The Recent Additive Manufacturing Efforts against the COVID-19 Pandemic

[1]Hari Narayan Singh and [2]Sanat Agrawal

Mechanical Engineering Department, National Institute of Technology, Uttarakhand, India,

[1]harinarayan.phd2020@nituk.ac.in, *[2]sanata@nituk.ac.in*

Abstract

COVID-19, a global pandemic, has caused a rapid increase in the demand of several medical devices and parts like testing swabs, face masks, emergency ventilator parts, and personal protective equipment (PPE). Filling this sudden increase in the demand of medical devices and PPEs has become a prime concern of the medical industry. Additive manufacturing which is extensively used for medical devices and other medical applications has been used to make such medical devices and PPE parts. In this work, several medical devices and parts like nasopharyngeal swab (NP swab), face mask, face shield, ventilator parts, and hands-free door opener fabricated by additive manufacturing technology have been reviewed. The additive manufacturing is found very helpful to combat with the COVID-19 pandemic by providing the customised face mask for frontline medical personal.

Keywords. Additive manufacturing, COVID-19 pandemic, 3D printing, rapid prototyping, and medical AM.

1. Introduction

The term additive manufacturing (AM) is referred to a group of technologies like rapid prototyping, 3D printing, layered manufacturing, free-form manufacturing and net-shaping. The ASTM International defines additive manufacturing, as “a process of joining the materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [1]. The AM fabricates 3D object directly from the virtual CAD model. The CAD model is converted into STL file format. The STL file is obtained by tessellating the surface of the CAD model and is a closed volume. The STL file is checked for possible errors in translation and rectified with the help of a correction software tool. The STL file is then sliced in several layers and transferred to AM system for additive fabrication. The AM system builds the physical model by depositing or curing material layer-by-layer on to the build platform. Once the fabrication is complete, the part is removed from the build chamber. Post-processing operations such as cleaning, post-curing, surface finishing operations and removal of support structure is done, as required, in the last step of additive fabrication. The major stages of additive manufacturing are shown in the flow diagram in Figure 1.

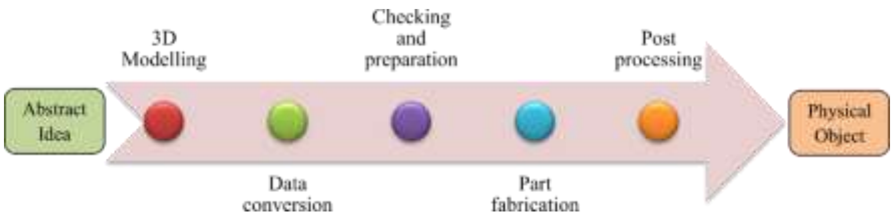

Figure 1. AM process chain to develop product from abstract idea.

The first human cases of COVID-19, the coronavirus disease caused by novel coronaviruses, SARS-CoV-2, were first reported in December 2019 from Wuhan City in China. The World Health Organization announced COVID-19 as a global pandemic on March 11, 2020 [2]. The patients suffer from a severe acute respiratory syndrome caused by the virus, SARS-CoV-2. A critical shortage of medical parts, devices and protective equipment is observed during a pandemic. Personal protective equipment (PPE), face shields and face masks for frontier health worker, and nasopharyngeal swab (NP swab) for collecting the patient samples are some of medical devices and equipment that are necessary to combat with COVID-19. Due to rapid increase in the counting of patients of COVID-19. The hospitals also face shortages of the emergency respirators and oxygen ventilators. It is a global challenge to fulfil the acute supply of medical parts and devices. The additive manufacturing comes in front to meet this challenge by fabricating the necessary medical parts. In this study, the endeavours made by the innovators and the organizations in helping the humanity fight the COVID-19 pandemic using additive manufacturing is reviewed.

