M.Tech (Production Engineerinag) [Gulshan kaur] 2021

WEAR AND FRICTION ASSESSMENT OF ABS SAMPLE FABRICATED USING FUSED DEPOSITION MODELLING

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT

FOR THE AWARD OF THE DEGREE

OF

MASTER OF TECHNOLOGY
IN
PRODUCTION ENGINEERING

Submitted by
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CANDIDATE’S DECLARATION

I, GULSHAN KAUR (Roll No. 2K19/PIE/03), hereby certify that the work which is being presented in this report titled “Wear And Friction Assessment Of ABS Sample Fabricated Using Fused Deposition Modelling” is submitted in the partial fulfilment of the requirement for degree of Master of Technology (Production Engineering) in Department of Mechanical Engineering at Delhi Technological University is an authentic record of my own work carried out under the supervision of PROF. RANGANATH M. SINGARI. (HOD, Department of Design, Delhi Technological University, Delhi) AND PROF. HARISH KUMAR (Associate professor, Department of Mechanical Engineering, National Institute of Technology, Delhi) The matter presented in this report has not been submitted in any other University/Institute for the award of Master of Technology Degree. Also, it has not been directly copied from any source without giving its proper reference.

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This is to certify that this report titled, “3d Printing: A review of Material, Properties and Applications” being submitted by Gulshan Kaur (Roll No. 2K19/PIE/03) at Delhi Technological University, Delhi for partial fulfilment of the Degree of Master of Technology as per academic curriculum. It is a record of Bonafede research work carried out by the student under my supervision and guidance, towards partial fulfilment of the requirement for the award of Master of Technology degree in Production Engineering. The work is original as it has not been submitted earlier in part or full for any purpose before.

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ABSTRACT

The current review is focuses on a comprehensive investigation of the process parameters such as height of layer, orientation, speed of printing, Air gap, fill density, Infill structure, Raster angle, Width of raster, temperature of bed and how they influence the tribological behavior of the ABS specimens fabricated using the Fused Deposition Modelling (FDM), The tribological properties of FDM build parts are highly affected by these process parameters. Due to this, researchers have explained optimum values of these parameters to enhance the tribological behavior. According to the application, for which the part is produced, these process parameters should be chosen cautiously. For a particular demand, some of process parameters are important than rest, so there is need to be identify and optimize these important parameters for these researchers have investigated and employed different Design of Experiments (DOE) which are discussed in this paper. Another way of improving tribological behavior of ABS is the addition of material such as, such as graphite, PTFE, Zirconia, CaCO3, and, carbon fiber etc. The addition of materials to polymers has a significant impact on the wear resistance quality. This not only affect wear but also improve the friction coefficient as compare to the pure polymer. This paper aims at reviewing recent research on improving tribological behavior of ABS parts produced using FDM process.

ACKNOWLEDGEMENT

I wish to express my profound gratitude and indebtedness to **Prof. Ranganath M. Singari** Department of Design, Delhi technology University, Delhi, and **Prof. Harish Kumar**, Associate professor, Department of Mechanical Engineering, National Institute of Technology, Delhi to introducing present topic and for their inspiring guidance constructive criticism and valuable suggestion throughout the project work.

I would like to express my deep and sincere gratitude to **Prof. R C Singh**, Assistant Professor, Department of Mechanical Engineering, Delhi technology University, Delhi for his valuable support during my experimental work. I would like to give a special thanks to **Ms. Meena Pant** for helping me in my project work.

I would like to extend thanks to my colleague **Mr. Rishabh Teharia** for giving an extra effort and motivation while helping me in my project and other colleagues who have supported me to complete my dissertation work directly or indirectly. I would like to thanks all the staff members of mechanical engineering department for their support and providing adequate lab facilities.

I am also thankful to staff members of department of Production Engineering, Delhi Technological University for their valuable support to complete my project work. I am also grateful to my seniors and classmates.

Lastly my sincere thanks to all my friends who has patiently extended all sorts of help for accomplishing this undertaking.

Gulshan kaur

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LIST OF SYMBOLS, ABBREVIATION, NOMENCLATURE

W	Specific wear rate
Δm	Mass loss of material
L	Sliding distance
F	Applied load
N	Speed of revolution
ρ	Density of ABS Material
n	Sample size
Yi	Wear rate of material
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
PoD	Pin-on-Disc
DOE	Design of Experiments
RSM	Response Surface Modal
BBD	Box Benkhen Design

CHAPTER 1

ADDITIVE MANUFACTURING: A BRIEF INTRODUCTION

1.1 Fused Filament Fabrication (FFF):

FDM facilitates like ease of process, low tooling and machinery cost, and long-term durability of build parts, because of these facilities it is regarded as the best rapid prototyping technique among other methods[1, 2]. Instead of using powder, array of lasers and resins, it utilizes filament of thermoplastic which is fed into the extruder, where it is heated at temperature known as extruder temperature, high enough to melt the filament. Then it is extruded from the nozzle tip [3] formation of layer on deposited layer to fabricate the part in layer-by-layer. The thickness of layer is always less than the diameter of nozzle tip used [4]. In this process first laid down the contour for outer boundary of layer then followed by internal structure using raster is formed [5] as required structure usually hexagonal is used in FDM[6]. By this methodology of layer formation results that the internal structure, dimensional accuracy, tribological properties and mechanical properties are mainly depend on the process parameters [5].

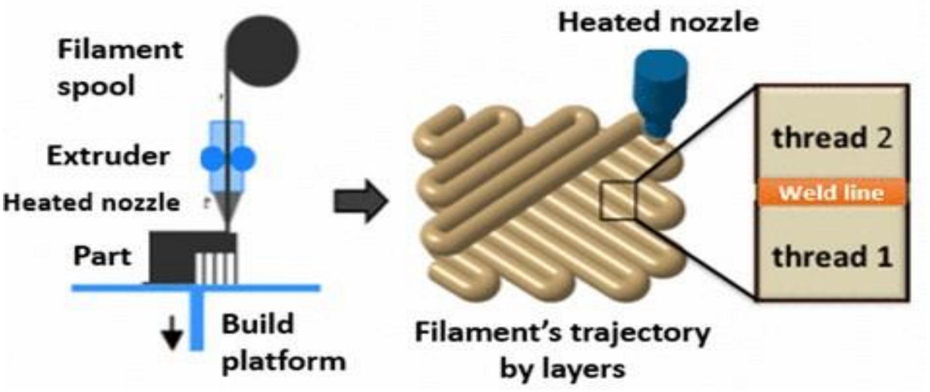


Figure 1 Working principle of FDM and classical trajectory deposition [7].

1.2 Process parameters:

There are many parameters of FDM process which affect the properties, build quality of parts and efficiency of process also. The important parameters are printing speed, thickness of layer, orientation, raster angle, fill pattern, fill density, Extrusion temperature and many other [8]. These processes are classified into three categories[3].

Table 1. Classification of Process parameter of FDM [3].

S.No.	**Classification**	**Process parameters**
1.	Process specific parameter	Layer thickness, Bed temperature, Nozzle temperature, density of structure, Printing speed, Infill speed, Retraction distance, Retraction speed, Initial layer height, Initial layer line width, Raster angle, Raster width, Air gap, Number of contours, Thickness of contours, Bottom/Top thickness, Outer structure printing speed, Inner structure printing speed.
2.	Machine specific parameters	Diameter of nozzle, Speed of material feeding filament, Thickness of Filament, Thickness of layer, Type of adhesion, Diameter of filament:
3.	Geometries specific parameters	Orientation of build part:

The parameters mentioned above are some of controllable but depend on the AM system which is adopted for manufacturing these parameters are Nozzle diameter, Bed temperature. Some of the important parameters are described below:

Printing speed: The speed of printing is presented as the speed of travel of nozzle during deposition of filament over the part of build structure. Printing speed is exactly proportional to the time taken in printing. It has dominating impact on the quality of build part [9], but on the other hand, the printing speed impact is insignificant in case of thinner layer printing[10].

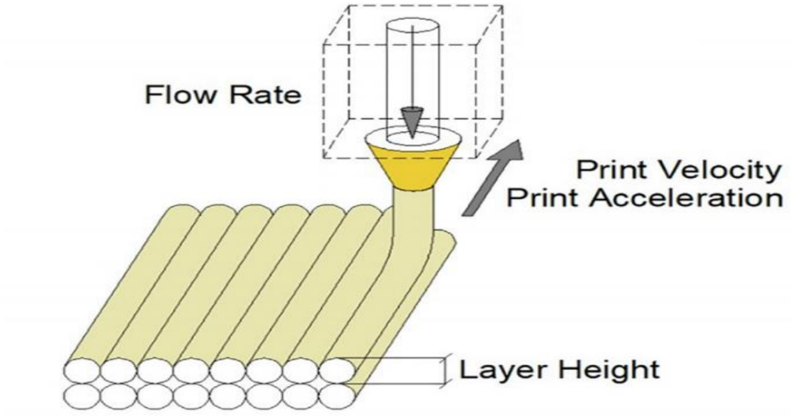


Figure 2. Representation of height of layer.[11]

Layer height: Height of layer is represented as the height of each printed layer. The height of layer is always less than the diameter of nozzle of the extruder that means the maximum layer height can be achieved is equal to the nozzle tip diameter. This parameter based on the diameter of extruder or type of nozzle used[4].

Fill density: The material volume printed on the build component is referred to as infill density. The percentage of infill material has a direct relationship with density. The tribological properties of a printed item are directly affected by infill density. Less density has a huge impact on properties, although the denser component provides improved properties but It takes more time, cost, and material to build the component [3].

Raster angle: Raster angle indicates the x-axis material deposition path in the used FDM machine along the build field. The raster angle can be anywhere between 0˚ and 90˚ [12]. Mostly the angle of raster is determined in respect of the x-axis. Es-Siad et al.[13] has explained that the 0˚ orientation has highest mechanical strength because of alignment of particles parallel to the stress axis whereas in case of 45˚ and 90˚ orientation has the lowest interlayer bonding, which can lead to layer delamination.

Build orientation: It explains the placement of part adjusted over the platform of build with respect to the machine tool’s three main axes i.e., X, Y, Z [14]. Ashtankar et al. [15] explained how the build orientation affect mechanical and compressive properties of ABS parts developed by FDM.

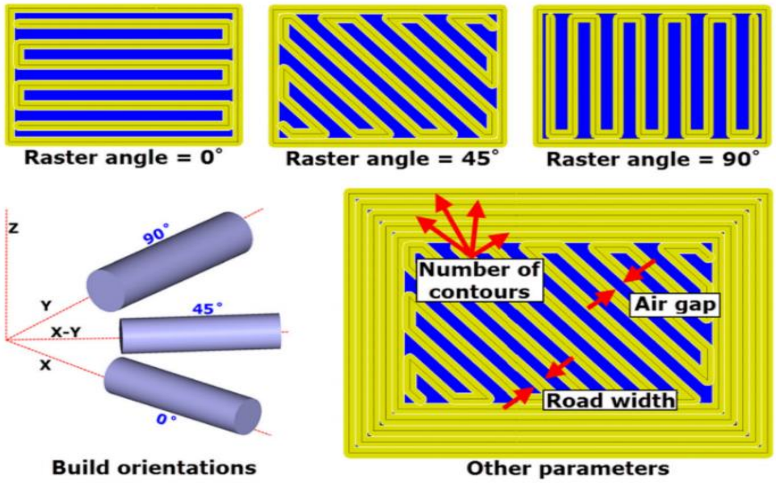


Figure 3. Graphical representation of FDM process parameter:[16]

Extrusion temperature: The temperature which is held within the heating nozzle of the FDM until the material is extruded, is known as extrusion temperature [8]. Viscosity of material is greatly affected by this parameter [17]. The higher Extrusion temperature also impact the characteristics of the part. The ideal temperature must be preserved because it influences the fluidity of the filament material, which results the quality of product being manufactured could be affected. As the material is extruded through the nozzle, the temperature drops from its initial temperature to the chamber temperature which results internal stress. This occurs as a change in speed of deposition, this internal stress can trigger deformation at inter and intra layer, which can lead to failure of fabricated component [18].

In fill structure: The internal structure of component refers as the infill structure of component being printed using FDM. The structure may be Hexagonal, Rectangular, Honeycomb, Linear, and Diamond etc. [14] Hexagonal structure is most commonly used in FDM process. [6] B. Liseli et al.[19] explains the correlation between the infill structure and properties of build part.

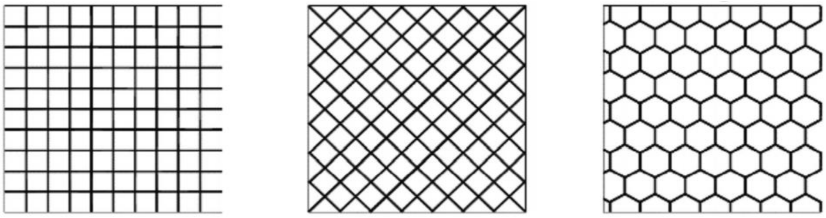

a. Linear structure
b. Diamond structure
C. Honeycomb structure

Figure 4. Types of infill structure as explained by Alafaghani et al. [20]

CHAPTER 2

LITERATURE REVIEW

Fused deposition modelling (FDM) is an economical and user-friendly additive manufacturing process used by researchers and hobbyist for physical prototyping. Fused deposition modelling is a process for producing three dimensional parts by adding material filament directly from a digital CAD file. There are many researchers who did experiments and use some techniques for optimize their results to observe how the process parameters are affecting Tribological properties of ABS printed parts. Some of these researches which are reviewed are as follows:

Table 2. Notation for Process parameters used in fabrication and testing.

Process Parameter used for fabrication	**Symbol**
Layer thickness (mm)	A
Fill density (%)	B
Raster angle (˚)	C
Infill pattern	D
Bed temperature (˚C)	E
Raster width (mm)	F
Air gap (mm)	G
Nozzle temperature (˚C)	H
Build Orientation (˚)	I
Number of contours	J
Testing Parameters	
Normal load (N)	N
Sliding Speed (m/s) or rpm	S
Run time (Sec)	T
Wear track Diameter (mm)	d

Table 3: Review of various research focused on tribological behavior of ABS

`	**Material/ Fabrication method/ Testing**	**Process parameter and level (See Table 1)**	**Optimization Technique**	**Observation**	**References**
1.	ABS P400	A= 0.127mm,	Quantum	-Wearing of FDM	[4]

		0.178mm, 0.254mm	behaved Particle Swarm Optimization (QPSO), ANOVA, and Anderson Darling (AD)	printed ABS part is complicated phenomenon. -Reduction of distortion in part build stage is necessary for improve tribological properties.	
		C= 0°, 30°, 60°			
	FDM – Vantage SE Machine	F=0.4064mm, 0.4564mm, 0.5064mm			
		G= 0mm, 0.004mm, 0.008mm			
	DUCOM TR-20LE-M5	I=0°, 15°, 30°			
		N=25N, S=1m/s, d=120mm			
2.	ABS P400	A= 0.127mm, 0.178mm, 0.254mm	N/A	-Reduction in distortion effect is required to improve the wear characteristics. -Distortion effect dominates the interfacial adhesive bonding.	[5]
		C= 0°, 30°, 60°			
	FDM – Vantage SE Machine	F=0.4064mm, 0.4564mm, 0.5064mm			
		G= 0mm, 0.004mm, 0.008mm			
	DUCOM TR-20LE-M5	I=0°, 15°, 30°			
		N=25N, S=1m/s, d=120mm			
3.	PC-ABS Thermoplastic	A=0.127mm, 0.254mm, 0.3302mm	Nelder-Mead simplex method, Robust Setpoint, risk analysis, and SEM	-The minimal wear rate was obtained at optimal input parameters such as layer thickness of 0.127mm, air gap is 0.275mm, raster angle of 81°, build	[16]
		I= 0°, 45°, 90°			
	Fortus 400 (Stratasys)	F=0.4572mm, 0.5177mm, 0.5782mm			
		G=0mm, 0.25mm,			

		0.5mm		orientation of 9°, road width of 0.4693mm and 5 contours	
		I= 0°, 45°, 90°			
	Nanovea T50 Tribometer	J=1, 5, 10			
		N=10N, S=300rpm, d=14mm			
4.	DUCOM TR-20LE-M5	A=0.007”, 0.013”	Full factorial Design of Experiment	-Wear rate initially increases than decreases as thickness of layer increases. -ABS have higher frictional force against an abrasive substance due to formation of the transition layer formation.	[21]
		B=45%, 80%			
	F170 Printer	C=45°, 90°			
		D= Single, Double			
	Tribometer TR-25 DUCOM	N= 25N, S=300rpm,			
		T=600sec			
5.	Esun’s ABS filament	A= 0.06mm, 0.13mm, 0.20mm	RSM-Box Benkhen Design (BBD), and ANOVA	-Surface roughness is mostly impacted by layer height and bed temperature. -As bed temperature rises surface roughness also increases due to thermal distortion.	[22]
		B= 30%, 65%, 100%			
	FDM ULT3 Extended	E= 80°C, 95 °C, 110°C			
6.	ABS	A=0.1mm, 0.15mm, 0.2mm	N/A	-Triangular behavior can be improved by using higher fill density and lower layer thickness. -Grid fill structure	[23]
	FDM-WOLENDER 3	B= 10%, 60%, 80%			
		D= Rectilinear, Triangular, Grid			

	Pin on Disc	N= 10N, S=1m/s		showed minimum COF and Wear.	
		T=1200sec, d=130mm			
7.	ABS M30	C= 0˚, 45˚, 90˚	Face centered central composite design (FCCCD), and ANOVA	-Surface roughness is largely affected by air gap	[24]
		E= 50˚C, 60 ˚C, 70˚C			
	Fortus 250mc (stratsys inc.)	F=0.3556mm, 0.5306mm, 0.7306mm			
		G=0.05mm, 0.1mm, 0.15mm			
	For surface testing- Taylor Hobson Sutronic 25	T= 10 sec, 20sec, 30sec			
		Smoothening cycle= 1, 2, 3			
8.	ABS Plus and Verogray grade	C= 0˚, 90˚	Scanning Electron Microscopy (SEM)	-At lower load condition ABS showed better wear resistance compared to Verogray. -Surface profile of ABS in case of 0˚ is consisted as compared to 90˚ (perpendicular orientation) on other hand it is vice versa for Verogray.	[25]
		N= 1N, 5N, 10N			
	Polyjet printing_Object® 1000	S= 8mm/s			
	Ball on plate Brunker Universal material Test (UMT)	T=3600aec			
9.	ABS	A=0.13mm,	Response	-Tribological	[26]

		0.15mm, 0.17mm	Surface Model (RSM) and ANOVA	behavior can be improve by optimizing layer height. -Hexagonal pattern shows lesser wear rate compared to line and triangular pattern.	
	Flashforge creator pr 03	D= Line, Hexagonal, Triangle			
		H=225˚C, 230˚C, 235˚C			
	Pin on Disc	N=39.24N, L=800m			
		S=600rpm			
10.	PC-ABS	A=0.127mm, 0.2540mm, 0.3302mm	Quadratic model, and Scanning Electron Microscope (SEM)	-Surface quality is improved by reducing layer thickness. - It is also observed that raster angle, layer thickness, build orientation, and number of contours are most affecting the wear performance. -Wear resistance is m by maximized by reducing the layer thickness and build orientation.	[27]
		C= 0˚, 45˚, 90˚			
	Fortus 400	F=0.4572mm, 0.5177mm, 0.5782mm			
		G= 0mm, 0.25mm, 0.50mm			
	Nanovea Tribometer T50	I= 0˚, 45˚, 90˚			
		J=1, 5, 10			
		N=10N, S=300rpm			
11.	ABS reinforced with nano zirconia and PTFE	%wt. zirconia = 0, 1.5, 3	RSM-Box Benkhen approach, ANOVA, Fuzzy model, SEM, and	-Tribological properties are improved by adding Zirconia and PTFE to ABS. -Optimum wear and friction have been	[28]
		%wt. PTFE= 0, 1.25, 2.5			
	Twin screw	N= 10N, 30N, 50N			

	extrusion and compression	S= 0.5m/s, 1.25m/s, 2m/s	Xray diffraction	found at 3% Zirconia and 2.5% PTFE with 10N load and 2m/s sliding velocity.	
	Pin on Disc Tribometer				
12.	3Dx TECH ABS and Carbonx ABS	N= 5N, 10N, 15N, 20N	N/A	-Carbon fiber reinforce ABS have higher load and bearing capacity which results high wear resistance as compared to pure ABS.	[29]
	FDM	S=0.63m/s, 1m/s, 1.5m/s			
	Pin on Disc	T= 180sec, 300sec			
13.	ABS	N= 5N, 10N, 15N	Face centered central composite design (FCCCD)	-Optimum wear condition has been obtained at 5N, 1.5m/s, and 45 ° orientation	[30]
	FDM	S= 0.5m/s, 1m/s, 1.5m/s			
	Pin on Disc	I= 0°, 45°, 90°			
14.	ABS with Varying content of $CaCO_3$	%wt. $CaCO_3$= 5,10,15	Grey relation analysis Taguchi DOE, and ANOVA	-Optimum specific wear rate (0.00070), and COF (0.14360) has been found at 5% of $CaCO_3$. 35N load, and 120rpm speed.	[31]
	Haake single screw extruder (Rheocord-9000)	N=15N, 25N, 35N			

	Multi-Tribotester Block TR 25 (DUCOM)	S=80rpm, 100rpm, 120rpm			
15.	ABS	N=5N, 10N, 15N	RSM-FCCCD, and ANOVA	-It is observed that not only strength and dimensional accuracy are important but wear and COF are also important for optimizing FDM process.	[32]
	FDM	S=0.5m/s, 1m/s, 1.5m/s			
	Pin on Disc	I= 0°, 45°, 90°			
16.	ABS with Varying content of $CaCO_3$	%wt. ZnO= 5,10,15	Taguchi Design of Experiment and SEM	-Optimum wear rate is found at high load and speed with high content of ZnO. -Friction coefficient is also decreasing as content	[33]
	Haake single screw extruder (Rheocord-9000)	N=15N, 25N, 35N			
	Multi-Tribotester Block TR 25 (DUCOM)	S=80rpm, 100rpm, 120rpm			
17.	PC-ABS with content of Graphite	%Wt. Graphite- 2.5%, 5.0%, 7.5%	SEM examination for wear tracks and	-Wear scar width decreases as graphite content increases even after	[34]

	YVROUD HE 25/28 Single screw extruder		worn surface examined on Philips XL 30 Microscope	10000 sliding cycle. -The friction coefficient and wear amount are lowest at 7.5% wt. of graphite content.	
	Reciprocating sliding Tribometer	N= 17.16N, S= 40rpm			

The present chapter was clearly discussed the Relationship between process parameters and tribological behavior of FDM fabricated ABS parts It is seen from the study that these parameters are influenced the properties of build parts. The properties may be tribological, mechanical and surface properties. In most of research it has been clearly seen that the tribological behavior of FDM builds parts can be improved by addition of material to the polymer [28,29,31,33,34] or by setting the values of process parameter at its optimum value [21- 34]. The wear can also be reduced by reduction in distortion during the part building stage because it weakens the interfacial adhesive bonds and increases wear of build parts [4,5].

