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IMPROVING THE PRINT QUALITY OF AN ADDITIVE-CAPABLE ROBOTIC CELL BY OPTIMIZING THE COOLING UNIT

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Abstract

Robotics and additive manufacturing are revolutionizing the manufacturing industry by enabling automated and personalized production. By combining the two technologies, it is possible to print large print objects such as a canoe for a person. This paper examines the importance of cooling in the additive manufacturing and how it can affect the shape, accuracy and surface finish of the printed part. It also discusses the use of an industrial robot to fabricate additive objects and the use of polylactide granules as the printing material. The paper addresses several factors that can affect the print quality of a 3D printer, specifically addressing melted layer aeration and cooling. The paper concludes with a discussion of a new cooling system implemented and its potential for further improvement. This new cooling system has made improvements both in terms of measured values and visually, but there is still potential for further improvement.

Keywords: Additive manufacturing; Extrusion process; Cooling; Industrial robot; Polylactide.

1. Introduction

Additive manufacturing (AM) processes have experienced a real upswing in recent years. Du to the simple applicability of additive manufacturing, it has found its way into the private sector in addition to industrial applications. FFF (Fused Filament Fabrication) is the most commonly used technology. [2]

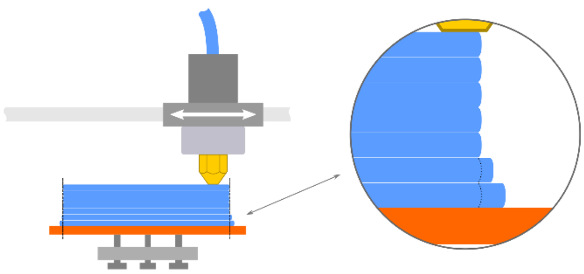

Fig. 1. Layer visualization with the FFF method [3]

FFF printing is a process in which thin layers of melted plastic filament are stacked to create a 3D object [4]. Cooling plays a crucial role in this process as the molten filament cools quickly and needs to solidify to retain the shape of the printed part. If the filament cools too quickly, it can cause warping and warping, negatively affecting the printed part's shape and accuracy. Inadequate cooling can also cause the material to contract unevenly, resulting in an uneven surface and poor lay-up. On the other hand, sufficient cooling can help the material contract evenly and form a smooth surface. [5]

Adequate cooling can also improve the strength and durability of the printed part as it helps the material cool in its defined shape. It is important to choose the right cooling strategy for each material used. For some materials, it is recommended to carry out the cooling as soon as possible to avoid distortion. For other materials, however, it may make sense to slow down the cooling to achieve a more even contraction.[6] The cooling unit is of greater importance as soon as an attempt is made to print more complex structures. That's because inaccuracies during the printing process can have a major impact on the final product. Specifically, this paper deals with an industrial robot that produces additive objects and offers the possibility of producing vertically printed objects. The printing system is divided into three main components, an industrial robot with six degrees of freedom (ABB IRB 2400/16) [7] and controller, the heated glass printing platform from Prangl [8] and finally the extruder from Noztek Xcalibur [9] with filament transport and cooling unit.

The printer to be examined uses PLA (polylactide) granules as the printing material. To be able to optimize the cooling system, the material used for printing plays a key role. PLA is a technical biopolymer based on lactic acid, which belongs to polyesters and is biodegradable [10]. Accordingly, PLA is obtained from regenerative sources and is therefore a biocompatible raw material, which can be composted under ideal conditions. However, an additive is usually added to the PLA, which specifically changes properties such as strength, elongation at break or color [11] Due to its low glass transition temperature, PLA is considered the plastic in the 3D printing sector, which is the easiest to process. The demands on the printer are very low here since a temperature-controlled construction space and a heated construction platform can be dispensed with if a good surface finish is not necessary[12].

In research and industry, the number of 3D printing robots is increasing. However, the print quality of the 3D printer is an important factor in the successful use of this technology. [13] To improve the print quality of the 3D printing robot, some steps can be taken.

Ventilation and cooling of the filament:
Good ventilation and fast cooling of the filament can improve the print quality of the 3D printer. At the same time, good ventilation can help dissipate excess heat and keep the print room cooler. Faster cooling of the filament can also lead to a smoother surface and thus better print quality. [14]

Extruder temperature:
Choosing the right extruder temperatures is an important factor in print quality. The optimal extruder temperature varies depending on the material and filament manufacturer. However, it is important to note that a higher temperature can result in a faster print speed and lower print quality. [15]

In summary, improving ventilation and thus cooling the filament is an important factor for better print quality. It is important to determine the optimal temperature and ventilation conditions for the filament used and the print engine to achieve the best possible print quality.

