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Structural Integrity Procedia 00 (2023) 000–000

Structural Integrity Procedia

www.elsevier.com/locate/procedia

Second International Symposium on Risk Analysis and Safety of Complex Structures and Components (IRAS 2023)

The Risk assessment of 3D printing FDM technology

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Abstract

Additive manufacturing or 3D printing is used nowadays in a variety of industries including aerospace, automotive, medicine, architecture etc. It is also extensively used for educational purposes. 3D printers are now used even in everyday life - by people without technical education. Although the application of 3D printing is widespread, its effects on human health and precautions are still not discussed in details. This article will be focused to the risk assessment of one of the most popular 3D printing techniques - Fused Decomposition Modeling (FDM). During FDM 3D printing movable printing head is used to melt a thermoplastic wire (filament), and to apply it layer by layer, forming model which is developed in Computer Aided Design (CAD) software. Due to low cost, the most frequently used materials are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid/Polylactide (PLA). A side product of filament melting is evaporation of chemicals, which exact amount and composition is still not established (as it depends on 3D printing conditions). FDM printing can also produce unhealthy levels of nanoparticles (particle in the range between 1 to 100 nanometers), Volatile Organic Compounds (VOCs) and gaseous material emissions. This article discuss the dangers and harms of FDM with performed basic risk assessment according to the Kinney methodology. Also, the protective measures which need to be applied during the 3D printing are proposed – taking into account the identified and quantified risks.

Keywords: 3D printing; FDM; risk assessment; work safety; hazardous chemicals.

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Peer-review under responsibility of the IRAS 2023 organizers

1. Risk assessment

The safety and health at work is very important issue and it is necessary to pay attention to it. In addition to moral responsibility, employers have realized that it is even cheaper to invest in safety at work than to pay workers' compensation. It enabled development of risk assessment and its methodologies.

Risk assessment should take into consideration what could cause injury or harm, identify the possibility and seriousness of any potential harm and take action to eliminate hazard, or if it is impossible, predict preventive or protective measures to control the risks.

According to the European Standard EN 292-1:1991 definitions of basic terms in this field, such as hazard, hazard situation, risk and risk assessment, are:

Hazard - a source of possible injury or damage to health.

Hazardous situation - any situation in which a person is exposed to a hazard or to hazards.

Risk - a combination of the probability and the degree of the possible injury or damage to health in a hazardous situation.

Risk assessment - a comprehensive estimation of the probability and the degree of the possible injury or damage to health in a hazardous situation in order to select appropriate safety measures.

Nowadays a large number of risk assessment methods are in use, such as: FMEA (Failure Modes and Effects Analysis) and its extension FMECA (Failure Mode, Effects, and Criticality Analysis), DRBFM (Design Review by Failure Mode), FTA (Fault Tree Analysis) and its extension ETA (Event Tree Analysis), HAZOP (Hazard & Operability Studies), HACCP (Hazard Analysis and Critical Control Points), What-if/Checklist etc. In this paper, it will be used KINNEY method, as one of the most widely used risk assessment methods.

The KINNEY method will be applied on risk assessment of 3D printing. This manufacturing process is used nowadays in a variety of industries, for educational purposes and even in everyday life. The first patent for 3D printer was filed in 1986 by Chuck Hull. It was Stereolithography (SLA) 3D printer. After 20 years, in 2006, patent expired caused a significant price reduction. Similar situation happened three years later with FDM technology. After that, the price of printers was affordable, which allowed the 3D printers to be used in the households of ordinary people. Widespread usage of 3D printers requires more research in the field of human health protection.

2. Three-dimensional printing

Three-dimensional (3D) printing is an additive manufacturing process of making parts by adding material layer by layer. The additive process is more sustainable then processes where material is removed in order to produce part, because there is less waste produced and used material can often be recycled or reused. The efficiency is another benefit. Unlike traditional manufacturing process, molds, machining or another tools are not required, which can save time and money. One of the main advantage is possibility to manufacture complicated geometries that would be challenging or impossible to produce using conventional manufacturing techniques. These reasons contributed to the widespread of 3D printing.

FDM (Fused Deposition Modeling) is the most common method of additive technology, which allows production of prototypes in a very short time. This method can operate both horizontally and vertically, depending on the movement of the extruder nozzle over the printing surface. Printers use a wide range of thermoplastic materials that reach their melting point during the process and then are extruded through the nozzle to form a 3D model layer by layer. The working principle of every FDM printer, as with all additive technologies, starts with a computer-designed 3D model that is then divided into two-dimensional layers of equal thickness and stacked on top of each another. This results in a three-dimensional shape with a visible stepped structure caused by layering, which is removed by finishing processing.

