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Health Risks of Additive Manufacturing Technology[6]

Despite the fact that additive manufacturing technology has been around for decades, its radical uptake has only been seen in recent years. Today, they are not only used in industrial areas, but also in everyday household applications. At the same time, accidents and injuries have also occurred that were solely the result of the easy access to 3D printers. The risks of accidents and injuries in additive manufacturing arise in different areas. Burns, injuries caused by moving parts, electrical shocks, chemical accidents, as well as fire hazards and ergonomic problems have been reported. Minimising risks is impossible without proper personal protective equipment and adherence to safety measures, as well as professional handling and maintenance of machinery. Our aim is to draw the reader's attention to the risk factors that can fundamentally influence the likelihood of injuries and accidents occurring.

Keywords: *health risks, 3D printing risks, occupational safety risks*

Introduction

The explosive development and increasing penetration of digital technology is opening up innovative and wide-ranging development opportunities, while also creating unprecedented challenges in different areas of work.

Additive manufacturing technology is one of the most innovative and fastest growing areas in modern industry, a manufacturing process where a three-dimensional object is built

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layer by layer, i.e. material is added only where it is needed, rather than removed. This process contrasts with traditional subtractive manufacturing, where material is removed from the workpiece, for example by milling or turning. The material can be plastic, metal, concrete or, in some cases, even living tissue. If today's technological possibilities are taken into account, it is clear that design determines production. With the right design software, we can create almost any three-dimensional shape in digital form, which can be built up layer by layer using the right printers. Additive technology has revolutionised manufacturing in many industries and offers a number of advantages that have many potentials. Such advantages include:

- cost reduction and time saving
- customised product production
- production of complex geometries and parts
- material saving, sustainability
- innovation and new product development
- automation and process optimisation
- customised and small series production
- potential for new industrial applications

Today, additive manufacturing technology is revolutionising production and industrial design by offering fast, flexible and cost-effective solutions for operators and end users alike. The ability to create complex geometries, the possibility of customisation, sustainability and the promotion of innovation all contribute to making additive manufacturing an increasingly important player in the industries of the future.

Despite the fact that additive manufacturing is gaining ground in areas such as the production of customised medical devices and implants, there are potential health risks that need to be taken into account, including the inherent dangers of the technology.

The risks inherent in the technology may include:

- risks of nanoparticles and volatile organic compounds
- bacterial and viral contamination risks
- biocompatibility and toxic substance risks
- accident and injury risks

Risks of nanoparticles and volatile organic compounds

Particulate matter (nanoparticles) and volatile organic compounds[7] (VOCs) are potentially harmful substances produced during additive manufacturing (3D printing), which can be hazardous to both health and the environment.

Fine particles (or particulates) are microscopic solids in the air that can cause various health problems if inhaled. In additive manufacturing, they are produced during the heating,

[7] Volatile Organic Compound (VOC): Any organic compound with a high vapour pressure at normal room temperature and a boiling point below 250 °C, which causes a large number of molecules to evaporate and enter the ambient air.

melting or injection moulding of printed materials (metals, plastics, ceramics). Based on the market segments, the products of the different manufacturers and the priorities for domestic sales, it can be concluded that the most commonly used raw materials are:

- Acrylonitrile butadiene styrene (ABS):[8] A thermoplastic with good impact resistance, high hardness and strength, good heat resistance and chemical resistance, which can be classified as an amorphous polymer.
- Polylactic acid (PLA):[9] A biodegradable thermoplastic produced from cereals with a high starch content.
- Resin: A UV-curable liquid plastic used[10] in stereo-lithography processes, specifically for 3D printing.
- Polyethylene terephthalate glycol (PETG):[11] A popular plastic in additive manufacturing technology because it has good mechanical properties, is easy to handle and less prone to deformation than other plastics such as ABS.

