Materials Physics and Mechanics 37 (2018) 124-132 Received: December 22, 2017

3D PRINTING OF FLEXIBLE PARTS USING EVA MATERIAL

Narendra Kumar[1*], Prashant K. Jain[1], Puneet Tandon[1], Pulak Mohan Pandey[2]

[1]PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, INDIA

[2]Indian Institute of Technology, Delhi, New Delhi, INDIA

[*]e-mail: narendra.kumar@iiitdmj.ac.in

Abstract. In the fused filament fabrication (FFF) process, filament buckling occurs during the processing of elastomers. Elastomer filament buckles between the rollers and liquefier head due to flexibility hence make difficult elastomer processing and extrusion through as mall nozzle. In this paper, ethylene vinyl acetate (EVA), an elastomer has been processed through the in-house developed CNC assisted material deposition tool (MDT). Instead of the filament, the developed system processes the material in the pellet form, which overcomes the limitations of FFF process in elastomer processing. An experimental study has been carried out to find the suitable set of process parameters setting for part fabrication. The fabricated parts show the flexibility similar to rubber, which is suitable for various end-use applications. The present study outcome shows that EVA material has the potential for additive manufacturing of flexible parts.

Keywords: additive manufacturing; 3D printing; pellet; screw extrusion; flexible; CNC milling machine; hybrid manufacturing; EVA.

1. Introduction

Additive manufacturing (AM) refers to the process of making three-dimensional objects in layer-by-layer fashion by using CAD data directly. Many AM processes have emerged over the time, and many more are in development stage [1]. Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is one of the very popular AM processes, in which an object is made by depositing melted material in a predefined tool path [2]. It builds 3D objects using a filament of polymeric materials, however, now a day polymer composite filaments are also available in the market. FFF uses the appropriate size filament material that uncoils from a spool and enters inside the liquefier head with the help of drive wheels. Thermoplastics such as acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and nylon, etc. are widely used FFF materials to produce parts for various applications [3 – 5]. Sometimes, the specific materials are needed for to fulfill the demand of customers. Therefore, the technology should be more generic and compatible to accept the wide range of materials [6]. However, in FFF, there are many obstacles in the use of new materials such as specific size and properties requirement in the filament. For example, the available materials to be used in FFF process should be sufficiently rigid to withstand the force exerted by the counter-rotating rollers [7]. As the elastomers have less rigidity and low column strength, existing feeding system of commercial FFF cannot process the filaments made by elastomers. When the rollers push the elastomer filament into the liquefier of the FDM machine, it buckles due to low column strength and flexibility. Furthermore, the high melt viscosity of the elastomers requires substantial force to push the filament into the liquefier head as compared to other polymeric materials, which cannot be fulfilled due to low column strength as shown in Fig. 1. These two properties contradict each other. These constraints make commercial FFF systems

http://dx.doi.org/10.18720/MPM.3722018_3

incompatible for processing flexible filaments. Some researchers have done the modifications in the existing feeding systems of FFF to print flexible parts [2]. Nevertheless, this modification in the existing FFF feeding system may create the problem in the processing of other polymeric materials such as ABS and PLA, etc. It is worthwhile to develop a generic solution for fabricating 3D flexible or rigid parts. Instead of the filament, development of pellet feeding, based AM process, can provide the solution for this problem.

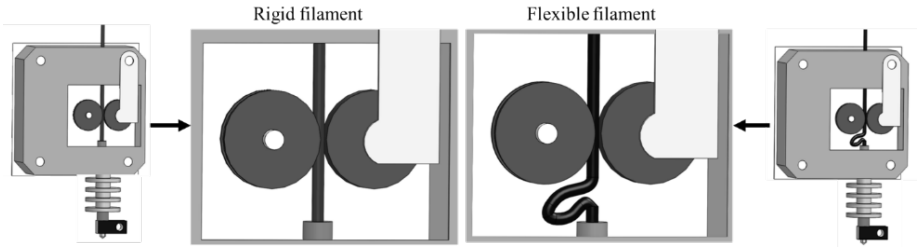

Fig. 1. Buckling issue in flexible filament feeding.

