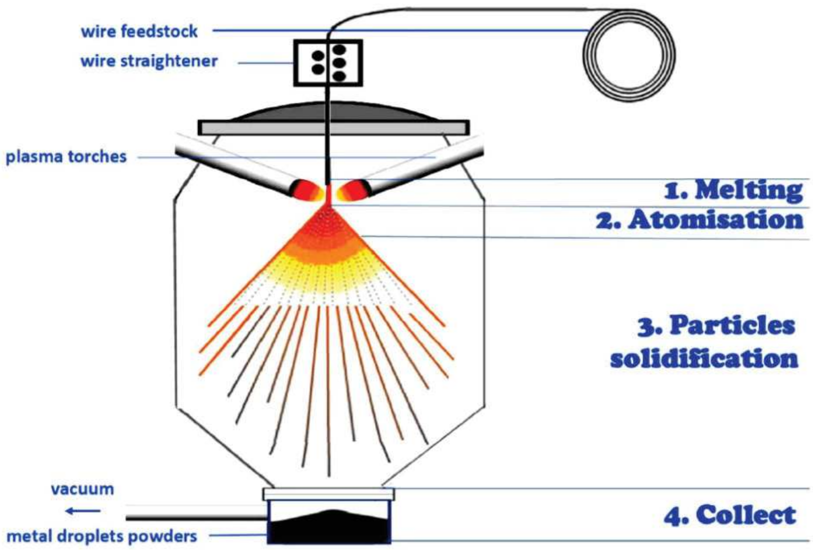

Fig. 7. Plasma atomisation scheme for the production of metal powders

In the last two decades, additive manufacturing (AM) technologies have widely spread for titanium and its alloys, but also alloys of other metals [2-28, 30-38, 59-111, 113-153]. Many technologies used for metals and ceramics require the use of powders. Among them, there areselective laser sintering (SLS) [8,11, 79-82, 93, 154-169] and Selective Laser Melting (SLM) [25-28, 30-37], which are mostly the same technology since sintering generally takes place with a 90% proportion of sintering with a liquid phase [170,171] electron beam melting (EBM) [93, 147-152], directed energy deposition/Laser Metal Deposition Laser Engineered Net Shaping/Direct Metal Deposition/Near-Net-Shape Manufacturing – DED/LMD/ LENS/DMD/NNSM, which correspond to the same technological process [93, 141-146], including metal injected moulding (MIM) [6, 172-174], hot isostatic pressure (HIP) [175-177], requiring high-quality powders in spherical oxygen concentration below 0.15% by mass.

Powders of titanium and its alloys can be produced by gas atomisation (GA) methods, which include free-fall gas atomisation (FFGA) [178-181] with atomisation by Ar or He. Therethe molten metal stream falls freely as a result of gravitational forces until solidification (Fig. 6). Close-coupled gas atomisation (CCGA) technology was developed to increase efficiency using fine powder [182-185], and although it was developed about 80 years ago [182], it was successfully used to produce spherical titanium powder only in the last a decade [183,184]. The electrode induction gas atomisation (EIGA) technology ensures that the manufactured powders are not in contact with refractory metals or other ceramic elements [186-189]. Inductively compressed plasma methods are also used to transform particulate, atomized and spongy powders into pore-free spherical powders. In GA technologies, the metal is melted using an induction coil or other sources, and the atomisation takes place in a stream of cold gas under high pressure. Gas atomisation technologies can cause the atomizing gas to become trapped inside the powder, creating gas pores or gas bubbles in it, which harms the properties of final products made from such powders [179,190].

The efficiency of fine powder production compared to conventional gas atomisation processes can be significantly increased using plasma atomisation PA (Fig. 7) [179,181, 191-196], e.g. by 40% for Ti-6Al-4V [191] and for Ti64 with 39.9% to 59.6% [179]. Although this process was developed back in 1996 [193], it proved to be useful for the production of fine and spherical powder from titanium alloys [179]. In the pre-alloyed method, a wire with a diameter of approx. 1.5-3 mm is melted on the front surface after heating up to approx. – 10,000 K by plasma torches. The melted wire is sprayed in a stream of argon into small drops, then subject to cooling at a rate of 10-1000 K/s. The efficiency of the plasma atomisation process is regulated by choosing the gas pressure at the inlet as well as the diameter and speed of the wire feed, changing the distance between the wire and the plasma outlet, and also by varying the angle of attack between the wire and the plasma nozzles [196]. Performance can also be improved by pre-heating the wire induction [179]. Plasma atomized titanium powder exhibits high purity since liquid metal does not come into contact with any refractory materials or other solids [179]. However, the main disadvantage of the method is the need for wire as the input material and the inability to use it for alloys from which wires cannot be made, e.g. intermetallic phases, including Ti_3Al [179]. The powder produced by GA and PA methods is small and has a diameter in the range of 10 to 300 μm [181].

Very high purity and almost perfect spherical shape are ensured by the rotating electrode process (REP) for powder production [193,194] (Fig. 8a) developed in 1960. The coarseness of powders manufactured by that method has a diameter of 50-350 μm, which do not meet the requirements of modern NNS technologies using metal powders. In the REP process, the alloy rod from which the powder is made, with a diameter of 89 mm or 63.5 mm, melts in an electric arc with the tungsten-tipped cathode. The rod rotates at 3000-15000 rpm [112], and the drops are ejected by centrifugal force in an inert atmosphere, usually helium. Over time, this process was improved by replacing the tungsten cathode with a plasma torch [195], creating the plasma rotating electrode process (PREP) [194,196-198]. In this process, the rotating electrode allows the material to disintegrate without contact with the nozzle, and melting is carried out using a plasma torch on the front surface of the rotating electrode in a helium or argon sheath (Fig. 8b). Due to centrifugal force, when the alloy is fed slowly enough, a fine powder of the highest purity is obtained. The efficiency of the PREP process can be improved by increasing the speed and diameter of the electrode, e.g. by 16%, at a speed of 30,000 rpm and a diameter of 100 mm electrode rod.