For the listed materials, it can be concluded that there are risks to be considered when using them in 3D printing, such as exposure[12] to nanoparticles and volatile organic compounds (VOCs). Despite the ongoing work of the European Chemicals Agency (ECHA) to set appropriate limit values for the hazards of a substance at both EU and national level, there are no agreed Occupational Exposure Limits (OELs) for nanoparticles[13] in many countries. Occupational exposure limit values (OELs) are regulatory values that indicate exposure levels considered safe (from a health point of view) for chemicals in the air at the workplace. The international literature provides a set of reference values to assess the exposure of nanoparticles generated during 3D printing.[14]

The most common sources of risks from "fine particles" (Particles) or nanoparticles are:

- In the case of plastics (e.g. PLA, ABS, PETG) harmful compounds evaporating from heated materials.
- In the case of metal printing, it is also the gases, vapours or tiny metal particles released due to the high temperatures required for the operation of metal printing machines.

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8 The basic properties of PLA are determined by its constituents. Styrene provides good processability, acrylonitrile provides hardness, heat resistance and chemical resistance, and butadiene provides flexibility and low temperature hardness. The addition of different additives and the ability to modify the proportions of the components allows the creation of 3D printing substrates with different specific characteristics.

9 PLA is soluble in many organic solvents, so these solvents are used in 3D printers to clean extruder heads.

10 The photosensitive resin can be cured by UV light or laser.

11 Especially in the food industry and medical applications. Although the number of toxic gases emitted by PETG printing is better than ABS, there are still risks.

12 Byrley et al. 2019: 395–407; Gu et al. 2019: 476–485; Kwon et al. 2017: 10357–10368.

13 Occupational Exposure Limit (OEL): Occupational exposure limits are regulatory values that indicate exposure levels considered safe (from a health point of view) for chemicals in the air at the workplace. In Hungary, the limit values are set out in ITM Decree 5/2020 (II. 6.) on the protection of the health and safety of workers exposed to chemical agents.

14 Garcia Gonzalez – Lopez Pola 2023.

All materials used for 3D printing may pose some health risks, in particular due to airborne substances released during printing. These risks can manifest as respiratory irritation, chronic respiratory diseases and sometimes lung tumours.

Toxic gases and their health risks in 3D printing

Toxic gas emissions from additive manufacturing pose a serious health risk. These compounds are released from certain solids or liquids in the form of gases. The gases released may contain chemicals that can have harmful effects on the human body in the short or long term. A contributing factor is that concentrations of volatile organic compounds can be up to ten times higher indoors than outdoors. This is particularly relevant in the case of 3D printing, as the technology using the materials mentioned above is almost invariably installed in enclosed spaces. The number of products emitting volatile chemicals is estimated in the thousands by the U.S. Environmental Protection Agency (EPA).[15]

The *Total Exposure Assessment Methodology (TEAM) Study* Volumes I–IV published by the Office of Research and Development of EPA found as early as the 1980s that levels of about a dozen common organic pollutants are 2 to 5 times higher inside homes than outside, regardless of their location.[16] This is important because while people (not necessarily workers) use products containing organic chemicals during the 3D printing process, they can expose themselves and their environment to very high levels of pollutants that can persist in the air for a long time after the activity has ended.

Different types of printing can release different types of toxic gases into the air, which can cause acute or chronic health problems if inhaled.[17]

Styrene, for example, is a pleasant smelling, highly refractive compound that is insoluble in water but soluble in many organic solvents and freely miscible with alcohol and ether. The compound is formed when the plastic reaches high temperatures (around 230–260 °C) during printing. Inhalation of styrene can cause acute respiratory irritation, coughing, headache and dizziness. Prolonged exposure to high concentrations of styrene can damage the central nervous system and some research suggests that styrene can cause cancer.

Printing and ABS printing in particular, can also produce small amounts of formaldehyde, a known carcinogen.[18] Formaldehyde is an irritant to the respiratory tract and eyes, and with long-term exposure can cause serious health problems such as lung cancer.

One of the by-products of PLA is lactic acid, which is the raw material for PLA. Although it is non-toxic among the gases produced during PLA printing, it can irritate the respiratory tract if inhaled in large quantities. However, lactic acid is much less dangerous than styrene or formaldehyde.