In order to overcome the limitations of FFF process, a pellet based innovative AM process has been implemented for fabricating flexible parts. A customized screw extrusion based material deposition tool (MDT) has been developed, which has pellet based feeding system to process the material. Hence, due to use of pellets, it unlocks the opportunities for the wide range of rigid as well as flexible polymeric materials. Ethylene vinyl acetate (EVA) is an elastomeric material and has many applications in the commercial market. However, the potential of this material has not been explored. Hence, the present study focuses on the investigation of EVA material for the use in additive manufacturing. Further, a study has been carried out to find the optimum process parameters. The printed parts of EVA have been tested for the flexibility.

2. Literature review

In the past decade, various efforts have been made towards the material development for the FFF process. The researchers focused on the new thermoplastics as well as hybrid polymer matrix composite materials for the use in FFF process. Masood et al. mixed the iron particles with the nylon matrix and developed metal-polymer composite material as feedstock for the FDM process [8]. This feedstock filament was loaded into the feeding system of FDM machine to fabricate 3D objects. The objects were fabricated successfully without doing any single modification in the machine components. Another study on the metal-polymer composite material was carried out by Nikzad et al. [9]. Composite materials of iron/ABS and copper/ABS were successfully prepared in filament form. Experimental results showed that significant improvement in the part strength was observed in the parts made of composite materials. Carneiro et al. explored the possibilities of polypropylene (PP) as a new candidate material for the FDM [10]. They evaluated the entire process chain from the filament production to the samples fabrication from the material. Mechanical characterization of the sample parts was done, and the effect of process parameters on the mechanical properties was evaluated through experimental work. Further, FDM printed samples results were compared with the samples, prepared by compression molding process. Boparai et al. investigated the nylon6-Al-Al_2O_3 as an alternative filament material for FDM process [11]. In their study, the filament exhibited good thermal and wear properties but inferior mechanical properties as compared to the ABS material filament. Also, some researchers explored the nanoparticles filled polymers in FDM process. The different weight percentage of nanofibers were added in the ABS polymer matrix by Shofner et al. to reinforce the filament for the FDM process[12]. In order to analyze the results, the composite filament was compared with unfilled ABS filament. Significant changes in the mechanical properties were seen in the swelling

behavior of the filament. In another work, Francis and Jain developed the polymer-layered silicate nanocomposites for the FDM applications [13]. The results showed the significant improvement in the part strength when compared with other macro-composites produced parts by other researchers. Lee et al. attempted a work on flexible part fabrication through ABS material by varying the process parameters. They measured the elastic performance of the ABS made prototypes with the help of custom-made apparatus [14].

It can be seen from the aforementioned literature that the most of the researchers have focused on the enhancement of the part strength by adding micro or nanoparticles in the polymer matrix. Moreover, some of them explored the new materials for this process, but most of the studies were focused on the rigid thermoplastic materials such as ABS, polypropylene, nylon, etc. The prime concern of researchers was the strength of the printed parts. However, very few studies were considered the flexibility aspect of the material. To the best of author knowledge, none of them considered the elastomers in their study to fabricate flexible parts.

3. Ethylene vinyl acetate

Ethylene vinyl acetate (EVA) is the copolymer of ethylene and vinyl acetate. It is very flexible similar to rubber and has many properties such as excellent toughness, transparency, cracks resistant and easy processability, etc. In general, EVA is frequently used for fabricating flexible parts in the shoe, biomedical and electrical industries and conventional techniques are used to process this material. The properties of EVA such as low melting and quick curing make it more suitable for additive manufacturing of flexible parts. In this study, pellets of 2 – 3 mm size have been used, which was supplied by Ananta Polyrubb Pvt. Ltd.

4. CNC assisted Material Deposition Tool (MDT)

In CNC assisted MDT, proposed in this work, pellets of EVA material are directly used to fabricate 3D parts. The screw extrusion based principle is used to process the EVA pellets. The viscous paste of EVA material extrudes at a controlled rate through a nozzle of 0.8 mm diameter. MDT has various components such as barrel, screw, heater, funnel, band heater, and temperature controller, etc., as shown in Fig. 2. The MDT is attached to the available three-axis CNC milling machine at the place of the cutting tool, which makes it capable of moving in *x*, *y* and *z* directions by *G* and *M* codes. The codes are generated through indigenously developed software in the MATLAB. The material is extruded in the form of the filament on the built platform, located on the CNC table. During deposition of material, MDT moves in *x* and *z* directions, at the same time, built platform moves in the *y*-direction. Once, a layer is completed, the MDT moves in the upward direction equal to the layer thickness.