2. State of the Art

Today, robotic additive manufacturing is emerging as a potential solution to increase manufacturing flexibility. This technology makes it possible to change the orientation of the material application unit during printing, producing complex parts with the optimized material distribution. [16]

However, in technology-leading countries in general, the additive manufacturing process for the production of end products is in its infancy. A national spread is not to be expected in the next 10 years. On the one hand, these processes do not yet have the technical performance characteristics that are required for industrial series production. On the other hand, traditional industrial series production, especially in the area of medium and large series, is characterized today by a high level of economic efficiency, which cannot be solved with additive manufacturing processes in the foreseeable future, despite current technical problems. This shows the potential of additive manufacturing processes today, especially in highly specialized applications for single and small-series production.[17] Nevertheless, the market for additive manufacturing shows a growth of 30 to 40 per cent every two years [18].

Robot arms are ubiquitous in industrial production and help companies to become more economical, and robots reduce production losses through their perfection. The combination of robotic arms and additive manufacturing allows for larger and more complex printed parts that are not possible with a traditional 3D printer. [19]

There are current robots in research that produce additively manufactured parts. The EP (extrusion process) method is mostly used here. This is because a large number of printable materials and supported functionality are possible. The EP simply enables object printing and a wide variety of physical properties such as flexibility, impact strength, compression, tension, thermal resistance, and electrical conductivity can be achieved. In general, the final object that comes out of the 3D printing machine does not require any finishing, cleaning or necessary sanding, but this only applies if no support is used in the production phase. [20]

Like any other process, EP printing has advantages and disadvantages. The advantages are inexpensive, quite stable production of objects. However, numerous 3D printing processes offer a finer surface, such as the stereolithography process. The process was developed and launched by Formlabs in 2012. The stereolithography process prints with resin, which has a significantly higher resolution and finer surface than can be expected from FML processes. [10]. The disadvantages of EP printing cannot be eliminated, but it is possible to keep them as small as possible by optimally setting the printing parameters so that they are minimally noticeable.

The dimensional and mechanical properties of a printed 3D model are affected by several printing parameters. A ventilation system that moves with the printhead was designed and installed by Lee and Liu [11] for an FFF printer to control the cooling of a print model. The quality of the model printed with PLA, including the dimensions and mechanical properties, was studied for different cooling air velocities.

It was found that the cooling air velocity had different effects on the dimensional properties and mechanical strength of the printed model. More specifically, a higher cooling rate resulted in better geometric accuracy but lower mechanical strength. At the highest and lowest cooling speeds of 5 m/s and 0 m/s, respectively, the tensile strengths of the printed models differed by a factor of 4. To determine an appropriate cooling air speed setting for each specific print material, a design model was proposed. The pressure parameters determined were used in the manufacture of a Rubik's Cube as an example. The composite cube showed satisfactory performances in terms of both dimensional properties and mechanical function. Therefore, the cooling air velocity can be used as an additional control parameter in 3D printing technology. [21]

Thus, the quality of the next layers or their overhangs can be improved using a higher airflow and the associated cooling [22]. It is also worth mentioning that the layer thickness in combination with powerful cooling has a significant influence on the bending properties of the printed part. Different layer thicknesses were analysed (0.1, 0.2, 0.3, 0.4, 0.5 [mm]). It was found that parts with a layer thickness of 0.4 to 0.5 mm had the greatest flexural strength and that the tensile strength first decreased and then increased with increasing layer thickness. [23] As the new hot layer is applied, the underlying layer reflows. The more of the cooled material is melted and the faster the upper layer is cooled, the better the layers bond. A better layer connection increases the resilience of the printed object. H. Bikas, P. Stavropoulos and G. Chryssolouris [24] also came to this conclusion.

