Thermal Modelling and Simulation of a Screw Extruder for Additive Manufacturing Technology

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Abstract

The performance of an extruder is critical to the success of an additive manufacturing process. This study presents a framework for the Finite Element Analysis (FEA) of an extruder for additive manufacturing. Aluminum based on its lightweight and stainless steel due to its hot hardness property were selected as the extruder component and its heating band respectively with adequate insulation. The thermal modelling and simulation of the extruder were carried out in the ANSYS R19.0 environment. The indicators for the evaluation of the modelled parts were the total heat flux, temperature distribution and the direction heat flux. The results show that there is an increase in the magnitude of the heat flux around the region occupied by the heating barrel where plastic deformation takes place as a result of heating. The heat flux input however was sufficient to plastically deform the polymeric material. The effect of the insulation around the heating barrel shows capacity for temperature reduction. Hence, this work will assist manufacturers who employs additive manufacturing technology for product development in the optimal design of an extruder. The FEA module can be incorporated into the overall framework for the extruder development to permit an iterative process.

Keywords
Additive manufacturing, Extruder, FEA, Thermal modelling, Simulation

1. Introduction

Additive Manufacturing deals with the creation of 3D objects with precise geometric shapes via Computer Aided Design (CAD) and subsequent deposition layer by layer which is in contrast to the traditional manufacturing which often requires machining (Manghnani, *et al.,* 2015; Regina *et al.,* 2018). Prominent among the additive manufacturing techniques are the selective laser sintering (SLS), fused deposition modelling (FDM), stereolithography, ink jet printing, fused filament fabrication (FFF) etc. These techniques have been employed for the development of products with excellent mechanical properties including high strength to weight ratio and aesthetics (Turner and Gold, 2015). There are several advantages of the additive manufacturing as opposed to the traditional form of manufacturing. First, the additive nature of manufacturing promotes material conservative during the manufacturing process thereby reducing wastages (Dylan, 2015). The reduction in the volume of wastes generated during the process of manufacturing contributes significantly to the cost effectiveness of the process and environmental sustainability. It also promotes the concept of circular economy which emphasizes zero tolerance for waste generation during its deposition manufacturing technique. Additive manufacturing technology also provides a realistic possibility for easy and quick production of 3D objects on demand thus reducing product's manufacturing lead time (Daniyan et al. 2020). The lead time is the interval between the time of ordering and delivery of a product. Since, the concept of additive manufacturing paves way for customized product design without the need for any complex machinery or tooling; thus, maintaining high possibility for product delivery on demand. Furthermore, the additive manufacturing technology has been proven to be suitable for rapid prototyping as well as the production of components with a near net shape form (Vaezi *et al.,* 2013; Haigh *et al.,* 2017). In addition, another merit of the additive manufacturing technology is the degree of freedom in product design and visualization which gives room for the development of products with intricate geometries without the need for any special tooling (Whyman *et al.,* 2018).

Therefore, the thermal modelling and simulation of an extruder for additive manufacturing technology is a critical aspect of the process design that can influence the performance of the manufacturing process. The analysis of the thermal requirement and behaviour of materials will enhance the phases of the product development. It will add to the understanding of the behaviour of the extruder in real time in order to improve its performance in terms of part quality, speed, and process repeatability. Temperature and other process parameters play critical roles in the determination of the manufacturing cycle time, process sustainability, part quality, conformity and finish. For instance, the process temperature which is a function of the heat distribution across the polymeric materials determines the rate of melting of the materials, the homogeneity of the melted material as well as the rate of extrusion according to Lužanin *et al.* (2013). Chaidas *et al.* (2016) investigated the effect of extrusion temperature and speed on the surface finish of the final product using the Fused Deposition Modelling technique. The findings indicate that the extrusion temperature and speed are important parameters which influence the homogenisation as well as the surface finish of the final product. When the process temperature is too low, there will be significant reduction in the rate of melting resulting in poor quality of the printed parts. On the other hand, when temperature exceeds the optimum value, the rate of energy consumption for the process will increase, thus, making it less sustainable. Besides, the polymeric may burn out thereby becoming less viscous with poor dimensional accuracy in the printed parts.