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15 U.S. EPA 2024.

16 Wallace et al. 1986: 289–315.

17 Rim 2023.

18 Carcinogenic substances directly damage the genetic make-up of cells. These genetic defects result in the proliferation of genetically damaged cells, which accelerates the process of malignant tumour transformation.

PLA can also release small amounts of acetone during printing, although not as much as printing ABS. Acetone is irritating to the respiratory tract, skin and eyes and gives off a strong, unpleasant odour.

A compound called acetaldehyde may be released when PETG 3D printing material is used. Acetaldehyde is a relatively mild toxic gas that can also irritate the respiratory tract and eyes. Prolonged planned exposure can cause circulatory problems, headaches and dizziness.[19]

However, we cannot forget the harmful effects of the gases produced by metal printing, as metal-based 3D printing (e.g. titanium, aluminium, stainless steel) can also produce toxic gases, but these processes are usually carried out in industrial environments where the necessary safety standards are more stringent. It could be argued that until metal printing is affordable for the average citizen, only the risk factors in industrial areas need to be addressed and monitored. However, as the world is based on economics and the development of technology cannot be limited, it is easy to imagine that, like plastic printing, metal printing will be in several homes within a few years. But what should we look out for when printing metals:

- If the material itself, which is a metal alloy, contains lead, lead poisoning can occur during melting and dissolution. So, lead itself can be a risk factor.
- Metal printing can produce nitrogen oxides (NO; NO_2; NO_3) due to the high temperatures and gaseous environments, which can irritate the respiratory tract and cause long-term damage to the lungs.
- Melting metals at high temperatures can also produce ozone, which can irritate the respiratory tract.
- The toxic gases listed above (styrene, formaldehyde, acetaldehyde and ozone) can have direct and long-term adverse effects on the human body and can lead to a number of health complications. Such adverse health effects may include:
- Respiratory irritation: In extreme cases, it may cause respiratory failure similar to choking. Long-term exposure may reduce lung function and increase the risk of respiratory diseases (e.g. asthma).
- Central nervous system effects: Styrene and VOCs (including other volatile organic compounds) can affect the central nervous system, causing dizziness, headaches, concentration problems, sleep disturbances and fatigue.
- Carcinogenic effects: Formaldehyde has been shown to increase the risk of developing nasal and throat cancers in particular.
- Skin and eye irritation: This can be a problem if the room is not properly ventilated during printing.

The question arises as to how to reduce exposure to these risk factors to the lowest possible level, i.e. how to minimise the hazards. These issues are now part of occupational safety and health and, within that, of occupational safety. Since we are talking about toxic gases, the main task is to reduce the concentration, i.e. by proper ventilation, the concentration levels can be significantly reduced. Printers should be operated in well-ventilated rooms or with

19 Wojnowski et al. 2022.

extraction systems that remove harmful gases and particles. In industrial areas this is feasible, but in civilian dwellings this technology is often not feasible or users do not want to spend the money.

Another solution is to use enclosed 3D printing systems. Closed systems collect and filter the gases and particles emitted during printing, thus also reducing the concentration of toxic substances in the air. For such systems it can also be stated (based on experience) that in industrial areas this technological change can usually be implemented quickly, but there is limited precedent for this in private use.

If we look at occupational health and safety activities, the use of appropriate protective equipment against toxic gases can be a solution. Workers are recommended to wear protective masks (several activated carbon filter masks) and other personal protective equipment, especially when printing in enclosed, poorly ventilated spaces. In case of public use, protective equipment is rarely used, because if it is not required or the user is not aware of the health risks, he will not protect himself against the harmful effects. This is precisely the issue of compliance with regulations, but also the requirements of the various standards. Strict compliance with industry standards for additive manufacturing and workplace safety regulations is essential, not only in industrial areas but also in private homes. Toxic gases do not distinguish between the air in industrial areas and that in private homes!