Another important parameter of the EP process is the relationship between print speed and the volume of material that is extruded through the extruder. These are crucial for a nice print result. For example, extruding too much material at too slow a speed will force excess material outward. This hurts the surface quality of the print object. An uneven relationship between print speed and material output can also cause material to deviate by as much as 20 per cent. [25]

On the other hand, the cooling process is an essential factor when it comes to overhanging or oblique print components. After an investigation in which an air-cooling system with different airflow speeds was used, it was found that with a low airflow compared to none at all, a temperature reduction of the PLA of 40 per cent could be achieved. A faster cooling process leads to better overhangs. Consequently, this results in better print quality. On the one hand, the material cannot deform without cooling. On the other hand, excessive ventilation during printing will damage the printed object. The damage occurs when the soft material is pushed away by the airflow when the new layer is printed on or hardens too quickly so that a fusion with the lower layer only takes place to a limited extent. As a result, excessive cooling leads to a deterioration in print quality and a low resilience of the printed parts. [26]

In addition, cooling too slowly will result in material distortion and this will result in a failed print. The material distortion of the printing part, during printing, causes partial or complete lifting of the printing part of the printing plate, due to the internal stresses in the material, which increase with slow cooling. It's also worth noting that warping only happens after some time. This result also corresponds to earlier studies by Sood et al. [27].[28] However, it is worth noting that the EP process can handle a variety of different materials that have different properties. Therefore, the cooling parameters must be set accordingly depending on the printing material [11].

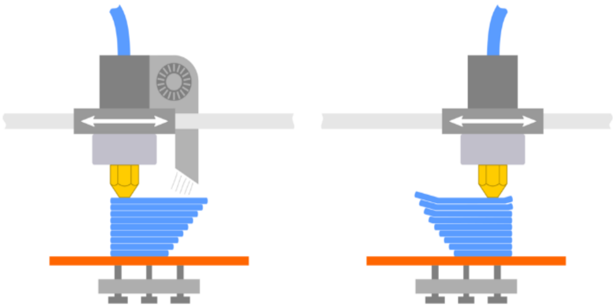

Fig. 2. A printed object with cooling on the left, a printed object without cooling on the right [3]

Fig. 2 illustrates the effects on the printed object if it is not cooled. The picture on the right shows a layer application without cooling the filament. A material distortion can be seen here. The picture on the left shows the same system with cooling. Here you can see that no distortion has taken place in the printed object.

3. Materials and Methods

To achieve better air cooling, four parameters can play a crucial role. These are air throughput, airspeed, air temperature and humidity.

Airflow:
Airflow is an important factor affecting the cooling performance. A higher airflow increases the cooling capacity, but also energy consumption. It is important to choose a balanced airflow that achieves an optimal cooling effect. [30]

Airspeed:
The airspeed can also be adjusted to achieve an optimal cooling effect. Higher air velocity can result in faster cooling but also higher noise levels. [31]

Air temperature:
Air temperature can also be an important factor, as cooler air provides better cooling. However, it is important to note that air that is too cold can increase energy costs. It is important to determine the appropriate air temperature for the specific application to achieve effective cooling without wasting energy unnecessarily. [32]

Humidity:
Humidity can also play a role in air cooling, particularly in material properties and part quality. High humidity can lead to material deformation and contamination. It is important to monitor and regulate appropriate humidity levels to ensure optimal print quality. [32]

Fig. 3 illustrates the currently installed cooling system. Importantly, the area around the nozzle must be free of parts that could cause collisions during printing. To that end, adjustments have been made to address these issues. To define the one area in which components such as the cooling system may be located, a maximum angle for the printing process must be defined. Note that this angle only represents the difference between one simplex print and the next simplex print. The actual maximum pressure angle at which the material will not adhere to the previous plane is determined by empirical testing. Since a cooling system is required to prevent the liquid material from flowing away from the object, it must be mounted as close to the extruder as possible to cool the freshly extruded material without affecting the actual printing process. Thus, a maximum angle difference of 30° has been defined between the two pressure directions, in which the cooling system can be accommodated. On the other hand, for a practical cooling system, more complex shapes must be created to further cool the extruded material without affecting the oblique printing process. The area of the collision cone must be used here. Compressed air is used as the source for sufficient cooling of the carrier material. Therefore, the goal of the cooling section is to supply and direct the actual air. For this purpose, a component was developed that blows compressed air from three sides at a distance of 120° onto the material exit point of the nozzle. In addition, this 120° approach reduces possible problems with single-sided cooling systems, such as B. Excessive force on printed parts that can damage fine structures. Additionally, support rings for the three air outlets keep them stable when air flows through them. Due to the structural complexity of this particular air delivery system, Selective Laser Sintering (SLS) was used to fabricate the ventilation system components. The disadvantage of this system is that the materials used have melting points similar to PLA. Each airline is inside the cone as shown in Fig.3, which is not a problem when printing at an angle. [1]