Most of researchers analyzed tribological behavior using various methodology including Full factorial DOE [21], Response Surface Modeling (RSM)- Box Benkhen Design [22], Face Centered Central Composite Design (FCCCD) [24], and Taguchi DOE [33]. To validate the data ANOVA [22, 26] and fuzzy logic [28] also used in the study. Surface morphology and worn surfaces are also examined by using Scanning Electron Microscopy (SEM) and Xray diffraction techniques (XRD) [25,27,28,33,34]. The greater part of the optimization techniques is based on statistical, instead of that research should be oriented to utilizing image processing, machine learning and Deep learning to optimize process parameters of FDM [35].

CHAPTER 3

TEST SPECIMEN FABRICATION

3.1 FUSEBOT 250$^+$

The specimen is fabricated by FUSE**BOT** 250$^+$ 3D printer which is based on the fused deposition modelling technique. This machine is a portable device used anywhere when there is demand for printing. This is a FDM based printer. The cube pro printer can be used for print different material parts. All the materials have their own specific properties and application.

3.1.1 Features of FUSEBOT 250$^+$

1. **Single Head Direct Drive Extruder:** Direct drive high performance all metal extruder. Which prevent filament clogging.
2. **Close and Rigid body:** FUSE**BOT** Series 3D printers has completely enclosed body and is made up of sheet metal body. Enclosed body helps chamber temperature stabilized and printing won’t get affected by surrounding temperature.
3. **Bed Leveling:** 4 Point easy bed leveling using knobs.
4. **Multi Material Compatibility:** A multi material printer, works with a wide range of modal materials so now can HIPS, PET-G, TPU and of course ABS & PLA.
5. **Unmatched Precision**: FUSE**BOT** series 3D printers are installed with HIWIN precision series liner guides provide 16-Microns positional accuracy along the length.
6. **Filament Detector Sensor:** Prevents failure of parts with the run-out of material.

3.1.2 Technical Specifications

Table 4: Technical specifications of FUSEBOT250$^+$

Technical Specifications	
Build Size	250mm x 250mm x 250mm
Nozzle Diameter	0.4mm
Extruder	Single

Noise Level	<60 dB
Printing Speed	200mm/s
Max Extruder Temperature	275˚C
Accuracy	80-150 Micron
Build Material	PLA, ABS, HIPS, PET-G, Carbon Fiber, Flexible Filament, Woodfill, Metalfill, Polycarbonate, etc.

Figure 5**:** Diagram of FUSEBOT250^{+}

3.1.3 Material of specimens:

ABS (Acrylonitrile Butadiene Styrene) is an opaque thermoplastic amorphous polymer. ABS is a polymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The composition may vary from 15 to 35% acrylonitrile, 5–30% butadiene and 40–60% styrene. They can be heated to an extrusion temperature of 225˚C-235˚C. It can be cooled and solidified without any significant degradation which makes it practically suitable for 3D printing. ABS is a thermoplastic material which can be heated to their melting temperature, cooled and reheated again without the significant changes [35].

Table 5 Specific property of ABS polymer material [35]

S.No.	Specific property	Value
1.	Material technical name	ABS
2.	Melting temperature	220-270˚C
3.	Tensile strength	46MPa
4.	Density	1.06g/c

3.1.4 Selection of printing parameters:

To obtain a profound set of results RSM Design of Experiment philosophy was used to design statistical set of experiments. In this philosophy values of a parameter or parameters are changed in a systematic manner to observe the response of desired output.

- **Layer thickness:** One of the major reasons behind poor tribological and mechanical behavior of FDM printed parts is, the presence of voids and other is the bonding within layers as well as in between the layers. Voids and imperfectly bonded filaments make the final printed part highly anisotropic in nature so the layer thickness taken in range of 100-200microns.
- **Nozzle temperature:** ABS have melting temperature limit of 220-270˚C, that's why Nozzle temperature 220-240˚C have been selected for printing wear test specimens.
- **Printing Speed:** Creating high resolution print jobs requires a decent amount of time to produce a print. It is obvious that the speed of printing is inversely proportional to the time to produce parts. speed of printing selected in the range of 30-50mm/sec because at high printing speed ABS might be melted because of heating effect between the wear pin and moving plate

- **Orientation:** The orientations are varied in such a way that the raster angles are kept at a constant magnitude. To do so, the object is rotated along any of the one axis fixed on the build plate i.e. x-axis or y-axis.

Generally, in fabricating a print with default settings, a combination of entities such as top surface, bottom surface, outer walls, infill, etc. is used to create a product with acceptable quality. Selecting inputs of a layer, is another interesting area for optimization. For the purpose of fabrication, the below tabulated data shows the values of inputs.

Table 6**:** Input parameters and their levels

S.No.	Process parameters	Level 1	Level 2	Level 3
1	Layer thickness (microns)	100	150	200

2	Nozzle Temperature (˚C)	220	230	240
3	Printing speed (mm/sec)	30	40	50
4	Orientation (˚)	0	45	90

3.2 Design of experiments: RSM

The printing of samples is performed by the instruction given to the 3D printer. Over all 27 specimens are printed which is relying on RSM Box Behnken design. This is used for reducing the number of data inputs instead of fabricating 81 designs set only 27 set are fabricated. The combination of control factors is overcome by using the MINITAB 2018. The table 3.4 shows combination of control factors with their levels.

Table 7: DOE: RSM for abs based 3d printed specimens

StdOrder	RunOrder	PtType	Blocks	Layer Thickness	Nozzle Temperature	Printing speed	orientation
26	1	2	3	150	240	40	90
22	2	2	3	200	230	50	45
24	3	2	3	150	240	40	0
21	4	2	3	100	230	50	45
23	5	2	3	150	220	40	0
25	6	2	3	150	220	40	90
20	7	2	3	200	230	30	45
27	8	0	3	150	230	40	45
19	9	2	3	100	230	30	45
17	10	2	2	150	240	50	45
18	11	0	2	150	230	40	45
11	12	2	2	200	230	40	0
10	13	2	2	100	230	40	0
16	14	2	2	150	220	50	45
15	15	2	2	150	240	30	45
12	16	2	2	100	230	40	90
14	17	2	2	150	220	30	45
13	18	2	2	200	230	40	90
7	19	2	1	150	230	30	90

9	20	0	1	150	230	40	45
6	21	2	1	150	230	50	0
4	22	2	1	200	240	40	45
8	23	2	1	150	230	50	90
5	24	2	1	150	230	30	0
3	25	2	1	100	240	40	45
1	26	2	1	100	220	40	45
2	27	2	1	200	220	40	45

3.3 Fabrication of Wear Testing Specimens:

Wear testing samples were fabricated using FUSE**BOT**250^{+}**.** The dimensions of sample were according to ASTM Standards for wear samples of metals and polymers.

3.4 Dimensions of specimens: ASTM G99 Standards

ASTM G99 test standard specification used for calculating the wear of metals and polymers under the dry sliding condition with the help of Pin-on-Disc machine set-up. The following table 3.5 gives the description of pin over which Pin-on-Disc test is performed. According to this standard diameter of the sample is 6.00 to 8.00 mm and the height of the specimen is 30.0mm. Physical aspects used in the fabrication of wear sample are as follows.

Table 8**:** Physical Aspects of Pin Specimen

Dimensions	**Value**
Diameter	8mm
Height	30mm

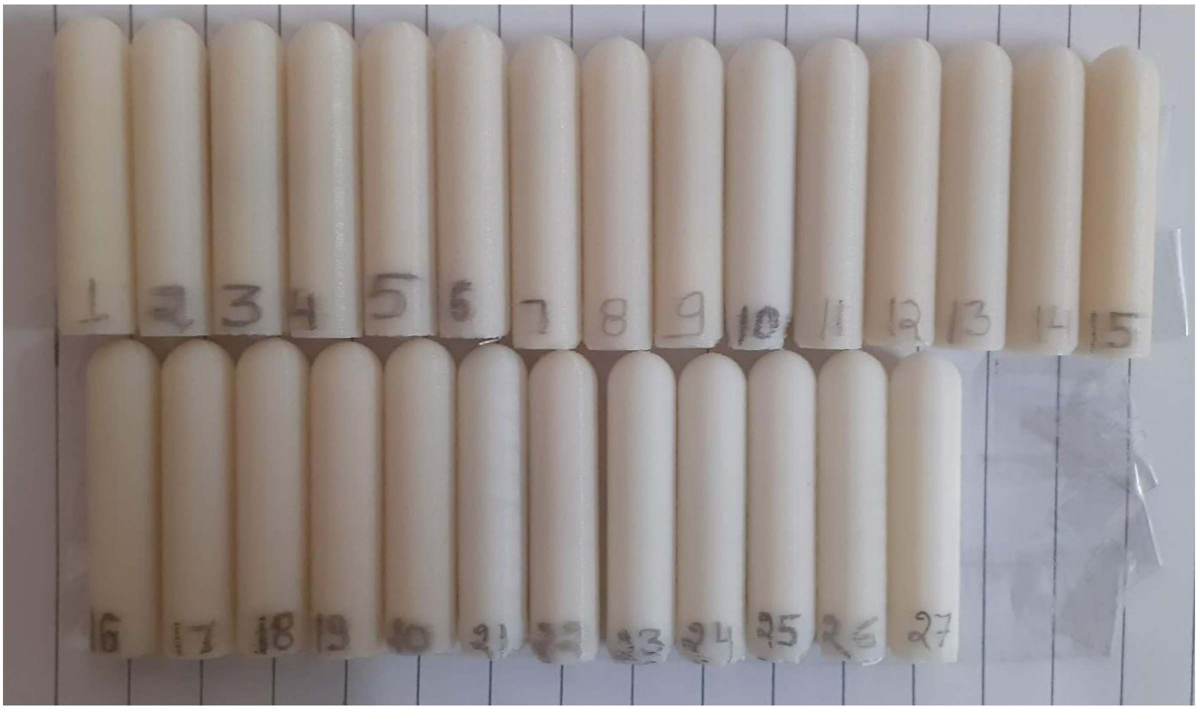


Figure 6 3D Printed Specimens For PoD

CHAPTER 4

TESTING AND ANALYZING RESULTS

4.1 Pin on Disc Experimental setup:

Ducom specialists proposed a special design equipment wear and friction monitor TR-20L E in field of tribology. The Pin on Disc machine set-up used in design and development of tribological property of metals, polymer plastics. It is also used to determine the wear and co-efficient of friction of metals and polymers under sliding contact. The different number of metals and polymer plastics is tested by PoD machine in order to predict the rate of wear in dry sliding conditions.

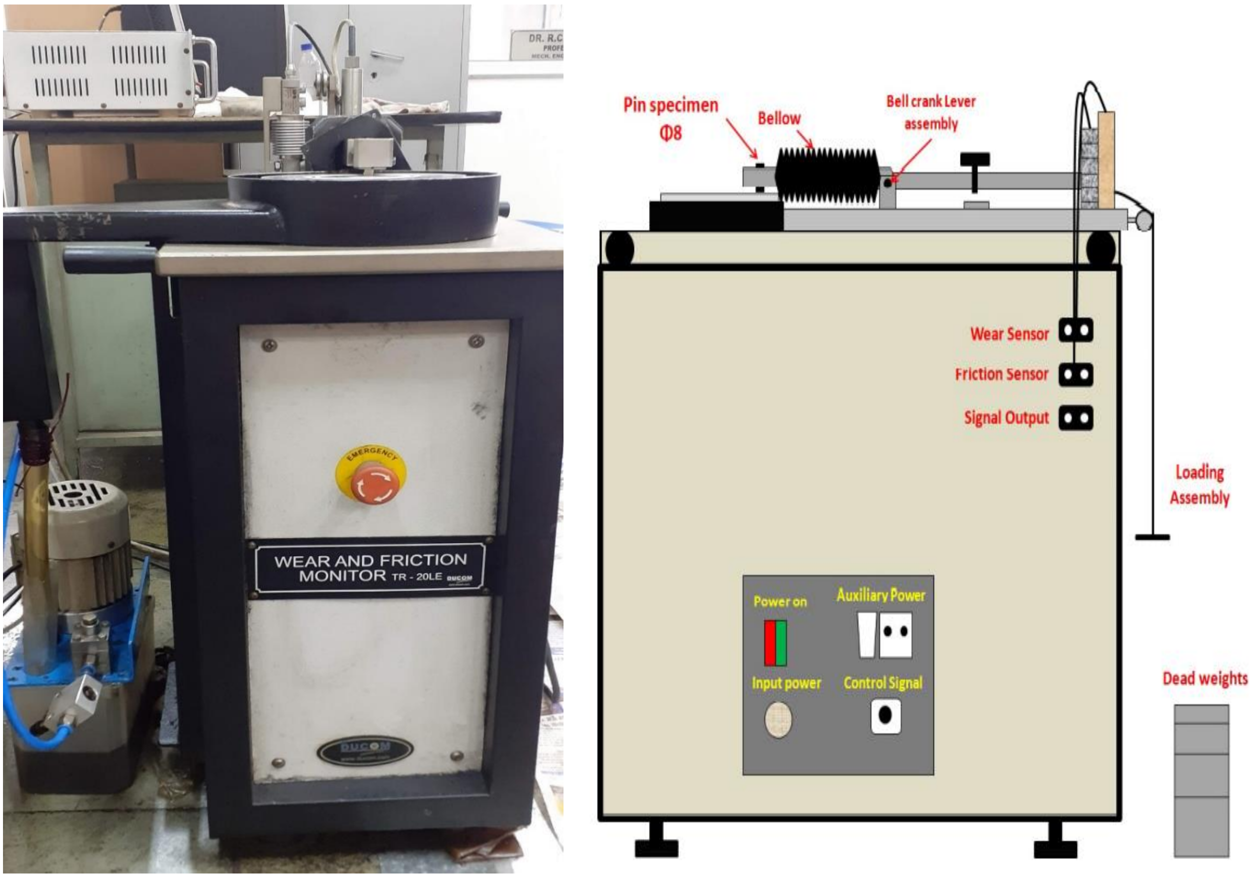


Figure 7 Front view to PoD experimental setup

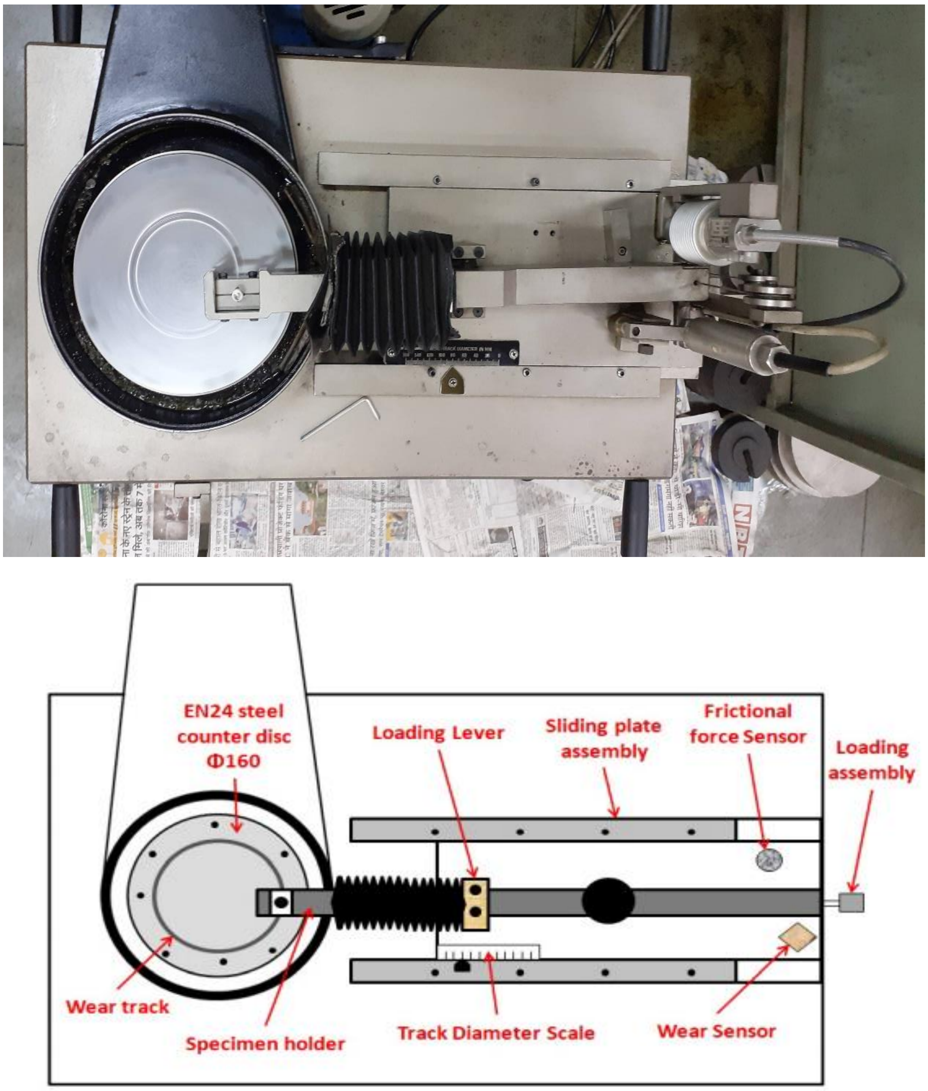


Figure 8 Top view of PoD experimental setup

The tester is operated with the pin positioned perpendicular to the flat circular disc. The test machine causes the disc specimen to revolve about the disc center, the sliding path is circular on the disc surface. The pin sample was fixed against the rotating disc. The disc may be composed of mild steel, aluminium and brass etc. The test is conducted for dry sliding wear there is no use of lubricant. A counter weight is applied on the pin which in turn exerted on the disc. All the information such as load, time speed of revolution and wear track diameters related to test procedure is fed into the controller. The WINDCOM 2008-computer software is used to generate the experimental data for wear rate and the frictional force. The mild steel disc diameter is 165.0 mm and the thickness is 8.0 mm. The surface of disc and pin specimen was clean by sand paper before testing, so there is a good contact between pin sample and the mild steel disc surface

Table 9 Experimental setup details

Material of pin	ABS
Pin Specifications	Diameter-8mm, Height-30mm
Material for disc	EN8 steel, Hardened to 64Hrc
Diemnsion of Disc	Diameter-160mm, Thickness-6mm
Applied load	3.5kg
Wear track diameter	80mm
Duration of test	10Min
Rotational speed	250rpm

The present experiment is conducted to improve the parameters of 3D printer machine. The machine setting details are shown in above table 4. During the test, machine setting parameters kept constant for each experimental run. The test is performed by using the following

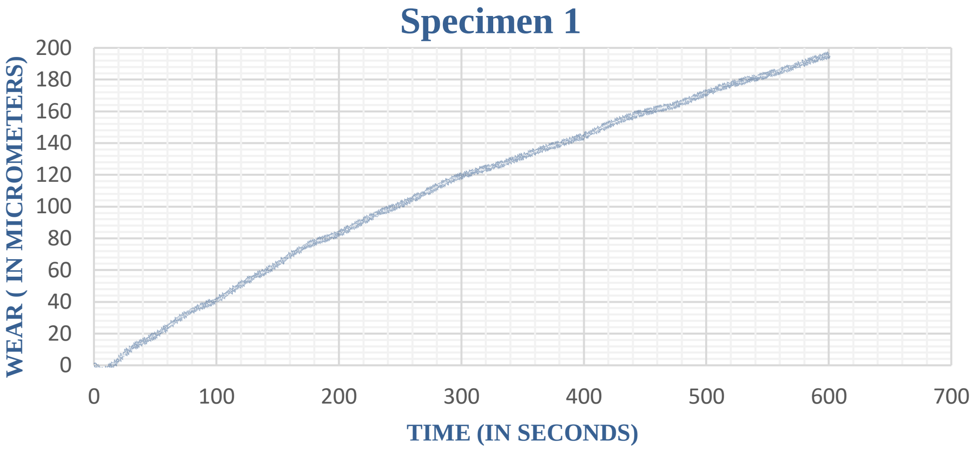
- Applied force for wear
- Diameter of wear track
- Duration of test
- Rotational speed of disc

it is important to weigh every sample Before and after testing with accuracy level up to 0.0001 gram. The PoD test method was conducted is used to predict the rate of wear, fictional force, and coefficient of friction of pin sample. For the current study, the steel disc rotated with constant speed. During the test, machine setting parameters kept constant for each experimental run. The test is performed by using the following parameters. Applied force for wear Diameter of wear track Rotational speed of disc important to weigh every sample with digital weighing 0.0001 gram. PoD test method was conducted for tribological properties. In this experiment is used to predict the rate of wear, fictional force, and coefficient of friction of pin sample. For the current study, the steel disc rotated with constant speed.