2. AM TECHNIQUES APPLIED FOR FIGHTING AGAINST COVID-19 PANDEMIC

During COVID-19 pandemic, mainly polymeric materials were used to additively fabricate the medical devices and parts. Major AM techniques and polymeric medical parts and PPE that were fabricated to meet COVID-19 challenges are listed in Figure 2.

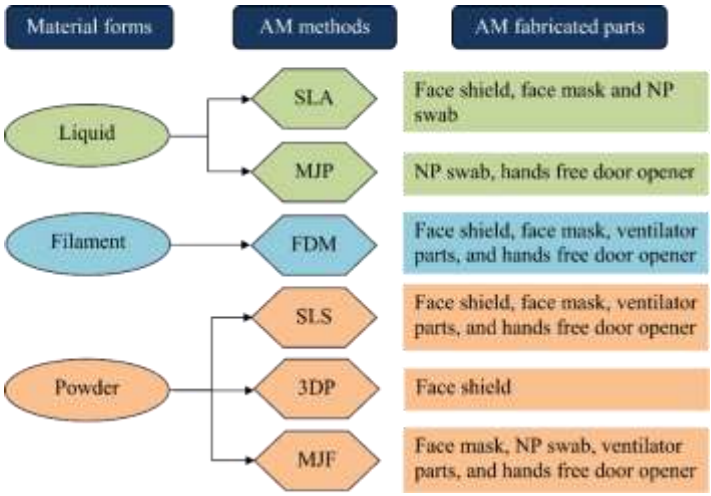

Figure 2. Additively fabricated medical parts in COVID-19 pandemic.

Photo-curing, laser sintering, and thermal melting are the primary manufacturing processes used by various technologies. The polymeric materials have been used in the following three states or forms: powder, filament and liquid, depending on AM technique used [3]. The AM technologies which are extensively being used to meet the acute demand of medical parts and devices in this COVID-19 pandemic situation are as follows:

- Stereolithography Apparatus (SLA)
- Multi Jet Printing (MJP)
- Fused Deposition Modelling (FDM)
- Selective Laser Sintering (SLS)
- 3D Printing (3DP)
- Multi Jet Fusion (MJF)

3. AM CONTRIBUTION TO FIGHT AGAINST COVID-19

To meet the acute demand of PPE parts, protective face-mask, NP swab, testing sticks and several medical parts necessary to combat COVID-19 are being fabricated with additive manufacturing. See Figure 3(a) and (b). The part design and development time is reduced significantly using 3D printing technologies to fabricate emergency respirator valve and ventilator parts as shown in Figure 4. Many other innovative ideas have also been additively manufactured to abate the expansion of SARS-CoV-2 virus, like the hands-free door opener shown in Figure 5. This hands-free door opener hand is designed and developed by Materialise Inc., Belgium, using MJF, SLS and FDM 3D printing technologies [4]. Many 3D printing industries have installed mass production units using several additive manufacturing technologies to fulfil the acute demand of medical parts and devices. The additively manufactured medical parts with production capacity of the AM system is summarized in Table 1 with the names of AM technologies, materials used, company, and country.

Figure 3(a) 3D printed emergency respirator valve by Isinnova and Weerg [5], reproduced with permission from Isinnova, and (b) NP swabs additively fabricated by Origin using SLA method [6].

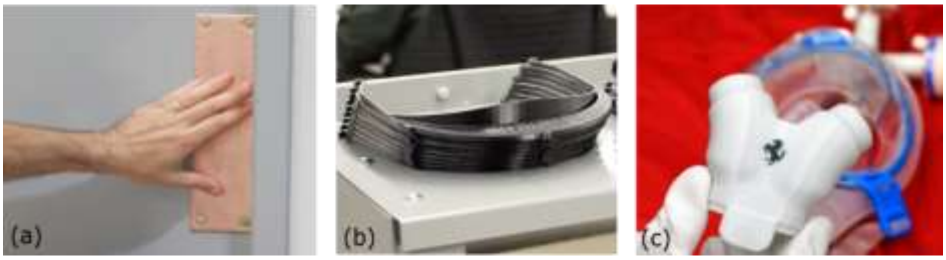

Figure 4 (a) Activated copper plate screwed on the face of door [7] reproduced with permission from SPEE3D (b) 3D printed face shield frame [8] (c) Respirator valve printed by Ferrari [9].

