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Review of methods of designing and additive manufacturing of gears

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Abstract. Additive manufacturing (AM) technology is one of the main components of the fourth industrial revolution known as Industry 4.0. Over the last decades, increase in the dynamics of the development of this technology manifests itself in the form of a wide spectrum of implementations of the methods in the production processes of many elements. This paper presents the latest achievements in the production of gears where the additive technologies have been applied with the use of polymers and metallic materials. The most frequently used methods in this field were indicated, as well as problems related to geometric accuracy or fatigue life of elements manufactured with the use of the methods mentioned. In addition, there were defined future directions of gear design, the implementation of which was possible thanks to the use of AM as well as the scope of research that should be undertaken in this area in the future.
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1. Introduction

The first mentions of gears were described by Aristotle in the 4th century BC. He studied the subject of the two gears that made up a gear train mechanism [1]. The foundations for a current form of gears were created by Philip de la Hire and later they were continued and developed by Leonhard Euler. It was Swiss scientist who first gave the gear teeth the form of an involute curve. Currently, this form of a tooth is the most commonly used in practice, due to insensitivity to changes in the distance of the gear rotation axis, as well as to the tooth profile displacement capabilities [2, 3]. However, the greatest development in the design and production of gears began in the 18th century, when the first industrial revolution commenced. It was possible owing to the invention and elaboration of the steam engine as well as other mechanisms and devices based on mechanical transmission. Since the 19th century, the technology has been still continuously developing. In recent times, thanks to another industrial revolution known as Industry 4.0, this development has become more dynamic, especially in the terms of production technology [4].

The form of the production process of gears depends on various factors, mainly on the gear type, material, accuracy requirements, and on the production volume. Conventional metal gears have been produced in three basic stages. The first stage includes the rough machining (subtractive method) or forming. The second stage is the heat treatment (if required) and the last stage is the finishing (if required) [5]. Production of various types of gears (bevel, spiral, worm etc.) with different modules, requires a huge workshop with a lot of tools and machines which generates significant costs. In practice, this results in formation of companies specialising in production of single types of gears. For gears made of polymers, the situation differs significantly. The manufacturing process includes rough machining that is also the final stage or some other methods, such as injection moulding or extrusion. However, the cost to ensure the flexibility of the production is large, too [4]. Therefore, the methods for gears production are still being sought. They should ensure less expenditure related mainly to the stock of machine tools and to the use of the amount of materials and these methods should ensure shorter production time. One of these methods is the additive manufacturing (AM) to which this work has been devoted.

2. Additive manufacturing

In accordance with ISO 52900:2015, additive manufacturing (AM) is a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing. The information source of the geometry is a file, which is designed in CAD software or received from a scan (elements of reverse engineering). The next thing is to convert the geometry of parts to the mesh through the polygonisation process. In effect, a .STL extension file is received. Subsequently, a batch file (.gcode) to 3D printer is created in special software dedicated to specific device and method. In this step, the operator selects numerous parameters related to material, temperature, printing speed, which have an impact on mechanical properties of the part and on geometrical accuracy. One the device has been prepared for printing and having finished the printing process, the last step is to carry out the post-processing. This is a set of activities that are generally based on removing the supports (if such supports exist) and in certain cases finishing surfaces to get roughness requirements or heat treatment [6–8]. All activities having been completed, the part is applicated into the dedicated mechanism. The whole printing process is presented in Fig 1.

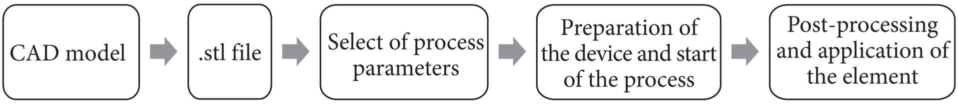

Fig. 1. Scheme of additive manufacturing parts

Currently, additive manufacturing technology can be used at various application levels. The literature mainly highlights three levels: [8–11]:

— Rapid Prototyping (RP),
— Rapid Tooling (RT),
— Rapid Manufacturing (RM).

Professor Hideo Kodama (Japan) and Prof. Charles Hull (USA, the inventor of stereolithography) are considered to be the pioneers in the field of Rapid Prototyping [12]. Rapid Prototyping allows producing a conceptual model which cannot be loaded or a functional prototype. However, the term "rapid" does not only refer to a short production time, but more to the possibility of making an element directly from CAD model to the finished product created by the 3D printer. Rapid Tooling is an RP-based concept but used in specific applications. RT is an area that uses additive technologies to produce moulds or tools that improve production processes, in which other methods are used, e.g., machining (RP and RT production quantity 10 to 500). RP and RT are the ways to use the Rapid Manufacturing that uses 3D printing for low-volume production of utility details, often personalised or adapted to special applications (RM production quantity from over 500 to a few thousand) [8, 9, 12]. The above concepts are well illustrated in the diagram in Fig. 2.