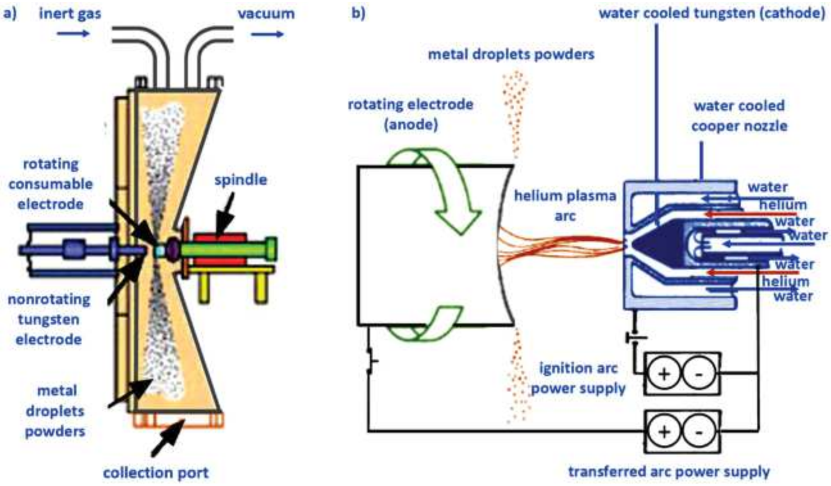

Fig. 8. Schematic of powder production processes using centrifugal force: a) rotating electrode process; b) plasma rotating electrode process

5. Modern technologies of the manufacturing metals and metals alloys powders

Modern NNS technologies for the production of products using metal powders and their alloys place stringent requirements regarding the chemical composition, especially low oxygen concentration and physical properties: high purity, sphericity and fluidity [199,200] and the lack of porosity caused by the internal presence of gas bubbles. The main disadvantage of all the aforementioned particular technologies for the production of powders, especially titanium and its powders, is the low efficiency determining the high costs of producing powders, so other new methods of producing powders with a diameter <45 μm are being developed.

Plasma Spheroidisation (PS) is currently a popular technology [201-207] used to produce various powders, including heat-resistant metals such as tungsten. In the method, the metal powder is melted using plasma torches, and the drops solidify until they fall to the bottom of the reactor chamber, achieving an almost perfect spherical shape and significant process efficiency [72]. The starting materials can be hydride-dihydride (HDH) powder or any irregularly shaped Ti powder produced by other processes. The PS process seems of little use in the production of titanium alloy powders from aluminium due to the increased evaporation of aluminium at plasma temperature. The availability of the method and the reduction in the cost of powder production have not found sufficient confirmation in the literature.

The works [112,179,208,209] discusses the new Granulation-Sintering-Deoxygenation (GSD) approach for the production of Ti spherical powder. In the first stage, they grind into relatively fine particles of Ti alloy hydride or Ti hydride with master alloy, i.e. hydrogenated from Ti sponge or Ti alloy scrap. Then, through spray-drying, granulation takes place into spherical particles of the desired size. Sintering ensuring that the titanium particles are compacted is the next stage. The GSD method is characterized by low cost, low waste, and efficiency is close to 100%. To produce spherical powders of less than 45 μm, the particle sizes of the fine initial powder must be less than a few micrometres because they have a better surface finish and sinterability. However, the final oxygen content in Ti powder increases with a decrease in the initial particle size, so it is necessary to find a balance between the achieving spherical morphology of particles and minimizing the content of interstitial elements. Oxygen content increases with the granulation, sintering, and other processes, so deoxygenation is needed for achieving the oxygen content lower to 0.1 wt.%. It is crucial to counteract the agglomeration of the particles [209]. The deoxidation stage can be used independently of the previous stages of the GSD process and for powders that have been used repeatedly, e.g. by 3D printing [210].

Hydrogen assisted magnesiothermic reduction (HAMR) process [210-212], treatment procedure to consolidate the powder and reduce the specific surface area of the powder, and the final step to deoxygenate the powder using Mg in a hydrogen atmosphere to reduce further the oxygen content is used to manufacture low oxygen titanium directly from TiO_2. Such an approach has significant potential to become a cost-effective method of manufacturing low oxygen titanium powder. Also, titanium hydride covering the powder surface is more resistant to surface oxidation than pure titanium, which becomes an additional advantage of the method. Manufacturing pure Ti powder is another significant advantage of using a hydrogen atmosphere.

Spheroidisation by mechanical means is also possible [179] by fast mixing or high-speed milling, e.g. jet milling [213]. The particles manufactured by the method have only a quasi-spherical shape, which may limit its use. This method can be hybridized with others, e.g. radiofrequency (RF) inductively coupled plasma spheroidisation [213].

In work [179], the features of various discussed methods of powder manufacturing were compared (Tab. 1).

Particular attention should be paid to the manufacturing of magnesium powders, due to the expectations of numerous industries for products manufactured from its powders. It concerns the aviation and automotive sectors, due to the minimization of the weight of aircraft and motor vehicles, and the arms industry. It is also used in implantology and prosthetics, including technical aiding of dentistry, due to the density similar to that human bones.

In the current decade, powdered and granulated magnesium has undergone rapid development, mainly in China. Early as 2005, production reached over 100,000 tonnes of magnesium powder or granules and is still growing [214]. However, magnesium can react with oxygen, nitrogen and carbon dioxide in the air [215]. Several cases of fire and explosion caused by magnesium dust have been reported worldwide [216-218], and there is a high risk of fire and explosion at magnesium powder manufacturing plants. A finer powder generally increases the risk of fire. The processes for manufacturing magnesium powder have developed rapidly and currently include several methods used [215]. Cutting milling is used to produce magnesium powders