The Photocentric Ltd., UK, fabricates the large quantity of face shields using 45 Magna printers. The printing capacity of the Magna printer farm is 50,000 face shields per day. The face shields fabricated by Photocentric is customizable and the face screens with inclined surfaces provide space at the front and give protection at the sides [10]. The imakr® has installed a production unit at Guy's & St Thomas' supply-chain center for rapid production of eye shields, PPE parts and NP swabs by establishing a 3D printing farm of 200 3D printers to achieve production capacity of 1000 units/day. Nexa3D is producing 10,000 face-shields per week and 500,000 NP swabs per week, using NXE400 SLA 3D printers. Honda uses indirect rapid tooling technique of additive manufacturing for mass production of face shields and has donated 70,000 shields to frontline health personnel in the United States of America. Honda initially used 3D printing to fabricate face shields at five manufacturing facilities. Later on due rapid increase in the demand, they scaled up the production with plastic injection moulding up to 3,000 face shields per hour [11]. 3D Systems Inc. produced 2,880 emergency ventilator parts on demand using SLS method of additive fabrication in the United Kingdom. 3D systems Inc. is also producing several medical parts to help the COVID-19 patients and health worker like PPEs, face shield frames without visors and with visors, stopgap face masks, surgical N95 respirators and NP swabs [8]. See Figure 4. Stratasys is producing nasal testing swabs and face shield frames in the USA. Azul 3D and its partners are fabricating 1000 face shields per day per printer using high-area rapid printing (HARP). Copper3D (2020) produced NanoHack masks as a last resort device for protection against airborne particles. They used polypropylene material in surgical masks. The NanoHack masks achieved an efficiency of filtration approximately 96% for microorganisms of 1 µ and 90% for microorganisms of 0.02 µ.

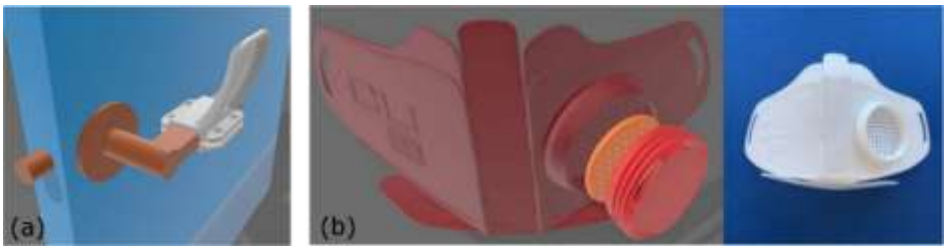

Figure 5(a) Hands free door opener designed by Materialise, Inc [4] and (b) NanoHack mask designed and fabricated by Copper3D [12].

To meet the shortage of face masks during the current pandemic, Filament Innovations in collaboration with St. Luke's University Health Network has designed and fabricated reusable 3D printed masks. The full mask is an assembly of four 3D printed parts: 3D printed guard, Laser cut acrylic plate, HEPA (High-Efficiency-Particulate-Air) filter, and mask frame. The parts have been fabricated using Filament Innovations' BFP-ICARUS-TP High Flow FDM 3D Printer. TPC (or PETG) material is used to print the parts and up to four (4) parts can be printed per build in three (3) hours [13]. Huaxiang Group designed and produced medical safety goggles using Farsoon 403P system. They used SLS, FDM and SLA method for fabrication of various parts of the safety goggles [14].

Table 1. AM contribution to meet the COVID-19 pandemic challenges.