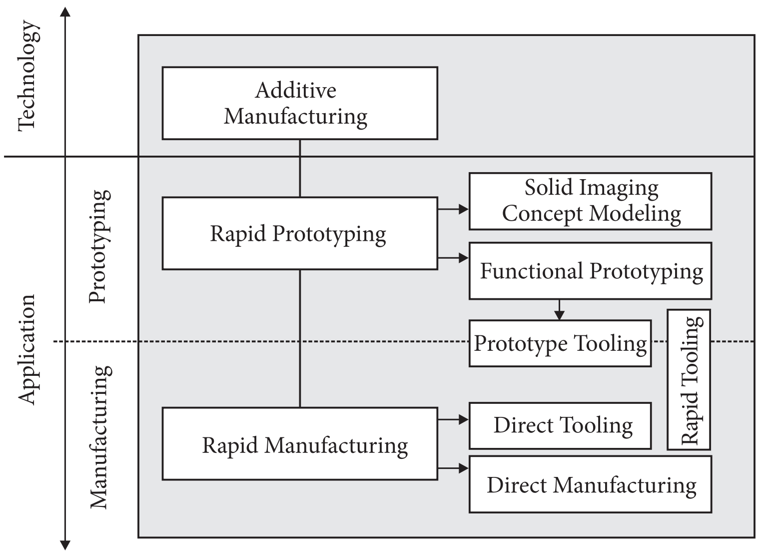

Fig. 2. Scheme of using additive technologies in the application area [8]

The type of additive manufacturing technology, that will be used for RP, RT, and very often in the RM aftermath, depends on mechanical properties, material, geometry, and accuracy requirements. Many different additive methods can be categorised according to multiple criteria. Currently, several classifications exist. One of the first classifications of additive technology was created by Kruth [13], who divided techniques according to the type of respective materials (powder, liquid, solid) or to shape building (direct 3D layers and 2D layer technique). Such approach was used by Pham et al. [9]. However, due to the development of existing techniques and development of new ones, these classifications have ambiguities and disadvantages. One of the most popular classifications is included in ASTM F2792 which was accepted by the ISO standard (ISO/ASTM 52900:2015) [14]. This document divided the additive manufacturing process into seven categories which are illustrated in Fig. 3 and they are briefly described.

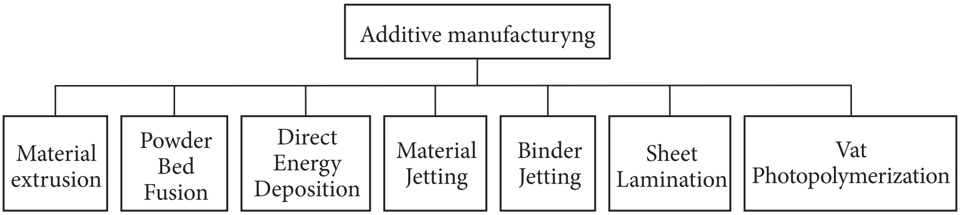

Fig. 3. Classification of additive manufacturing technologies recording to ISO/ASTM 52900 [14]

One of the most frequently used groups of methods is the Material Extrusion (ME). Generally, within the technics belonging to this group, filament-shaped polymers or composites constitute the input material. Under temperature, materials are plasticised and through the nozzle extruding one path on the workarea [7]. The paths generate layers from which the final detail is created. One of the most popular methods, belonging to this group, is FFF/FDM (Free Form Fabrication/ Fused Deposition Modelling). This method is used in various areas, such as automotive and aerospace industries, or in medical applications [14, 15]. The materials which are most often used in this method are the following: PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), PP (Polypropylene), PET-G (Polyethylene Terephthalate Glycol), PC (Polycarbonate), and more technical PP with CF (Carbon Fibber), ULTEM (material based on Polyetherimide), PEEK, PAEK (materials based on Polyether Ether Ketone), [15, 16].