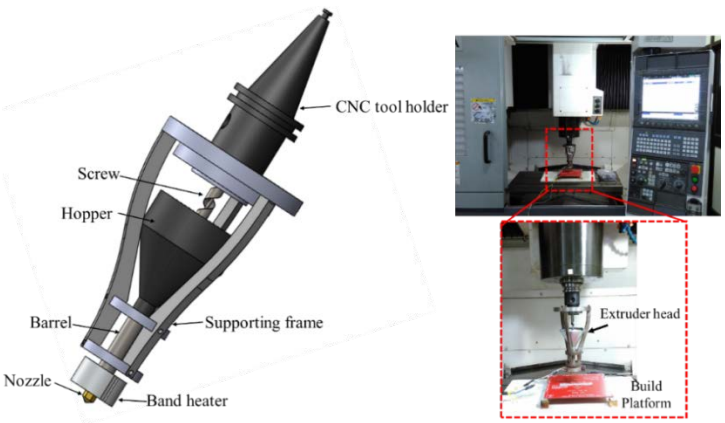

Fig. 2. Developed CNC assisted MDT system.

Since MDT is attached to the CNC milling machine, therefore, commercial tool path planning software of milling cannot work for additive manufacturing of the parts. Due to the limitations, a program was developed in the MATLAB software, which is capable of reading, slicing the part geometry in STL file. Further, tool path for each layer can be prepared by embedding the standard *G* and *M* codes of the milling machine. The user can change the process parameters such as layer thickness, deposition speed, road gap, etc., as per the need. Some features of the developed program are shown in Fig. 3.

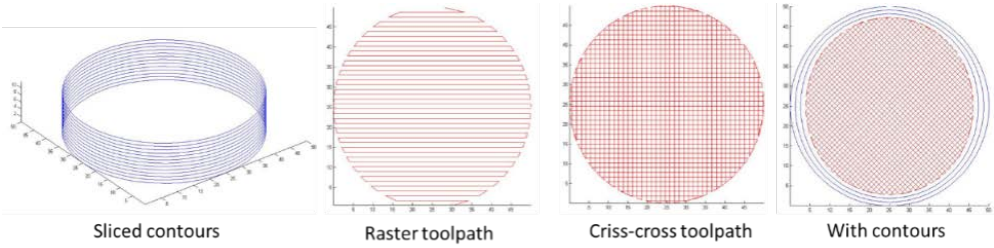

Fig. 3. Slicing contours and different types of the toolpath.

5. EVA behavior under different extrusion process parameters

An experimental study was carried out before flexible part fabrication to see the behavior of EVA material under different process conditions. Preliminary experiments were conducted to see the crucial parameters and based on the experimental results, barrel temperature and screw speed were selected as the input parameters as shown in Table 1, while flow rate and change in diameter were the output parameters.

Table 1. Selected parameters and their range.

Input Parameter	Selected Levels					
	1	2	3	4	5	6
Barrel Temperature (°C)	100	110	120	130	140	150
Screw Speed (RPM)	50	55	60	65	70	75

Determination of flow rate is necessary to examine because the material deposition speed can be obtained, which is very essential to fabricate the excellent quality parts. The diameter of the extrudate is considered due to its importance during the selection of appropriate road gap and layer thickness during the part fabrication. To study the extrudate diameter, the study was conducted in two phases. Firstly, the material was extruded vertically in the space without any deposition on the built platform while in the second phase the material was deposited onto the platform in a prescribed pattern as shown in Fig. 4. This is done because of the shape of extrudate changes after the deposition due to its weight. This change in shape depends on the viscosity of the deposited material. The shape of extruded remains circular before deposition due to the circular nozzle; it will be elliptical after the deposition onto the built platform. This cross-sectional change affects the dimensional accuracy and the part strength.