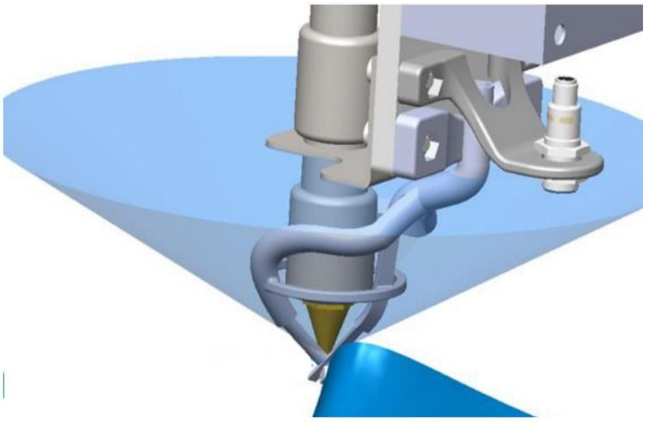

Fig. 3. Currently installed cooling within the conical collision-free sector [1]

To be able to properly evaluate the built-in cooling system, the above parameters must be measured and calculated. In this way, the ACTUAL values of the system can be determined to enable a comparison of the parameters between the old and new system in the event of a redesign with a new system.

In order to measure air cooling, various parameters must be recorded like air speed and air temperature. To measure the air temperature and humidity, a psychrometer from the brand RS PRO [33] is used, which can measure hot air up to 100 degrees. An anemometer of the DT-8880 from RS PRO [34] is used to measure air speed, which can measure air speeds of up to 25 m/s and also offers the possibility of measuring air temperatures of up to 50 degrees. Furthermore, it is necessary to measure and record the temperature of the freshly applied layer a few cm after extrusion in order to be able to make a comparison between the old and new cooling systems. In addition, there is an RS-833 infrared thermometer from RS PRO [35] that can measure up to 750 degrees. To do this, a device must be installed that enables the sensor to be mounted a few cm after the nozzle. It should be noted that a measurement is only possible when applying a straight layer.

To ensure consistent print conditions, a print model constructed with Fusion 360 serves as a test object. This is shown in Fig. 4 and has dimensions of 30x30x30 mm. In addition, a chamfer, and rounding of 30 mm each are integrated to include more complex geometries in the test.

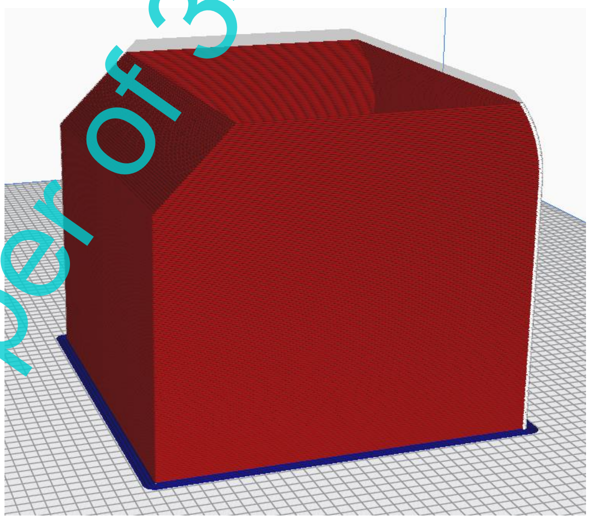

Fig. 4. Print model in CAD

Fusion 360 software is also used for the redesign of the ventilation unit to design new concepts and print them out with a 3D printer (Prusa i3). The generation of the airflow is an important factor of the system and can significantly affect various parameters such as humidity and temperature.

Before the practical part is carried out, it is necessary to select suitable fans for the cooling system. For this purpose, three different axial fans are compared with each other by measuring their maximum air velocity under current. The results of this comparison are shown in Table 1.

Fan	TITAN PWM	FAN 2510	EBM Papst
Dimension [mm]	120x120x25	25x25x10	80x80x25
Operatingvoltage [V/DC]	12	12	12
Rotational speed [U/min]	2100	9600	3100
Air flow rate [m³/h]	36,05	5,1	65
Measured air velocity [m/s]	3,37	1,83	7,10

Table 1. Metrics of TITAN PWM [36], FAN 2510 [37] and EBM Papst [38]

Due to the limited installation space available for the cooling system, only a fan with maximum dimensions of 120x120 mm could be used. The EBM-Papst fan achieved the best measurement results and was smaller in its dimensions than the TITAN fan. The FAN 2510 fan was the smallest in the comparison but achieved insufficient values for the application. Based on these results, the cooling system was implemented with three EBM Papst fans. To operate the fans, an inverter from TDK-Lambda [39] was used to convert 230V AC to 24V DC. In addition, an adjustable DC/DC Stepdown Modul from DEBO [40] was used to achieve the required 12V DC. The output voltage could be adjusted by a regulator in the module to control the operation of the fans. Fig. 5 illustrates the circuit.