The next group is a Powder Bed Fusion (PBF). In most of the PBF technologies, the laser is the source of energy, therefore it is often called in literature Laser-based Powder Bed Fusion (L-PBF) [16]. This group of methods is represented by Selective Laser Melting (SLM), Selective Laser Sintering (SLS) or Direct Metal Laser

Sintering (DMLS) [17]. The EBM method is an exception here, where an electron gun becomes the source of energy. In any case, the building process begins with coating a thin layer of powder obtained from metal alloys or polymers. Subsequently, the next step involves the scanning of a specific area with the laser or electron beam. Next, the build platform lowers and the process is repeated. Generally, this group of techniques is considered more precise than material extrusion and it is the most often used in the additive manufacturing area to direct production of metal and polymer parts. Metal alloys are often used, ferrous metals like stainless steel or non-ferrous metals such as titanium, nickel or copper alloys [18], while widely used polymers are PA12 (polyamide) [19] or various composites based on this material, for example PA12-CF (CF — carbon fiber) [20].

Direct Energy Deposition is a group of additive technologies where the material is deposited in a given place in a form of a powder stream or wire and melted by laser/electron beam or plasma/electric arc. Constant depositing and melting of the material results in creation of the part layer by layer [21, 22]. DED methods, apart from producing separate parts, could be used to repair surface or whole elements, whose re-manufacturing is much more costly. The group of DED techniques includes, among others, LENS (Laser Engineering Net Shape) or LMDS (Laser Metal Deposition Shaping) it is possible to deposit two different materials to produce a multi-material structure or gradient elements [23, 24]. Furthermore, some works have been reported of combining powder and wire in one process [25, 26].

VAT Photopolymerisation (VP) is one of the basic groups of additive manufacturing. VP includes the oldest SLA technique (Stereolithography) which was invented by Charles Hull [27]. The second method of the VP group is DLP (Direct Light Processing). Both methods use photo-curable resins to produce elements. The main difference is the light source, SLA uses a laser and a galvanometric mirror system, while DLP uses a digital projector. In both cases, the process begins with filling the tank with resin and submerging the build plate. Then, the first layer is exposed and hardened. It is possible due to the bottom being made of thin foil. Next, the build platform is moved up by the thickness of the layer and the process is repeated [28].

Sheet Lamination is a group of techniques, where the parts are created by joining a thin metal sheet plate. The most popular techniques in this group are UAM (Ultrasonic Additive Manufacturing) or UC (Ultrasonic Consolidation). It is a process of joining thin sheets of the metal layer by layer using ultrasonic welding of metals. Each of the applied layers is processed using a CNC machine in accordance with the given geometry [29, 30]. The great advantage of this group of techniques is the ability to combine various materials such as aluminium or copper alloys. Additionally, due to the lack of direct remelting of the material, electronic circuits or other elements that are susceptible to damage, due to high temperature, can be placed inside the manufactured elements [31].

The last two groups (Fig. 3) are similar because in both cases the process is analogous to the process involving an inkjet printer. Material Jetting technology uses liquid material which is jetted onto the build platform and it immediately cured with UV light. [32, 33]. In the case of the Binder Jetting group of technologies, the resin substitute as a building material is a polymer powder. After spreading a thin layer, the particles are combined using appropriate inks. The Multi Jet Fusion method, which belongs to BJ, can produce multi-coloured parts, but after the production of the element, its surface must be covered with a special liquid that will emphasize the individual colours.

The number of presented techniques shows the dynamics of the development of additive technology over the last 30 years since the first method was developed. Currently, the area of their application covers many different industries, including the production of machine components. However, there is still a need to carry out a lot of research in the field of the properties of materials produced with the use of AM and the shape-dimensional accuracy of the manufactured elements, as well as their fatigue life.

3. Additive manufacturing of gears

The issues, related to the production of gears, mainly concern the costs generated by the need to have a well-equipped production workshop, in terms of machines and tools, which significantly reduces the rapid response of manufacturers to the constantly changing customer needs [34]. Therefore, attempts were made to develop other methods allowing for more effective use of machines and devices. Currently, one of the solutions to this problem is the use of 5-axis numerically controlled machine tools for machining of toothed wheel rims [35-37]. However, in recent years, an attempt has been made to implement additive techniques in this area [4, 38-40]. In the further part of this paper, current achievements in the field of gear manufacturing with the use of AM will be described in terms of the techniques, materials, manufacturing accuracy, and strength properties.

3.1. Additive manufacturing of polymer gears

Polymer gears are characterised by relatively low production costs and lower weight compared to metal gears. In addition, these gears do not require a lubricant and they are also characterised by silent-running and corrosion resistance. Polymer gears are conventionally made using machining or injection moulding [41]. The first available studies on the use of AM in the production of polymer gears date back to 1992, where the authors mentioned the possibility of producing entire gears using the SLA technique [42]. The available research works focus on several aspects, in particular on the impact of manufacturing parameters on manufacturing time and weight, dimensional accuracy, tooth flank roughness [43-46], and durability of manufactured gears [47, 48].