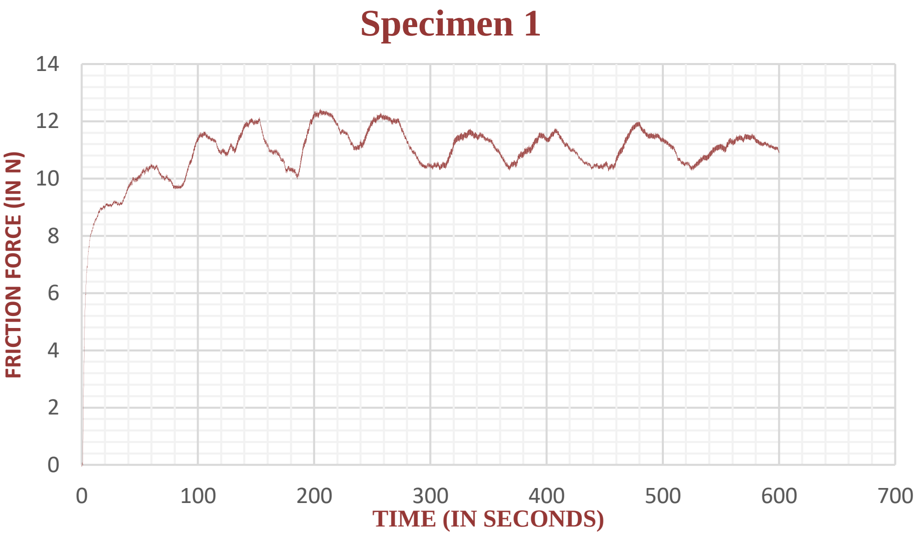
4.2 Experimental Results:

Specimen 1

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	240	40	90	35	600	1.04	80



Graph 1 Figure 4 Variation of wear rate with duration of test for specimen 1

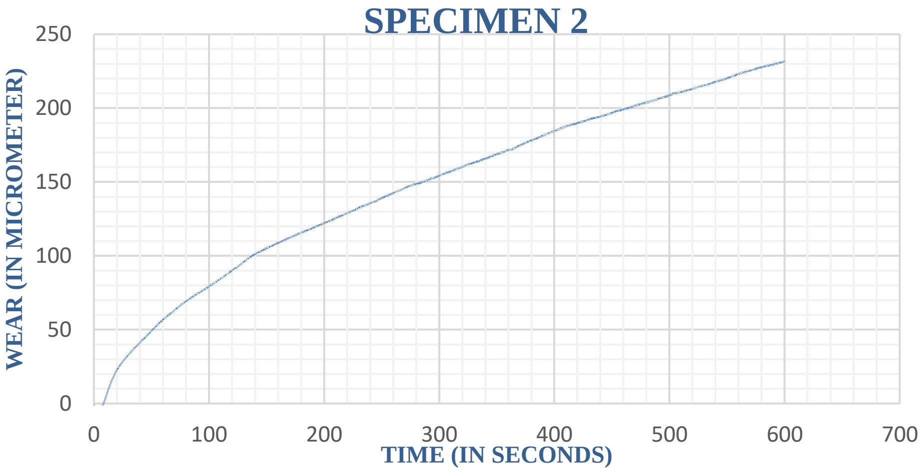


Graph 2 Variation of friction force with duration of test for specimen 1

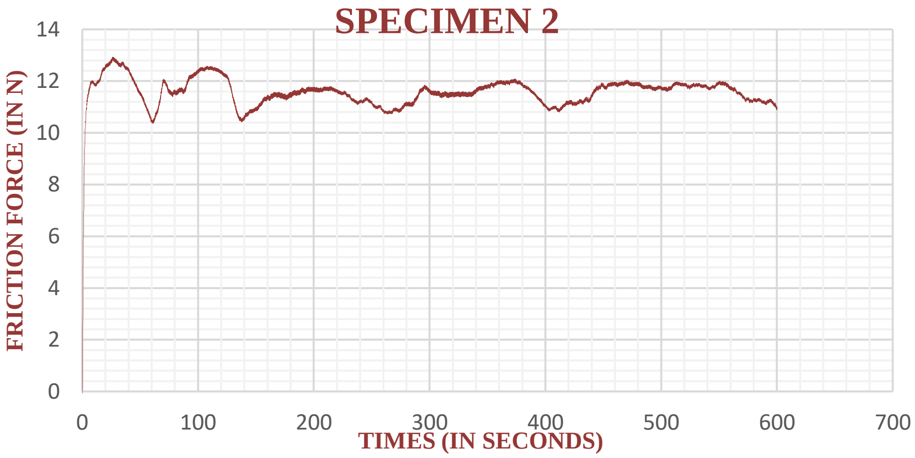
- Maximum Wear- 195.662 µm
- Maximum friction force-12.43N

SPECIMEN 2.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
200	230	50	45	35	600	1.04	80



Graph 3 Variation of wear rate with duration of test for specimen 2

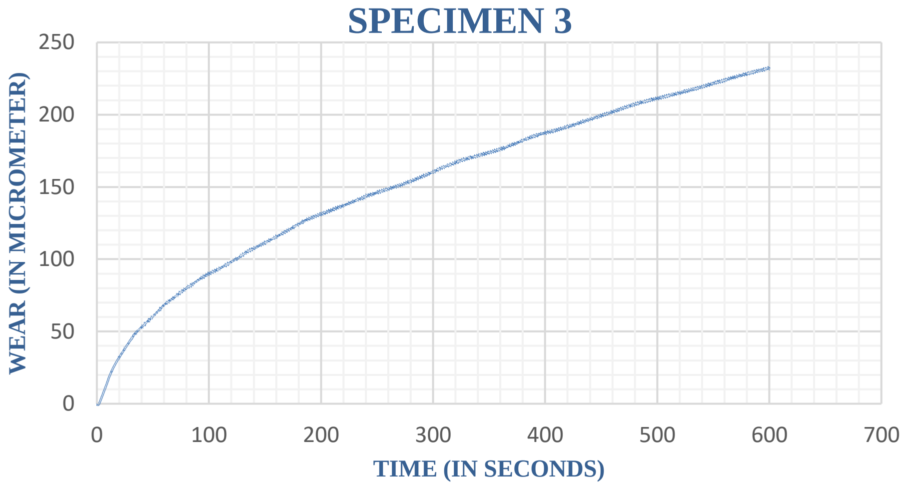


Graph 4 Variation of friction force with duration of test for specimen 2.

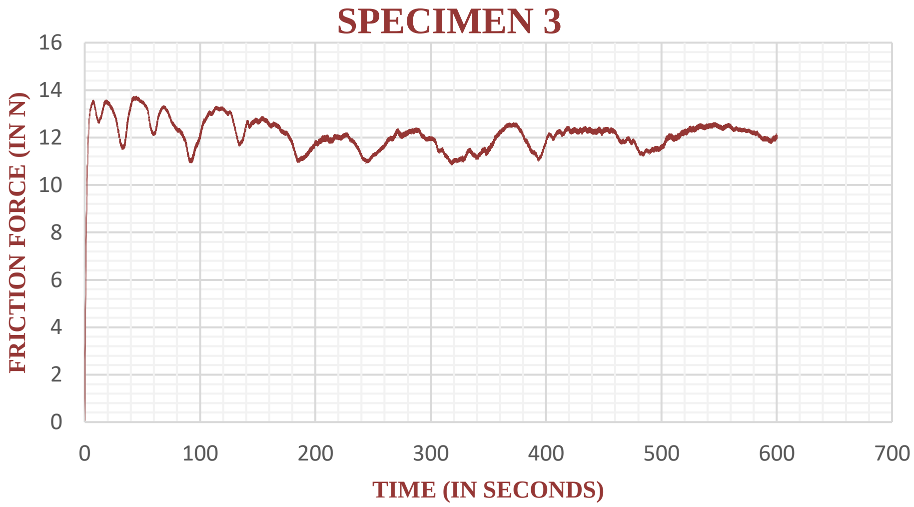
- wear- 231.707µm
- Maximum friction force-12.93N

SPECIMEN 3.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	240	40	0	35	600	1.04	80



Graph 5 Variation of wear rate with duration of test for specimen 3

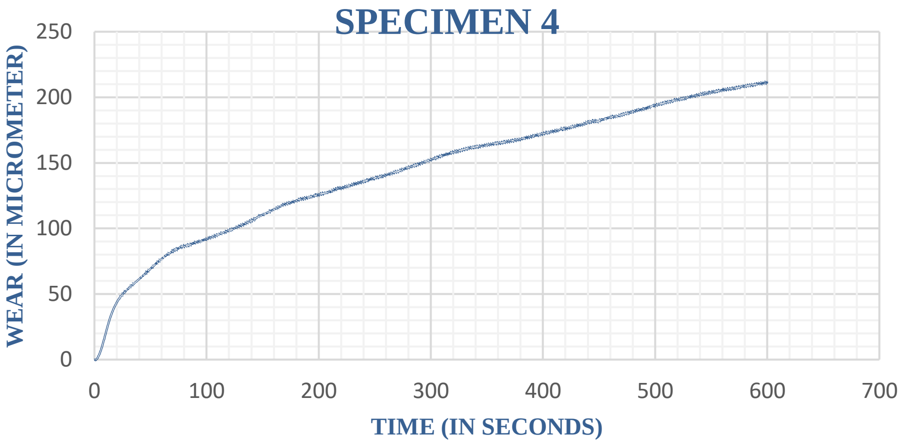


Graph 6 Variation of friction force with duration of test for specimen 3.

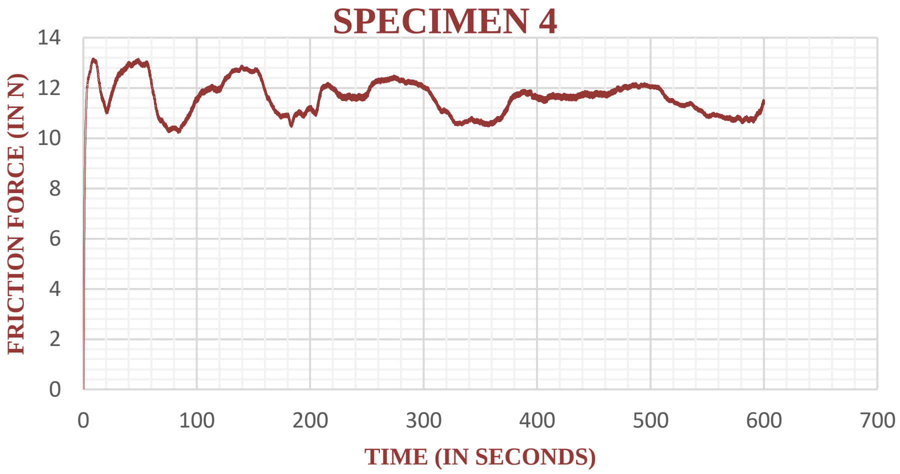
- Maximum Wear-232.314µm
- Maximum friction force-13.736N

SPECIMEN 4.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
100	230	50	45	35	600	1.04	80



Graph 7 Variation of wear rate with duration of test for specimen 3

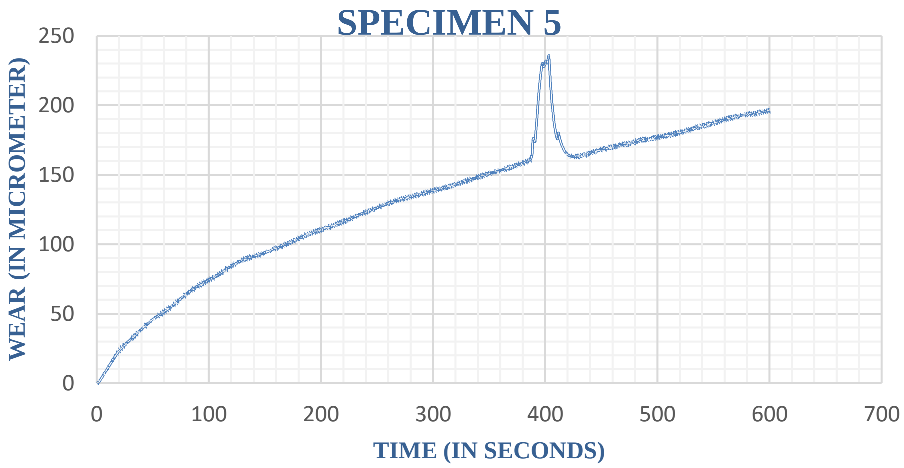


Graph 8 Variation of friction force with duration of test for specimen 4

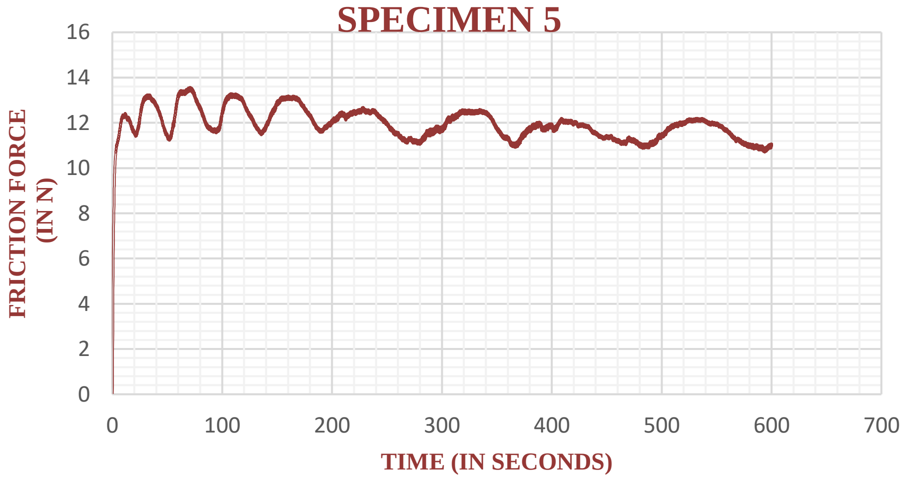
- Maximum Wear-211.421 µm
- Maximum friction force-13.171N

SPECIMEN 5.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	220	40	0	35	600	1.04	80



Graph 9 Variation of wear rate with duration of test for specimen 5

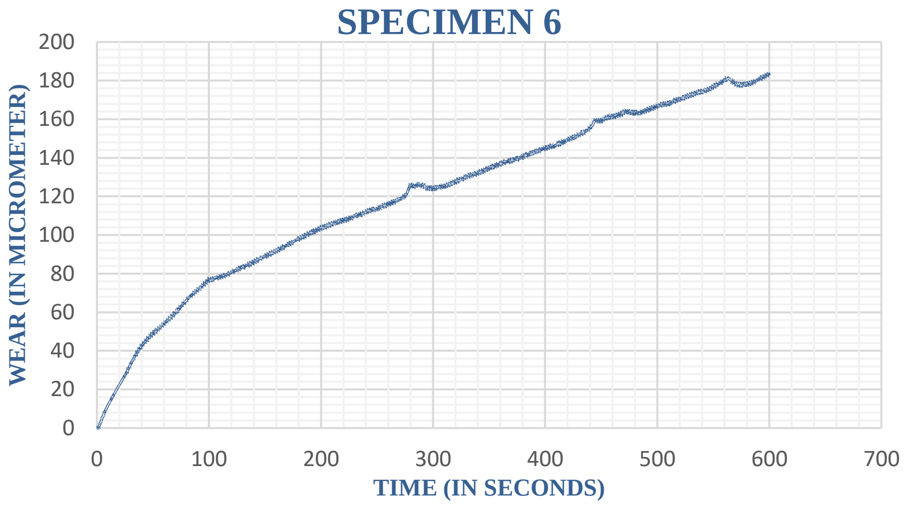


Graph 10 Variation of friction force with duration of test for specimen 5

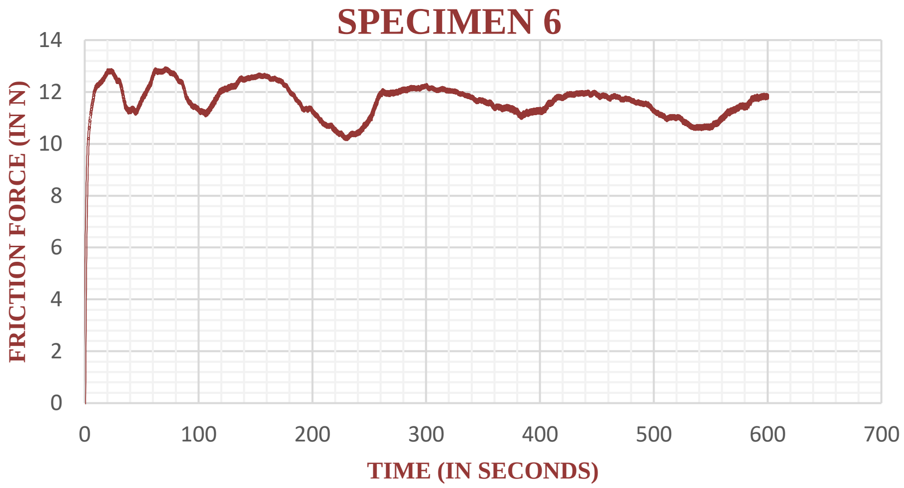
- Maximum Wear- 235.745µm
- Maximum friction force-13.569N

SPECIMEN 6.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	220	40	90	35	600	1.04	80



Graph 11 Variation of wear rate with duration of test for specimen 6

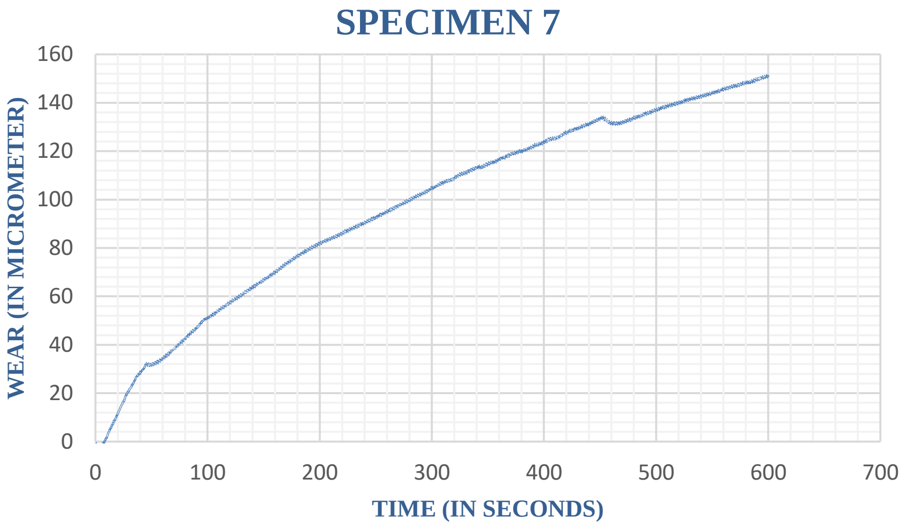


Graph 12 Variation of friction force with duration of test for specimen 6.

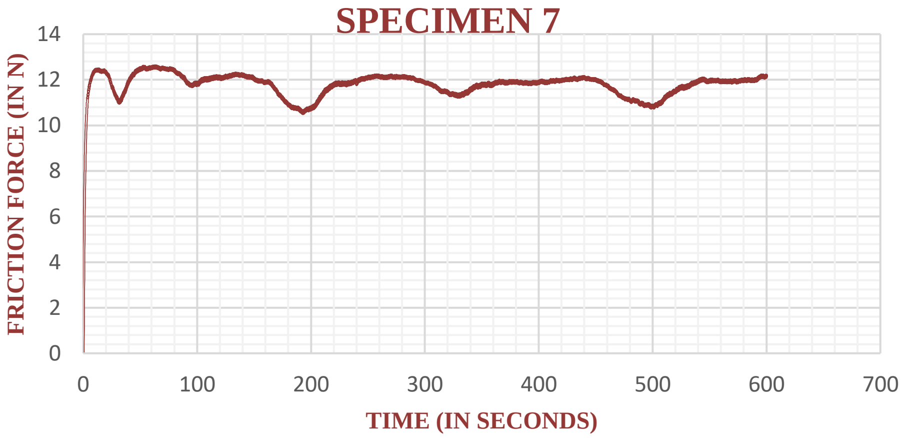
- Maximum Wear-183.488 µm
- Maximum friction force-12.937N

SPECIMEN 7.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
200	230	30	45	35	600	1.04	80



Graph 13 Variation of wear rate with duration of test for specimen 7

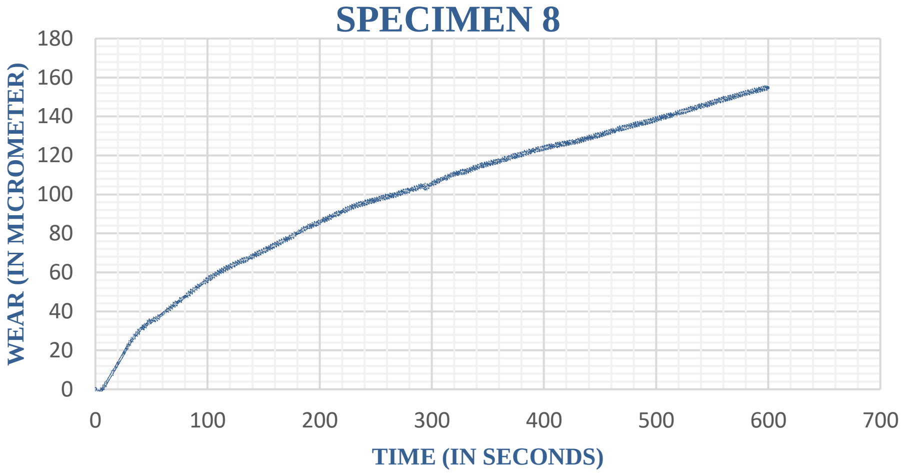


Graph 14 Variation of friction force with duration of test for specimen 7.

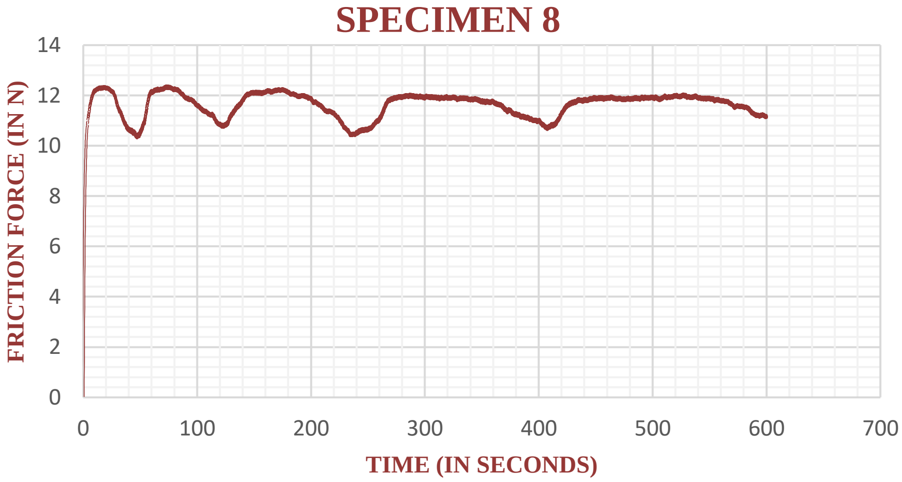
- Maximum Wear-151.046 μm
- Maximum friction force-12.616N

SPECIMEN 8.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	40	45	35	600	1.04	80



Graph 15 Variation of wear rate with duration of test for specimen 8

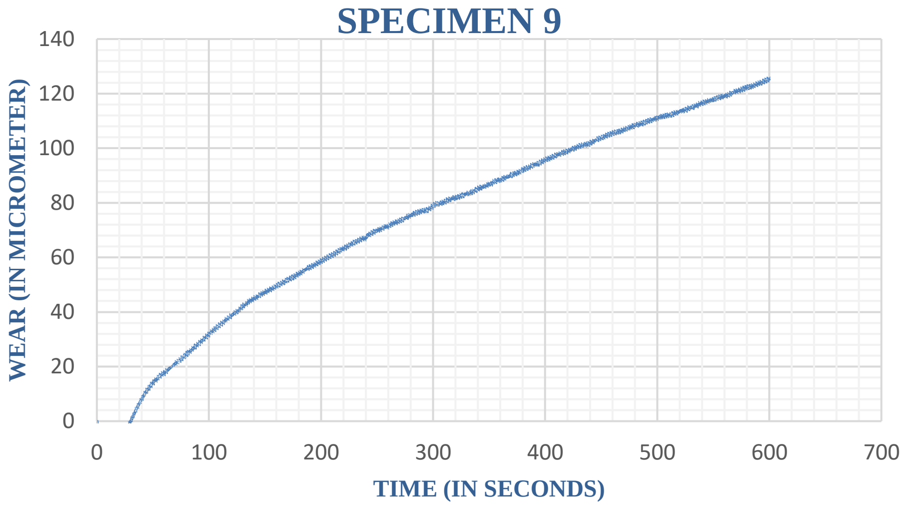


Graph 16 Variation of friction force with duration of test for specimen 8

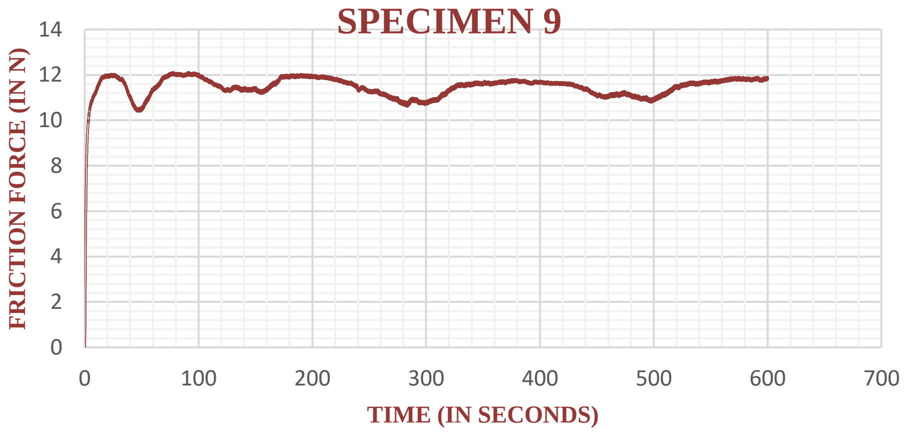
- Maximum Wear-155.076 µm
- Maximum friction force-12.386N

SPECIMEN 9.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
100	230	30	45	35	600	1.04	80



Graph 17 Variation of wear rate with duration of test for specimen 9

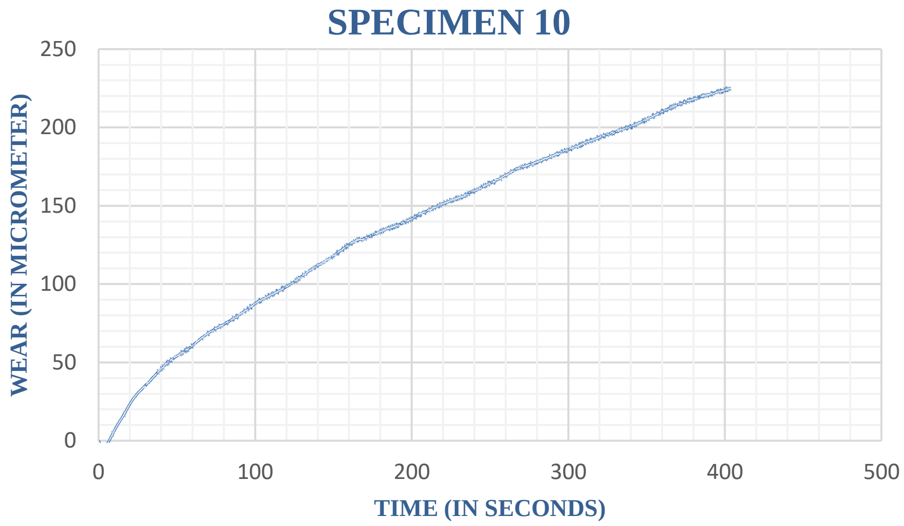


Graph 18 Variation of friction force with duration of test for specimen 9.