Table 1.
Critical features of various spherical methods for producing Ti powder

No	Method	Size range, μm	Feed material	Strength	Weakness
1	Free-Fall Gas Atomisation FFGA	<300	Elemental/ Ingot/bar	A broad range of alloys and a large selection of feedstock materials	Satellite particles around the powder particles; possible porosity inside coarse powder particles; possible ceramic contamination
2	Electrode Induction Gas Atomisation EIGA	<200	Bar	Relatively high yield of fine powder manufacturing	Possible porosity inside coarse powder particles; relative high Ar consumption
3	Plasma Atomisation PA	<300	Wire	Fewer satellite particles around the powder particles; relatively high yield of fine powder manufacturing	The high cost of feedstock wire; possible porosity inside coarse powder particles
4	Plasma Rotating Electrode Process PREP	50-350	Bar	High purity; no satellite particles around the powder particles	Relatively low yield of fine powder manufacturing
5	Plasma Spheroidization PS	>5 (as the feed powder)	Powder	Relatively low cost, relatively high yield of fine powder manufacturing	Subject to availability of low-oxygen feedstock powder
6	Granulation-Sintering-Deoxygenation GSD	10-100	Scrape/ elemental	Relatively very high yield of fine powder manufacturing; minimal satellite particles around the powder particles; relatively low cost	Not perfect spherical shape; possible porosity inside coarse powder particles

from magnesium blocks pretreated to remove an oxidized layer with rhombic or irregular shapes and a diameter of 833-1651 µm [215], intended for the production of pyrotechnics and desulphurization in the steel industry. Ball milling is used to produce magnesium powder with an average diameter >147 µm using metal balls of different diameter. Changing the grinding time and ball size affects the control of the average diameter of the powder particles [219]. In the emulsification method, magnesium is mixed uniformly with liquid and boracic flux. Then the molten magnesium is emulsified into fine spherical particles, which after milling and sieving and covering by salinity have a diameter of 280-833 µm. The vortex milling method consists of pre-milling bulk magnesium into crumbs of a given size and then pulverizing it by sieving particles with a diameter of 173-833 µm. Atomisation involves spraying pure liquid magnesium using an inert gas stream and then solidifying a spherical powder that requires screening with a diameter of 43-1651 µm. Sieving can ensure powder with particle size of up to 0.1 µm and purity greater than 98.5%. A particular method of manufacturing magnesium powder with a diameter of fewer than 10 µm was patented in China [218]. The airflow milling method was developed in the 1990s. High-pressure airflow causes coarsening of coarse magnesium particles, ensuring very high purity of the spherical shape powder. The very fine-grained powder is obtained, while the method has no industrial significance so far, due to very high costs [215].

The risk of fire and explosion is mainly affected by atomisation and airflow milling methods for the production of magnesium powder as a result of ignition, both due to electrostatic discharges, mechanical impacts and friction. Ball milling, emulsification, and vortex milling show less risk of explosion or fire, while is low in case of cutting milling. Magnesium dust is deposited in tanks, silos and bunkers, especially the dispersion of magnesium powder in the cloud [215].

Among the physicochemical methods for manufacturing of powders, a few technologies can be listed. Manufacturing from the gas phase, including solidification and decomposition of carbonyls, electrolysis of aqueous solutions and molten salts, reduction of compounds, including aqueous salt solutions, molten salts and thermal reduction of chemical compounds, and among others synthesis from solutions belong to this group of technologies.

The manufacturing of metal powders with a relatively low boiling point consists in evaporation of the metal and subsequent solidification of its vapours. Fine-grained powders with a spherical shape and layered structure, including iron, cobalt and nickel powders, are produced by the thermal reduction of carbonyls. Carbonyls, e.g. $Fe(CO)_5$, $Ni(CO)_4$, $Co_2(CO)_8$, are manufactured in high-pressure reactors on metal ore or scrap metal, which are then heated above the boiling point when they decompose to clean metals and carbon monoxide chemically. Carbonyls are volatile and highly toxic, and the process is environmentally burdensome and expensive [28].

The electrolysis method allows the production of powders of all metals and some alloys, including high purity iron, nickel, manganese and chromium [28]. As a result of the electrolysis of water solutions or molten anode salts, metal sponges deposited on the cathode come from the dissolving anode. The anode may be insoluble to obtain metals in solution or soluble because the composition of the electrolyte does not change as a result of replenishment with anode ions. The spongy metal deposited on the cathode is subjected to drying which finally comminutes it into powder.

High purity refractory metal powders are obtained by reducing metal salts or oxides at a temperature of about 1070 K in the slurry, pusher or belt furnaces in an atmosphere of hydrogen from dissociated ammonia or as a result of the reaction of steam with methane at a temperature of about 1270 K. For example, iron powders are obtained by reducing iron oxides with hydrogen or by reducing carbonite magnetite ores enriched to 71.5% iron. Porous iron is achieved in a tunnel kiln at a temperature of about 1470 K loaded with layered crushed iron ore, coal and limestone, which is then mechanically crushed and reduced again at a temperature of about 1070 K with simultaneous use of solid and gaseous media [28,214,215], e.g. hydrogen from dissociated ammonia.

6. Physicochemical methods of the manufacturing metals and metals alloys powders

Other methods of powders manufacturing by physicochemical methods include precipitation, co-precipitation, thermal decomposition of salt solutions, hydrothermal synthesis, and the sol-gel ones [28, 215]. Co-precipitation is used to produce powders of oxide materials, including Al_2O_3 [28,216], and consists in dissolving a mixture of salts or hydroxides with a precipitation solution and separating the precipitate from the liquid by filtration and subsequent calcination. In the process of freeze-drying, water salt solutions are dispersed at 195 K in a hexane bath $CH_3(CH_2)CH_3$ to freeze in the form of drops [28]. Then they are heated to sublimate the ice, and the dried spherical salt aggregates (e.g. $MgSO_4$) are converted to the appropriate oxides (e.g. MgO) as a result of calcination. The sol-gel method is used to produce spherical powders with a diameter from submicron scale up to about 2000 µm [217]. A SiO_2, TiO_2 or Al_2O_3 sol is obtained by hydrolysis of salts, e.g. $SiCl_4$, $AlCl_3$ or by dispersing precipitated hydroxides, e.g. of aluminium, silicon, titanium, iron in a liquid with the required pH. The sol is added to the water-removing liquid to change into a gel due to coagulation, which in turn undergoes drying and calcination at a temperature of 670-1070 K. The powders produced by this method have a developed surface, which allows them at a much lower temperature than powders produced by other methods.