There are several basic problems in the production of gears using the FDM / FFF or SLA techniques. One of them is orientation of the gear in relation to the build platform. Skawiński et al. [45], in the work on the production of gears using the FDM technique from PLA material, showed that the most appropriate orientation of the element on the build platform is the position of the rotation axis, so that it is parallel to the Z-axis of the 3D printer. Other variants have negative impact on manufacturing time and on dimensional accuracy, i.e., due to the necessity to use the supporting structures, what is also indicated by the authors of the works [39, 46, 49]. Apart from the orientation, with respect to the build platform, an important aspect from the point of view of the stiffness of the toothed wheel rim produced with the FDM / FFF technique is the number of external contours that are defined at the time of preparing the batch file for the printing device. With 100% of filling of the element and the standard number of contours (usually approx. 3), the internal structure of the teeth is built of parallel paths, what results in a non-uniform distribution of stiffness along the circumference of the circle (Fig. 4a). Therefore, it has been proposed that the toothed wheel rims, produced using the FDM technique, consist only of outer contours as the strength of a single fiber is greater than the connection between layers [45] (Fig. 4b). The above thesis is also confirmed by the work of Kim et al. [50] which also takes into account the direction of the reinforcement of the composite material used (PA+CF).

a) b)

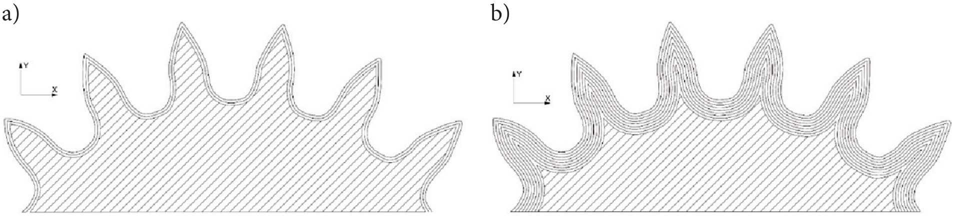

Fig. 4. The way the paths are arranged in a single model layer depending on the number of perimeters: a) 3 outer outlines b) 8 outer outlines [45]

In their works, the researchers also raise issues related to the geometric structure of the surface [46, 51] and the dimensional accuracy of gears manufactured by AM with the use of polymers [52, 53] including post-process processing [54]. The biggest problem, related to the roughness of tooth flanks, concerns the FDM/FFF method. Mitrovic et al. [51] determined the effect of a single layer height on the roughness of tooth flanks (made of PLA) in two directions (through the layers and in the direction of the fiber). The measurements performed through the layers showed that a change in its thickness from 0.1 mm to 0.3 mm causes a simultaneous increase in the Ra parameter from 10.199 μm to 22.330 μm. Diametrically different values were obtained as a result of measurements carried out in accordance with the direction of the fiber arrangement. For the previously mentioned layer heights, it was 0.212 μm and 0.603 μm, respectively. Such a large differentiation is not favourable from the point of view of the wear course during their exploitation and fatigue life. The Sa (Rrithmetic average surface deviation from the average surface) parameter, which was used in the work, gives a better overview of the roughness of the tooth flanks [55]. The roughness of the side surfaces of the tested cylindrical gear made of ABS and ULTEM was similar and amounted to about 10 μm, while the gears made of PEEK were characterised by the value of the Sa parameter at the level of over 7 μm, which is still not the value that is required in practice. Unfortunately, for other techniques (e.g. SLA or SLS), there are no data in the literature on the measurement of the roughness of the side surfaces of the teeth, apart from the generally presented measurement profiles shown in the research work papers [49]. On the basis of other works, related to the discussed topic, it can be concluded that using the SLA technique, the side surfaces of the teeth will have a Ra parameter value of less than 1 μm [56] and in the case of SLS it is about 7 μm [57]. However, these values depend on the manufacturing parameters used.

The use of AM, as a method for producing complex geometries that can be directly used in target applications, requires, inter alia, accuracy not only in terms of surface roughness but also the appropriate dimensional tolerance of the entire element. This aspect is particularly important in the case of gears. In the available literature, the geometry of gears, produced with the use of AM, is very often assessed using a 3D scanner. This allows for the determination of the deviation values of individual parts of the manufactured gear in relation to the reference model designed in the CAD software. Table 1 presents the literature data on the deviation values of the side surface as well as the entire gear in relation to CAD models for various gears manufactured using the most popular additive techniques employing polymers.