Bacterial and viral contamination risks

Additive manufacturing can be used in many fields, including healthcare, for example 3D printing of prostheses, implants or medical devices. In these devices, as in any other healthcare field, it is particularly important to maintain hygiene, i.e. to ensure that the manufacturing process takes place in a hygienic environment. Printers and the materials used, such as powders, must be handled properly to avoid the risk of infection. Why is this important? Bacterial and viral contamination can pose a serious risk in healthcare and other industrial environments, as these microorganisms can cause serious infections and diseases. Of course, in these cases, we cannot talk about private use, not only because of the costs involved, but also because of the quality assurance requirements of the products. Coming back to the area of health care use, it is of paramount importance that bacteria and viruses as contaminants can enter the environment and the human body in various ways. These microorganisms can also pose a significant risk in many industrial, medical and food applications. Appropriate hygiene and safety measures should be applied to prevent and control contamination.[20]

Bacterial contamination

Bacteria are single-celled microorganisms that are found in many environments and can cause various types of infections. Sources of bacterial contamination can include humans, animals, water, air and solid surfaces. When it comes to 3D printed medical devices, prostheses and

[20] Jackson et al. 2024.

implants, the hospital is always the bottleneck where patients are most at risk. This is logical, since that is where the surgical procedures and implantations are performed and the patient is usually returned to the civilian environment already cured. The main objective is therefore to prevent hospital-acquired infections (nosocomial infections). In healthcare institutions, bacteria can easily multiply because patients enter with weakened immune systems and doctors often use invasive devices such as catheters, surgical instruments and ventilators. The sterilisation of these devices is particularly important as they come into direct contact with the patient's body or with 3D printed objects that are to be implanted in the patient's body. Inadequately sterilised devices can harbour bacteria and cause infections, serious complications and, in extreme cases, death. Some of the most common bacterial hospital-acquired infections include Staphylococcus aureus (especially the methicillin-resistant variant, MRSA), Escherichia coli, Clostridium difficile and Pseudomonas aeruginosa.

Another common problem is food safety risk. Bacteria in food can also cause serious complications during rehabilitation or surgical treatment of patients. The most common bacteria that cause food poisoning include Salmonella, Campylobacter, Listeria monocytogenes and Escherichia coli. Despite the fact that bacterial infections are only an indirect risk in the application or use of 3D printed products, they are one of the most common risk factors in the healthcare sector and therefore, even if rare, serious consequences should be considered.

Preventing bacterial infections can be prepared for by following and enforcing several key measures together. Since these microorganisms are easily killed, the most common method of protection is regular hand washing and disinfection. Regular hand washing and disinfection is essential for medical staff and patients to minimise the spread of bacteria. Another solution is continuous sterilisation and disinfection. Medical equipment, operating theatres and other surfaces must be properly sterilised and disinfected to kill bacteria. Adherence to (enforcement of) anti-infection standards and protocols is of paramount importance. Healthcare institutions must follow strict anti-infection protocols and standards such as ISO 14644 and EN 13795. By adhering to and enforcing these standards, and by also applying the necessary drug therapy for patient treatment, patients can be spared the harmful consequences of bacterial infections when using 3D printed implants, prostheses and other ancillary devices.

Virus contamination

A virus is a microscopic biological organism that is not cellular and can only replicate as a parasite in the cells of living organisms. Viruses, such as influenza, HIV, hepatitis and coronaviruses, can be easily spread through the air, bodily fluids, or direct contact. As with bacteria, we should also mention hospital-acquired viral infections and food and water-borne viruses.

In case of hospital-acquired viral infections, it should be seen that viruses can spread rapidly in hospitals and clinics, especially with diseases such as Hepatitis B and C, HIV and influenza viruses. Seasonal influenza virus and SARS-CoV-2 (Covid–19) can also be easily spread from patients and staff through respiratory droplet infection.[21]

[21] Longhitano et al. 2021: 32–34.

In case of food and waterborne viral infections, we are talking mostly about the Hepatitis A virus, which can enter the body through contaminated water or food, or on 3D printed medical accessories, devices and the aforementioned implants.