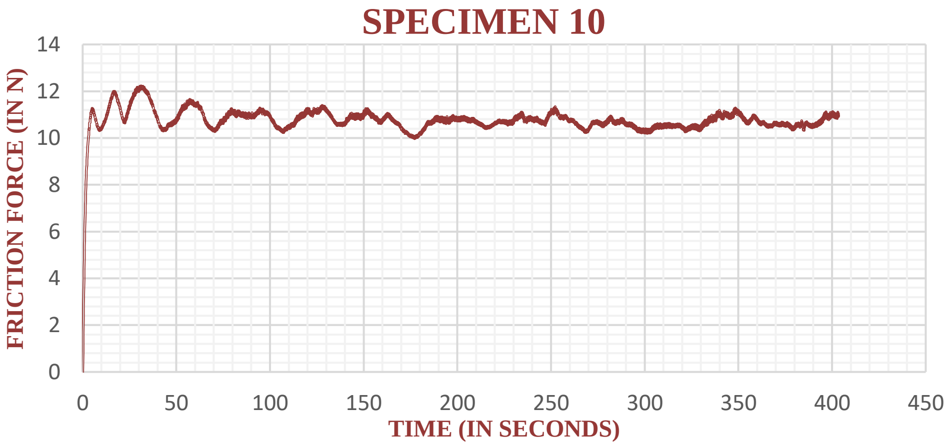
- Maximum Wear- 125.367 µm
- Maximum friction force- 12.109N

SPECIMEN 10.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	240	50	45	35	600	1.04	80



Graph 19 Variation of wear rate with duration of test for specimen 10

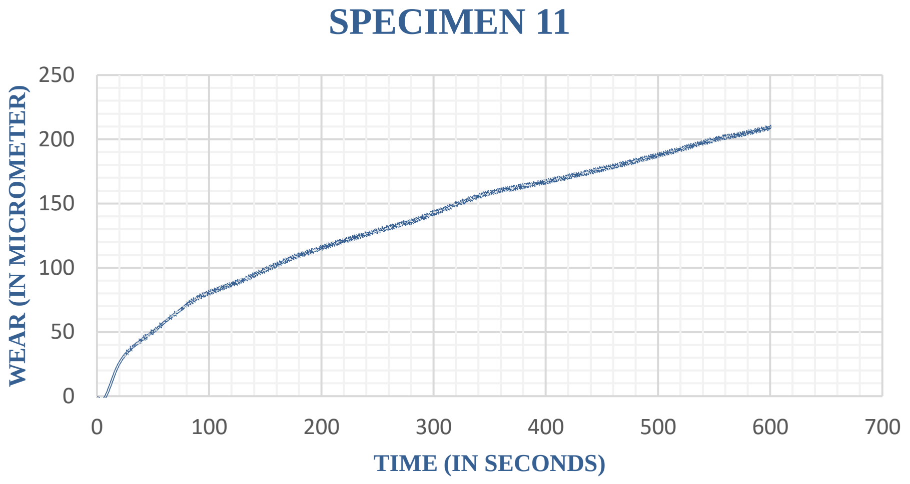


Graph 20 Variation of friction force with duration of test for specimen 10.

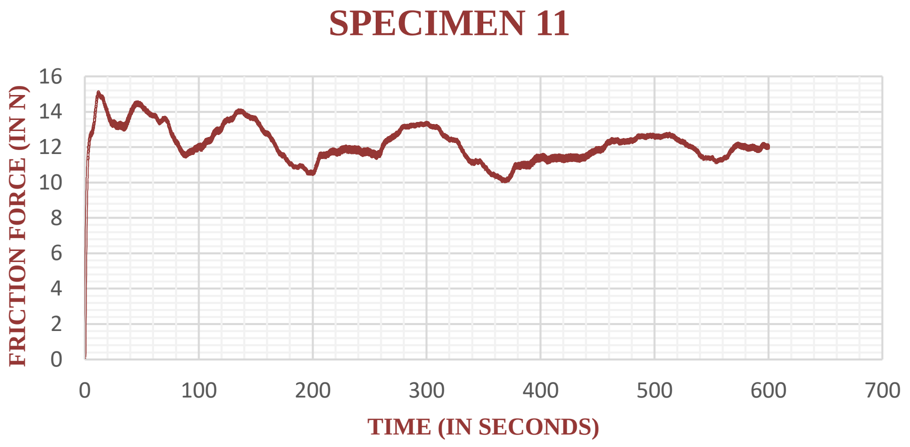
- Maximum Wear-225.111 µm
- Maximum friction force- 12.23N

SPECIMEN 11.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	40	45	35	600	1.04	80



Graph 21 Variation of wear rate with duration of test for specimen 11.

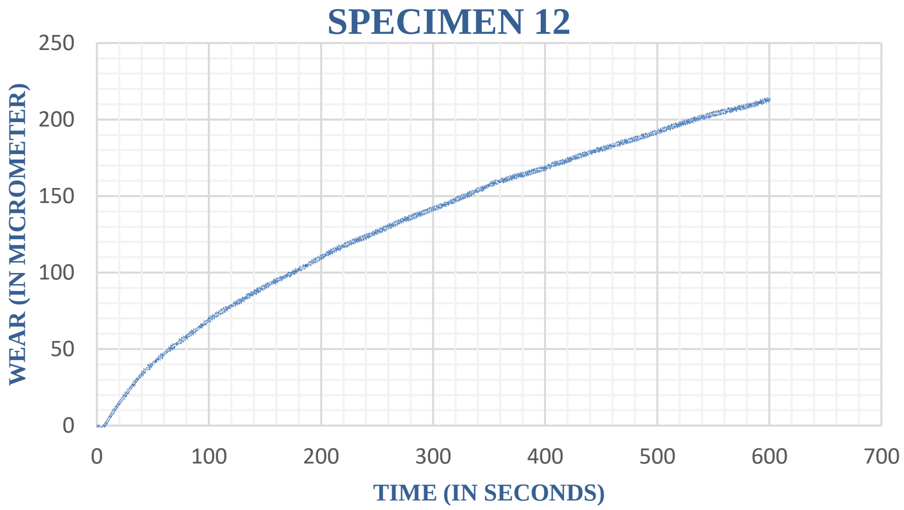


Graph 22 Variation of friction force with duration of test for specimen 11.

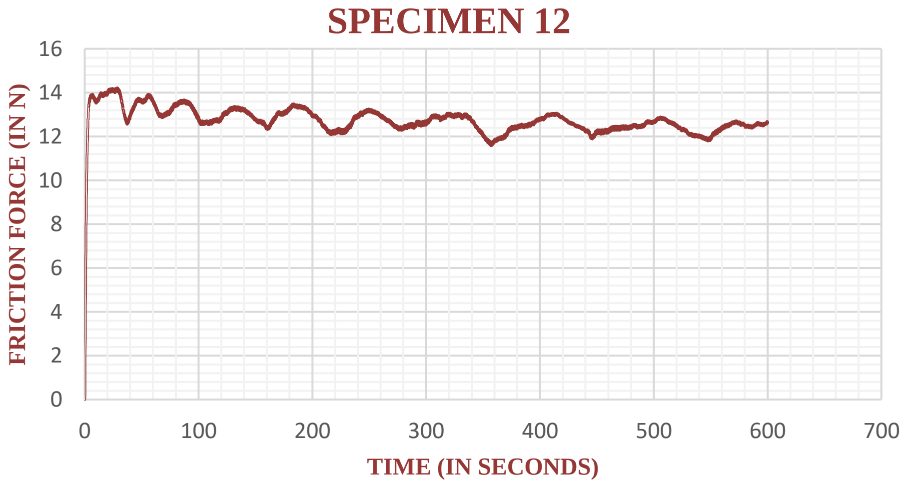
- Maximum Wear- 209.279 µm
- Maximum friction force- 15.134N

SPECIMEN 12.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
200	230	40	0	35	600	1.04	80



Graph 23 Variation of wear rate with duration of test for specimen 12.

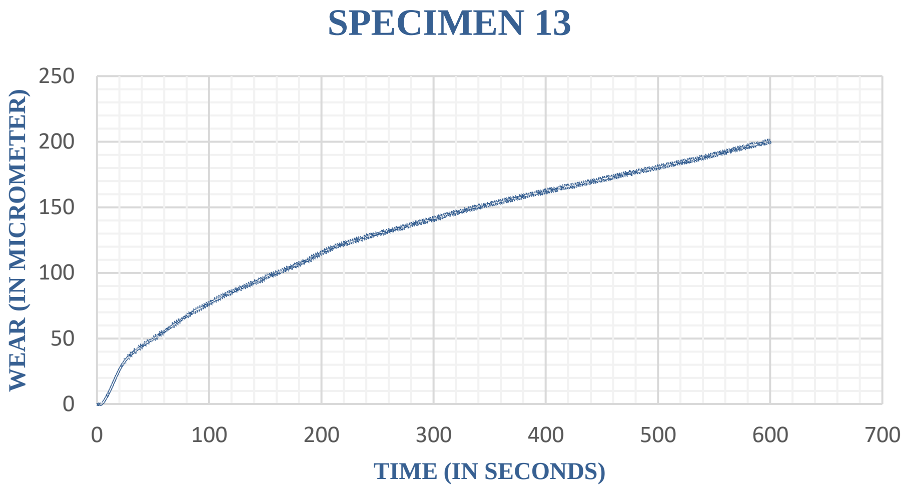


Graph 24 Variation of friction force with duration of test for specimen 12.

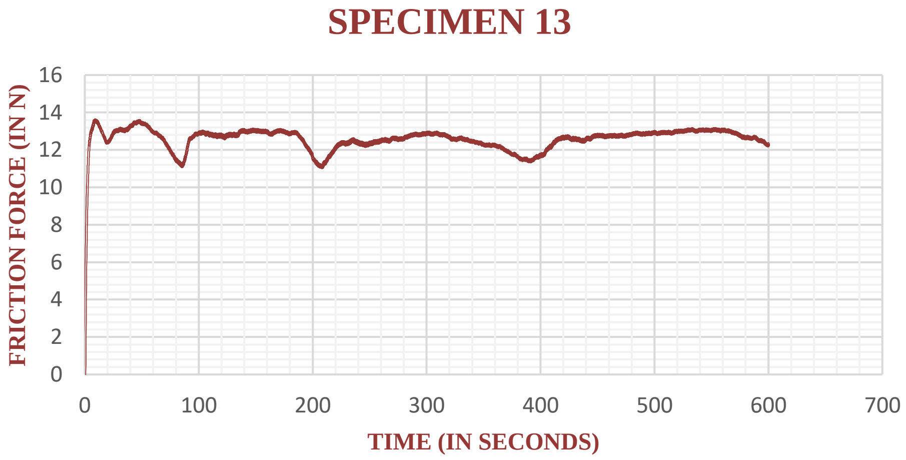
- Maximum Wear- 213.137 µm
- Maximum friction force- 14.211N

SPECIMEN 13.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
100	230	40	0	35	600	1.04	80



Graph 25 Variation of wear rate with duration of test for specimen 13.

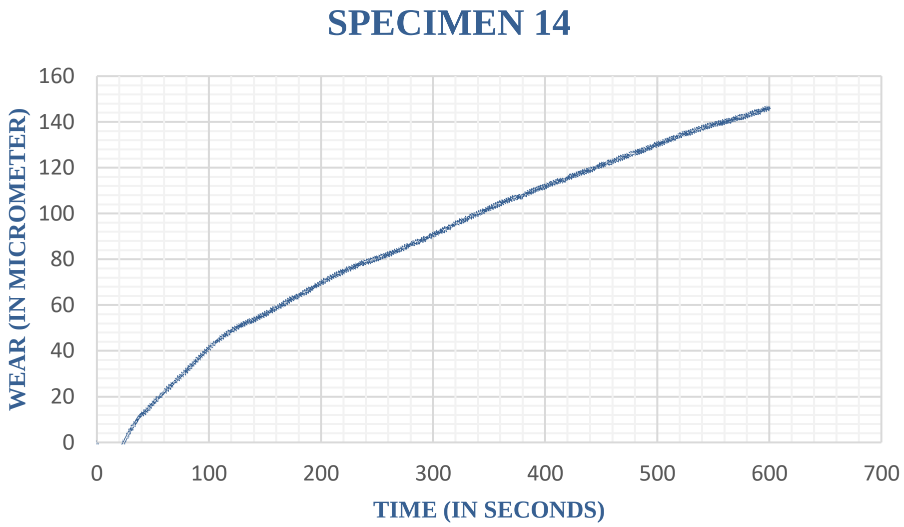


Graph 26 Variation of friction force with duration of test for specimen 13.

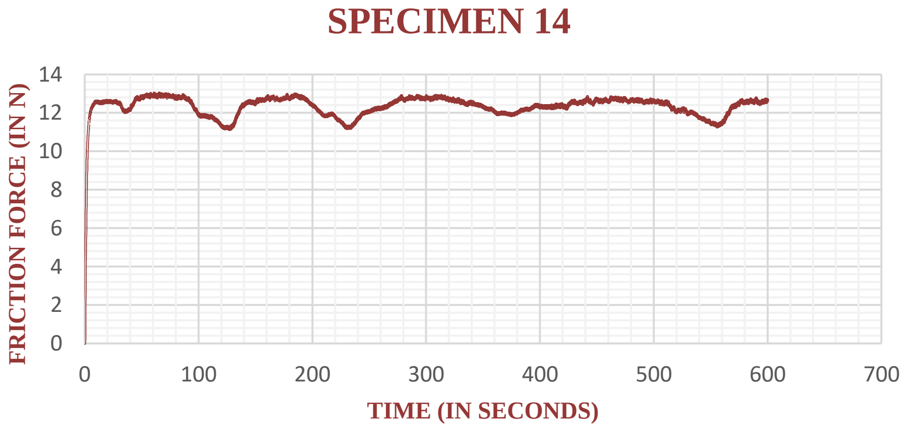
- Maximum Wear- 200.537 µm
- Maximum friction force- 13.608N

SPECIMEN 14.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	220	50	45	35	600	1.04	80



Graph 27 Variation of wear rate with duration of test for specimen 14.

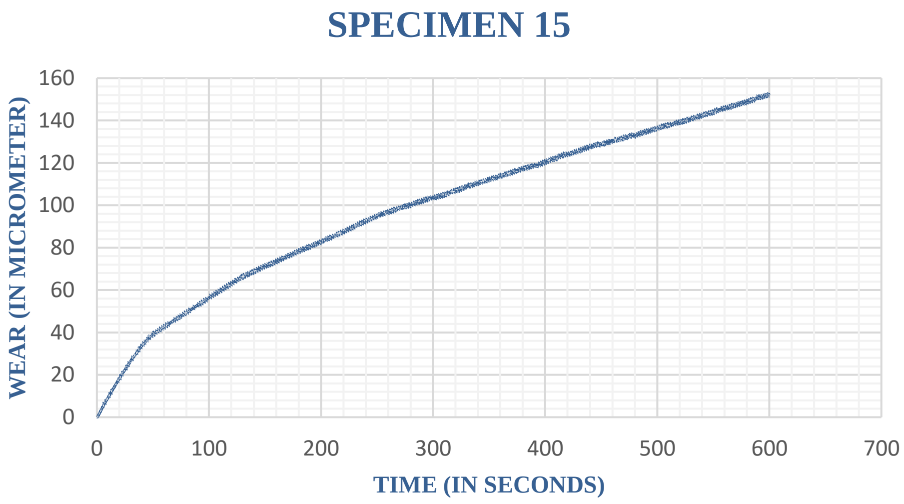


Graph 28 Variation of friction force with duration of test for specimen 14.

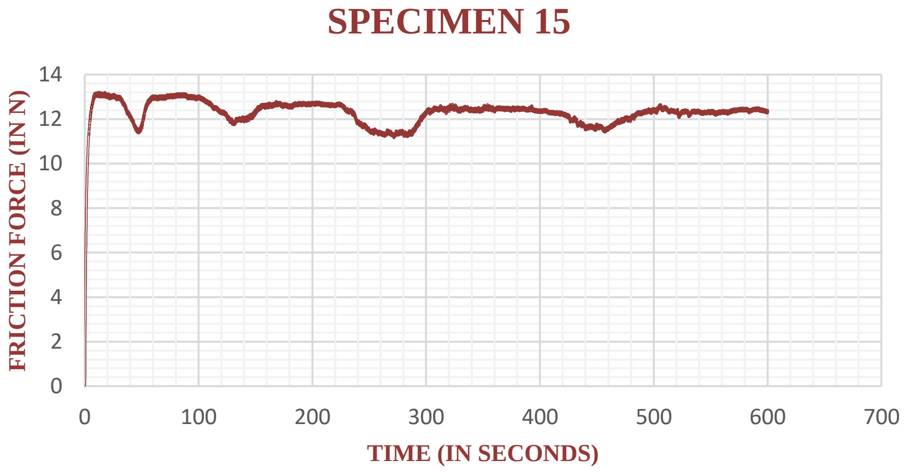
- Maximum Wear- 146.116 µm
- Maximum friction force- 13.044N

SPECIMEN 15.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	240	30	45	35	600	1.04	80



Graph 29 Variation of wear rate with duration of test for specimen 15.

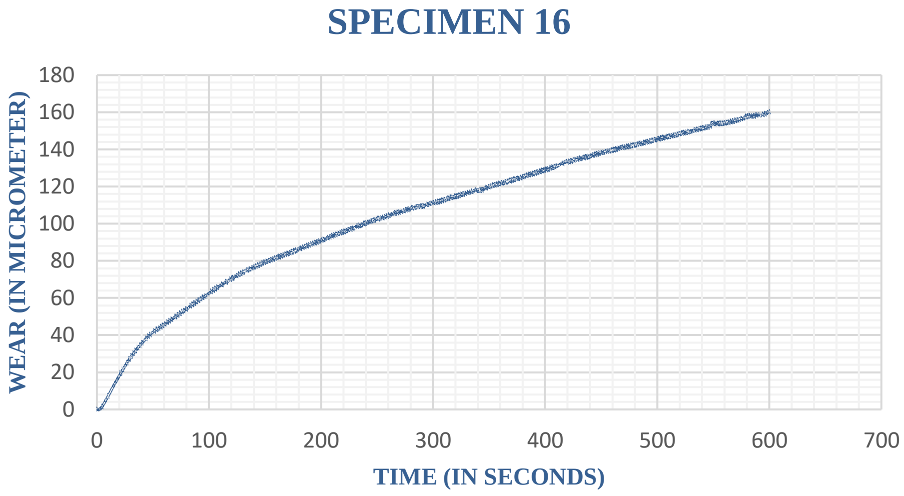


Graph 30 Variation of friction force with duration of test for specimen 15.

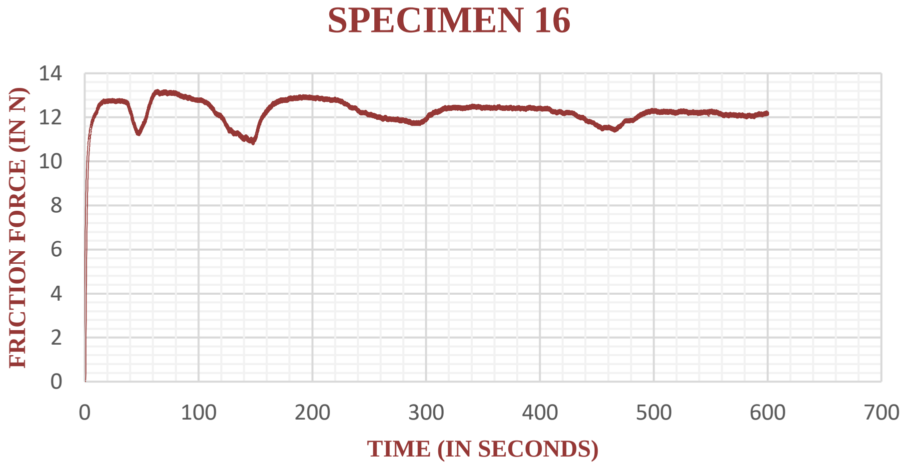
- Maximum Wear- 152.373 µm
- Maximum friction force-13.209N

SPECIMEN 16.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
100	230	40	90	35	600	1.04	80



Graph 31 Variation of wear rate with duration of test for specimen 16.