The highest deviation values in global terms are characteristic for gears manufactured by the SLS method with the use of Precimid 1170 (polyamide). This is mainly caused by material shrinkage or uneven fusion during the manufacturing process [52]. Additionally, an attempt was made [54] to determine the effect of abrasive blasting (sandblasting) on the geometry of a gear, also produced using the SLS method, from the same material. Finishing treatment, as a result of removing a part of the material, negatively affects the values of the deviations. In addition, the authors of the publication noticed that the layer of material removed is not uniform, possibly as a result of a change in the distance between the sand nozzle and the workpiece. The most dimensionally stable are gears manufactured using techniques with photocurable materials. However, it should be remembered that all kinds of resins are susceptible to increasing their hardness, and thus brittleness as a result of their exposure to UV radiation, which may have a negative impact on the durability of the manufactured gears. Data contained in Table 1 show that the deviations in most cases have positive and negative values, which makes it difficult to determine the appropriate allowance for finishing or the values of any correction factors for the manufactured geometry. In practice, the accuracy of gears is described by the accuracy classes defined in the standards. According to available studies, using additive technologies with polymers, it is possible to produce the gears that meet the requirements of 11 or 12 accuracy class (DIN 3962) [51, 55, 59], but in some cases, these gears do not fit in any of the defined classes [47, 55].

Table 1

Geometric accuracy of additive manufactured polymer gears

Gear type	Manufacturing methods	Materials/ postprocesing	The value of the geometric deviation (tooth flank) [mm]	The value of the geometric deviation (entire gear) [mm]
Spur gear — pinnion [52]	SLS	Precimid 1170	from –0.068 to +0.079	from –0.270 to +0.204
Spur gear — gear [52]	SLS	Precimid 1170	from –0.064 to +0.059	from –0.565 to +0.159
Spur gear [54]	SLS	no data on the material, abrasive blasting (sandblasting)	from –0.123 to +0.030	from –0.297 to +0.190
Bevel gear [58]	FDM	ABS	no data	from –0.160 to 0
	SLA	SL5170	no data	from –0.060 to 0
Spur gear [53]	PolyJet	FullCure720 RGD720	no data	from –0.064 to +0.069
	SLS	Precimid 1170	no data	from –0.33 to +0.428
Bevel gear	FDM	PLA	average value 0.15 (±0.096)	average value 0.22 (±0.142)

From the user's point of view, however, the most important aspect is the fatigue life. Polymer gears carry much less loads than metal gears and thus, the wear mechanisms are influenced by slightly different aspects. The durability tests of additive manufactured gears are most often carried out on specially prepared test devices which were presented in the works [40] [48] or standard FZG stands. An extensive article on the durability of gears has been presented by Pisula et al. [55]. The work investigates fatigue tests of gears manufactured using the FDM method from ABS M-30, ULTEM 9085, and PEEK. The carried out tests showed that the most wear-resistant gears were made with PEEK (with pressures of approx. 3.5 N/mm^2), despite their lowest manufacturing accuracy. The main reason for the highest durability was the material's resistance to generating high temperature during operation (approx. 30°C), which is one of the main causes of damage to gears made of polymers [47, 60]. Fatigue life tests were also carried out by Zhang et al. [61]. The obtained test results show the possibility of producing polyamide gears under the trade name Nylon 618, having a higher fatigue life than the gears produced by the injection method. Figure 5 shows the mechanisms of wear or damage to toothed rims during the tests, depending on the load. At low load values, abrasive wear predominates. An increase in the value of the loading moment also increases the generated temperature in the meshing area, which at the same time leads to a change in the mechanism of damage — plastic deformation of the teeth.