2.1. Main components of 3D printer

Main components of 3D printer are: extruder, print bed, hot end, filament.

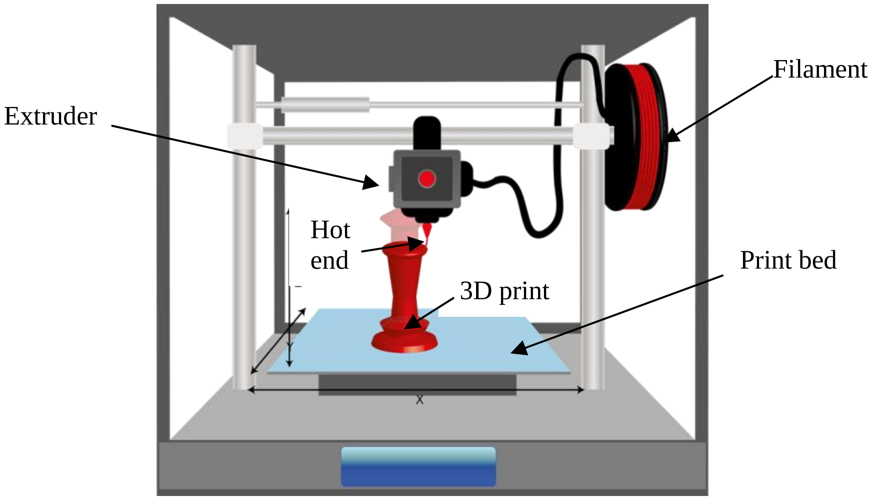

Fig. 1. Main components of 3D printer

The extruder is moving element, so it is mechanical hazard. The hot end and print bed have high temperature and they can cause burns (thermal hazard). Three-dimensional print is formed by melting filament, which cause evaporation of harmful substances (chemical hazard).

2.2. Materials

The most frequently used materials in 3D printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid/Polylactide (PLA).

ABS is an amorphous material, which means that it has an undefined melting point. ABS typically requires a higher printing temperature than some other filaments, typically between 220-260°C. ABS has a tendency to warp or lift from the build plate during printing, so it's important to use a heated bed and adhesive to improve adhesion. The recommended bed temperature is usually around 80-100°C. Furthermore, ventilation is necessary when working with this thermoplastic because the fumes could be unpleasant.

PLA is recyclable material, made from organic materials such as corn starch or sugar cane. Therefore, fumes from this material smell like candy. Typically requires a lower printing temperature than ABS, between 180-220°C. PLA had good adhesion properties and usually has no need for a heated bed.

Various color options of this materials are available. In general, a printer can only print one color at a time, although there are models with multiple nozzles which each nozzle can print with a different color filament.

3. 3D printer temperature

Temperature is crucial while using a 3D printer, mostly because of the filaments. The 3D printing might not succeed if the 3D printer cannot achieve the necessary temperature since the filament won't be able to melt. Therefore, temperatures must be carefully analyzed before choosing or utilizing a 3D printer.

The temperature at which the 3D printer operate is one of the factors that should be considered while analyzing the risk. Components which can lead to burns are hot end and print bed.

3.1. Hot End

The hot end is a critical component of a 3D printer that is responsible for melting and extruding the filament material. It is located at the top of the printer's extruder assembly. Its' temperature depends on the melting point of the filament. At the bottom of the hot end the small metal tip is located and its' purpose is to control the size and shape of the extruded filament called nozzle. The nozzle diameter can range from 0.2mm to 1.2mm or larger, depending on the printer and the desired print quality. The temperature of the hot end usually equals 180-250^{o}C.

3.2. Print bed

This is the surface on which the printer creates the 3D object. It can be made of glass, aluminum, or other materials, and may or may not be heated depending on the printer and filament. For example, ABS requires heated bed in order to improve adhesion. That temperature of the print bed is usually around 80-100°C, which can cause burns.

4. Fumes during 3D printing

The FDM method is based on melting thermoplastic string, called filament. The melting process takes place in extruder. Through nozzle melted filament is applied layer by layer on printing bed forming a 3D print. High temperature cause evaporation of chemicals from filament. Some released particles and volatile organic compounds (VOCs) are dangerous for human health, but exact amount and structure is not yet defined. Emission depends on the color of filament, added additives and type of filament material.

Researches have shown that temperature is important factor on emissions. Increasing the printing temperature raises the emission level. That is why it is recommended to use the lowest possible print temperature.