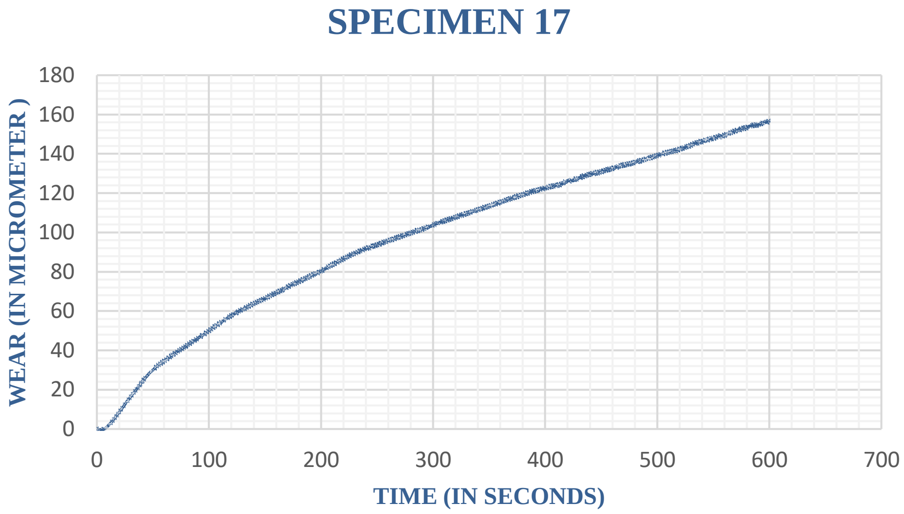


Graph 32 Variation of friction force with duration of test for specimen 16.

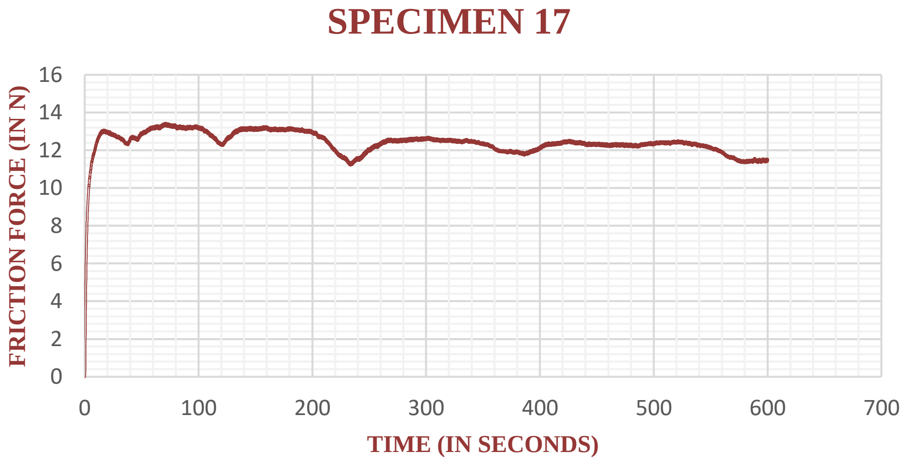
- Maximum Wear- 160.292 µm
- Maximum friction force- 13.218N

SPECIMEN 17.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	220	30	45	35	600	1.04	80



Graph 33 Variation of wear rate with duration of test for specimen 17.

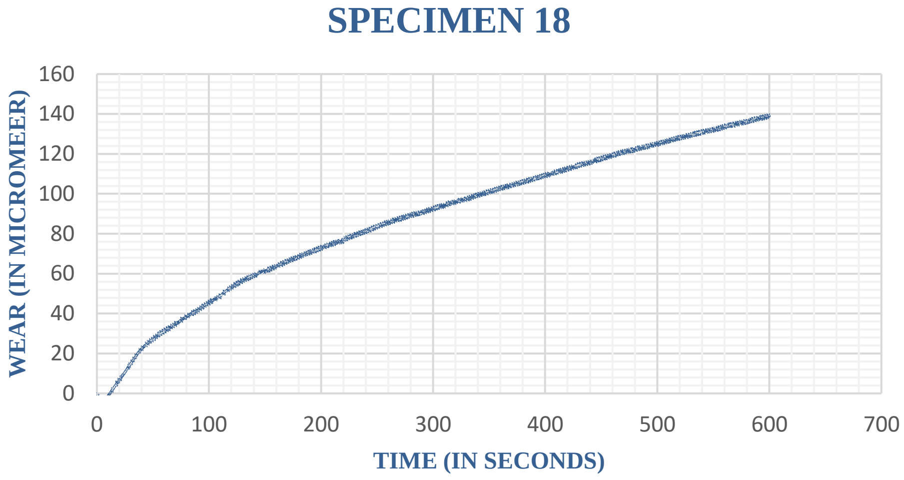


Graph 34 Variation of friction force with duration of test for specimen 17.

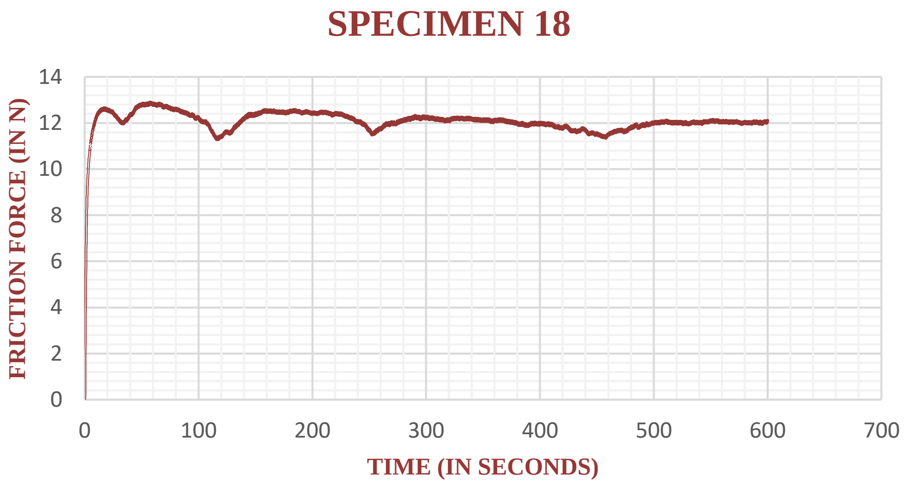
- Maximum Wear- 156.743 µm
- Maximum friction force- 13.432N

SPECIMEN 18.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
200	230	40	90	35	600	1.04	80



Graph 35 Variation of wear rate with duration of test for specimen 18.

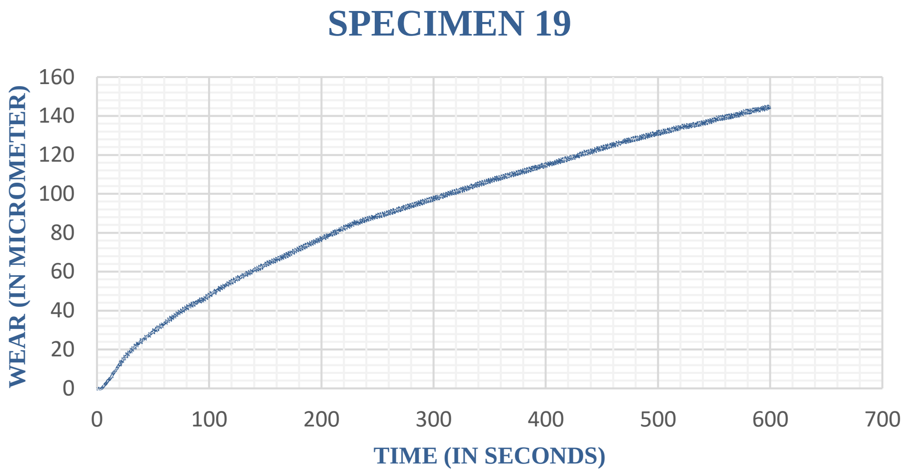


Graph 36 Variation of friction force with duration of test for specimen 18.

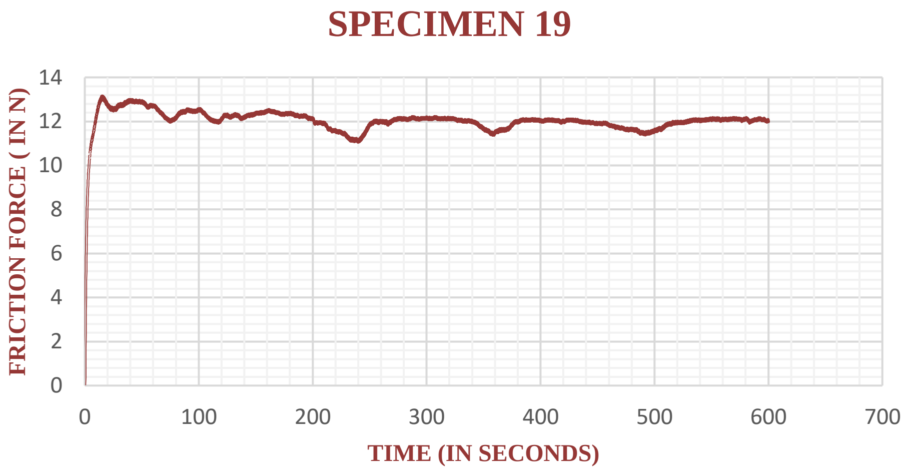
- Maximum Wear- 139.092 µm
- Maximum friction force- 12.916N

SPECIMEN 19.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	30	90	35	600	1.04	80



Graph 37 Variation of wear rate with duration of test for specimen 19.

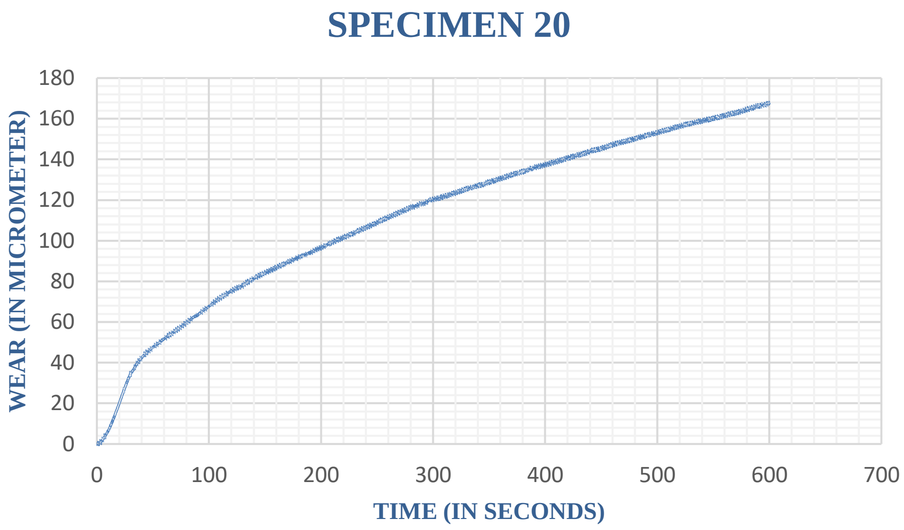


Graph 38 Variation of friction force with duration of test for specimen 19.

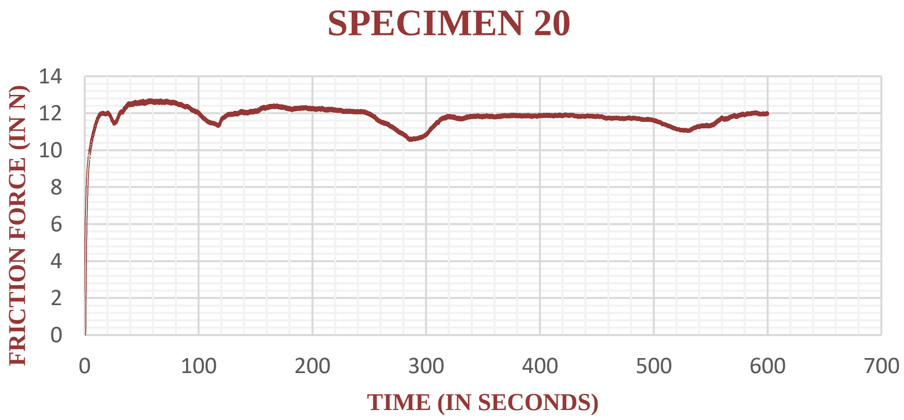
- Maximum Wear- 144.548 µm
- Maximum friction force- 13.158N

SPECIMEN 20.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	40	45	35	600	1.04	80



Graph 39 Variation of wear rate with duration of test for specimen 20

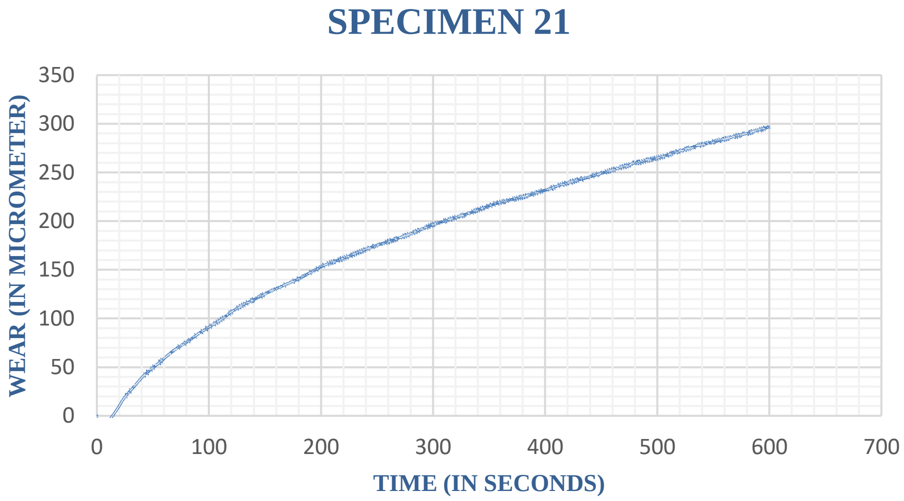


Graph 40 Variation of friction force with duration of test for specimen 20.

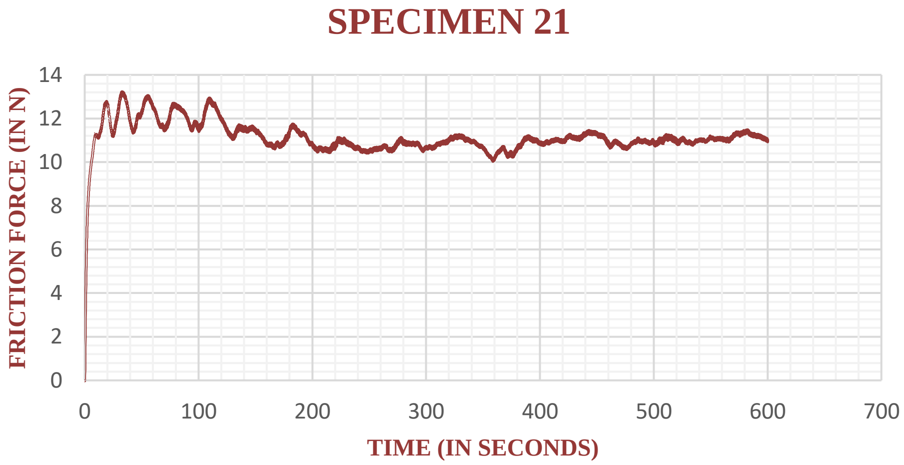
- Maximum Wear- 167.971 µm
- Maximum friction force- 12.737N

SPECIMEN 21

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	50	0	35	600	1.04	80



Graph 41 Variation of wear rate with duration of test for specimen 21.



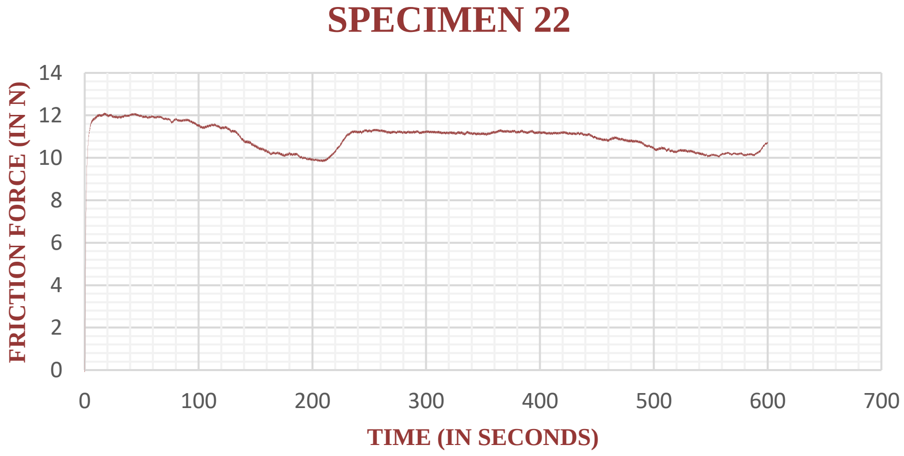
Graph 42 Variation of friction force with duration of test for specimen 21.

- Maximum Wear- 296.898 µm
- Maximum friction force- 13.229N

SPECIMEN 22.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
200	240	40	45	35	600	1.04	80

Graph 43 Variation of wear rate with duration of test for specimen 22.

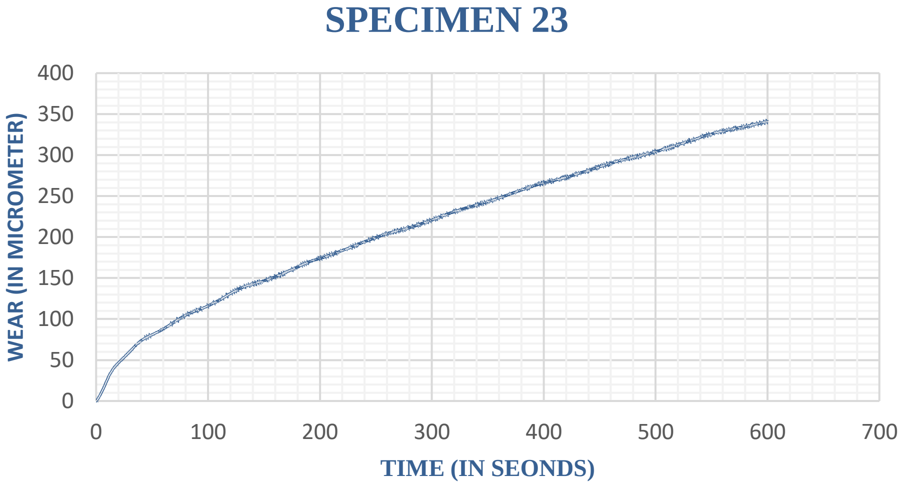


Graph 44 Variation of friction force with duration of test for specimen 22.

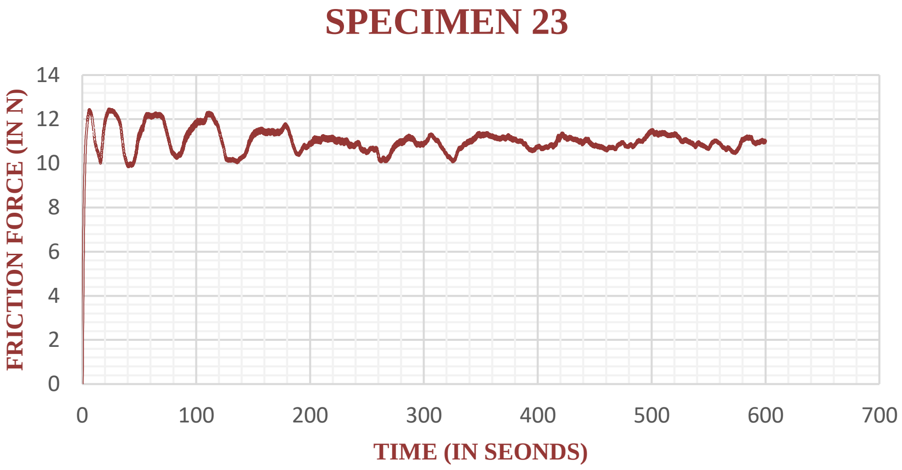
- Maximum Wear- 69.98 µm
- Maximum friction force- 12.119N

SPECIMEN 23.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	50	90	35	600	1.04	80



Graph 45 Variation of wear rate with duration of test for specimen 23

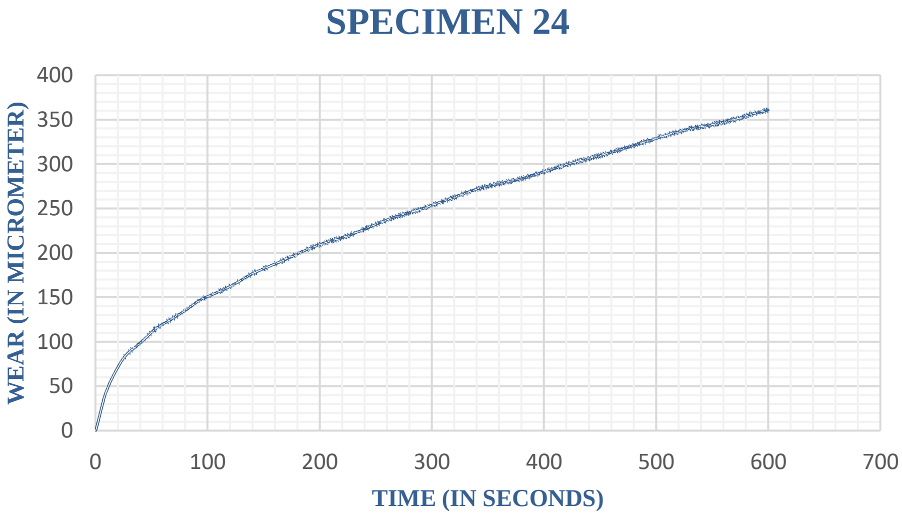


Graph 46 Variation of friction force with duration of test for specimen 23.