Medical parts	Manufacturer/AM System	Material used	Production capacity	Country	Citation
Face shield	Photocentric Group Model: LC Magna Printer	Photopolymer resin	50,000/day	UK	[10]
	iMakr Model: SLS and FDM	PLA & PETG (Poly Ethylene Terephthalate Glycol)	1000/day	USA	[11]
	Nexa3D Model: NXE400 SLA 3D printer	proprietary material	10,000/ week	USA	
	Honda AM system: 3D printing, injection moulding.	NA	3000/hour	USA	
	3D Systems Model: ProX SLS 6100 Printer	Medical grade nylon	100/day	UK	[8]
	Stratasys Model: FDM	ABS	Total: 275,000 units	Israel	[15]
	Azul3D Model: High-Area Rapid Printing	Proprietary material	20,000/ week	USA	[16]
Face masks and fitting s	Filament Innovations Model: BFP-ICARUS-TP High Flow FDM 3D Printer	TPC/TPU & PETG	35/day	USA	[13]
	Farsoon Technologies AM system: Polymer Laser Sintering	Farsoon FS3300PA	1000/day	USA	[14]
	Pneumask Model: NA	PLA & ABS	Total: 23,534 units	California	[17]
	3D Systems, Inc. Model: Multi-Jet Fusion (MJF)	Powder Bed Fusion Nylon	NA	UK	[18]
	CIIRU CTU & CARDAM Model: HP MJF 540 Printer	PA 12	10,000/day	Czech Republic	[19]
	Copper3D AM system: FDM	PLACTIVE® and MDflex®, Nanocomposites developed by Copper3D	NA	Canada	[12]
Nasopharyngeal (NP) swabs	EnvisionTEC Model: Envision One cDLM Printer	Soft C-29C resin	112,000/ day	USA	[20]
	Origin and Stratasys AM system: Origin One Printer	Proprietary material	190,000/ day	Israel	[8]
	Forecast 3D and Abigenix, Inc. AM system: HP's MJF Printer	Proprietary material	100,000/ day	USA	[21]
	Markforged Model: Markforged Industrial Series Printer	Nylon base and Rayon	10,000/day	USA	[11]
	Hospital virtual Valdecilla AM system: Form 2 SLA Printer	Surgical Guide resin	324/print	Spain	[22]
	Nexa3D Model: NXE 400	Nexa3D material	500,000/ week	USA	[11]
	Formlabs Model: Formlabs SLA Printer	Surgical Guide resin	112,000/ day	USA	[23]
	Carbon3D Model: Carbon DLS™	KeySplint Soft®	1000,000/ week	USA	[24]
Emergency valves, respiratory masks, and Ventilator parts	Weerg with Isinnova and FabLab Brescia AM system: HP's MJF 5210 Printer	PA 11 and PA 12 Nylon	500/day	Italy	[25]
	Materialise, Inc.	Materialise Passive NIP	NA	Belgium	[26]
	CRP Technology Model: High Speed Sintering	Windform® P1 isotropic material	NA	Italy	[27]
	Ferrari AM system: FDM	ABS	NA	Italy	[9]
	Isinnova, Lonati Model: FDM, SLS	PLA	100/day	Italy	[5]

	3D Systems Model: SLS	Medical Grade Nylon	720 sets (total: 2,880 parts)	UK	[8]
Hands-free door opener	Materialise, Inc. AM system: MJF, SLS, and FDM	PLA	NA	Belgium	[4]
	Sintratec Model: Sintratec S2 SLS 3D printer	Sintratec TPE powder	NA	Switzerland	[28]
Anti-microbial copper	SPEE3D 3D Model: Light SPEE3D machine	ACTIVAT3D (Anti-microbial) copper	NA	Australia	[7]
Diagnostic platform (lab-on-a-chip)	3D Systems Inc. Model: Standalone 3D printer MED-AMB 10	MED-AMB 10, PRO-BLK-10, and RUBBER-65A BLK	NA	UK	[29]