Hence, the need for thermal analysis in order to determine the optimum process temperature that will enhance the manufacturing process. Furthermore, there is also a need to incorporate real time process monitoring and control devices in the extrusion system to keep the operating temperature within the optimum range during the manufacturing process. This is because the optimum range of the process variables may be offset due to the dynamics of the manufacturing processes and conditions. Such variations can be adequately compensated in real time with the aid of the monitoring and control devices. Many researchers have reported on several approaches to promote part quality and enhance the overall sustainability of the additive manufacturing process. For instance, Daniyan et al. (2020) proposed an interactive model which incorporates the CAD tools and features for product development and its topological optimization in relation to the service requirements. Ali *et al.* (2016) proposed the use of multi-nozzle extrusion system for 3D printer for 3D printing with multicolours and multi-materials. The proposed extrusion model enables the printing of different materials with different colours with the use of multi-nozzles which operates simultaneously without halting the manufacturing process thereby reducing the non-value added time. Whyman *et al.* (2018) developed an extrusion system for 3D printing biopolymer pellets. The compact and light-weight extrusion system shows capability for biopolymer pellets just like the filament-based materials.

The aim of this work is to carry out the thermal analysis and finite element analysis of a screw extruder. The significance of this work stems from the fact that there is still dearth of information about the thermal modelling and simulation of the extruders employed for additive manufacturing. Oyesola *et al.* (2020) pointed out the feasibility of achieving the benefits of cost reduction and production performance via an integrated manufacturing system for additive manufacturing. Hence, this work can assist manufacturers who employs additive manufacturing technology for product development in the optimal design of extruder. In addition, the Finite Element Analysis module (FEA module) can be incorporated into the overall framework for the development of an extruder to permit an iterative process for the determination of the optimum range of temperature based on the required service requirements and the material's properties.

2. Methodology

The framework for the thermal modelling and simulation of the extruder for additive manufacturing is presented in Figure 1. This aims to breakdown the knowledge into discrete sections, describing their function and operating parameters, address the process needs and provide a logical and simple approach to the design, material selection, thermal modelling as well as FEA and simulation.

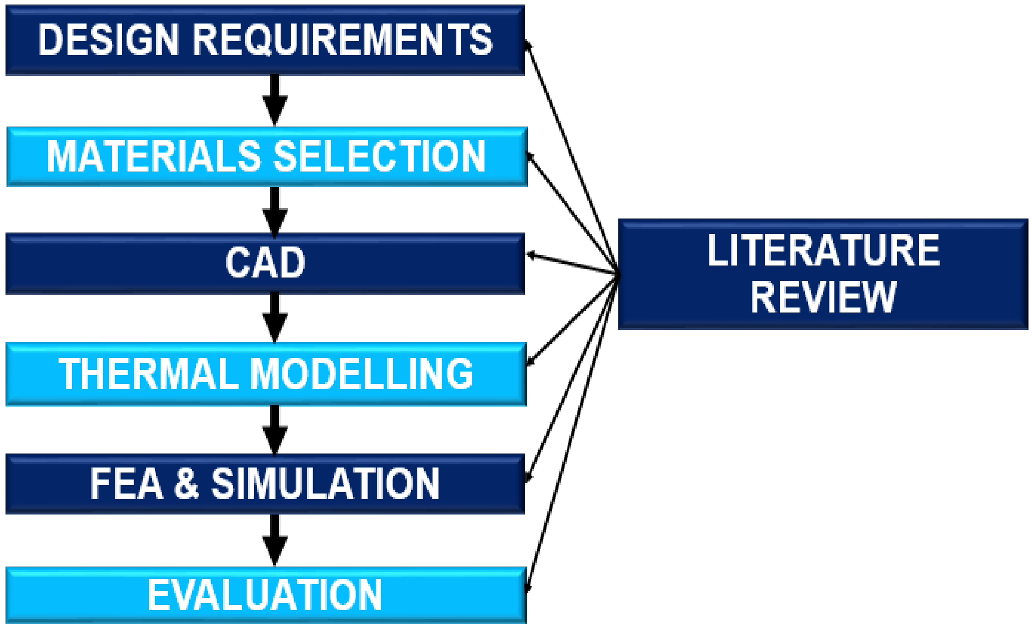

Figure 1. The framework for the thermal modelling and simulation of the extruder

The extruder designed in this case is the screw type which usually comprises of a hopper at the inlet through which polymeric material in pellets form are fed into it. Under gravity, the pellets flow directly into the screw channel where they are transported via the screw action towards the nozzle opening. The barrel and the screw are heated with the aid of a heater placed near the nozzle in order to plastically deform the polymeric materials. As soon as the melting temperature of the pellet is reached, plastic deformation takes place and the plastic material flows through the screw channel, and it is compressed near the exit of the nozzle. The screw extruder boast of high resolution and printing speed compared to existing plastic printers (Dylan, 2015).