Obtained results for melt flow speed. The results obtained for melt flow speed for barrel temperature and screw speed are shown in Figs. 5 and 6, respectively. It can be seen that melt flow speed of the extrudate increases with the rise in barrel temperature (BT) and screw speed (RPM) both. This is because the temperature is rising, the considerable changes in the viscosity are occurring. As the temperature rises, the viscosity decreases, hence flowability of the extrudate improves. That is why melt flow speed of the material is increasing with temperature. Moreover, increase in screw speed increases the pressure gradient. Hence the considerable increment in melt flow speed can be observed. It means that

if the high value of screw speed and barrel temperature are considered for part fabrication, then the deposition speed will be high as compared to the other combination of process parameters.

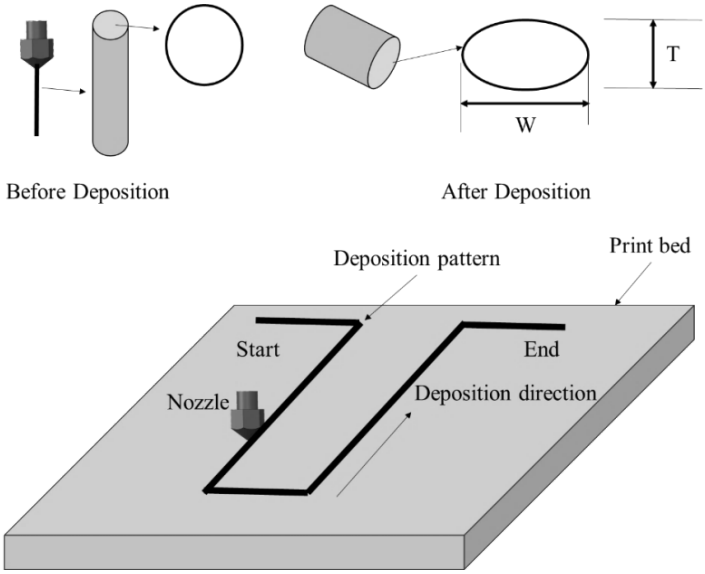

Fig. 4. Used material deposition pattern.

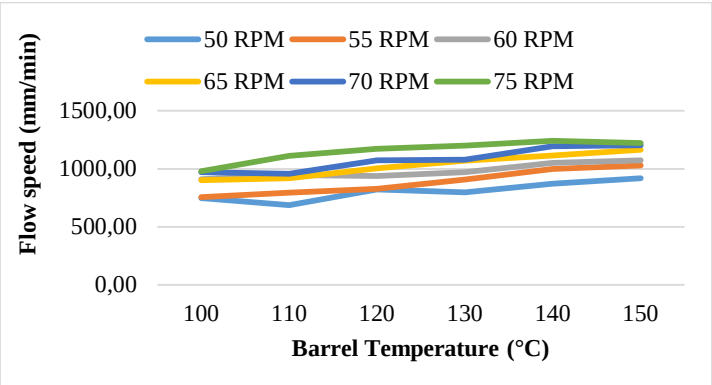

Fig. 5. Effect of barrel temperature on flow speed.

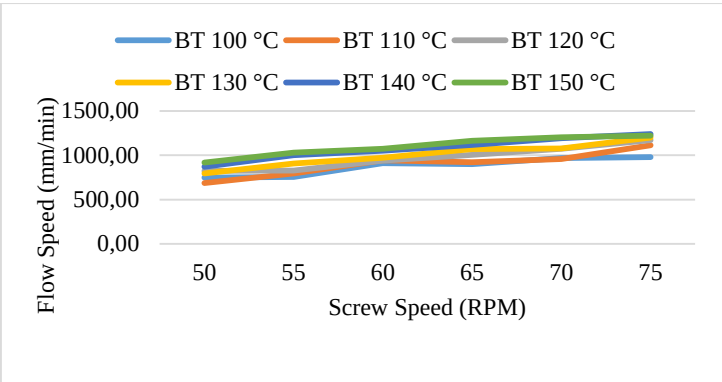

Fig. 6. Effect of screw speed on flow speed.