5. Analysis of potential hazards and harms

Table 1. Analysis of potential hazards and harms

Hazard group	Code	Hazard subgroup	Hazards Yes/No
1) Mechanical hazards that arise from using work equipment, such as:	(1)	Insufficient safety due to rotating or moving parts	No
	(2)	Free movement of parts or materials that can cause harm to employees	No
	(3)	Internal transport and movement of working machines or vehicles	No
	(4)	The use of dangerous work equipment that can cause explosions and fires	No
	(5)	The inability or limited ability to timely remove oneself from the workplace, exposure to closure, mechanical impact, etc.	No
	(6)	Other factors that may appear as mechanical sources of danger	Yes
2) Hazards that arise in relation to the characteristics of the workplace, such as:	(7)	Hazardous surfaces (floors and all types of walking surfaces, surfaces that employees come into contact with that have sharp edges, spikes, groups of surfaces, etc.)	Yes
	(8)	Working at height or in depth, in terms of occupational health and safety regulations	No
	(9)	Working in a cramped, limited, or dangerous space (between two or more fixed parts, between moving parts or vehicles, etc.)	No
	(10)	Possibility of slipping and tripping (wet or slippery surfaces)	No
	(11)	Physical instability of the workplace	No
	(12)	Possible consequences or disruptions due to the mandatory use of personal protective equipment at work	No
	(13)	Effects due to the performance of work processes using inappropriate or unsuitable methods of work	No
	(14)	Other hazards that may arise in connection with the characteristics of the workplace and the method of work	No
3) Hazards that arise from the use of electrical energy, such as:	(15)	Hazards from direct contact with live electrical installations and equipment	No
	(16)	Hazard from direct contact	No
	(17)	Hazard from thermal effects caused by electrical equipment and installations (overheating, fire, explosion, electric arc or sparking, etc.)	Yes
	(18)	Hazards resulting from lightning strikes and atmospheric discharge	No
	(19)	Hazard from harmful effects of electrostatic charging	No
	(20)	Other hazards that may arise from the use of electrical energy	No

4) Harmful effects that arise or occur during work processes, such as:	(21)	Chemical hazards, dust and fumes (inhalation, suffocation, introduction into the body, penetration into the body through the skin, etc.),	Yes	
	(22)	Physical harm (noise and vibration)		No
	(23)	Biological damage (infections, exposure to microorganisms and allergens)		No
	(24)	Harmful effects of microclimate (high or low temperature, humidity and air flow speed)		No
	(25)	Inadequate brightness		No
	(26)	Harmful effects of radiation		No
	(27)	Harmful climate impacts (work on open)		No
	(28)	Harms caused by the use of dangerous substances in production, transport, packaging, storage or destruction		No
	(29)	Other harms that appear in the work process, and which can be the cause of an employee's injury at work		No
5) Harmful effects arising from mental and psychophysical efforts that are causally related to the workplace and jobs that employees perform, such as:	(30)	Efforts or physical exertion		No
	(31)	Non-physiological position of the body (long-term standing, sitting, crouching, kneeling, etc.)		No
	(32)	Efforts in the performance of certain jobs that cause psychological stress (stress, monotony, etc.)		No
	(33)	Responsibility in receiving and transmitting information, use of appropriate knowledge and abilities, responsibility in rules of conduct, responsibility for rapid changes in work procedures, etc.		No
6) Harmful effects related to work organization, such as:	(34)	Work longer than full time, work in shifts, reduced working hours, night work, preparedness in case of interventions	Yes	
7) Other harmful effects that occur in the workplace, such as:	(35)	Damage caused by other persons (violence towards persons working at counters, etc.)		No
	(36)	Working with animals		No
	(37)	Work in an atmosphere with high or low pressure		No
	(38)	Working near water or under water surface		No
	(39)	Other hazards and harms		No

6. Consequences of existing hazards and harms

Table 2. Consequences of existing hazards and harms

The work for which the risk assessment is carried out	Danger/Harm	Consequences
3D printing	Sharp objects that can be obtained during 3D printing; Moving and rotating elements, dangerous surfaces (floors and all types of treads, surfaces with which employees come into contact, which have sharp edges, spikes, rough surfaces, etc.)	Lacerations and cuts
	High temperatures of the printing platform and other parts of the 3D printer	Danger of potential burns
	Danger of thermal effects developed by electrical equipment and installations (overheating, fire, explosion, electric arc or sparking, etc.)	Danger of potential burns and electric shocks
	Chemical hazards, dust and fumes (inhalation, suffocation, introduction into the body, penetration into the body through the skin, etc.)	Potential headache, nausea or poisoning from harmful fumes that can be released during printing
	Working longer than full time, working in shifts, reduced working hours, night work, preparedness in case of interventions; Printing of demanding parts of larger dimensions that require longer printing time and intervention in case of some interruptions	Physical fatigue