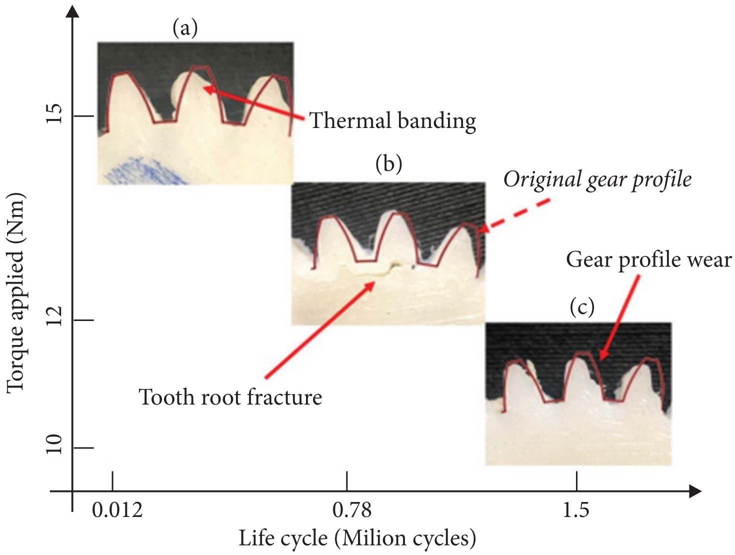

Fig. 5. The mechanism of damage to gears made of Nylon 618 depending on the given load [61]

3.2. Additive manufacturing of gears with the use of metals alloy

Gears made with the technologies that involve metal materials are used in gearboxes that are subjected to much higher loads. However, compared to polymer-based techniques, they have significantly higher costs and they also require longer process setup times. Moreover, determining the correct production parameters is not a trivial activity as in the case of other techniques from the ME or VATP group. In addition, due to the requirements regarding the level of generated noise and vibrations, these gears should be performed with much greater precision (accuracy class 6-7 according to DIN 3962), and the materials used in the process must meet the requirements of fatigue strength.

The main issue in the case of using additive technologies for the production of metal gears is the availability of materials intended for this type of application. This problem is significantly emphasised in a recent report by the American Gear

Manufacturers Association [62]. The most widely used alloys are from the group of stainless steels [63-65], tool steels [66], maraging steels [67], and titanium or aluminium alloys [68, 69]. The availability of materials, dedicated to the production of gears with additive manufacturing, is limited to a few items presented in Table 2. It should also be noted that all the above-mentioned materials are available in the form of powders, which proves the widest use of the PBF (L-PBF) group of methods in the discussed area.

Table 2

Materials dedicated to the manufacturing of gears with additive technologies [62]

Material name	Material type
AISI 9310	Carburising steels
Pyrowear 53	
Pyrowear 675	
Ferrium C64/64	
20MnCr5	
16MnCr5	
AISI 52100/ 100Cr6	Bearing steel for hardening

As already mentioned, for gears made of metal alloys, the precision aspect of the workmanship is of particular importance. As in the case of polymer gears, there are works in the literature on checking the correctness of mapping the geometry produced by printing devices. Budzik et al. [63] used the 3D scan technique to determine geometrical deviations of a gear produced with the DMLS technique from GP1 steel (stainless steel). The authors of the study noticed that the manufactured gear did not have uniform geometry deviations along the circumference of the toothed rim. According to the researchers, the observed phenomenon is a consequence of material shrinkage as a result of high temperature gradients during the process. In addition, they indicate the need for additional finishing. Similar tests were carried out [64], where the authors of the study stated that the gears manufactured using the DMLS technique do not meet the requirements of any of the accuracy classes of the DIN 3962 standard. Moreover, the surface roughness of the gears in the state after printing is too high, as evidenced by the value of the Sa = 12 μm (which may have a negative effect on the fatigue life). Only the application of the finishing machining in the form of milling allowed the manufactured gears to achieve the accuracy class 7 and the roughness of the tooth flanks at the level of 0.37 μm. Due to the aspects related to the low quality of the tooth flanks and the large values of geometrical deviations of the toothed wheel rims compared to conventional manufacturing techniques, the authors of the work [70] proposed the use of methods from the PBF group for the production of elements using the NNS (Near Net Shaping) technique, i.e., details with a geometry close to the target geometry. Positive aspects of this approach are noted in the work [67] where the gears were manufactured in two stages. The first one involved the production of elements with appropriate material allowances using the DMLS technology, and then, using milling, finishing of the required surfaces was carried out. This form of the process saves up to 35% of the material needed to manufacture the same gears using conventional methods. The last aspect concerns the fatigue life of additive manufactured gears. This issue was discussed in relatively few works [65, 68, 71, 72]. The bending fatigue strength of teeth was described in the work by Kamps [72], where gears manufactured by means of DMLS from 16MnCr5 carburising steel were tested. The author managed to produce model elements with a density of 99.97%. In addition, the thermo-chemical treatment allowed to obtain a hardened layer with a thickness of 0.7 mm and its maximum hardness was 800 HV. The gears, in order to ensure the appropriate surface roughness, have been treated with the finishing process. The bending fatigue strength, at the base of the teeth (with a 50% probability of failure occurrence), was σ_{Flim}, 50% = 830 N/mm^2. Similar studies were carried out by Concli [65]. The authors tested gears made of 17-4PH stainless steel using the PBF technique, but in this case the fatigue life was σ_{Flim} = 450 N/mm^2. The fatigue fractures, presented in Fig. 6, show the main cause of cracking of the teeth at the base during the examination. Defects in the form of pores, formed during the manufacturing process, are natural fatigue notches. In addition, as a result of the finishing process, the pores located at the surface of the detail (in the state after printing) were opened and at the same time became the source of crack initiation. In both cases, the fatigue life of gears manufactured using AM is similar to gears manufactured using the same materials using conventional methods.