Fig. 5. Electrical construction

4. Results

Fig. 6 shows the finished construction of the cooling system, consisting of a bracket with three air ducts. Each air duct contains an EBM Papst fan. The air ducts have an elongated design to avoid sucking in warm ambient air. The walls of the air ducts are 5 mm thick and consist of two 1 mm thick outer walls with a 3 mm gap between them. This prevents heat transfer from the outer walls to the inner walls to avoid heating of the cooling air.

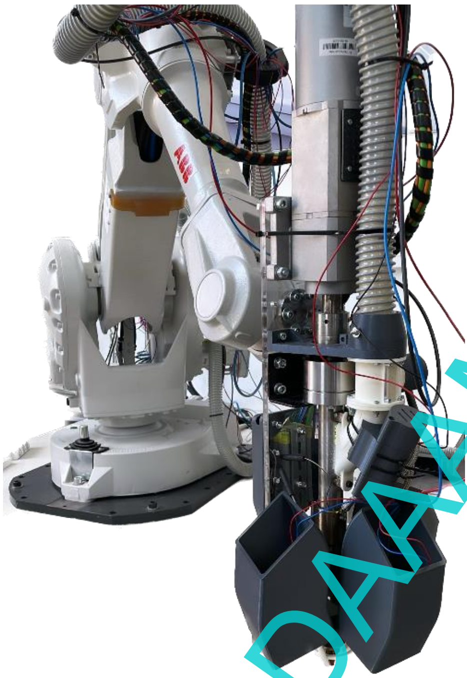

Fig. 6. Robot with the new cooling system

Fig. 7 shows the test cube printed with the new cooling system compared to the test cube printed with the old cooling system. A significant improvement in the surface finish of the test cube is visually apparent. The uneven surface of the old test cube is caused by the fact that the hot PLA does not solidify immediately after application and flows to the side. The rapid cooling of the PLA by the new cooling system prevents this trickling and thus produces a smoother surface.

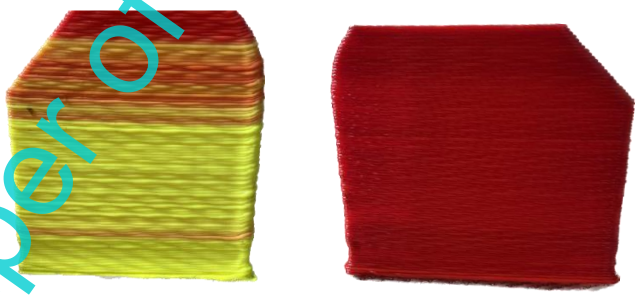

Fig. 7. Printing difference between old cooling (left) and new cooling system (right)

The measurement results also show a significant improvement. The new cooling system achieves an air velocity of 6.68 m/s and an air temperature of 26.1°C immediately below the nozzle tip. In comparison, the old cooling system achieves only 2.45 m/s at an air temperature of 26.2°C under the same measuring conditions. When measuring the air velocities, it is found that the old cooling system generates strong air turbulence. This can be observed on the propeller of the anemometer, which rotates irregularly. This could be due to uneven distribution of the air in the three air ducts. The new cooling system, on the other hand, achieves a constant air flow below the Nozzle.

When measuring the freshly applied layer with the old cooling system, the average temperature was 192.7 degrees. This value was determined from ten measurements. The new cooling system, on the other hand, produced an average temperature of 158.3 degrees. It should be noted, however, that the PLA warmed up somewhat after the air flow moved away from the measuring point. A plausible explanation for this could be that the inner hot material heats up the surface somewhat afterwards.

5. Conclusion and outlook

With the new cooling system, improvements were achieved both in terms of the measured values and visually. Nevertheless, there is still potential for improvement. The switch to electrically driven axial fans has brought about an enormous improvement. However, the old cooling system with the compressed air system was not used. A new concept combining both variants - axial fans and compressed air - could bring about a further improvement in the cooling system and should be investigated further.

In addition, there is currently no communication between the cooling system and the robot or extruder. For example, the cooling system could communicate with the robot controller to turn it on and off and integrate control of the cooling system. For example, the cooling system could ramp up the fans to maximum speed during overhangs and vertical pressure and ramp down the cooling system during horizontal pressure. However, this would require new circuitry and some consideration of the interface between the robot controller and the cooling system.

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