Tungsten carbide is the main component of cemented carbides requires intensive mixing of tungsten powder with a particle size of 0.5-5 μm with carbon in the form of carbon black and subsequent reactive annealing in a hydrogen atmosphere at 1400-2000°C in graphite tube furnaces [220]. TiC, NbC and TaC titanium, niobium and tantalum carbides are produced by direct reduction and carburization of their oxides, TiO_2, Nb_2O_3 and Ta_2O_5, respectively, at 1700-2300°C. The products of those reactions should be ground into powder in ball mills [221].

Powder manufacturing methods also include grinding to provide the required granularity. In the case of classic powder metallurgy, those methods are included in the ones of powder preparation for further technological operations. The feed preparation processes, in such a case, include powder segregation into various particles fractions, mixing in appropriate proportions, adding lubricants and blowing agents, as well as powder granulation [222,223]. Powder crushing occurs as a result of grinding, and depending on the method of application of external forces, the area of their impact and the rate of their growth, the type of powder particle cracking is different. With a slow increase of compressive forces, powder particles crumble, when with a rapid increase of those forces, the influence is impacted, and the grinding occurs by abrasion, which ensures the powder's fine-graininess and slight dispersion of its size.

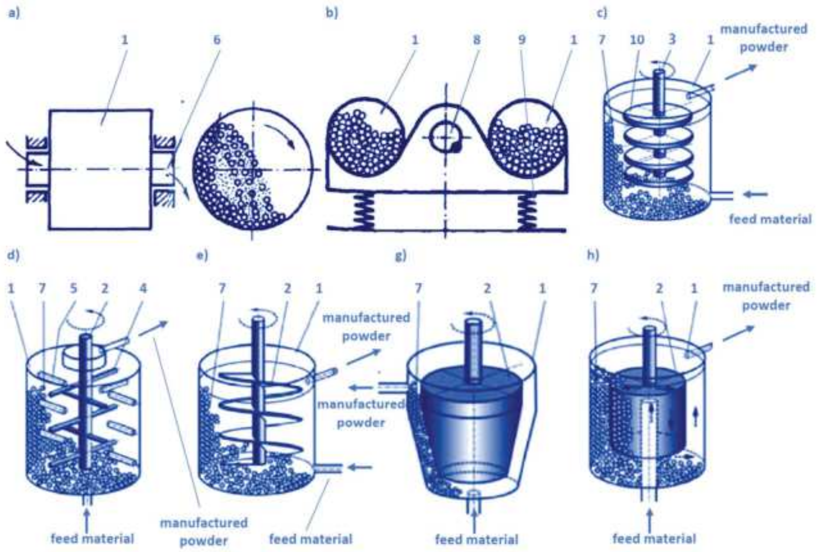

Fig. 9. Sample diagrams of several mills used to crush metal powders and alloys; a) ball mill; b) vibrating mill; c) agitator mill with a full rotor; d) agitator mill with a mandrel rotor with fixed mandrels; e) screw rotor mill; f) mill with a cylindrical-conical rotor; g) cup mill rotor; 1 – container with balls, 2 – rotor, 3 – rotor axis, 4 – mandrels, 5 – fixed mandrels, 6 – tenons, 7 – grinders, 8 – drive, 9 – elastic support, 10 – discs

Both of those mechanisms usually occur to various degrees, mainly depending on the type of device used. Coarse grinding mills are mainly used for grinding natural minerals and are not used to obtain fine metal powders, alloys and ceramics [224]. Figure 9 shows, for example [225] diagrams of several mills used to crush metal powders and alloys.

To grind metal powders and alloys, among others, gravity, planetary (centrifugal) mills, jet, vibration, rotary-vibration, ring and friction mills of the "attritor" type [226-233]. Some of those devices are also used for the mechanical production of metal powders and alloys. Gravity mills for grinding powders of materials hard and brittle can have balls of various types, among others cylindrical, cylindrical-conical ones. They can be multi-chamber and with shoulder protrusions segregating grinding balls. Ball mills usually work dry, but if necessary, the segregation of particles of crushed powder due to the shape, density and sizes wet milling is used, using water, gasoline or alcohol.

The most commonly used device for grinding powders is a cylindrical ball mill made of a rotary cylindrical container filled with grinders in the form of balls, rollers or barrels is most often used. The container of the mill should be filled with grinders in 20-40%, while the ground powder should fill the remaining space. During grinding, both abrasion and crushing of the powder particles occur. During dry milling, agglomeration of its particles and powder coating of the container walls and the surface of the grinders are also glued. Glycols, alcohols, amines, naphthenic soaps or oleic acid in an amount not exceeding 0.3% by mass and the use of small size grinders reduces those adverse effects. Small grinders ensure a low dispersion of the size of produced powder particles, although they minimise kinetic energy, making it difficult to grind the most massive particles [227].

When using continuously operating cylindrical-conical (Hardinge's) mills, multi-chamber and with spirally twisted protrusions on the cylindrical surface, the problem of compromise between the size of produced particles and kinetic energy does not occur. The size of the grinders can be adapted to the requirements of the current grinding stage [234]. In the cylindrical-conical mill, the most massive grinders ensure the initial grinding of the powder in the cylindrical part of the container, and the final grinding of the powder using small grinders takes place in the conical section. Three to five chambers of multi-chamber mills are separated from each other by perforated plates enabling the flow of powder particles rather than grinders, which allows grinding the powder with the most massive particles in the first chamber, and the finest in the last. In a mill with spiral projections on the cylindrical surface, the grinders are segregated by the rotation of the mixing chamber. The smallest area is in the mill outlet.

In planetary mills consisting of two or four containers rotating around their own and common axis, fragmentation takes place due to the centrifugal force of the grinders several times greater than the force of gravity. The powder is crushed dry and wet in batch or continuous operation. The cost of those mills is about two times lower than ball mills [28,227].