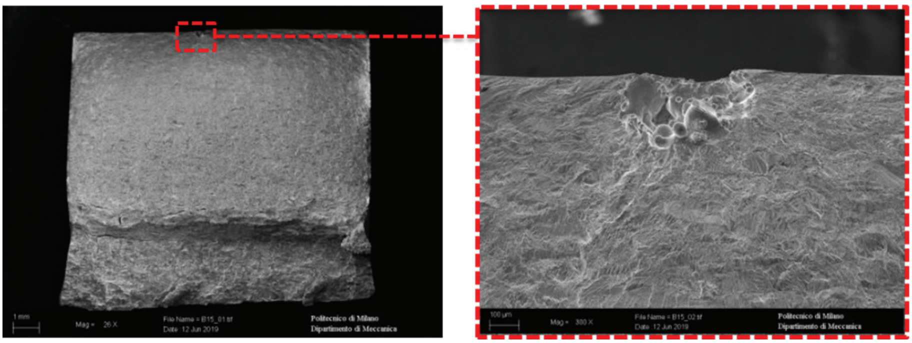

Fig. 6. View of the fracture surface with marked spot of the crack initiation [65]

The issue of fatigue life to surface pressures was discussed in the works of Tezel et al. [68, 71]. They discussed the aspects related to the wear of the tooth flanks produced using the DMLS method from an aluminium and titanium alloy as well as 316L steel and 420 steel. In each case, the tooth flanks had numerous particles of unfused grains which made them highly rough. This caused the lubrication film to break during operation and wear in the form of scuffing to occur. In addition, the existing depressions on the surface were places for the accumulation of the lubricant under high pressure, which resulted in the formation of pitting damage.

4. Design directions of metal alloy gears using AM

The works, presented in Chapter 3, dealt with gears with standard geometry that can be obtained using traditional methods. However, the ever-increasing requirements related to increasing energy efficiency and reducing the negative environmental impact of production processes make it necessary to look for other design solutions related to drive systems. Additive manufacturing allowed for the delineation of three new directions in the design of metal alloy gears, which are shown in Fig. 7.

The first solution is to use conformal cooling known from injection moulds. The channel system is designed to lower the operating temperature in the tooth contact area and thus, it reduces the amount of oil inside the gearbox body. The work [75] showed that the use of such solution allows reducing the temperature of the toothed rim during operation by even 40°C, while the authors of the other work [76] confirmed the increase in the strength of the toothed wheel rim to scuffing by 30%.

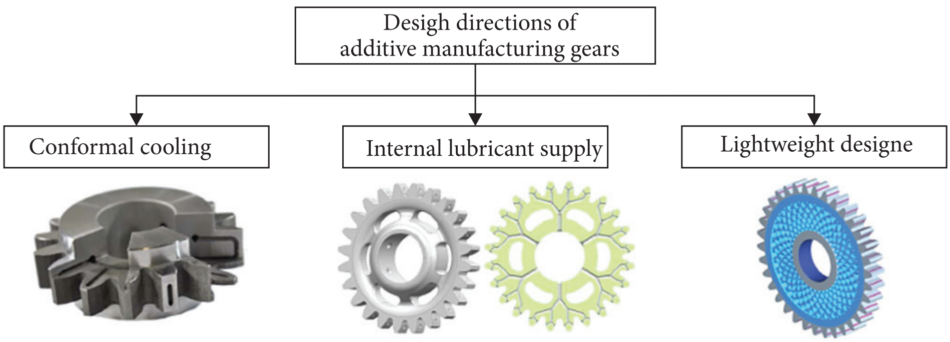

Fig. 7. Design directions of additive manufacturing gears: conformal cooling [73], internal lubricant supply [72], lightweight design [74]