Obtained results for diameter. The values of filament diameter were recorded at different locations of filament after and before extrusion. The average diameter of the

filament was then finalized as the actual diameter of the filament. Mitutoyo digital micrometer was used to measure the values at different locations.

Before deposition. The nozzle of 0.8 mm diameter is used in the present study, but the obtained diameter of the EVA extrudate was quite larger as compared to nozzle diameter. It was due to the considerable amount of swell in the extrudate during the extrusion. The diameter of the filament was varied in the range of 1.65 to 1.95 mm for barrel temperature (see Fig. 7) while for the screw speed, it was varied from 1.47 to 1.65 mm as shown in Fig. 8. The diameter trend line for barrel temperature goes direction upward while the trend line approximately goes downward for the screw speed. In general, extrudate diameter decreases with increase in barrel temperature for other polymers but in the current study, the trend line shows the opposite results with temperature. The reason might be the reduction in melt elasticity at colder temperatures, which lead to increment in the molecular disentanglement.

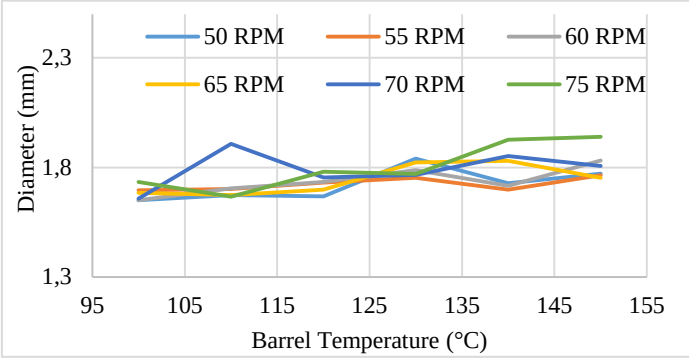

Fig. 7. Effect of barrel temperature on filament diameter before deposition.

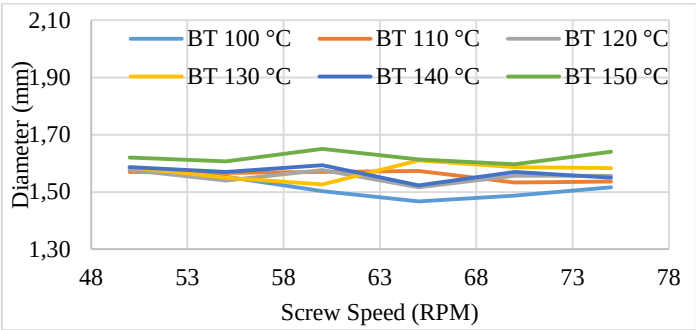

Fig. 8. Effect of screw speed on filament diameter before deposition.

After deposition. Elliptical shape filament was obtained after deposition onto the build platform due to the self-weight of the filament. Therefore, the value was recorded for maximum and minimum diameter. The maximum value was recorded as the filament width while the minimum value as filament thickness. The results for filament thickness and width are shown in Figs. 9 – 12 for screw speed and barrel temperature. It can be seen that filament width is increasing with the increase in barrel temperature while filament thickness is decreasing. Flowability of extrudate improves at high temperature due to a reduction in viscosity due to which extrudate flows and increase the filament width at the cost of filament thickness.

6. Part fabrication

Based on the experimental results, the optimum process parameters were selected as deposition speed 938 mm/min, barrel temperature 120 °C, screw speed 60 rpm, bed temperature 50 °C and layer thickness 1.42-mm. Different types of parts with different geometries were fabricated using these process parameters as shown in Fig. 13. It can be seen

that additive manufacturing of EVA is possible with developed CNC assisted MDT system and can be useful for various end-use applications such as shoe and soft robotics industries.