Looking at the ways viruses are transmitted, we can see that these microorganisms can be spread through the air – by droplet infection – or by direct contact (the virus can be transmitted directly by contact with the skin or mucous membranes of an infected person), or by touching already infected surfaces (for example, noroviruses, adenoviruses and rotaviruses).

Just as with bacterial infections, the spread of infection can be prevented by strict hygiene measures (regular hand washing, hand disinfection, wearing masks and other protective equipment used to prevent disease). Seasonal vaccinations are also a good protection (vaccination against influenza and other respiratory infections is a way of preventing the spread of the virus). The protection options listed above are an indirect way of promoting the use and application of the 3D medical devices mentioned above. Direct protection can be achieved by ensuring adequate ventilation and continuous air purification. It is essential for hospitals and public institutions to have adequate ventilation systems in place to minimise the risks of respiratory infections.

Of course, another solution that should never be left out when we talk about protection in healthcare facilities is disinfection. Medical devices and surfaces that could potentially be contaminated with viruses need to be disinfected regularly and this includes 3D printed supplies.

Biocompatibility and toxic substance risks

The issue of biocompatibility and toxic substances is particularly important for medical devices and medical applications, as medical devices come into direct or indirect contact with the human body and affect its physiological systems. Biocompatibility means that a substance is able to interact safely with the body without causing adverse reactions, whereas the presence of toxic substances in medical devices can pose serious health risks. Additive manufacturing (3D printing) and other modern manufacturing technologies that use biocompatible materials also face a number of challenges, as they not only have to meet mechanical properties but also have to take care of biosafety and avoid toxic effects.

Biocompatibility in medical devices

Ensuring biocompatibility is particularly important for implants (e.g. prostheses), surgical devices, catheters, dental devices and other medical applications where materials come into direct contact with the body or its fluids. These devices should not have any adverse effects on the body, even if they are often exposed to biological agents for long periods of time and at high levels. If the main factors of biocompatibility are taken into account, it can be stated that medical devices made by additive manufacturing techniques must fulfil the following criteria requirements:

- Cytotoxicity: The material should not have toxic effects on cells to avoid cell death or tissue damage.

- Avoidance of allergic reactions: Substances used in medical devices should not cause allergic reactions or hypersensitivity in the user.
- Carcinogenicity: Substances must not contain ingredients that are carcinogenic.
- Immunological reactions: Substances should not trigger immune responses in the body, such as inflammatory reactions or rejection, especially when implants are involved.
- Physical and mechanical stability: The material should maintain its integrity and stability in the body, and should not disintegrate or corrode.

In order to avoid biocompatibility, we must use substances that do not pose a risk to the human body. Therefore, the following materials are suitable for products made by additive manufacturing technology in direct contact with the human body:

- Titanium and titanium alloys: Titanium is highly biocompatible and is commonly used for implants (bone replacements). It is extremely well tolerated by the human body and does not trigger an immune response. The authors of this paper have not yet found any examples of titanium itself or its alloys being used in 3D printing, but it is possible to coat the surface of a manufactured product with this material.
- Polymers: Biocompatible polymers such as PEEK[22] (polyethylene ether ketone) and PVA (polyvinyl alcohol) can be used for the production of various medical devices (assistive surgical devices, prostheses). The biocompatibility of these materials is suitable for promoting cell growth and supporting healing processes.
- Silicone: Silicones are highly biocompatible and are often used in, for example, dental devices, implants or catheters.
- Ceramic materials: Ceramic-based materials, such as zirconia and alumina, are also biocompatible and are often used in implants and prostheses.

