Effect of Build Orientation on the Wear Behaviour of 17-4-PH SS Printed using Laser Powder Fusion Bed

Pooja Angolkar
Research Scholar, Department of Mechanical Engineering,
JNTU Hyderabad, India
21pooj@gmail.com

M. Manzoor Hussain
Professor in Mechanical Engineering and Registrar
Jawaharlal Nehru Technological University Hyderabad India
manzoorjntu@jntuh.ac.in

Qutubuddin S.M.
Associate Professor, Industrial and Production Engineering Department
P.D.A.College of Engineering
Kalaburagi, Karnataka, India
syedqutub16@gmail.com

Abstract

In the present work, we have investigated the sample orientation effects on the wear behaviour of laser powder bed fusion (LPBF) processed 17%Cr-4%Ni precipitation hardenable (P.H) steel. The samples were printed in three directions (horizontal (0º), vertical (90º) and inclined (45º) in the build platform using DMLS system. (EOS M 290) machine. 17%Cr-4%NiP.H steel samples were given rough polish, medium polish and fine polish. The microstructure was studied for both as printed and surface modified conditions using scanning electron (SEM) microscopes. The wear test was tested for all three orientations. The input parameters selected were: applied load of 10N, sliding distance of 1000m, rubbing time of 30min with ambient working temperature. The wear rate was measured and compared among orientations for as printed and surface modified conditions to identify the best orientation. The post worn surface was analysed using SEM to identify wear mechanisms. The key findings from the present work are;

1. LB-PBF 17-4 PH SS as-built specimens have high wear rate as compared to polished conditions. This is most likely related to the hardness of LB-PBF 17-4 PH SS.
2. Medium finish- Horizontal built LB-PBF 17-4 PH SS possesses higher wear rate as compared to rough and fine finished samples. This is attributed to the lath martensite and austenite formed on the surface a result of higher surface roughness of LB-PBF specimens.
3. Fine Finish –Horizontal built specimens showed least wear loss, but on an average the inclined built specimens in all polishing conditions showed least wear loss.
4. Adhesion was the dominant wear mechanism, while abrasion and surface fatigue were the wear mechanisms.

Keywords:
Additive manufacturing, stainless steel, orientation, wear, polished.

Introduction:

Laser powder bed fusion (LPBF) is an additive manufacturing (AM) technology that generates 3D structures layer by layer by selectively melting powdered material with a laser. It is possible to create components with sophisticated geometry that would be impossible to create using traditional methods without spending a significant amount of time, money, and resources. There is no need for costly tooling, which allows for the rapid manufacture of one-of-a-kind designs.

Adopters must introduce new product strategies for product qualification, quality assurance, production, and post-processing requirement to implement LPBF in industry.Adeyemiet.al. (2018) discovered parameters to be critical in the changing characteristics of the powder bed-based laser additive manufacturing process. This paper provides an overview of the selective laser sintering and selective laser melting processes used in the powder bed laser additive manufacturing of stainless steel.For manufacturing items with complicated structures, laser powder bed fusion is the ideal AM process. A laser beam selectively melts the powder layer. The platform is then gradually lowered before a new powder coating is applied. The laser beam melting operation is then repeated. DMLS is a trademark of EOS GmbH, a German additive manufacturing company that works identically to SLM. Despite the use of the term "sintering," full melting occurs. DMLS is a 3D printing technology that utilizes a computer-controlled, high-power laser beam to melt and fuse layers of metallic powder together. Direct metal laser sintering (DMLS) is a 3D printing technology used in industry to make fully functional quick metal prototypes and production parts.A variety of metals are employed to develop final products that can be employed in aerospace, biomedical, electric vehicles, and the gas and oil industries.