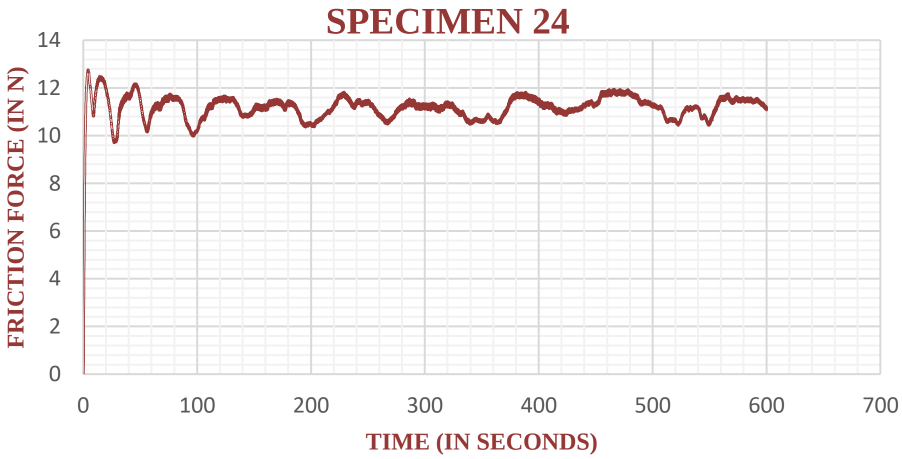
- Maximum Wear- 341.086 µm
- Maximum friction force- 12.466N

SPECIMEN 24.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
150	230	30	0	35	600	1.04	80



Graph 47 Variation of wear rate with duration of test for specimen 24.

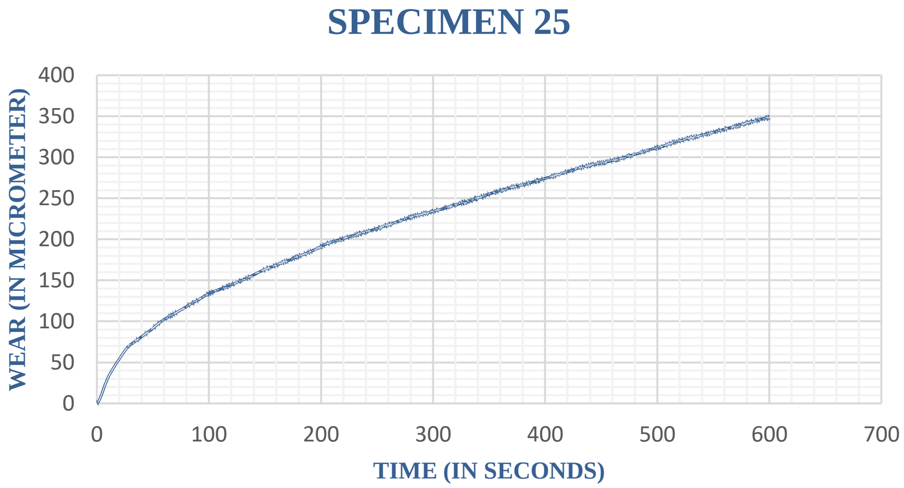


Graph 48 Variation of friction force with duration of test for specimen 24.

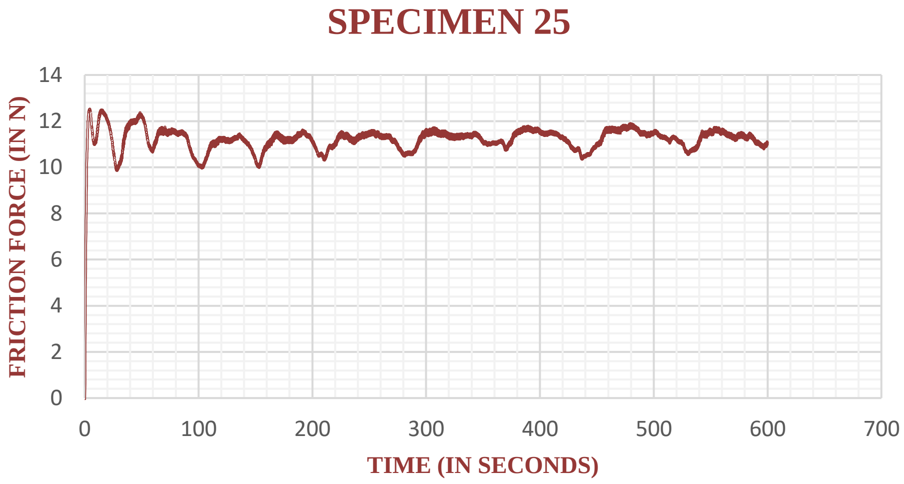
- Maximum Wear-360.848 µm
- Maximum friction force- 12.759N

SPECIMEN 25.

LAYER THICKNESS (mm)	**NOZZLE TEMPEATURE (˚C)**	**PRINTING SPEED (rpm)**	**ORIENTATION (˚)**	**LOAD (N)**	**TIME (sec.)**	**SLIDING VELOCITY (m/sec)**	**WEAR TRACK DIA. (mm)**
100	240	30	0	35	600	1.04	80



Graph 49 Variation of wear rate with duration of test for specimen 25.

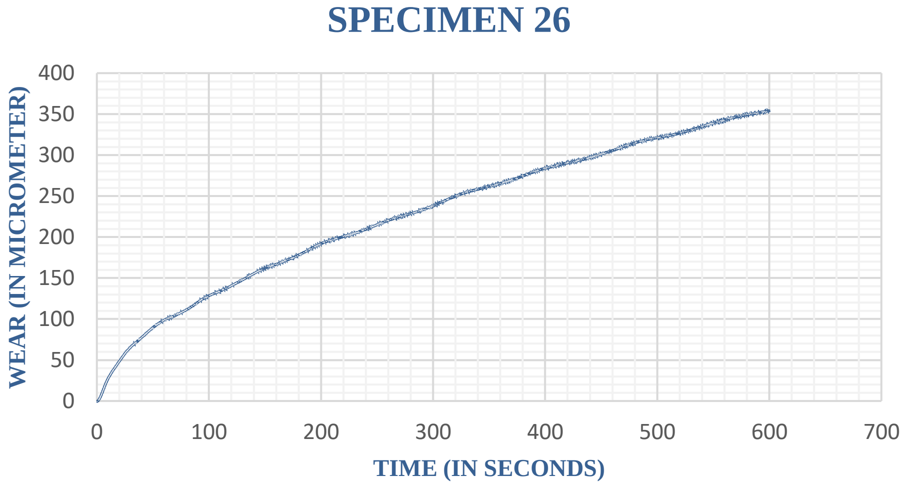


Graph 50 Variation of friction force with duration of test for specimen 25.

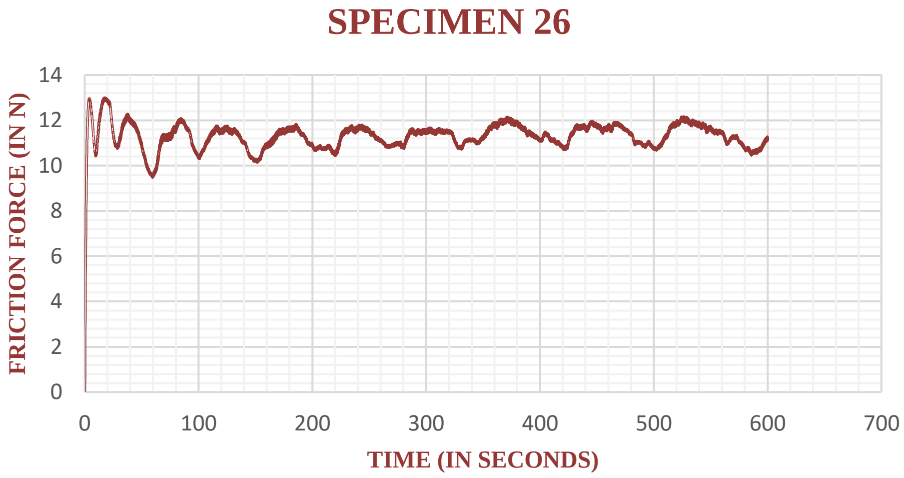
- Maximum Wear- 348.524 µm
- Maximum friction force- 12.528N

SPECIMEN 26.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	WEAR TRACK DIA. (mm)
100	220	40	45	35	600	1.04	80



Graph 51 Variation of wear rate with duration of test for specimen 26.

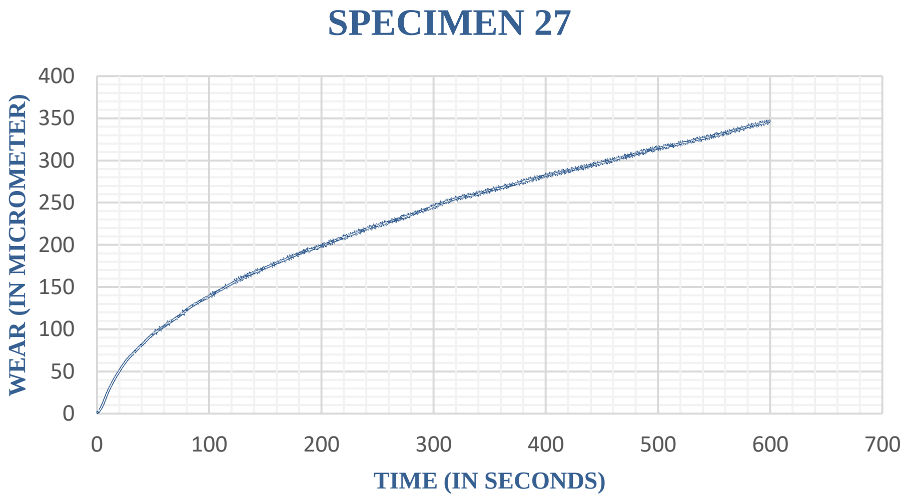


Graph 52 Variation of friction force with duration of test for specimen 26.

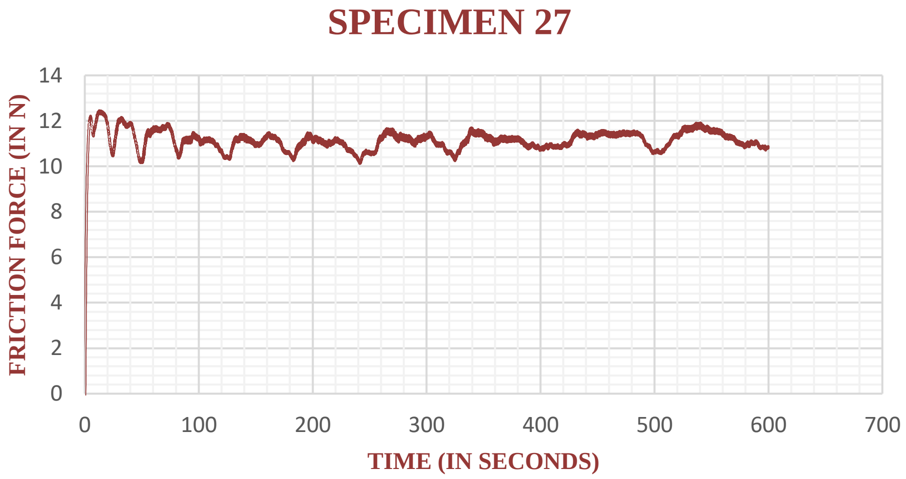
- Maximum Wear- 354.02 µm
- Maximum friction force- 12.999N

SPECIMEN 27.

LAYER THICKNESS (mm)	NOZZLE TEMPEATURE (˚C)	PRINTING SPEED (rpm)	ORIENTATION (˚)	LOAD (N)	TIME (sec.)	SLIDING VELOCITY (m/sec)	EAR TRACK DIA. (mm)
200	220	40	45	35	600	1.04	80



Graph 53 Variation of wear rate with duration of test for specimen 27.



Graph 54 Variation of friction force with duration of test for specimen 27.

- Maximum Wear- 345.844 µm
- Maximum friction force- 12.45N

Table 10 Results obtained from the experiments

SPECIMEN NO.	INITIAL MASS (g)	FINAL MASS (g)	MASS LOSS	WEAR RATE (µm)	FRICTION FORCE (N)
1.	1.3551	1.3437	0.0114	195.662	12.43
2.	1.2884	1.2761	0.0123	231.707	12.93
3.	1.3710	1.3585	0.0125	232.314	13.736
4.	1.3471	1.3380	0.0091	211.421	13.171
5.	1.3778	1.3687	0.0091	235.745	13.569
6.	1.3797	1.3715	0.0082	183.488	12.937
7.	1.3714	1.3632	0.0082	151.046	12.616
8.	1.3697	1.3629	0.0068	155.076	12.386
9.	1.3518	1.3460	0.0058	125.367	12.109
10.	1.3413	1.3275	0.0138	225.111	12.23
11.	1.3542	1.3425	0.0117	209.279	15.134
12.	1.3763	1.3635	0.0128	213.137	14.211
13.	1.3508	1.3418	0.0090	200.137	13.608
14.	1.3500	1.3426	0.0074	146.116	13.044
15.	1.3690	1.3624	0.0066	152.373	13.209
16.	1.3462	1.3398	0.0064	160.292	13.218
17.	1.3586	1.3518	0.0068	156.743	13.432
18.	1.3604	1.3544	0.0060	139.092	12.916
19.	1.3639	1.3574	0.0065	144.548	13.158
20.	1.3407	1.3341	0.0066	1677.971	12.737
21.	1.3327	1.3108	0.0219	296.898	13.229
22.	1.2868	1.2759	0.0109	69.98	12.119
23.	1.3000	1.2762	0.0237	341.086	12.466
24.	1.2005	1.1771	0.0234	360.848	12.759
25.	1.1896	1.1670	0.0226	348.524	12.528
26.	1.2011	1.1775	0.0236	354.02	12.999
27.	1.3206	1.2959	0.0247	345.844	12.45

4.3 Analysis of Specific wear rate and co-efficient of Friction

The experimental WINDCOM-2008 software gives the value of wear rate and Friction force at applied machining condition. To calculate the value of Specific Wear rate and Co-efficient of friction consider following formula.

$$W = \frac{\Delta m}{F * L * \rho}$$

$$cof = \frac{f}{F}$$

Where

W= Specific wear rate

Δm= Mass loss

F, Applied load = 3.5*9.81 = 35N

L, Sliding distance $L = \frac{\pi DN}{60}$

ρ, Density of ABS material= 1.06g/cm^3

f = Friction force in N

Using above formula, we will be calculated specific wear rate and cof for all specimens these are as followed:

Table 11 Analysis for Specific wear rate and Co-efficient of friction.

Layer Thickness	**Nozzle Temperature**	**Speed**	**Orientation**	**Specific wear rate**	**Coefficient of friction**
150	240	40	90	0.000299	0.3551
200	230	50	45	0.000322	0.3694
150	240	40	0	0.000327	0.3924
100	230	50	45	0.000238	0.3763
150	220	40	0	0.000238	0.3876
150	220	40	90	0.000215	0.3696
200	230	30	45	0.000215	0.3604
150	230	40	45	0.000178	0.3538
100	230	30	45	0.000152	0.3459
150	240	50	45	0.000362	0.3494
150	230	40	45	0.000306	0.4324
200	230	40	0	0.000335	0.4060
100	230	40	0	0.000236	0.3888
150	220	50	45	0.000194	0.3726

150	240	30	45	0.000173	0.3774
100	230	40	90	0.000167	0.3776
150	220	30	45	0.000178	0.3837
200	230	40	90	0.000157	0.3690
150	230	30	90	0.000170	0.3759
150	230	40	45	0.000173	0.3639
150	230	50	0	0.000574	0.3779
200	240	40	45	0.000285	0.3462
150	230	50	90	0.000621	0.3561
150	230	30	0	0.000613	0.3645
100	240	40	45	0.000592	0.3577
100	220	40	45	0.000619	0.3714
200	220	40	45	0.000648	0.3557

All the calculated values are analyzing and optimizing using RSM and ANOVA techniques that will be discussed in next chapter

CHAPTER 5

OPTIMIZATION OF RESULTS

5.1 Introduction:

Design of experiment is a statistical methodology to conduct experiments in a statistical manner so that the uncontrollable factors which influence the end result of the study are minimized. The results obtained from statically designed experiments are easy to analyze and a clear and sound conclusion is inferred from the results. The test was performed on the specimens which are fabricated using the ASTM G99 test standard as a reference. The process parameters chosen for study are concluded from the literature survey and capabilities of the FUSE**BOT250+**. The study employs RSM philosophy to conduct experiments. Samples prepared with different combinations of FDM machine parameters are prepared and tested for the wear rate. The experimental results are examined thoroughly using the statistical techniques in the following section.

5.2 RSM-Box Behnken Design:

Response Surface Regression: wear rate versus layer thickness, temperature, speed, orientation

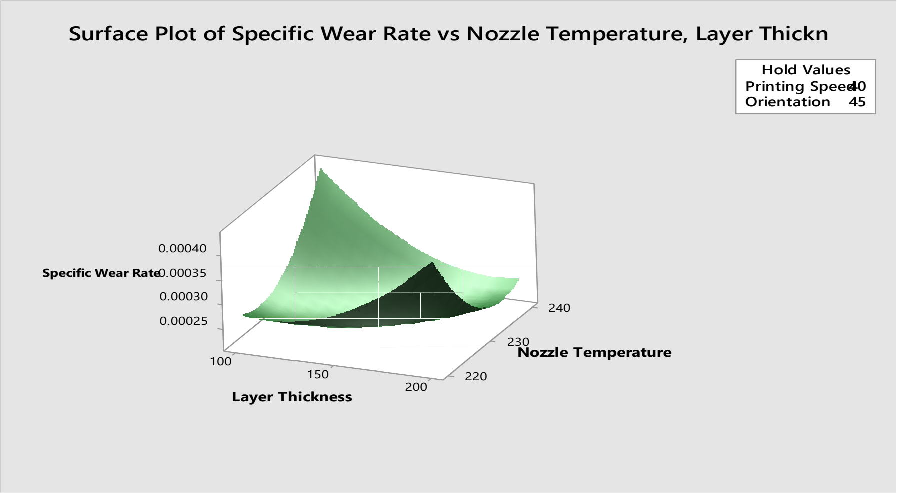


Figure 9 Surface Plot of specific wear rate vs Nozzle temperature, Layer thickness