The design requirement specifies the ability of the extruder to promote plastic deformation of the polymeric material via effective heat distribution. The materials for the heating band should possesses lower coefficient of thermal expansion and exhibit hot hardness. In other words, it should be suitable for high temperature application without undergoing plastic deformation due to thermal loading. The material considered for this design of the extruder in this study is the stainless steel AISI 304. The thermal modelling as well as the finite element analysis and simulation of the extruder were carried out in the ANSYS R19.0 environment. The thermal properties of the stainless steel (AISI 304) employed for the development of the heating band are presented in Table 1.

Table 1. The Thermal property of stainless steel AISI 304

Property	Value
Latent heat of fusion (KJ/Kg)	285
Maximum service temperature (K)	1198
Melting point	1723
Specific heat (J/kg.K)	530
Thermal conductivity (W/m.K)	14
Thermal expansion ($\mathbf{10^{-6}/K}$)	18
Resistivity ($\mathbf{10^{-8}}$ ohm.m)	77

Source: Azo materials (nd).

The incorporation of the FEA module into the framework for the development of an extruder will permit an iterative process for the determination of the optimum range of temperature based on the required service requirements and the material's properties. It will also assist in the analysis of the effect of power losses and thermal energy from friction which will add to the understanding of the system's behaviour. In order to obtain significant accuracy and precision in the thermal transient finite element analysis, the mesh must have sufficient intrinsic temporal and spatial resolution of the model of the extruder and the time steps must be sized such that it would represent proper mathematical transient behaviour for mesh employed. With the thermal boundary conditions set, at room temperature, a uniform, constant heat flux is imposed on the free surface of a uniform material. The model of the extruder was first created and the model was thereafter meshed into finite elements. This was subsequent followed by the surface heating and thermal loading of the 3D finite elements to a maximum temperature of 175ºC. The maximum temperature of 175ºC was found to be the average melting temperature for most polymeric materials such as acrylonitrile butadiene styrene, (ABS) plastic, epoxy resin and polytetrafluoroethylene often employed in additive manufacturing (Ali *et al.,* Bates-Green & Howie, 2017; MPDB, 2019). The indicators for the evaluation of the modelled extruder were the total heat flux, temperature distribution and the direction heat flux. The results obtained from the FEA analysis are discussed under the results and discussion section. The design model of the extruder is shown in Figure 2.

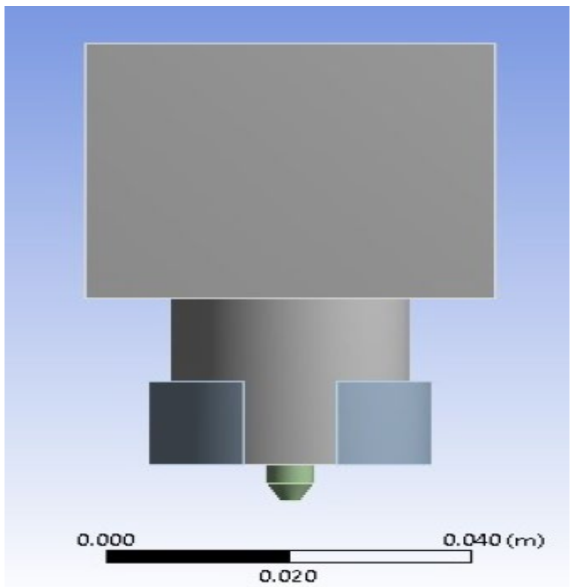

Figure 2. Design model of the extruder

The heat flux q_o is the quantity of heat across the surface per unit time per unit area, which is a function of the rate of heat energy transferred across the given surface. The heat flux conducted into the pelletized polymeric material is only a proportion of the total heat flux q_a. Hence, this proportion X is obtained from Equation 1.

$$q_o = q_a X \tag{1}$$

The total heat flux q_a varies as a function of the position in the contact zone. This is expressed as Equation 2.

$$q_a(y) = q_b(y)X \tag{2}$$

The thermal path resistance (R) and thermal capacitance (C) are expressed by Equations 3 and 4 respectively.

$$R = \frac{L}{kA} \tag{3}$$

Where L is the length of the path of heat flow (mm), k is the thermal conductivity (W/m.K)), A is the cross sectional areas in the direction of heat flow (m^2).

$$C = C_p \rho L A \tag{4}$$

Where; C_p is the specific heat of the material (J/kg.K) and ρ is the material's density (kg/m^3).