In jet mills, grinding and simultaneous segregation of powder occurs as a result of mutual collisions of particles at a sound speed or greater caused by a stream of air or other gas, without the use of grinders [28]. Centrifugal jet mills with nozzles in the cylindrical part of the chamber for the flow of compressed air are most commonly used. The swirling motion of the powder is ensured due to the deviation of the nozzle axis from the radial direction, and the centrifugal force depends on the mass of the powder particles. Larger particles are thus successively comminuted, and only small enough can leave the system. Powder particles produced by the method have a small size distribution, but the method can be used for single-phase materials with initial sizes less than 200 µm.

In vibrating mills, a 70-90% grinding chamber filled with grinders is placed on springs [28] and is set in vibrating motion at a frequency of 17-50 Hz. In this way, the grinders achieve acceleration 3-12 times higher than the acceleration due to gravity, and the efficiency of the mills is several times higher than in the case of ball mills and enables the manufacturing of powders with a diameter of up to approx. 0.5 µm. The largest vibrating mills can hold several tons of grinders.

In rotary-vibration mills, the chamber's rotational motion with an angular velocity of 3.6-14 rad/s is combined with an oscillating motion at a frequency of 8-12 Hz. Sub-micron size particles can only be obtained as a result of wet milling because dry agglomeration of ground particles occurs secondary [28].

Powder particles with a diameter less than one µm can be produced in ring mills consisting of a stationary tube-shaped stator and a roller-shaped rotor located inside driven at a speed of 100-800 rpm. 70-85% of the volume of the narrow space between those elements is filled with grinders in the form of small balls with a diameter less than 10 mm. The shredded material is supplied as a water suspension or dry and is subject to abrasion. To prevent overheating, the mills have a water jacket.

"Attritor" abrasive mills with about ten times higher capacity than gravity mills enable the manufacturing of powders with sub-micrometre dimensions and a slight distribution of particle size. In a water-cooled chamber filled with grinders and crushed powder, a shaft equipped with transverse arms rotates at a speed of over 100 rpm by turning the grinding media to grind the crushed material [28].

7. Overview of the morphology of metals and metals alloys powders manufactured by different methods

In numerous Authors' own research concerning the manufacturing of various sintered materials, powders of various elements and phases produced by different methods were used. The effect of such technological diversity is the different geometrical forms of these powders, which causes differentiation of their properties and determines the different predispositions for the manufacturing of materials or other technologies described in this paper. For example, Figure 10 shows selected spherical powders of titanium, Ti6Al4V alloy and CoCr25W5Mo5Si1 alloy produced by inert gas atomisation and used, among others for the production of the additive method of selective laser sintering.

The following figures show, for example, powders manufactured by various methods, including by grinding, used, among others for the manufacturing of composite materials with a matrix of aluminium alloys (Fig. 11b), intermetallic phases (Fig. 11a), cemented carbides (Fig. 11c, 12a, 12d, 13) other sintered materials (Fig. 12c), as well as sintered and composite materials with special magnetic

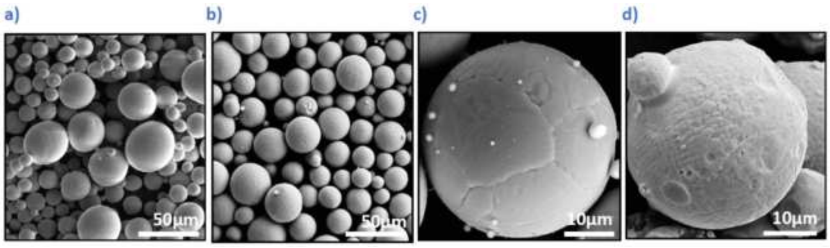

Fig. 10. Morphology of spherical powder manufactured by inert gas atomisation: a) titanium; b, c)

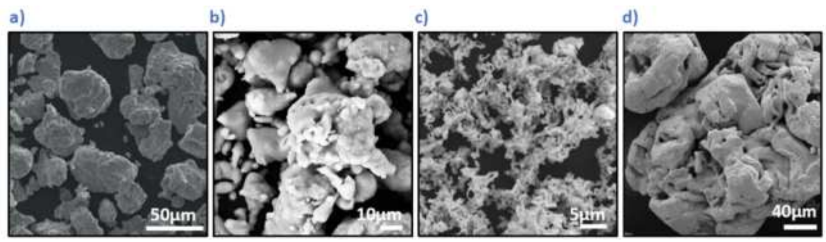

Fig. 11. Powder morphology used for powder metallurgy a) intermetallics Ti_3Al; b) AlMg1SiCu; c) pure cobalt; d) sponge iron (SEM)

properties (Fig. 14). Those powders were made using various previously described technologies.

8. The participation of technologies using powders in the development of global markets

The value of society, the increase in efficiency, effectiveness and productivity of people are the initiative and technological progress as well as the implementation of ever newer technologies, access to modern materials, enabling access to modern products, improvement of people's living conditions and general level of health in order to extend life. The ethical and bioethical aspects of technology require compliance with the principle of sustainable development and zero-emission technology. Industry and its social, spatial and economic functions, and above all, industrial production is the main factor in the growth of society. Programmed trends in the area are defined in 17 sustainable development goals SDGs of the United Nations. The Japanese government announced the Society 5.0 programme focused on social well-being while further developing the information society. In Europe and many other countries, among others, the idea of Industry 4.0 dominates in Southeast Asia and China, and America, including the USA. The fourth stage results from the assumption that the measure of progress is the achievement of the next stages of development of the industrial revolution, from steam engines in the Industry 1.0 stage to the current Industry 4.0 stage related to the automation and robotic processes and intensifying their digitisation. Unfortunately, the Industry 4.0 model published so far does not apply to all aspects of industrial development but is, in fact, an IT component of industrial development. The image of the advancement of the contractual level of interaction of materials, manufacturing processes, machines and technological devices, as well as cyber-physical systems, remains in the model. Therefore, the author's extended holistic model Industry 4.0 was developed. It was demonstrated in such a way that both engineering materials and numerous processing technologies used to manufacture products are essential. Among those technologies, a considerable role is played by multiple technologies for the production of powders, mainly metals and their alloys, as well as ceramics, from which materials or finished products are subsequently manufactured.