It should also be mentioned that there may be significant potentially toxic compounds present in the materials used in the manufacture of medical devices, especially if inappropriate materials are selected during manufacture or if biocompatibility testing is not sufficiently careful. Toxic substances cannot only damage tissues directly, but can also accumulate in the body over long-term use and lead to chronic diseases. Among the most commonly found toxic substances in medical devices are:

- Bisphenol-A (BPA): BPA is commonly used in the manufacture of plastics (e.g. polycarbonate). Although there are no immediate hazards with low toxic concentrations in many applications, BPA has been linked to long-term potential endocrine effects, reproductive disorders and cancer. BPA is often used in the manufacture of dental materials, medical devices and implants, for example, and the use of BPA-free materials is essential in the manufacture of medical devices.

[22] Partly crystalline plastic with excellent heat resistance. Versatile processing, extrusion, injection moulding. It has a wide range of applications, from high strength and hardness to excellent chemical and hydrolysis resistance, including hip replacements and dental prostheses.

- Phthalates: Phthalates – di-(2-ethylhexyl) phthalate, or DEHP – used to plasticise plastics are potentially toxic and can cause endocrine disruption. The presence of phthalates in the manufacture of medical devices such as catheters, infusion tubes and other plastic-based products is of particular concern as they can be severely toxic to the human body.
- Silicones: Although silicones are biocompatible and widely used in medical devices, some types, if not properly manufactured, can be contaminated with toxic substances (e.g. manufacturing by-products) that can be harmful to the body.
- Heavy metals: Lead, mercury and cadmium are heavy metals that can pose serious health risks in medical devices. They and other heavy metals can bioaccumulate in the body and cause a range of toxic symptoms, nervous system problems and kidney damage.
- Formaldehyde and other chemicals: Formaldehyde, used to solidify certain plastics and polymers, is a known toxic and carcinogenic compound.

Considering the options for protection, it can be concluded that biocompatibility risks can be protected against by targeted testing. Prior to the manufacture of medical devices, the materials used must undergo rigorous biocompatibility testing for cytotoxicity, allergic reactions, genotoxicity, carcinogenicity and other toxic effects. The material can be used if these tests indicate that the substances do not cause adverse effects in body tissues. Of course, in case of finished products, the tests must be repeated. Alternatively, the requirements of ISO 10993 standards for medical devices, including procedures for testing different types of toxic effects, must be fully complied with. However, the simplest solution is for manufacturers to use alternative materials for 3D printed products that are guaranteed to be free of harmful substances.

Accident and injury risks

Additive manufacturing technology, while offering many advantages for both industrial and home applications, like all industrial processes can cause accidents and injuries. Accidents and injuries can usually be avoided with a little care and common sense, but there are also unforeseen situations and incidents that occur despite the utmost care and caution. The risk of accidents and injuries depends on a number of factors, such as the type of material being printed, the technology of the printer being used, the experience of the workers and compliance with workplace safety measures. Residential use is not an organised work, is not legally covered by health and safety obligation, but the rapid spread of 3D printing ignores this. It is also often pointed out that, while employers have obligations in the workplace, residential users do not. Consequently, there is no full spectrum control over the production process. The following is a detailed description of common accidents and injuries and their possible prevention in additive manufacturing.

Burn injuries

The most common 3D printing technology is the FDM[23] – Fused Deposition Modelling – involves building a model by melting and depositing a plastic wire, layer by layer. Where the material is melted using heat, there are a number of thermal hazards, including the potential for burns. During the printing process, the table (the build surface) can reach temperatures of 100 °C, the print head (the extruder) can reach temperatures of nearly 200–300 °C, which can cause severe burns if someone accidentally comes into contact with these components.

Of course, protection against this type of risk is not too complicated. On the one hand, a set of rules must be established and, of course, observed to ensure that the user of the device does not have access to hot surfaces. This can be achieved by simple enclosures. On the other hand, a system of rules must be put in place to ensure that the operator of the device does not touch the printed product or any other part of the machine until it has cooled down. If all this does not work, there is still the option of using protective equipment, i.e. wearing heat-resistant gloves if immediate access to components is necessary.