The relationship among the thermal diffusivity (α), specific heat (C_p) and thermal conductivity (k) is expressed by Equation 5.

$$\alpha = \frac{k}{C_p \rho} \tag{5}$$

Using the ANSYS R19.0 software the meshing information employed for this study which produced an optimized response time is presented in Table 2.

Table 2. The meshing information

Property	Value
Model designation	e=5 unif
Element size (Microns)	5.08
No of element	75
Response time (microsecond)	0.5

3. Results and Discussion

The understanding of the screw extruder design principles in a simplified and practical approach will lead to faster product development. Figure 3 shows the heat flux for the extruder. The proportion of heat flux X depends on the type of the material employed, contact length and specific energy. From Figure 3, the maximum and minimum value of the total heat flux was 56503 W/m^2 and 144.72 W/m^2. The result show that there is an increase in the value of the heat flux around the region occupied by the heating barrel where plastic deformation of material takes place as a result of heating. The heat flux input however is sufficient to plastically deform the polymeric material.

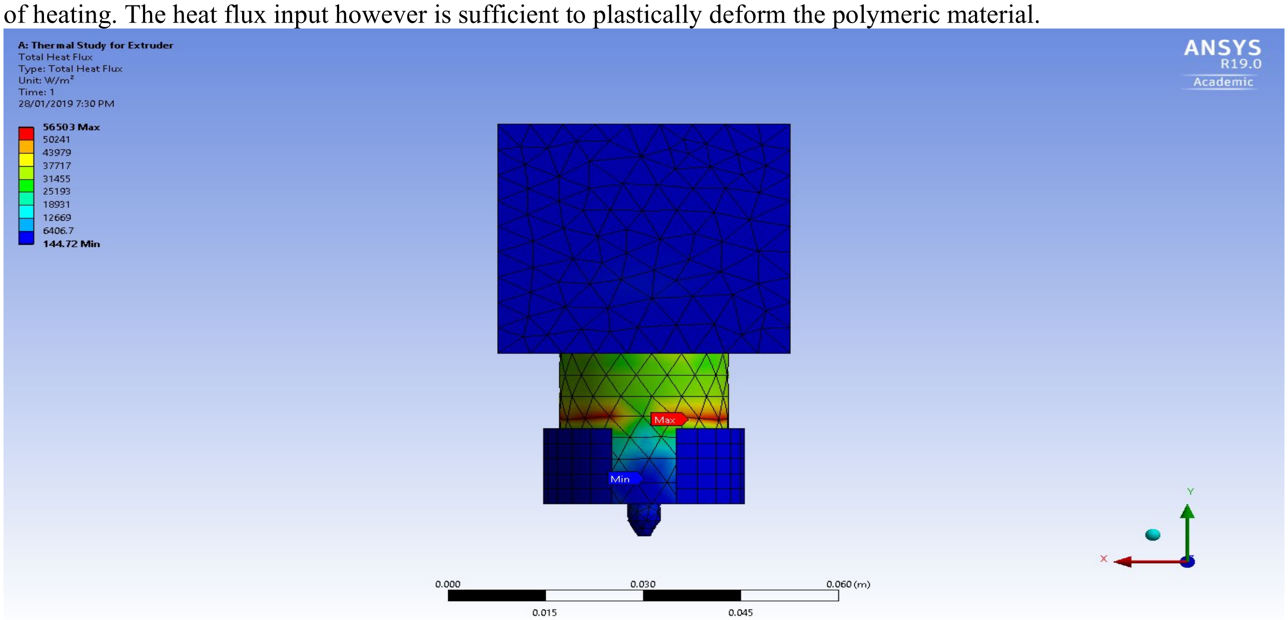

Figure 3. Total heat flux of the extruder

Figure 4 shows the temperature distribution over the extruder. The effect of insulation around the heating barrel significantly shows the tendency for reduction in the effect of temperature. A thermistor can be connected to the electronics board to allow the measurement and regulation of the temperature of the heating barrel. This will assist in keeping the value of the temperature within the optimal range during the manufacturing process. Hence, the distribution of heat around the heating barrel was significantly controlled to prevent fluctuations in the viscosity of the molten material. During the manufacturing process, this will prevent the transfer of heat from the heating barrel to the cold part, which consists of printed parts in order to prevent further plastic deformation of already printed materials. From the Finite Element Analysis (FEA) carried out, the values of the maximum and minimum temperature was 185.01^{o}C and 181.56^{o}C. Since the average melting temperature of polymeric materials used for the basis of this design was 175^{o}C, the result indicates that plastic deformation will occur. However, increase in temperature beyond 183.86^{o}C may no longer be desirable as this may lead to burn out, increase in the energy consumption of the process and further plastic deformation of the material with increased dimensional inaccuracy.