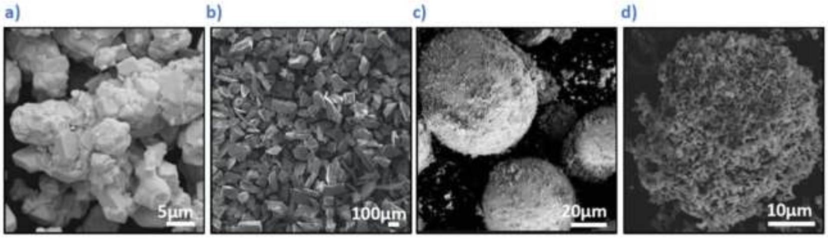

Fig. 12. Powder morphology used for powder metallurgy a) tungsten carbide; silicon carbide; c) aggregate granules of yttria-stabilized zirconia (YSZ) in which the cubic crystal structure of zirconium dioxide is made stable at room temperature by an addition of yttrium oxide; d) aggregate granules of tetra as a mixture of 33.3 wt.% of WC, 33.3 wt.% of TiC, of 26.6 wt.% of TaC and 6.8 wt.% of NbC (SEM)

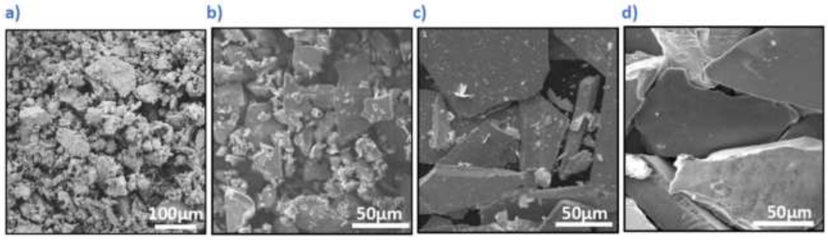

Fig. 13. The morphology of powders used in connection with the manufacturing of cemented carbides; a) vanadium carbide; b) niobium carbide; c) tantalum carbide; d) titanium carbide (SEM)

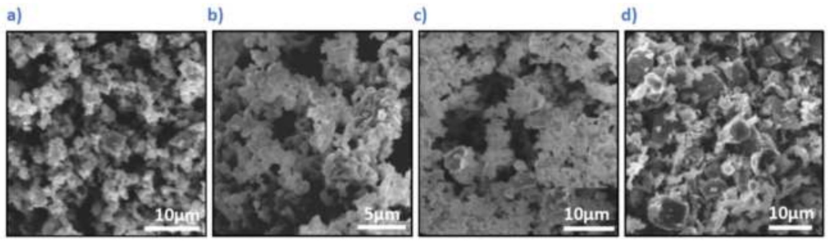

Fig. 14. The morphology of powders used to manufacturing sintered and composite materials with special magnetic properties: a) TbDyFe; b) FeCuNbSiB; c) CoFeMoSiB; d) NdFeCoB (SEM)

Table 2 presents the general classification of methods for producing metal powders and their alloys and technologies in which those powders are used to manufacture finished products. Generally, those technologies are classified into four categories, in particular:

- Powder production technologies,
- powder metallurgy technologies,
- pure and hybrid additive technologies,
- surface layers deposition technologies.

The importance of technologies using powders of metals, their alloys and ceramics can be appreciated by analysing various reports on the development of different segments of the global market prepared by BCC Research Reports (Tab. 3).

Table 2.
The general classification of methods for manufacturing metal and their alloys powders, and technologies in which those powders are used to manufacture final products

Powder manufacturing technologies					
1	AFM	Airflow milling	10	PM	Planetary milling
2	AM	Abrasive milling	11	PPM	Physicochemical powders manufacturing
3	BM	Ball milling	12	PREP	Plasma roating electrode process
4	CM	Cutting milling	13	PSF	Plasma sferoidisation
5	EM	Emulsification	14	QA	Quench atomisation
6	GA	Gas atomisation	15	RM	Ring milling
7	GSD	Granulation-Sintering-Deoxygenation	16	VM	Vibratory milling
8	MS	Mechanical sferoidisation	17	VXM	Vortex milling
9	PA	Plasma atomisation			
Powder metallurgy technologies					
18	ASP	ASEA-Stora Process	24	MCP	Microclean Process
19	CPS	Conventional pressing and sintering	25	MA/ODS	Mechanical alloying & Oxides Dispersion-Strengthened
20	HIP	Hot isostatic pressing	26	PE	Powder extrusion
21	HP	Hot pressing	27	PF	Powder forming
22	IF	Infiltration	28	PIM	Powder injection moulding
23	MA	Mechanical alloying	29	SPS	Spark plasma sintering
Pure and hybrid additive technologies					
30	APPS	Additive preform preparing & sintering	33	SF	Spray forming
31	DED	Directed Energy Deposition	34	SLS	Selective laser sintering
32	EBM	Electron beam melting			
Surface layers deposition technologies					
35	AS	Arc spraying	41	FS	Flame spraying
36	CC	Conventional cladding	42	GPMAC	Gas powder metal arc cladding
37	DGS	Detonation gun spraying	43	HVOF	High-velocity oxy-fuel
38	EBPD	Electron beam powder deposition	44	LAF	Laser alloying/feeding
39	FC	Flame cladding	45	LC	Laser cladding
40	FGMM	Functional gradient materials manufacturing	46	PC	Plasma cladding
			47	PS	Plasma spraying

The titles of the individual reports correspond to the ranges given in the global market column from 2018 and 2019, and therefore no reference was made to particular items in the bibliography. Admittedly, almost none of the dozen or so mentioned technologies and products explicitly provides information on a specific group of technologies, but indirectly each of them includes the production and use of powders, even the one regarding dental implants, where all zirconium implants are made by sintering.

Analysis of Table 3 indicates that in each case a strong development of those markets is observed, and compound annual growth rate, CAGR,% increases from 5 to 22.8%, respectively, in the case of materials for 3D printing. Thus, the whole area belongs to actively developing ones.