Injuries caused by moving parts

3D printers often have moving parts, such as extruders, stepper motors and turntables. Collision with moving parts or human error can cause serious injuries, such as finger or hand injuries. Not directly related to the most common injuries, but there is a possibility that the printing device itself is not properly positioned and the fall of the device itself causes serious injuries. Of course, examples of this can also be found in the creative placement methods used by the general public. While in the former cases, injury to the hand or fingers may also be a risk factor, in the latter, injury to the lacteal body may be a risk factor. These injuries can range from simple abrasions or sprains to severe cuts, bruises or fractures.

A possible solution is to avoid touching moving parts while the printer is in operation. If you do need to intervene in the printing process, do so when the machine is stopped and the power is off. Another solution (for large printers) is to mark moving parts with some kind of warning signal, which could be a pictogram or even an acoustic signal.

Electronic accidents

3D printers are always powered by an electrical network via electrical equipment. The dangers of this may be familiar to even the most lay reader, as electricity and its distribution points are part of our everyday lives. The overloading of various power supplies, distribution lines and outlets is slowly becoming a common problem in everyday life. Improper handling of these

[23] It is also known as FFF – Fused Filament Fabrication. The technology was developed by Steven Scott Crump and his wife, Lisa Crump. According to company history, Scott wanted to make a toy frog for his daughter in 1988 with a glue gun filled with a mixture of polyethylene and candle wax. The idea only worked by creating the shape layer by layer. The toy turned out so well that he and his wife began to think about how to automate the process.

electrical appliances can lead to electric shock. Power supplies and other electrical components of printers can be dangerous if they are not properly maintained or if the user does not take care of the safety of electrical connections. In this regard, residential users should also strive to use a residual-current device/ground fault circuit interrupter in their homes. This is an electrical switching device that disconnects the network behind it if it detects a (relatively small) leakage current. Such a situation could occur, for example, if a conductor or a load becomes earthed or if someone accidentally touches live parts of the network. In this case, you will be electrocuted for the time it takes for the device to react, but the short time it takes to reach the device means that it is unlikely to cause any permanent damage.

The above-mentioned contact hazard can also be prevented by constantly checking the printer's electrical systems and cables for breaks or worn insulation. An important piece of advice is also to disconnect the power supply (not only switching it off, but also unplugging it). It is also of paramount importance to use protective plugs and other safety devices when using such devices to prevent electric shock.

Chemical accidents

The various plastics, inks and medicines used in additive manufacturing can have harmful effects on health if not handled properly. Improper storage and fumes produced during printing can pose a hazard. Hazards include skin and eye irritation. Some materials, such as ABS, emit toxic gases (e.g. styrene) when printed due to heat, which can irritate the skin and eyes. This will of course depend on individual sensitivity, but like all irritant reactions, it can take on extreme forms.

These chemical accidents can be prevented by the constant use of protective equipment, gloves and goggles when handling chemicals and by avoiding direct contact with the printer. The importance of ventilation was highlighted at the beginning of this publication, as the risk of inhaling harmful fumes is reduced if printing activities are carried out in a well-ventilated area. The simplest solution is to comply with and require compliance with safety regulations for materials that are properly chemically separated and stored.

Fire risk

During the operation of 3D printers, as we have already pointed out, several components can heat up and reach temperatures of up to several hundred degrees Celsius. The use of these extruders and thermocouples increases the risk of fire, especially if the operator leaves the printer table. As a significant proportion of printers (still today) use some form of plastic – such as ABS – which is particularly prone to ignition at high temperatures, the risks are real. But it is not only the inside of the printer that can create a fire hazard, the electrical network that runs it can also create a thermal effect that increases the risk of ignition. In extreme cases, if the printer is installed and operated in an inappropriate location, combustible gases, vapours or dusts may be present in the immediate vicinity of the printer and, if the parameters are not right, an explosive atmosphere may be created, the source of ignition being the heated component of the printer itself. In the latter case, the solution may be to use appropriate ventilation. It is important to note that, to avoid the risk of fire, the printer should never be left unattended, especially if high temperature materials are used during printing. Printers should always be placed on fireproof base plates, and it should be ensured that no flammable materials are present in the printer's environment.