7. KINNEY method for risk assessment

The KINNEY method is widespread technique for risk assessment. The risk is assessed based on probability that the risk occur, frequency of exposure to danger and magnitude of consequences for employee and environment in case of hazard. The formula for calculating risk factor is:

$$frequency(F) \times probability(P) \times consequences(C) = risk(R)$$

The values of these factors are determined based on the Table 3.

Table 3. Description of the criteria for assessing the probability

F	Criteria for frequency	P	Criteria for assessing the probability	C	Criteria for assessing the consequences
1	Rare (yearly)	0,1	Virtually impossible	1	Disease, injury which requires first aid and any other treatment
2	Monthly	0,2	Practically impossible	2	Medical treatment by a doctor
3	Occasional (weekly)	0,5	Plausible, but unlikely	3	Serious – disability, serious violation with individual hospitalization and lost days
6	Regular (daily)	1	Improbable, but possible at boundary conditions	6	Very serious – individual accidents with lethal outcome
10	Permanent	3	Unusual, but possible	10	Catastrophic – with multiple lethal outcomes
		6	Possible		
		10	Predictable		

8. Risk analysis

According to value of factor R, risks are classified into five categories: acceptable risk, possible risk, substantial risk, high risk and very high risk.

Table 4. Classification based on risk level

Risk level (R)	Classification	Description of the classification
R<20	Acceptable risk	No measure required
20 - 70	Possible risk	Monitoring
71 - 200	Substantial risk	Measuring is required
201 - 400	High risk	Improvements
R>400	Very high risk	Activity cessation

By determining the factors and multiplying them, the values of the risk level for all the listed hazards were obtained and shown in table 5. Also, an overview of protection measures for that hazards is given.

Table 5. Risk level and safety measures

Hazard	F	P	C	Risk level	Safety measures
Sharp objects that can be obtained during 3D printing and printed part post processing;	6	6	1	36	Use safety equipment (protective gloves, goggles, coat etc.)
Moving and rotating elements, dangerous surfaces (floors and all types of treads, surfaces with which employees come into contact, which have sharp edges, spikes, rough surfaces, etc.)	10	10	1	100	Use safety equipment (protective gloves, goggles, coat).

Hazard	F	P	C	Risk level	Safety measures
High temperatures of the printing platform and other parts of the 3D printer	10	10	2	200	It is necessary to wait 20 minutes before removing the finished part from the platform in order for the temperature of the platform and other parts brought down to a safe temperature. Avoid touching parts of the printer that reach high temperatures.
Danger of thermal effects developed by electrical equipment and installations (overheating, fire, explosion, electric arc or sparking, etc.)	1	3	6	18	Before putting the machine into operation, all components that could cause the mentioned accidents should be checked.
Chemical hazards, dust and fumes (inhalation, suffocation, introduction into the body, penetration into the body through the skin, etc.)	10	10	3	300	Printers should be placed in an enclosures and in ventilated rooms. Also, use protective masks. Use the lower possible print temperature.
Working longer than full time, working in shifts, reduced working hours, night work, preparedness in case of interventions; Printing of demanding parts of larger dimensions that require longer printing time and intervention in case of some interruptions	10	10	2	200	In accordance with if possible, avoid the mentioned cases.

9. Conclusion

The widespread usage of 3D printers causes the need to pay more attention on risk assessment of that process. The focus of this paper was on the most widely used technology (FDM) and materials (ABS and PLA). An overview of all the hazards during the printing is given. Therefore the probability that the risk occur, frequency of exposure to danger and magnitude of consequences was evaluated for employee and environment in case of hazard. Based on these values, the risk factor was determined. It has been shown that the greatest risk is of chemical hazards. For identified level of risk it is necessary to make some safety measures, such as, placing printer in an enclosures and in ventilated rooms. Also, using the lowest possible printing temperature is recommended in order to reduce the vaporized substances. Since all harmful substances can't be removed from the work place, it is necessary to wear a protective mask.

Risk caused by mechanical and thermal hazards are on a substantial level. In order to avoid relevant consequences from those hazards it is necessary to use safety equipment (protective gloves, goggles, coat) and do not touch heated surfaces until the temperature of the components reach safe temperature.

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Figure 1 was downloaded from https://pixabay.com/.