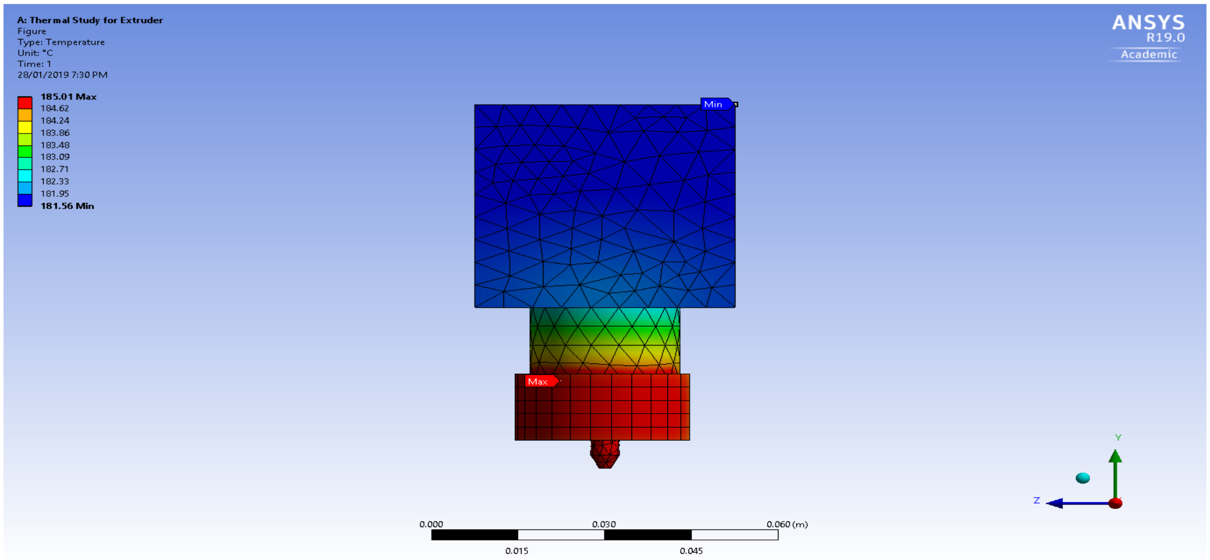

Figure 4. Temperature distribution of the extruder

Figure 5 shows the directional heat flux of the extruder. This is a function of the change in temperature, thermal conductivity as well as the direction of the heat transfer. The magnitude of the directional heat flux of the extruder ranges between a minimum value of -6851.8 W/m^2 and a maximum value of 564662 W/m^2 respectively.