Ergonomic risks

Ergonomic risks are often overlooked and not taken seriously enough as potential health hazards. 3D printing is usually a lengthy process, especially if the working conditions are not properly adjusted, and this can lead to ergonomic problems. Just think, when you watch something interesting on a monitor and do it for a long time, your neck, back or waist may indicate that your posture was not ideal during the activity. The same is true if we are printing and we have to be near a machine or machines and we are doing it in a workplace with poor ergonomics. A number of factors is needed for the ideal conditions, such as avoiding improperly adjusted furniture, inappropriate clothing, but also forced postures. Muscle aches and joint problems are an immediate sign of something that is not ergonomically perfect. Constant bending, sitting for long hours, and poorly adjusted workstations can cause back and neck pain, as well as hand and arm problems.

Addressing these problems, while simple, it can be costly. When setting up a print room, the simplest solution is to equip it with comfortable workstations, ergonomic chairs and desks. The workstation is set up to avoid excessive bending or prolonged poor posture. Even if it is hard work, regular breaks should be taken to avoid muscle fatigue and mental exhaustion.

Summary

Although the effects of additive manufacturing on human health and the human body have been investigated, there are still no adequate benchmarks, due to the rapid expansion of additive manufacturing in recent years. As the technology has become more widespread, we have seen an increase in accidents and injuries, which leads us to conclude that, although the technology is now mature in industrial terms, users in households are not yet adequately prepared for its use.

The risks of accidents and injuries in additive manufacturing can occur in different areas, such as thermal injuries, injuries caused by moving parts, electrical shocks, chemical accidents, fire hazards and ergonomic problems. To minimise the risks, it is essential to wear appropriate personal protective equipment (gloves, goggles, protective clothing), to comply with safety measures (e.g. fire safety regulations) and to handle and maintain the machines professionally.

In addition to avoiding injuries and preventing accidents, it is also necessary to be prepared to deal with health problems associated with the use of the technology and to adapt preventive measures. It may take years or even decades of exposure to assess the adverse health effects.

Exposure to the gases, vapours, mists and dust produced by 3D printers can lead to various lung diseases and can cause mild or severe symptoms depending on individual sensitivities.[24] It is also important to note that the use of this technology should only be undertaken with great caution and after appropriate medical examinations, so it is worthwhile to be aware not only of the condition of the person printing (supervisor) but also of the health of people in the immediate vicinity of the printer.

The substances produced during various types of nylon printing can irritate not only the lungs but also the eyes and mucous membranes and, in extreme cases, can cause neurological damage. When printing with nylon material, CO_2 concentrations higher than the established limit have been measured and carbon monoxide, hydrocarbons, ammonia, caprolactam and hydrogen cyanide have been detected in various tests.[25]

We must not forget the skin surfaces in direct contact with different substances. Coloured filaments may contain aluminium, arsenic, zinc, copper, tin, nickel, chromium and other chemicals, and reactive oxygen forms may be generated during printing. There are also examples of ozone levels of 9 $\mu g/m^3$ being detected in a closed printer. The interaction of ozone with unsaturated volatile organic compounds can produce reactive products such as carbonyl compounds and secondary organic aerosols.

The development of filaments is driven by their very popular use, but this requires the use of mostly cost-effective additives such as inorganic dyes, metal particles, nanomaterials, metal-containing flame retardants, antioxidants, thermal stabilisers and catalysts. The use of these substances not only has a negative impact on the environment, but also stresses and impairs living tissues, including the human body.

The hazards of metallic powders and resin printers are also under continuous investigation, but here too the reference values are still scarce. It is certain, however, that while aluminium, chromium, nickel and cobalt can cause damage in the former case, cleaning alcohol mixed with resin can cause damage in the latter case.

We see the benefits of the technology itself every day, but we still know little about the potential application problems and adverse effects. Researchers are constantly investigating the dangers and hazards of 3D printing, but in many cases, we can still only guess at the negative effects that technological development and its explosive growth could have on the health and well-being of users and those living in the immediate vicinity of the technology.

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