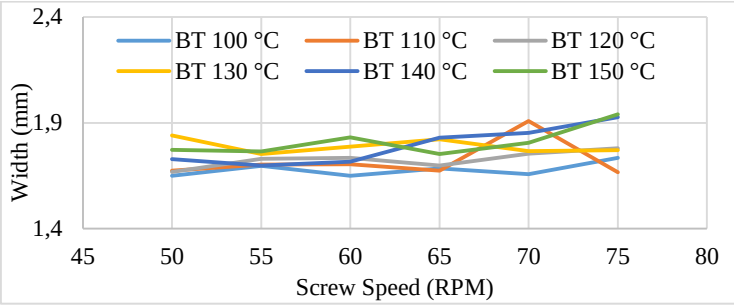

Fig. 9. Effect of screw speed on filament width after deposition.

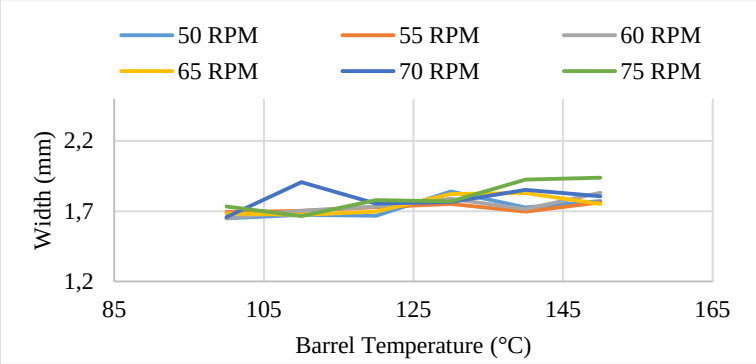

Fig. 10. Effect of barrel temperature on filament width after deposition.

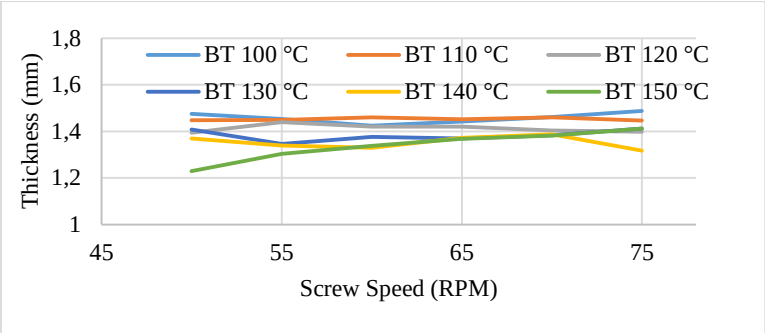

Fig. 11. Effect of screw speed on filament thickness after deposition.

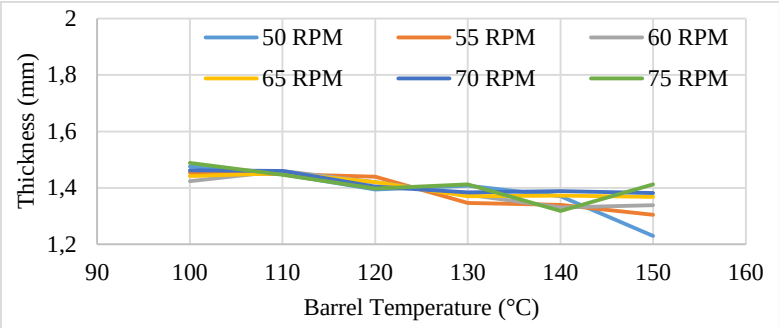

Fig. 12. Effect of barrel temperature on filament thickness after deposition.

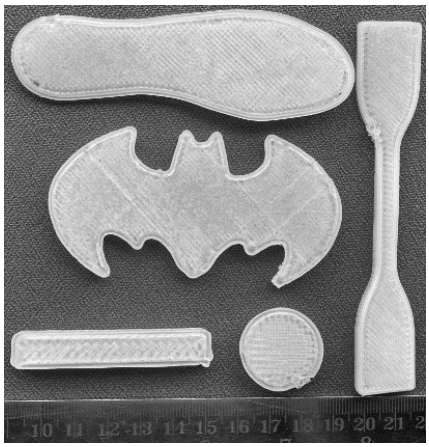

Fig. 13. Fabricated parts.

To show the part flexibility, a fabricated part was twisted manually as shown in Fig. 14. The twisting results show that EVA can twist similar to rubber and also can recover its original shape after removal of the load.