Novak and Loy (2020a) have reviewed several projects initiated prior to April 01, 2020, utilizing various AM technologies. There were 91 such projects. These projects were aimed at fabricating a range of health and medical products for combating COVID-19 on-demand and close to the point of need. They declared that 65% of the products were for PPEs out of that 60% were face shields. FDM technology was mostly used to fabricate medical products to combat COVID-19 [30]. Novak and Loy (2020b) have performed an analysis of face shields and face masks fabricated by various AM technologies during COVID-19. They have investigated fabrication of 37 types of face shields and 30 types of facemasks varying in the company or institution producing them or AM machine being used. The timeline for the design of these face shields and face-masks is May-June 2020. They have demonstrated a range of considerations in fabricating PPE parts using AM such as the type of AM technology used, the quality of products to be fabricated, the amount of material required and the cost of manufacturing. They found that the face shields take almost half the time to additively fabricate compared to the face masks and require approximately half the filament material. They have concluded that printing face-shields is cheaper than printing face masks. The authors have also found that the AM technologies allowed use of distributed manufacturing for producing PPE parts during COVID-19 [31].

A diagnostic platform has been developed by Dr. Pantelis Georgiou using 3D Systems, Inc. This lab-in-a-chip rapid testing device can give the test report within 30 minutes [11]. Taking an initiative to help patients in this pandemic situation, Ferrari S.p.A. has started fabricating respiratory valves and other devices for protective masks from thermoplastic materials. See Figure 4. They use 3D printers at its car prototyping department in the Maranello plant [9]. Charlotte valve and Dave valve have been designed and developed to turn a normal mask into C-PAP mask by Isinnova and Weerg. These valves shown in Figure 3 connects the mask to the oxygen dispenser [5]. SPEE3D has developed a antimicrobial copper plate. The existing metal part is coated with copper by SPEE3D printers. This ACTIVAT3D copper push plate is mounted on doors to reduce the spread of virus as shown in Figure 4. The clinical trial results showed that 99.2% of SARS-CoV-2 virus killed within five hours whereas 96% of SARS-CoV-2 viruses were found dead within two hours with this antimicrobial copper plate while there is no reduction of virus presence with stainless steel plate [7].

4. CONCLUSIONS

In the present work several medical parts and devices fabricated by additive manufacturing technologies to help combat COVID-19 have been discussed. The manufacturing process of six AM methods, which were mainly used to fabricate the medical parts in this pandemic situation, are also explained. The effort by different manufacturers of AM systems all over the world is tabulated to summarize how AM has helped humanity during this pandemic. The list is not exhaustive. However, it gives a fairly good idea of how the AM technology has been useful in responding to the COVID-19 needs. The suitable AM technique and material used by AM industries for mass production of medical parts with their production capacity have also reviewed. Certainly, the additive manufacturing played very important role to save the lives of many frontline heath-workers and patients by readily providing the customized face-masks, face-shields, emergency respirator valves, and other testing parts and devices.

REFERENCES

[1] C.K. Chua, K.F. Leong, C.S. Lim, “3D Printing and Additive Manufacturing: Principles and Applications”, World Scientific Publishing Co. Pte. Ltd, 5th ed. Singapore, 2019.

[2] D. Cucinotta, and M. Vanelli, “WHO Declares COVID-19 a Pandemic”, Acta Biomedica, vol. 91 (1), pp. 157-160. Italy, 2020.

[3] M.S. Tareq, , T. Rahman, , M. Hossain, and P. Dorrington, “Additive manufacturing and the COVID-19 challenges: An in-depth study”, Journal of Manufacturing Systems, 2021.

[4] Materialise Inc., “Hands-free 3D-printed door openers to help against the spread of coronavirus”, 2021.

[5] Isinnova, “Easy COVID”, Mar., 2021, from https://isinnova.it/archivio-progetti/easy-covid-19/.

[6] Origin, “Origin 3D-printed COVID-19 test swabs clinical trial and validation completed with Beth Israel Deaconess Medical Center”, 2021.