The second possible design direction concerns a similar design solution, however, the duct system is an open system. The individual channels run from the gear hub to the heads or flanks of the teeth where they exit. This solution was developed at work [72], unfortunately only in theoretical terms. In addition to the cooling function of the entire element, the channel system is to splash the lubricate inside the entire gearbox and better supply oil to the meshing zone. However, the analyses that were carried out in the work showed the risk of reducing the fatigue life of the gear as a result of voids in the form of channels inside the gear structure. The last direction concerns the modification of the geometry of the circle by the use of cellular structures. This solution is mainly aimed at reducing the weight of the gear, which is confirmed by the following works [72, 74, 77] in which the obtained material savings were even at the level of 36%. Additionally, Ramadani et al. [69] presented the possibility of filling the cellular structure with polymer, which additionally allowed reducing the level of vibrations and the intensity of sound generated by the gearbox.

5. Summary and conclusions

Over the last several decades, the technology of additive manufacturing has been developing very dynamically. The number of available techniques makes it possible to implement them in almost every branch of industry. The use of RT and RP techniques allows reducing the costs related to the introduction of new solutions into the market, and may also improve the efficiency of production processes. The use of the RM technique for the production of gears may be useful in the case of unit production due to its energy and cost efficiency, as well as susceptibility to changes in the geometry of the manufactured elements. On the basis of the review, some trends have been noticed that currently accompany the production of polymer or metallic powders gears with the use of AM:

- Perpendicular orientation of the gear rotation axis on the build platform in the additive manufacturing process is the most advantageous in terms of minimising the presence of supports within the tooth flanks, which has a positive effect on the geometry and duration of the process.
- The main groups of additive technologies used in the production of polymer gears are Material Extrusion (FDM / FFF), VAT Photopolymerisation (SLA / DLP) and Powder Bed Fusion (SLS).
- A large group of materials (ABS, PA, POM) used in the production of polymer gears by conventional technologies is available in the production of gears using AM technologies.
- The maximum accuracy class with which it is possible to create model elements using AM from polymers is 11, which significantly differs from the accepted practice (class 8 for injection moulding).

— The main cause of damage to polymer gears during operation is high temperature which causes plasticisation of materials and deformation of the tooth profile or complete damage to the gear rims.
— The most widely used group of techniques used for production of metal gears is the PBF group (SLM and DMLS).
— In the production processes of metal powder gears, the NNS approach is currently applied due to the need to implement finishing machining that allows obtaining the appropriate accuracy class (6-7 class).
— Pore defects are the source of fatigue cracks in PBF gears, with pitting and scuffing being the predominant forms of wear on the side surfaces (in the case of gears after printing).

Despite the relatively large number of available scientific papers on the issues discussed, this area is not fully investigated. There are still many aspects that are not sufficiently explored and could become the subject of future research. These are mainly the following:
— An attempt to use a wider group of materials conventionally used in the manufacturing processes of AM-based gears, including their heat treatment.
— Determination of new post-process machining that allows additive manufactured gears to meet the requirements of individual performance accuracy classes.
— Tests in the field of bending fatigue life at the tooth base and surface pressures, as well as a description of the course of fatigue cracking of gears produced with the use of PBF techniques from conventionally used materials.
— Determining the suitability of application in terms of energy and cost efficiency of new directions in the design of gears manufactured with the use of PBF and the influence of the applied geometries on their fatigue life.

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J. ŁUSZCZEK

Analiza metod projektowania oraz wytwarzania kół zębatych z wykorzystaniem technologii przyrostowych

Streszczenie. Technologia wytwarzania przyrostowego jest jednym z głównych składowych czwartej rewolucji przemysłowej określanej mianem Przemysł 4.0. W ciągu ostatnich kilkunastu lat, dynamiczny rozwój tej technologii przejawia się w formie szerokiego spektrum wdrożeń poszczególnych technik w procesy produkcyjne wielu części maszyn. W pracy przedstawiono ostatnie osiągnięcia z zakresu wytwarzania kół zębatych przy użyciu technik addytywnych z wykorzystaniem polimerów, jak i materiałów metalicznych. Wskazano techniki, najczęściej wykorzystywane w tym zakresie, a także problemy związane z dokładnością geometryczną, czy trwałością zmęczeniową elementów wytwarzanych z ich wykorzystaniem. Ponadto, określono przyszłe kierunki projektowania kół zębatych, których implementacja była możliwa dzięki wykorzystaniu AM, a także zakres badań, który w przyszłości powinien zostać podjęty w kolejnych pracach naukowych.

Słowa klucze: inżynieria mechaniczna, techniki wytwarzania, wytwarzanie przyrostowe, koła zębate
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