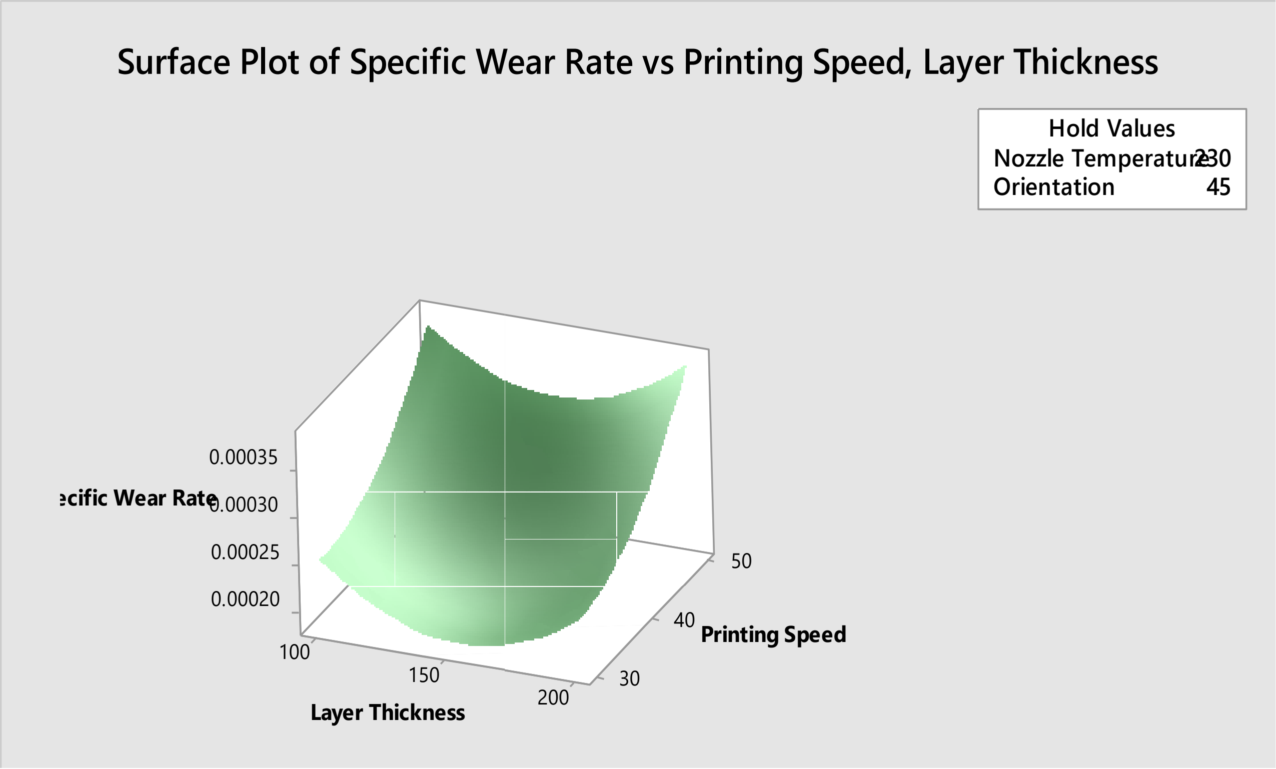


Figure 10 Surface Plot of specific wear rate vs Printing speed, Layer thickness

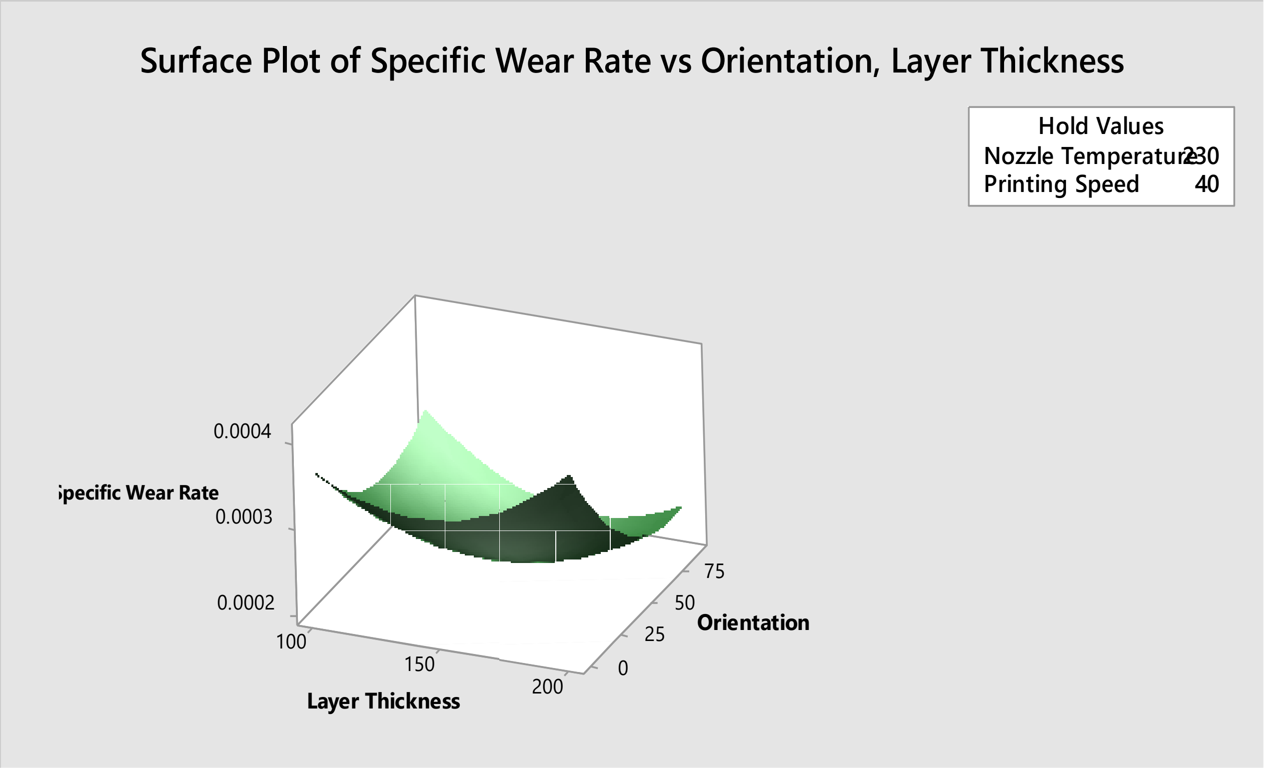


Figure 11 Surface Plot of specific wear rate vs Orientation, Layer thickness

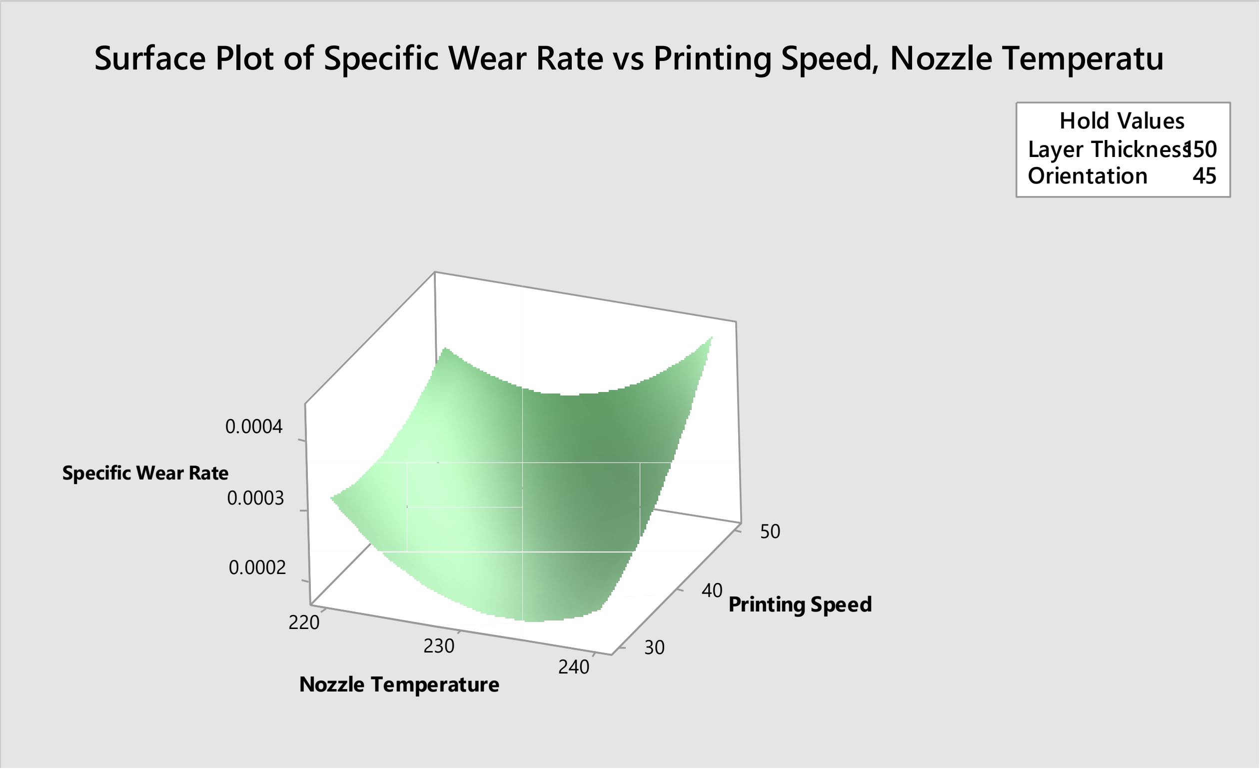


Figure 12 Surface Plot of specific wear rate vs Printing speed, Nozzle temperature

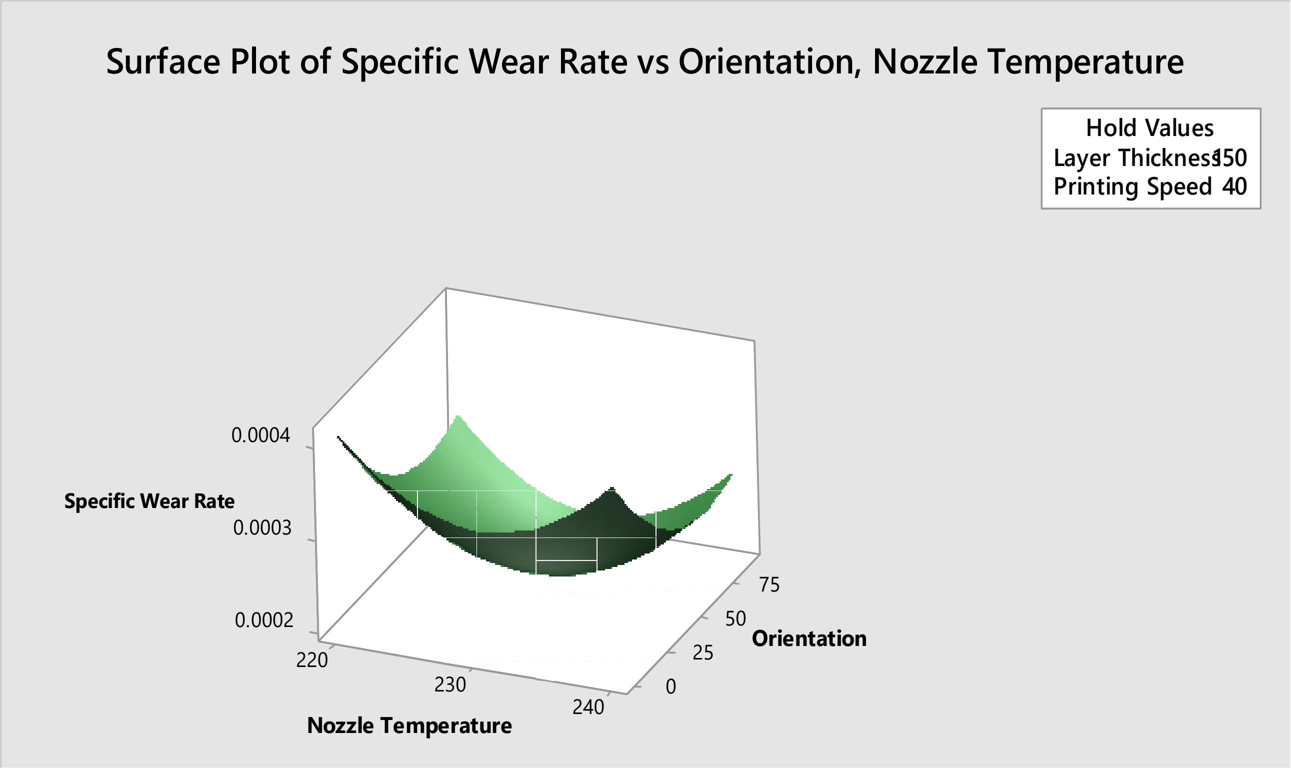


Figure 13 Surface Plot of specific wear rate vs Orientation, Nozzle temperature

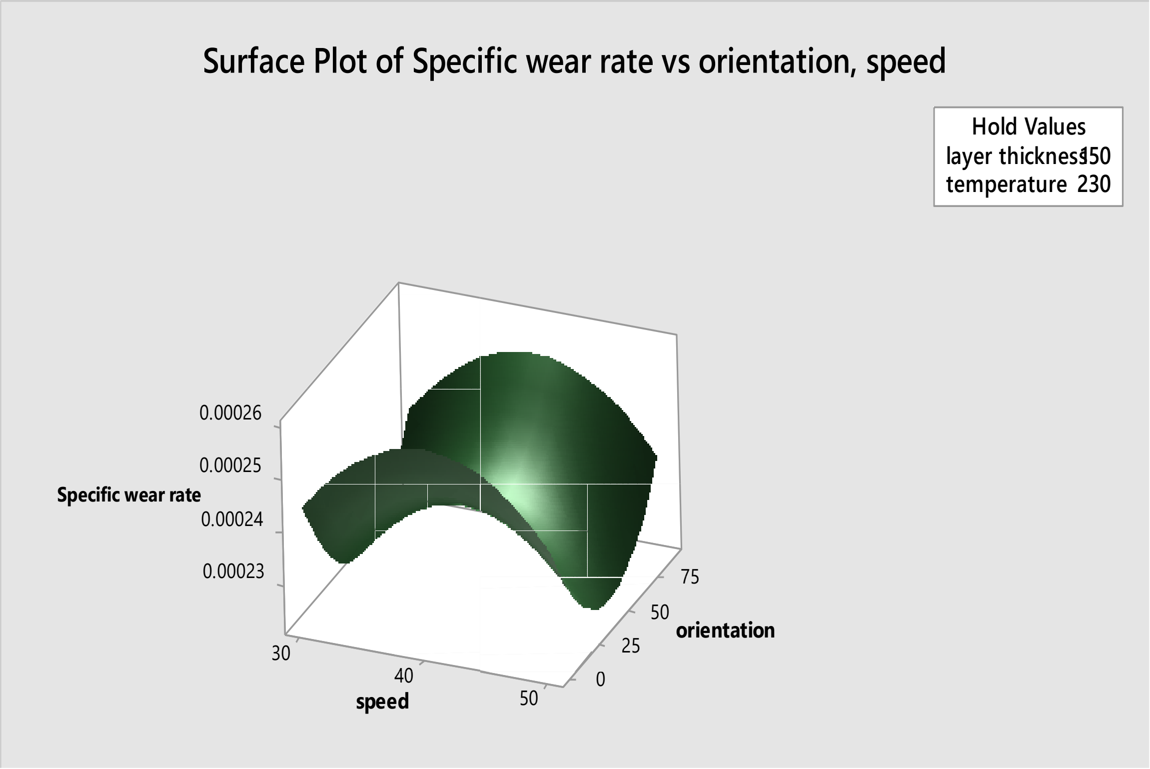


Figure 14 Surface Plot of specific wear rate vs Orientation, speed

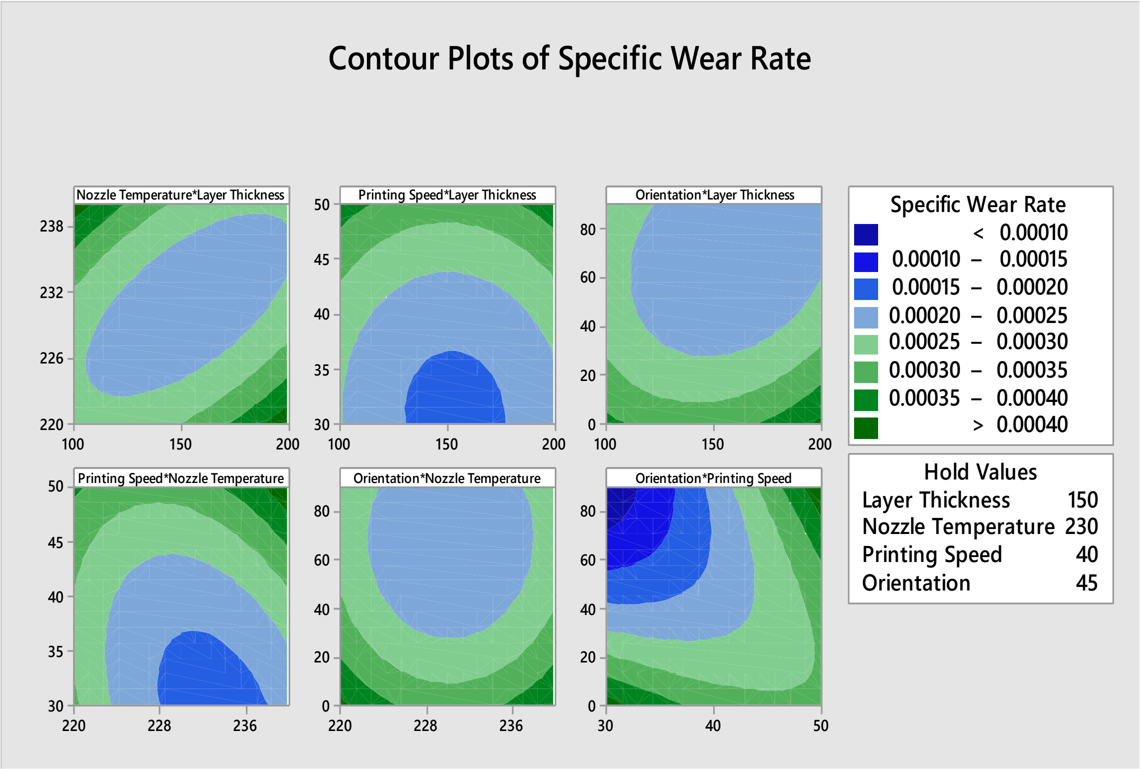


Figure 15 Contours plots of specific wear rate

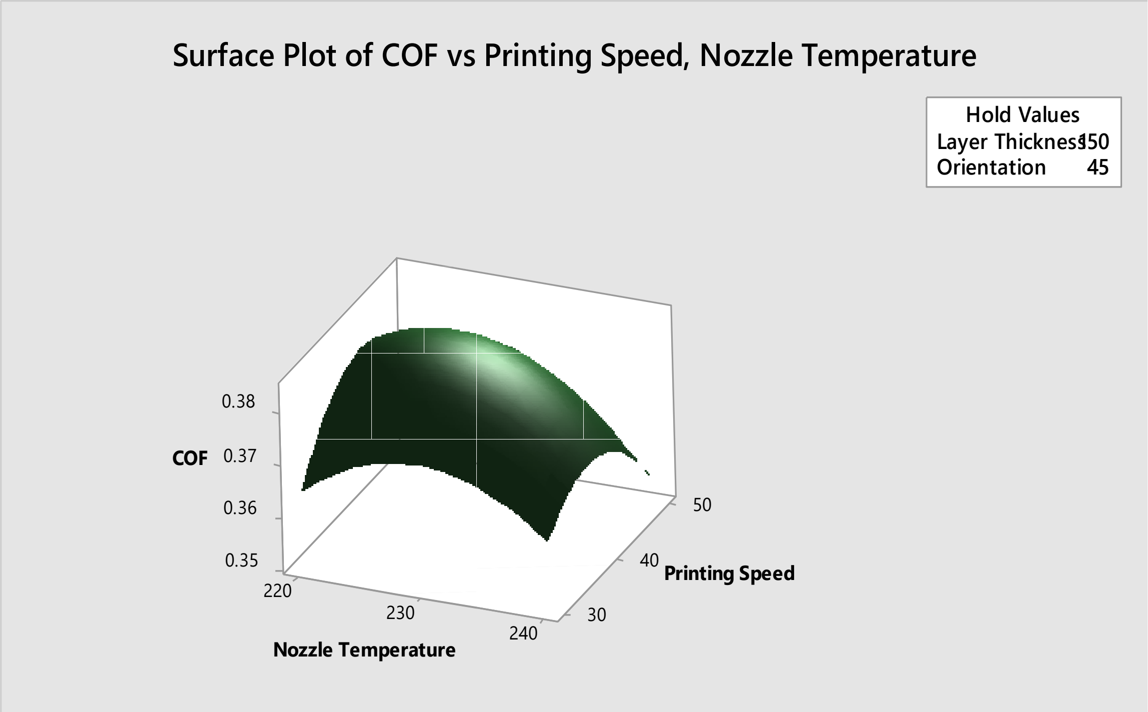


Figure 16 Surface Plot of Co-efficient of friction vs Printing speed, Nozzle temperature

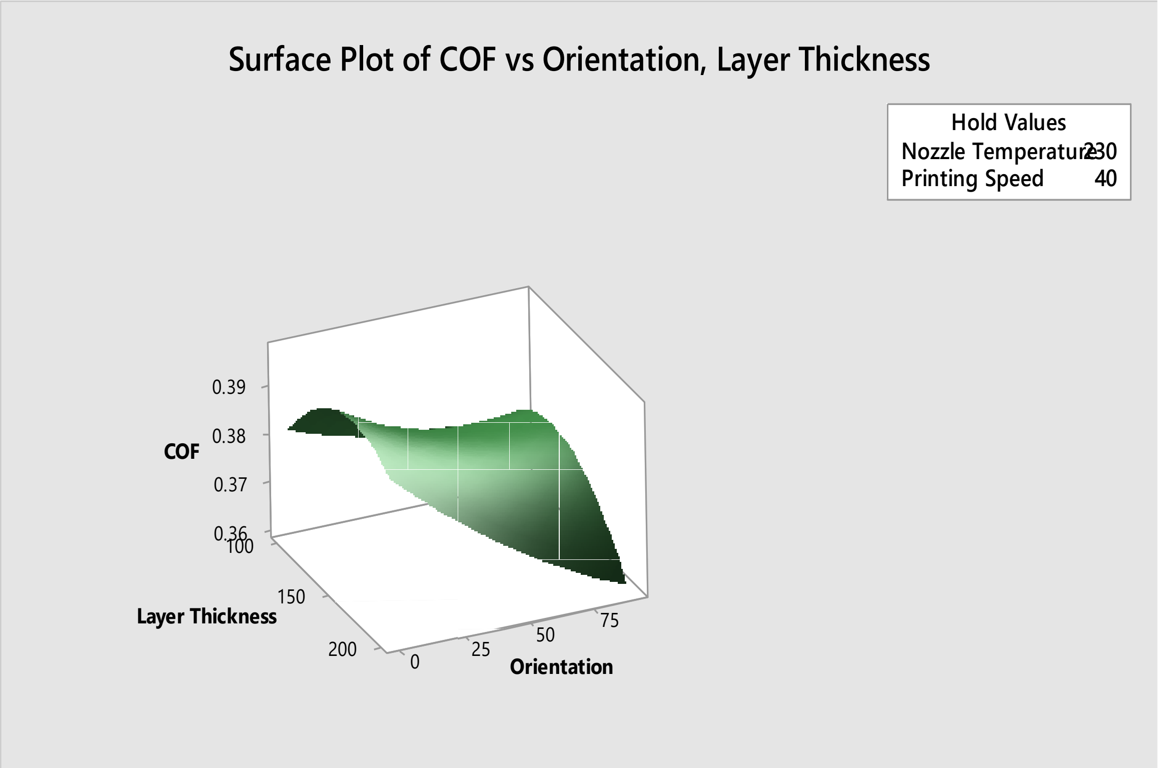


Figure 17 Surface Plot of Co-efficient of friction vs Orientation, Layer thickness

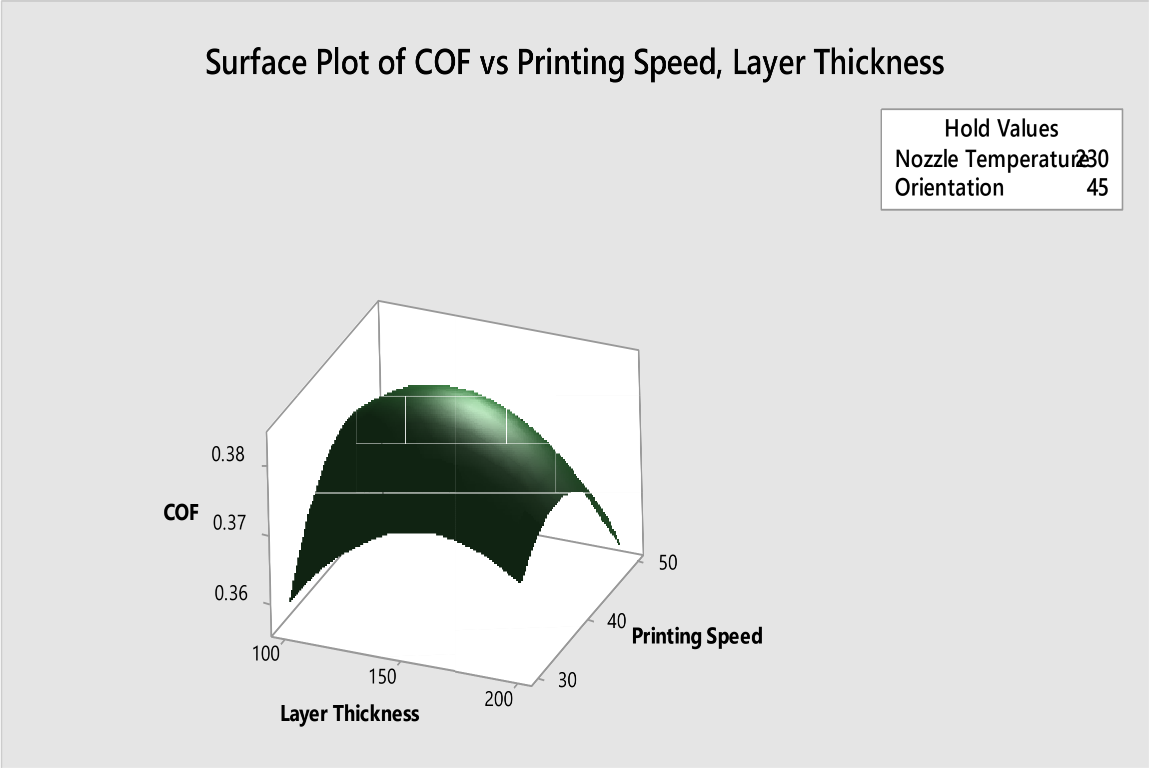


Figure 18 Surface Plot of Co-efficient of friction vs Printing speed, Layer thickness