9. Comparative analysis of technologies using powders in terms of their potential and attractiveness

The procedural benchmarking method was used [4,16,29,153,223, 235-237] to obtain more representative comparisons of individual and numerous technologies presented in this paper. The method is based on a comparative analysis of those technologies in terms of their potential and attractiveness. The manufacturer's point of view, which faces the choice of manufacturing technology that will ensure its success in business is adopted.

Table 3.
Growth forecasts for various global markets related to the production of metal powders and ceramics and the production of products using them based on data developed by BCC Research Reports

No	Global market	Market value in 2018, bilion USD	Market value in 2023, bilion USD	Compound annual growth rate, CAGR, %	Period of growth, %
1	Powder metallurgy[1]	5.2	7.2	6.6	2018-2023
2	Advanced ceramics and nanoceramics powders[2]	16.2	24.5	8.6	2018-2023
3	Metal and ceramic injection moulding[3]	3.0	5.0	11.0	2018-2023
4	Spark plasma sintering and other advanced sintering technologies[4]	0.915	1.3	6.6	2017-2022
5	Industrial coatings[5]	64.9	82.7	5.0	2018-2023
6	Powder coatings[6]	10.4	13.6	5.4	2017-2022
7	High-performance ceramic coatings[7]	1.5	2.3	9.2	2018-2023
8	Advanced materials for 3D printing[8]	0.8457	2.4	22.8	2018-2023
9	Thick film materials[9]	15.1	25.2	10.8	2018-2023
10	Metals/ceramics abrasion resistant coatings[10]	3.1	4.3	6.8	2018-2023
11	Anti-corrosion coatings[11]	23.3	31.0	5.9	2017-2022
12	Dental implants[12]	3.6	5.0	6.5	2018-2023

[1] Only Asia-Pacific Region; iron-based powder 91.35% in 2017, rest copper-based powder
[2] Advanced ceramic 81.9% in 2017, rest nanosized ceramic
[3] Asia-Pacific 34.52% in 2017, North America 34.0%, Europe 4.22%
[4] 2017-2022; Electromagneticradiation-assisted sintering ca. 70.76% in 2015, vacuum-assisted sintering 19.33%, current-assisted sintering 8.11%
[5] Asia-Pacific 46.38% in 2017, Europe 24.73%, North America 18.94%
[6] 2017-2022; value of powder coatings 75.82% in 2016, rest equipment and services
[7] North America only; thermal spray 51.75% in 2017,PVD & CVD total 39.51%
[8] Metals 13.12%, ceramics 0.56%
[9] Automotive 5.83% in 2017, others 15.18%
[10] Metals/ceramics 40.68% in global abrasion resistant coatings in 2017
[11] Asia-Pacific 59.68% in 2016, Europe 17.94%, North America 11.90%
[12] Titanium 75%, zirconium 25%

The costs of initial investment related to the purchase and commissioning of the machine park, as well as the costs of implementing the production process were taken into account as part of the expert assessment of technology potential. The quality of the product was also assessed. It means the precision of workmanship, which in the case of powders, relates to ensuring the repeatable size and shape of powders. While in the case of products the accuracy of mapping geometric dimensions, the level of complexity of manufactured elements and the lack of pores is the most significant disadvantage of parts produced by powder metallurgy and other technologies using powders to manufactured products. The next criterion for assessing the potential is production efficiency, which means the possibility of applying a given technology on a production scale, including mass. The potential of the technology is also determined by eco-friendliness, including the level of energy consumption, the use of recycled raw materials, production safety, key for example in the production of magnesium powders, as well as the issue of waste. In this respect, powder metallurgy technologies using powders have a significant advantage over traditional waste technologies, because the waste is not generated or is insignificant. The unused powder goes back to the production cycle and can be successfully used in the next iteration of the manufacturing process, although it may require some revitalization operations.

When assessing the attractiveness of technology, experts took into account the range of applications in various industries. Some of the technologies are versatile, allowing for the production of multiple products from different types of materials. In contrast, others only occupy niches, suitable for specialized applications, e.g. the manufacturing of a

Table 4.
Potential and attractiveness criteria of technology expert analysis

Potential criteria		Weight	Attractiveness criteria		Weight
P1	Machine park cost	0.25	A1	Application range	0.30
P2	Technological process cost	0.25	A2	Technological advancement	0.25
P3	Product quality	0.20	A3	Return on investment time	0.20
P4	Production yield	0.15	A4	Development perspectives	0.15
P5	Eco-friendship	0.15	A5	Scientific research realisation	0.10

narrow group of materials that cannot be produced by other methods. The attractiveness of technology is also evidenced by technological advancement, the level of which reflects the stage of the technology life cycle, ranging from emerging embryonic technology to outdated technology, which is doomed to leave the market and give way to more modern solutions. Another criterion of attractiveness is the time of return on investment, informing how quickly the manufacturer will manage to exceed the break-even point and start earning after the exhausting stage of costs related to the equipment of the machine park and production start-up. The attractiveness also includes development perspectives, covering the current and projected increase in interest in the method and the implementation of scientific research. The attention of scientists in a particular technology translates into expected improvements or even breakthroughs, and the number of papers, books, patents and projects related to a given solution indicates a progressive development that can be translated into profits in the company.

The assessment of technology in terms of those criteria of potential and attractiveness was made using a universal scale of relative states. It is a unipolar positive scale without zero, where one is the weakest and ten is the best. Besides, each of the analysed criteria, which is summarized in Table 4, is given a weight that determines the importance of a given criterion for the overall assessment of a given technology. The higher the weight, the more important the criterion affects the weighted average.

The numerical results (from 1 to 10) of the expert judgment are calculated using the author's computer software to present a dendrological matrix (Fig. 15) graphically. The matrix consists of four fields, whose names, referring to trees, intuitively indicate to the reader the current significance and development perspectives of the analysed technologies. Technologies with high potential and attractiveness are found in the "Spread oak" quadrant. The "Rooted mountain pine" field includes proven, mature technologies that have high potential. "Soaring cypress" is a quarter in which high-attractiveness technologies are placed, which bode well for the future, but require investment and strengthening to find their place on the market. The weakest quarter is "Trembling Aspen". The field includes technologies with low potential and attractiveness, i.e. technologies that will be supplanted by other, better solutions in the coming years.