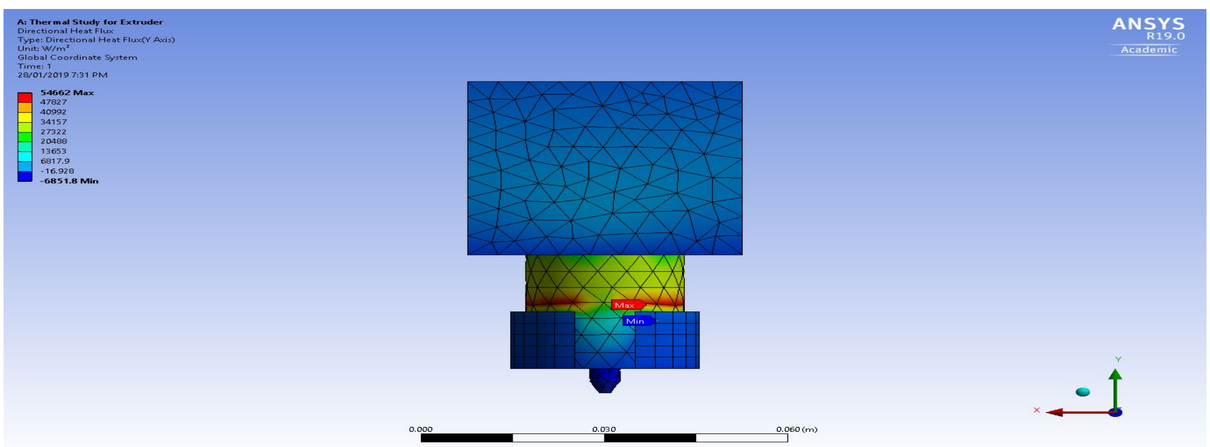

Figure 5. Directional heat flux of the extruder

4. Conclusion

The discussion above focused on a specific product application amounting to a framework for the development of an extruder for an additive manufacturing technology as presented. The thermal modelling as well as the finite element analysis of a screw type extruder for additive manufacturing were carried out in the ANSYS R19.0 environment. The results show effective heat distribution within the heating and the magnitude of the heat flux around the region occupied by the heating barrel which indicate evidence of plastic deformation of material without burn out of the polymeric material due to heating. Hence, this work will assist manufacturers who employ additive manufacturing technology for product development in the optimal design of extruder. The Finite Element Analysis module (FEA module) could be incorporated into the development framework to permit an iterative process for the determination of the optimum range of temperature based on the required service requirements and the material's properties. Future works can consider the use of physical experimentations in order to validate the results obtained numerically before advancing to the prototyping stage.

References

Ali, M. H., Mir-Nasiri, N. and Ko, W. L. Multi-nozzle extrusion system for 3D printer and its control mechanism. *The International Journal of Advanced Manufacturing Technology,* vol. 6, pp. 999–1010, 2016.

Azo Materials. Stainless steel grade 304. Available at https://www.azom.com/properties.aspx?ArticleID=965, 22 June 2020.

Bates-Green K. and Howie T. 2017. Materials for 3D printing by fused deposition. Edmonds Community College, pp 1–21, 2017.

Chaidas, D., Kitsakis, K., Kechagias, J. and Maropoulos, S. 2016. The impact of temperature changing on surface roughness of FFF process. *IOP Conf Ser Mater Sci Eng*, vol. 161:012033 pp. 1–9, 2016.

Daniyan, I. A., Balogun, V., Mpofu, K. and Omigbodun, F. T. An interactive approach towards the development of an additive manufacturing technology for railcar manufacturing. *International Journal on Interactive Design and Manufacturing,* vol. 14, pp. 651–666, 2020.

Daniyan, I. A., Mpofu, K., Daniyan, O. L., Fameso, F. and Oyesola, M. computer aided simulation and performance evaluation of additive manufacturing technology for component parts manufacturing. *The International Journal of Advanced Manufacturing Technology,* vol. 107, pp. 4517–4530, 2020.

Dylan, T. J. D. Design of a screw extruder for additive manufacturing. A Master's Thesis submitted in partial satisfaction of the requirements for the degree in Mechanical Engineering, University of California, San Diego, 2015.

Haigh, J. N., Dargaville, T. R and Dalton, P. D. Additive manufacturing with polypropylene microfibers. *Mater Sci Eng C*, vol. 77, pp. 883–887, 2017.

Manghnani, R. The impact of additive manufacturing on the automobile industry. *Int. J. Curr. Eng. Technol.* Vol. 5, no 3, pp. 3407–3410, 2015.

Lužanin O, Movrin D, Plančak M. 2013. Experimental investigation of extrusion speed and temperature effects on arithmetic mean surface roughness in FDM built specimens. *J Techn Plast.* Vol. 38, no, pp. 180–189, 2013.

MPDB, Material Properties Database Software Program. Dassault Systèmes SolidWorks Corporation, United States, 2019.

Oyesola, M. O., Mpofu, K., Mathe, N. R. and Daniyan, I. A. 2020. Hybrid –additive manufacturing cost model: a sustainable through-life engineering support model for MRO in the aerospace. *Procedia Manufacturing,* vol. 49, pp. 199-205, 2020.

Regina, F., Lavecchia, F. and Galantucci, L. M. Preliminary study for a full colour low cost open source 3D printer, based on the combination of fused deposition modelling (FDM) or fused filament fabrication (FFF) and inkjet printing. *Int. J. Interact. Des. Manuf.* vol. 12, pp. 979–993, 2018.

Turner, B. N. and Gold, S. A. A review of melt extrusion additive manufacturing processes: II. Materials, dimensional accuracy, and surface roughness. *Rapid Prototyp J.* vol. 21, no 3, pp. 250–261, 2015.

Vaezi, M., Seitz, H., and Yang, S. A review on 3D micro-additive manufacturing technologies. *Int J Adv Manuf Technol.* vol. 67, pp. 1721–1754, 2013.

Whyman, S., Arif, K. M. and Potgieter, J. Design and development of an extrusion system for 3D printing biopolymer pellets. *Int J Adv Manuf Technol.* vol. 96, pp. 3417–3428, 2018.

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