[7] SPEE3D, “3D printing a metallic coating of antimicrobial copper to fight the spread of COVID-19”, 2020, from https://spee3d.com/activat3d-copper/.

[8] 3D Systems Inc., “COVID-19 Call to Action”, UK, 2021.

[9] Ferrari S.p.A., “Ferrari continues its efforts to fight the COVID-19 pandemic” 2020.

[10] Photocentric, “The Creation of Magna Printer Farm”, 2020.

[11] S. Davies, D. O’Connor, and L. Griffiths, “The latest 3D printing efforts against COVID-19”, TCT Magazine: 3D printing and additive manufacturing intelligence, 2020.

[12] Copper3D, “NanoHack, the open source face mask”, 2020.

[13] St. Luke’s University Health Network and Filament Innovations, “3D Mask - SLUHN and Filament Innovations”, 2020.

[14] Farsoon, “Farsoon Technologies – Open for industry”, 2020.

[15] Stratasys, “Stratasys helps: Responding to the COVID-19 crisis”, 2020.

[16] Azul3D, “Azul 3D Protects Healthcare Workers Facing COVID-19 Crisis-Printing 1,000 Face Shields Per Day Per Printer”, 2021.

[17] T. Amenabar, “Stanford has made a reusable mask from scuba gear-and it’s shipping it to the front lines of the pandemic”, The Washington Post, 2021.

[18] C. Richburg, “Stopgap Surgical Face Mask (SFM)”, 2020.

[19] A. Novakova, “Mass production of original Czech mask with the highest degree of protection”, 2020.

[20] EnvisionTEC, “EnvisionTEC to 3D print mass quantities of nasopharyngeal swabs for COVID-19 testing based on successful clinical trial”, 2020.

[21] Forecast 3D, “Forecast 3D now producing nasopharyngeal swabs for COVID-19 test kits”, 2020.

[22] Hospital Virtual Valdecilla, "Sample collection – Swabs", 2021.
[23] Formlabs, "3D printed COVID-19 test swabs", 2020.
[24] Carbon, "Resolution medical using Carbon DLS™ technology to 3D print nasopharyngeal swabs for COVID-19 testing", 2020.
[25] Weerg, "Weerg 3D prints valves for emergency respiratory masks", 2020.
[26] V. Brigitte, "Materialise 3D-Printed non-invasive PEEP masks aim to alleviate ventilator shortage", 2020.
[27] CRP Technology, "CRP Technology on the front line in the fight against COVID-19", 2020.
[28] Sintratec, "Door opener against COVID-19 spread", 2020.
[29] 3D Systems Inc., "Rapid Diagnostics Device Developed Using Figure 4® Standalone", 2020.
[30] J.I. Novak and J. Loy, "A critical review of initial 3D printed products responding to COVID-19 health and supply chain challenges", Emerald Open Res., 2020.
[31] J.I. Novak and J. Loy, "A quantitative analysis of 3D printed face shields and masks during COVID-19", Emerald Open Res., 2020.

Biographies

Hari Narayan Singh received the bachelor's degree in mechanical engineering from Uttar Pradesh Technical University in 2013, the master's degree in computer aided design and manufacturing from Motilal Nehru National Institute of Technology in 2019, and pursuing the philosophy of doctorate degree in mechanical engineering from National Institute of Technology Uttarakhand, respectively. His research areas include application of additive manufacturing in fabrication of patient-specifics medical implants.

Dr. Sanat Agrawal received the bachelor's degree in Mechanical Engineering from IIT Kanpur in 1988, the master's degree in Mechanical Engineering with specialization in Machine Design Engineering from University of Roorkee in 1990 and PhD in Mechanical Engineering from IIT Kanpur in 2002. He is currently working as the Associate Professor and Head, Mechanical Engineering Department, NIT Uttarakhand. His research areas are computer-aided design and additive manufacturing.