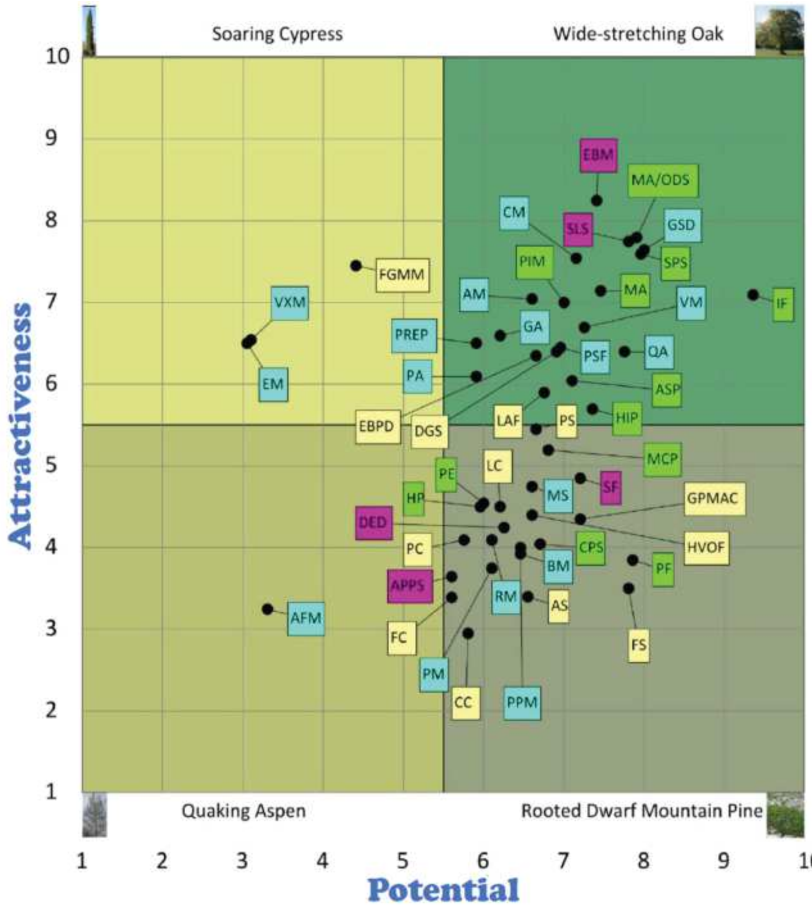

Fig. 15. Dendrological matrix of technologies using powders of metals, alloys and ceramics; symbols of particular technologies are given in Table 2

Throughout this paper, 47 detailed technologies for the production of products using powders of metals and their alloys as well as ceramics have been analysed and described based on a comprehensive review of the literature. All those technologies were included in the dendrological matrix. The dendrological matrix applied technologies that were divided into four groups. Powder production technologies are marked in blue, Powder metallurgy technologies – in green, Pure and hybrid additive technologies – in pink, and Surface layers deposition technologies – in yellow.

Among the technologies for the production of powders, Granulation-Sintering-Deoxygenation was the most promising, which is characterized by a wide range of applications, low cost and pro-ecological, because it is practically waste-free. Atomisation, in gas and quench variants, is also essential here. Plasma-based technologies are becoming increasingly popular, as evidenced by the high position of plasma atomisation, plasma rotating electrode process and plasma spheroidisation. Among the technologies that enable the production of increasingly popular magnesium powders, the cutting milling method is the highest, which allows for the safe production of these powders and thus overtakes abrasive milling and vibratory milling.

The mechanical alloying took a high position and its variant enriched with Oxides Dispersion-Strengthened, enabling sintering of aluminium in the powder metallurgy technologies group.This area is still growing in demand due to the desire to minimize mass in many industries, including automotive, aerospace and space. High hopes are associated with spark plasma sintering, which ensures easy operation and high reliability as well as accurate sintering energy control. At the same time, the scope of its applications is rapidly expanding, covering ever newer areas, including nanotechnology. The widely used powder injecting moulding and hot isostatic pressing, as well as ASEA-Sora Process, allows the production of large-size blocks, billets and rods from tool steels, including high-speed ones. The position of infiltration is also promising, which, due to its specificity, allows the formation of new composites with better properties, even for special applications.

The latest trends in the area of additive technologies are marked by selective laser sintering and electron beam melting, which, differing in their energy source, enable more and more accurate and precise production of increasingly complex and durable elements.

In the group of technologies for applying surface layers using metal powders, metal alloys and ceramics, attention should be paid to electron beam powder deposition, detonation gun spraying and laser alloying/feeding. Those methods are becoming more and more popular, allowing the application of permanent coatings using modern equipment with even better performance and environmental friendliness.

10. Summary

Due to the spread of various technologies using powders of metals, their alloys and numerous ceramics, the traditional understanding of this engineering area as powder metallurgy has long survived and is currently adequate only to its part. The innovation of engineers and scientists, as well as a constantly growing business, needs to be manifested in significant increases in compound annual growth rates of many global markets in which those powders are fully or partly used indicates the need to introduce a more general concept, fully adequate to the range of currently known, used and issues discussed in this paper. It seems that powder engineering is now the more appropriate name for this complex technological area. It is also the suggested name for the series of review papers on this subject.

It should also be emphasized that powder materials engineering is a crucial technological area on the technology platform of the generalized holistic augmented Industry 4.0 model (Fig. 2). It is particularly susceptible in all varieties to computer control, including computer-aided design and manufacturing of products with its participation and all possible aspects related to this to cloud computing and augmented reality. It makes that area of engineering particularly attractive in light of the forecasted development and, above all, the prevalence of this approach. The authors remain deeply convinced of the crucial role of these technologies in modern industry. On the other hand, the development of manufacturing in the Industry 4.0 phase is mainly dependent on the development of powder materials engineering.

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