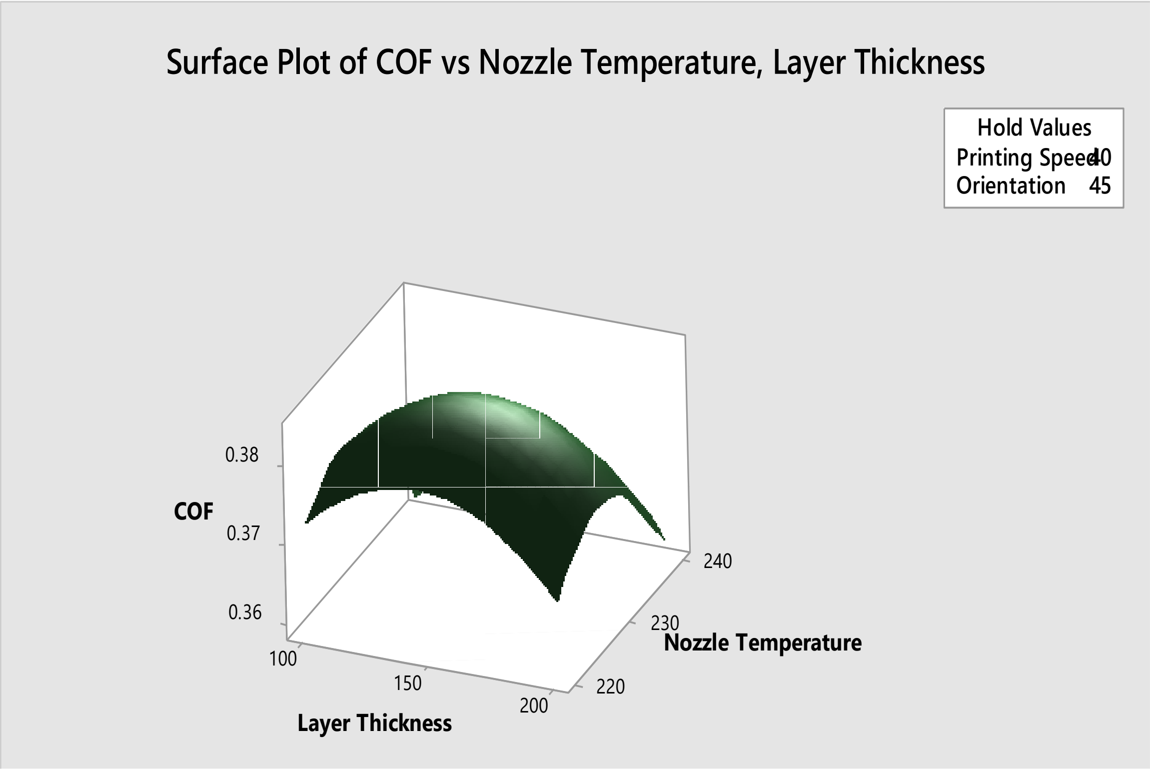


Figure 19 Surface Plot of Co-efficient of friction vs Nozzle temperature, Layer thickness

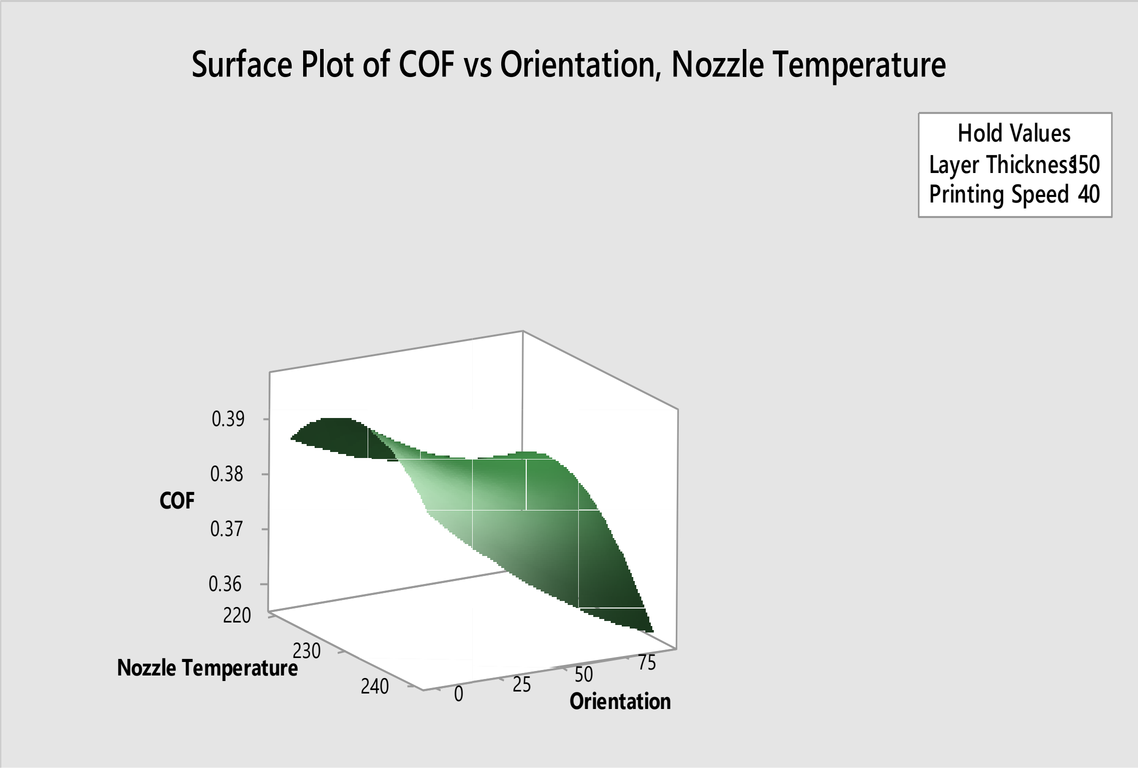


Figure 20 Surface Plot of Co-efficient of friction vs Orientation, Nozzle temperature

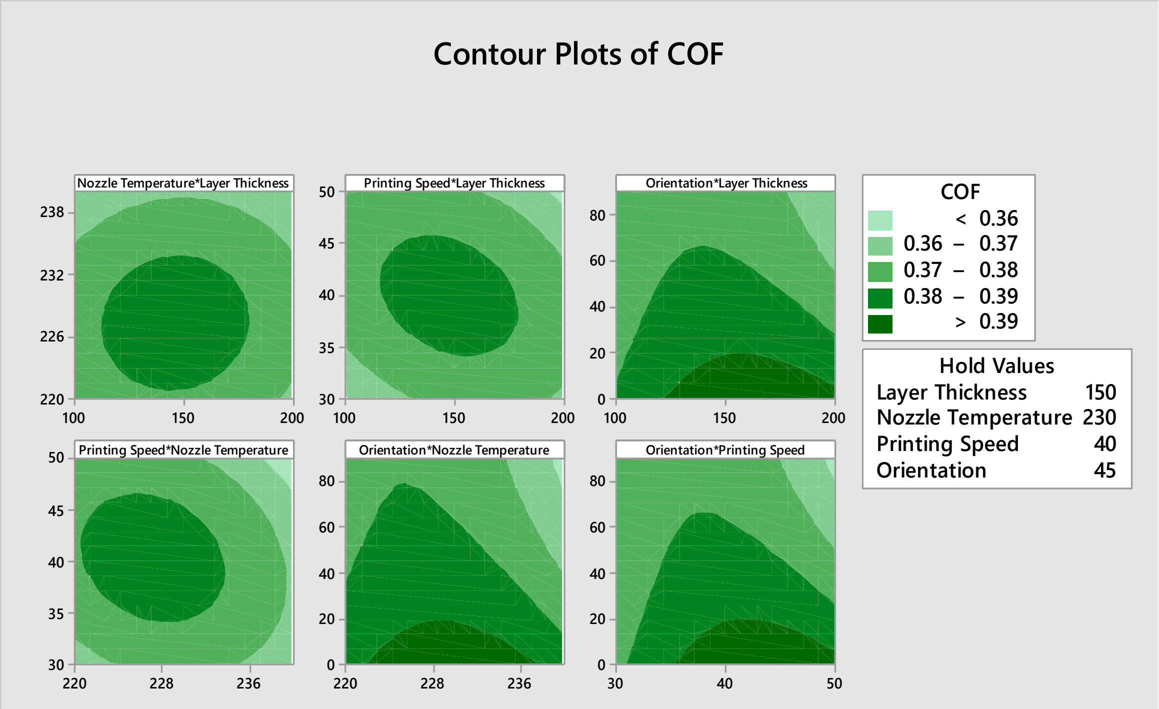


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Figure 21 Contours Plot of Co-efficient of Friction

Table 12 Response Optimization of Parameters for wear rate:

Response	**Goal**	**Lower Target**	**Upper**	**Weight**	**Importance**

wear rate	Minimum	0.000178	0.000619	1	1

Our goal is to minimization of wear rate for this RSM gave following predicted value based on the experimental data.

Table 13 Multiple Response Prediction

Variable	Setting
layer thickness	185.859
temperature	220
speed	30
orientation	39.0909

Table 14 Response fit for Wear Rate

Response	Fit	SE Fit	5% CI	95% PI
wear rate	0.000102	0.000027	(0.000044, 0.000160)	(0.000017, 0.000187)

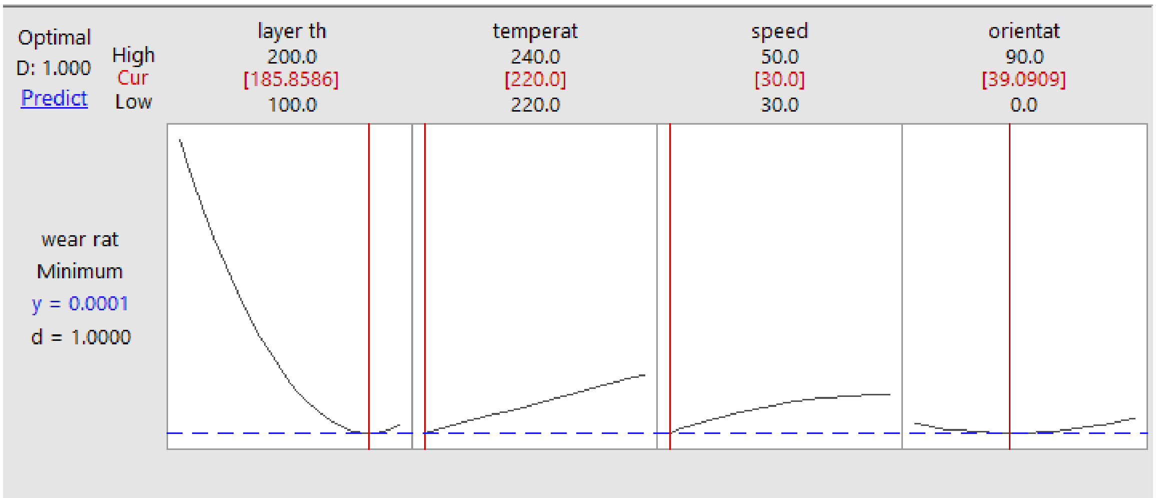

Figure 22 Optimization Plot for wear rate

5.3 Analysis of Variance (ANOVA):

ANOVA is a set of statistically models which judges the significance of factors under study and also acts as a confirmatory test to validate the experimental data. A general linear regression model is used analyses the experimental data in MINITAB. The results obtained are tabulated in the following content.

Table 15 ANOVA results of Wear rate

Source	F-Value	P-Value

Model	67.14	0.000
Linear	0.89	0.000
Layer thickness	1.87	0.000
Temperature	1.59	0.231
Speed	0.00	1.000
Orientation	0.08	0.779
Square	2.83	0.000
Layer thickness*layer thickness	6.02	0.000
Temperature*temperature	0.00	0.984
Speed*speed	1.54	0.238
Orientation*orientation	2.34	0.152
2-Way Interaction	0.84	0.564
Layer thickness*temperature	0.23	0.640
Layer thickness*speed	0.00	1.000
Layer thickness*orientation	0.00	1.000
Temperature*speed	4.55	0.054
Temperature*orientation	0.25	0.628
Speed*orientation	0.00	1.000

We will analyze in the P-Value column, in this look for value <0.05 because the default confidence level that is 95%. Then the layer thickness is significant as the corresponding P-value <0.05.

Table 16 Model Summary for wear rate

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
0.0000281	98.74%	97.27%	92.74%

In the model summary table, S indicates the standard deviation of residuals and that is 2.81x10^{-5}.

R-Sq value indicates how much variation in response can be explained with the model and is 98.74%. which is good. The balanced 1.26% variation cannot be explained by the model and is random.

R-Sq(adj) is modified R-Sq value. There is not large difference between these two values. Large difference between the R-Sq and R-Sq(adj) shows presence of insignificant factors in the model.

R-Sq(pred) is 92.74% and shows predictability of the model for new observations.

5.4 Regression Equation:

Specific wear rate

$$
\begin{aligned}
&= 0.000345 + 0.000271(\text{layer thickness}_{100}) - 0.000105\ (\text{layer thickness}_{150}) \\
&- 0.000166\ (\text{layer thickness}_{200}) - 0.000010\ (\text{temperature}_{220}) \\
&- 0.000000\ (\text{temperature}_{230}) + 0.000010\ (\text{temperature}_{240}) \\
&- 0.000005\ (\text{speed}_{30}) + 0.000010\ (\text{speed}_{40}) - 0.000005\ (\text{speed}_{50}) \\
&+ 0.000009\ (\text{orientation}_{0}) - 0.000012\ (\text{orientation}_{45}) \\
&+ 0.000004\ (\text{orientation}_{90})
\end{aligned}
$$

5.5 Prediction for wear rate:

General Linear Model Information

Table 17 Factor Setting

Variable	**Setting**
Layer thickness	200
Temperature	240
Speed	40
Orientation	45

Table 18 Predicted results

Fit	**SE Fit**	**95% CI**	**95% PI**
0.0001873	0.0000158	(0.0001541, 0.0002204)	(0.0001209, 0.0002536)

Table 19 ANOVA results for Co-efficient of friction

Source	**F-Value**	**P-Value**
Model	4.84	0.005
Linear	6.57	0.005
Layer thickness	6.93	0.001
Temperature	4.75	0.050
Speed	1.79	0.205
Orientation	2.79	0.121
Square	7.66	0.003
Layer thickness*Layer thickness	25.15	0.000
Temperature*Temperature	1.02	0.332
Speed*Speed	0.03	0.868

Orientation*Orientation	0.08	0.786
2-Way Interaction	1.81	0.179
Layer thickness*Temperature	1.13	0.309
Layer thickness*Speed	0.00	1.000
Layer thickness*Orientation	0.00	1.000
Temperature*Speed	1.37	0.264
Temperature*Orientation	8.37	0.014
Speed*Orientation	0.00	1.000

Similarly, as we discussed above, we will analyze in the P-Value column, in this look for value <0.05 because the default confidence level that is 95%. Then the layer thickness and nozzle temperature are most significant as the corresponding P-value <0.05.

Table 20 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0064471	84.96%	79.42%	83.38%

In the model summary table, S indicates the standard deviation of residuals and that is 6.44x10^{-3}. R-Sq value indicates how much variation in response can be explained with the model and is 84.96%. which is not bad. The balanced 15.04% variation cannot be explained by the model and is random.

R-Sq(adj) is modified R-Sq value. There is difference of 05.54 between these two values. Large difference between the R-Sq and R-Sq(adj) shows presence of insignificant factors in the model.

R-Sq(pred) is 83.38% and shows predictability of the model for new observations.

Table 21 Predicted values for wear rate, coefficient of friction using ANOVA and absolute percentage error in predicted and experimental results

layer thickness	**Temperature**	**Speed**	**Orientation**	**wear rate**	**COF**	**Predicted COF**	**Predicted wear rate**	**Absolute percentage error in wear**	**Absolute percentage error in cof**
150	240	50	45	0.000178	0.3538	0.3664	0.000183	3.019663	3.575466
150	220	30	45	0.000178	0.3837	0.3795	0.000192	8.356742	1.081574
150	230	40	45	0.000238	0.3763	0.3763	0.000238	2.28E-14	2.95E-14
200	240	40	45	0.000178	0.3538	0.3477	0.000187	5.196629	1.70765
100	220	40	45	0.000619	0.3714	0.3711	0.000603	2.544426	0.056094

150	230	40	45	0.000238	0.3763	0.3763	0.000238	2.28E-14	2.95E-14
100	230	40	90	0.000619	0.3714	0.3676	0.000629	1.703016	1.016424
150	240	40	90	0.000299	0.3551	0.3670	0.000264	1.4409	3.374636
200	230	40	0	0.000178	0.3538	0.3585	0.000187	1.0721	1.3355
150	230	50	90	0.000238	0.3763	0.3710	0.000239	0.49019	1.408451
150	240	40	0	0.000327	0.3924	0.3733	0.000219	7.59684	4.867482
100	230	40	0	0.000619	0.3714	0.3738	0.000634	2.45692	0.657422
150	220	50	45	0.000238	0.3763	0.3745	0.000221	0.5567	0.460625
150	220	40	0	0.000238	0.3763	0.3814	0.000248	4.60434	1.359731
150	230	50	0	0.000238	0.3763	0.3772	0.000243	2.45098	0.2436
200	220	40	45	0.000178	0.3538	0.3558	0.000166	6.32022	0.58649
150	230	40	45	0.000238	0.3763	0.3763	0.000238	2.28E-14	2.95E-14
100	230	30	45	0.000619	0.3714	0.3719	0.000598	3.372375	0.15482
100	230	50	45	0.000619	0.3714	0.3669	0.000598	3.372375	1.18695
150	230	30	90	0.000238	0.3763	0.3759	0.000239	0.490196	0.084153
100	240	40	45	0.000592	0.3577	0.3630	0.000623	5.363176	1.502656
200	230	50	45	0.000178	0.3538	0.3516	0.000161	9.199438	0.600622
150	220	40	90	0.000238	0.3763	0.3752	0.000244	2.643557	0.29232
150	240	30	45	0.000238	0.3763	0.3714	0.000233	1.943277	1.293294
200	230	40	90	0.000178	0.3538	0.3523	0.000193	8.450375	0.421613
150	230	30	0	0.000238	0.3763	0.3822	0.000243	2.45098	1.567898
200	230	30	45	0.000178	0.3538	0.3566	0.000161	9.199438	0.807895

- Average absolute percentage error in wear rate= 4.9738%
- Average absolute percentage error in Coefficient of friction=1.0979%

Table 22 All possible sets (81) value and their predicted wear rate and cof using ANOVA.

S.No.	**Layer thickness**	**Temperature**	**Speed**	**Orientation**	**Predicted wear**	**Predicted cof**
1	100	220	30	45	0.000588	0.3732
2	200	220	30	45	0.000152	0.3579
3	100	220	50	45	0.000588	0.3682
4	200	230	40	90	0.000193	0.3523

5	100	240	40	90	0.000640	0.3607
6	150	240	50	0	0.000254	0.3703
7	200	220	50	0	0.000173	0.3568
8	200	240	50	90	0.000188	0.3425
9	150	220	30	90	0.000229	0.3772
10	100	240	30	0	0.000630	0.3690
11	150	230	50	45	0.000223	0.3733
12	100	220	40	90	0.000620	0.3689
13	200	240	30	45	0.000172	0.3498
14	200	240	40	0	0.000208	0.3516
15	100	220	50	0	0.000609	0.3721
16	100	240	50	45	0.000609	0.3601
17	100	220	30	0	0.000609	0.3771
18	200	240	50	45	0.000172	0.3448
19	100	240	40	0	0.000645	0.3670
20	100	230	40	0	0.000634	0.3738
21	100	240	30	90	0.000625	0.3628
22	200	220	40	45	0.000167	0.3559
23	100	230	30	0	0.000619	0.3759
24	200	230	30	45	0.000162	0.3567
25	150	220	40	45	0.000228	0.3775
26	150	230	30	45	0.000223	0.3783
27	150	240	40	45	0.000249	0.3694
28	150	240	30	0	0.000254	0.3753
26	150	240	30	45	0.000233	0.3714
30	200	220	50	45	0.000152	0.3529
31	200	230	40	0	0.000198	0.3585
32	100	230	50	90	0.000614	0.3647
33	100	220	40	45	0.000603	0.3712
34	200	230	50	0	0.000183	0.3556
35	200	230	50	90	0.000178	0.3493
36	100	230	30	90	0.000614	0.3696
37	200	240	40	45	0.000187	0.3478

38	100	230	30	45	0.000598	0.3720
39	150	230	30	0	0.000244	0.3822
40	100	230	40	90	0.000630	0.3676
41	200	230	50	45	0.000162	0.3517
42	150	220	50	0	0.000234	0.3785
43	200	240	50	0	0.000193	0.3487
44	100	230	40	45	0.000613	0.3700
45	150	220	30	0	0.000234	0.3834
46	200	240	40	90	0.000204	0.3454
47	150	230	40	45	0.000238	0.3763
48	150	230	30	90	0.000239	0.3760
49	100	230	50	45	0.000598	0.3670
50	200	220	30	90	0.000168	0.3556
51	150	240	50	45	0.000233	0.3665
52	200	220	40	90	0.000183	0.3535
53	150	240	40	0	0.000269	0.3733
54	200	220	40	0	0.000188	0.3598
55	150	240	50	90	0.000250	0.3641
56	100	240	50	0	0.000630	0.3640
57	150	240	30	90	0.000250	0.3691
58	150	230	50	0	0.000244	0.3772
59	100	240	50	90	0.000625	0.3578
60	150	220	50	90	0.000229	0.3722
61	150	220	40	90	0.000244	0.3752
62	100	230	50	0	0.000619	0.3709
63	100	220	50	90	0.000604	0.3659
64	100	220	40	0	0.000624	0.3751
65	200	240	30	90	0.000188	0.3474
66	150	230	40	0	0.000259	0.3802
67	150	240	40	90	0.000265	0.3671
68	150	230	50	90	0.000239	0.3710
69	150	230	40	90	0.000254	0.3740
70	150	220	30	45	0.000213	0.3796

71	200	220	50	90	0.000168	0.3506
72	200	220	30	0	0.000173	0.3618
73	100	240	40	45	0.000624	0.3631
74	150	220	50	45	0.000213	0.3746
75	200	230	30	0	0.000183	0.3605
76	150	220	40	0	0.000249	0.3814
77	200	240	30	0	0.000193	0.3537
78	100	240	30	45	0.000609	0.3651
79	200	230	30	90	0.000178	0.3543
80	100	220	30	90	0.000604	0.3709
81	200	230	40	45	0.000177	0.3546

- Average wear rate=0.000341567
- Average co-efficient of friction=0.36528333

5.6 Results and discussion:

At the current scenario, additive manufacturing process is a most focusing area in the industry. Among all the AM process Fused deposition modelling process parts provides many advantages to the day to day industrial requirements. The present thesis emphasizes the understanding of 3D printing process parameters, which is prime importance to understand the tribological properties like wear rate, loss of mass, and coefficient of friction has been investigated. In this experimental study, a pin (ASTM G99) fabricated through FDM process is tested against the steel disc. RSM and ANOVA optimization techniques used to investigate the optimum process parameters of 3D printing at which the wear of specimen pin is very less. The following conclusion was drawn while analyzing the data obtained from Pin on Disc experiment.

1. From the investigation it has been seen that layer thickness is most significant parameter for improving wear rate.
2. The samples which are fabricated using FDM process, in this case maximum wear has been seen in sample fabricated at lower layer thickness (100microns), and the minimum wear rate seen at the layer thickness of 200microns.
3. The optimum value for minimum wear rate was obtained using optimization of parameters using RSM are: Layer thickness- 185.859microns, Nozzle temperature-220˚C, Printing Speed-30mm/sec, Orientation-39.0909˚.
4. The value of wear rate and Cof for all possible sets (81) of process parameters were predicted using ANOVA.
5. Experimental and predicted values were compared and calculate the absolute percentage

error for both wear rate and cof. Average absolute percentage error in wear rate is 4.9738%, Average absolute percentage error in Coefficient of friction in 1.0979%.

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