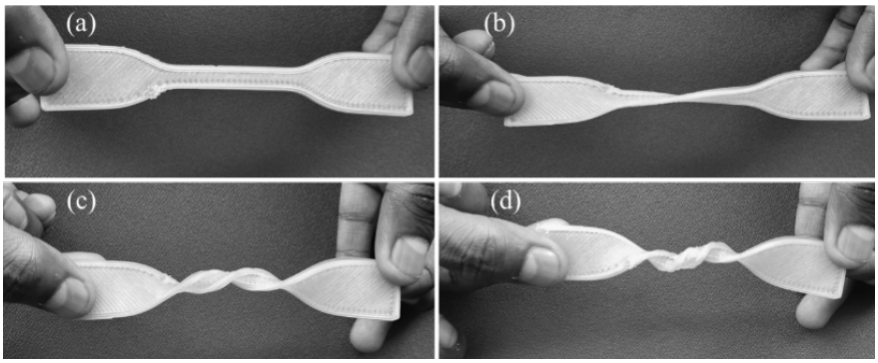

Fig. 14. Flexibility in fabricated parts.

7. Conclusion

The need of 3D flexible parts is very frequent in many industries. However, the fabrication of flexible parts through well-established FFF faces many issues. In the present work, flexible parts fabrication has been done using EVA material by developing an in-house CNC assisted MDT system. An exhaustive experimental study has been performed to determine the optimum process parameters setting. Screw speed and barrel temperature were considered as input process parameters while melt flow speed and filament diameter before and after deposition were considered as the measured responses. Based on experimental results, optimum process parameters were selected. Different types of 3D flexible parts were fabricated using the optimum process parameters. Overall, the current study indicates that flexible parts can be fabricated by developing pellet based AM systems with the ease. In future, many more materials and their composites can be explored on this type of systems.

Acknowledgment. *Authors would like to thank DST-SERB for providing financial support. Present work has been carried under the DST-SERB sponsored project "Development of Additive Subtractive Integrated RP System for Improved Part Quality" (SB/S3/MMER/0043/2013).*

References

[1] H. Bikas, P. Stavropoulos, G. Chryssolouris // *Int. J. Adv. Manuf. Technol.* **83(1–4)**

(2016) 389.
[2] M. Taufik, P.K. Jain // *J. Manuf. Sci. Eng.* **138(6)** (2016) 1.
[3] N. Kumar, S. Shaikh, P.K. Jain, P. Tandon // *Int. J. Rapid Manuf.* **5(2)** (2015) 186.
[4] S. Shaikh, N. Kumar, P.K. Jain, P. Tandon, *CAD/CAM, Robot. Factories Future* (Springer India, 2016) 751.
[5] M. Taufik, P.K. Jain // *Int. J. Manuf. Technol. Manag.* **27(1/2/3)** (2013) 47.
[6] B.N. Turner, R. Strong, S.A. Gold // *Rapid Prototyp. J.* **20(3)** (2014) 192.
[7] N. Venkataraman, S. Rangarajan, M.J. Matthewson, B. Harper, A. Safari, S.C. Danforth, G. Wu, N. Langrana, S. Guceri, A. Yardimci // *Rapid Prototyp. J.* **6(4)** (2000) 244.
[8] S. Masood, W. Song // *Mater. Des.* **25(7)** (2004) 587.
[9] M. Nikzad, S.H. Masood, I. Sbarski // *Mater. Des.* **32(6)** (2011) 3448.
[10] O.S. Carneiro, A.F. Silva, R. Gomes // *Mater. Des.* **83** (2015) 768.
[11] K.S. Boparai, R. Singh, H. Singh // *Rapid Prototyp. J.* **22(2)** (2016) 217.
[12] M.L. Shofner, K. Lozano, F.J. Rodríguez-Macías, E.V. Barrera // *J. Appl. Polym. Sci.* **89(11)** (2003) 3081.
[13] V. Francis, P.K. Jain // *Virtual Phys. Prototyp.* **11(2)** (2016) 1.
[14] B.H. Lee, J. Abdullah, Z.A. Khan // *J. Mater. Process. Technol.* **169(1)** (2005) 54.