Laser Powder Bed Fusion has several advantages, notably reduced material waste and cost (superior buy-to-fly ratio), shortened development timelines for production, Rapid prototyping and low-volume production are achieved. Capable of producing functionally graded components, Parts are fully customised on a batch-by-batch basis, eliminating set designs. When compared to other additive manufacturing technologies, it has a high resolution. Unmelted powder can be recycled effectively. The ability to join a broad array of material grades, such as ceramics, glass, plastics, metals, and alloys, Elimination of the requirement for machining fixtures. Mahmoudi, M.et.al(2017) analysed the influence of four major elements on the mechanical characteristics and microstructural features of 17-4 precipitation hardening (PH) stainless steel: building orientation, heat treatment (solution annealing and ageing), thermal history, and process parameters (SS).Due to its combination of high tensile strength, high toughness, and high corrosion resistance at temperatures below 315°C (Lin et al., 2012), 17-4 PH SS is one of the most widely used types of PH SSs (Smith, 1981), making it suitable for applications such as pump enclosures and steam turbine shafts and blades, for which AM is a worthy choice for fabrication due to their complex geometries. Mahmoudi, M.et.al(2017)The goal of this work is to analyze the influence of four major elements on the mechanical characteristics and micro structural features of 17-4 precipitation hardening (PH) stainless steel: building orientation, heat treatment (solution annealing and ageing), thermal history, and process parameters (SS).Gratton, Alexander(2012) revealed that when compared to typical procedures, the mechanical characteristics of 17-4PH stainless steel are fairly good in the unprocessed form. If a precipitation hardened stainless steel component manufactured using DMLS is required at this time, it is advised that 17-4PH stainless is not yet ready for usage.Gu.et.al stated the effects of energy density on the porosity and microstructure of SLM 17-4PH stainless steel pieces are investigated in this research.Rebecca F. Schalleret.al(2017) compared traditional wrought material, the corrosion susceptibility of a laser powder bed fusion (LPBF) additively generated alloy, UNS S17400 (17-4 PH), was investigated. A reduction in the greater range of porosity caused by a lack of particle fusion, whether achieved by processing or post-processing treatments, would be expected to significantly improve corrosion resistance.Because of their excellent weldability and their austenitic/martensitic microstructure, PH SS have been widely used in metal-based AM. Mahmoudi, M.et.al(2017).Analyzing and describing SLM 17-4 PH SS components has recently piqued the interest of researchers. Jerrard et al. (2009) discovered metastable austenite in SLM-fabricated 17-4 PH SS components. They conducted some experimental research on powder mixes for the SLM technique, which resulted in unique architectures when powder combinations of austenitic 316L SS and martensitic 17-4 PH SS with varied composition ratios were used. Facchini et al. (2010) examined a mainly austenitic 17-4 PH SLM SS with excellent work hardening. The phase composition of the component was reported to be 72% extensively faulted austenite and 28% strongly dislocated and twinned martensite. Murr et al. (2012) studied 17-4 PH SS powders generated by atomization in either argon or nitrogen atmospheres, which corresponded to martensitic or mainly austenitic powders, respectively. Several 17-4 PH SS components were made. Because argon has a lower thermal conductivity than nitrogen, the authors stated that the products were martensitic using either an austenitic or martensitic pre-alloyed 17-4 PH SS powder. Murr et al. (2012) investigated the production of metastable austenite and its transition to martensite during SLM of 17-4 PH SS powders. It was demonstrated that depending on the powder composition, SLM settings, and heat treatment, the microstructure and phase compositions of metal alloy components produced by SLM might differ significantly from those generated by traditional techniques. Gu et al. (2013) investigated the effect of energy density on the microstructure and porosity of 17-4 PH SS SLM components. However, the wear properties of the SLM processed parts have only rarely been reported.

To suggest a material in any field of application, it is necessary to run numerous physical, chemical, mechanical, and tribological tests on it. Wear is the term used to describe material removal in the main body of tribology. They were classified into many types based on various means, including abrasion, adhesion, erosion, chemical, fretting wear, and corrosion. Wear is a result of surface interactions, more precisely the removal and distortion of material as a result of mechanical action on one surface by another.

2. Experimentation

2.1 Preparation of 17-4 PH SS alloy

The 17-4 PH SS alloy specimen was printed using PHILLIPS, EOS M 290 metal 3D printer having building volume of 250 mm x 250 mm x 325 mm. The machine has Yb-fiber laser source with 400 W, precision optics of F-theta-lens, scan speed of 7.0 m/s, focus diameter of 100 µm, power supply of 32 A and compressed air supply of 7,000 hPa. The fabrication was done based on the procedure followed. A direct melt laser sintering method was followed to print the 17-4 PH SS alloy. Figure 1(a) shows the EOS M 290 machine used in this present study. Figure 1(b) shows the build direction model and geometry. Table 1 shows the chemical compositions of the 17-4 PH SS alloy.

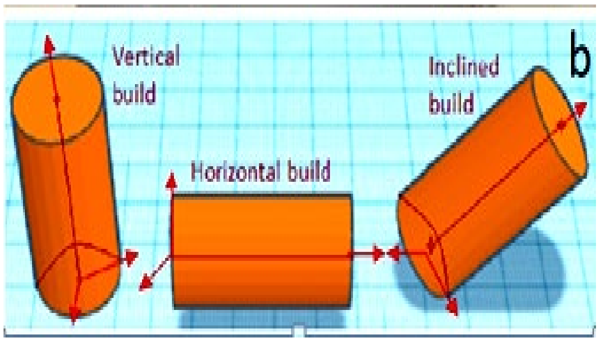

Figure 1 (a) Metal 3D printing machine used and (b) Build geometry, Pooja Angolkaret.al

Figure.1(c) Pin-on disc equipment used.

Table 1. Chemical composition of 17-4 PH SS alloyLPBF

Chromium	Nickel	Copper	Silicon	Manganese	Phosphorus	Sulphur	Carbon	Nb+Ta	Fe
16.25	4	4	1	1	0.040	0.030	0.07	0.3	Balance

2.1.1 Surface finishing process

Surface finishing was performed on printed 17-4 PH SS alloy test specimens in various build directions. In order to evaluate how the surface finished 17-4 PH SS alloy products are acting under wear loads, three distinct types of surface finishing grits, namely rough finish, medium finish, and fine finish were used. Since those products are employed in the aircraft industry, their assembly calls for greater surface polish. Rough, medium, and fine grit sandpaper in sizes 60, 120, and 240 were used in this operation to polish the surface. For a good result, the finishing process took around 20 minutes.

Fig 2 shows the variation of surface roughness w.r.t. surface finish conditions. It is noted that the as-printed 17-4 PH SS alloy gives surface roughness values of9.745,9.869and7.582 µm for horizontal, vertical and inclined build direction respectively surface finish of 1.425, 1.603 and 1.582µm for rough finish, 0.902, 0.918 and 0.862 µm for medium finish and 0.442, 0.57and 0.451 µm for fine finish respectively.

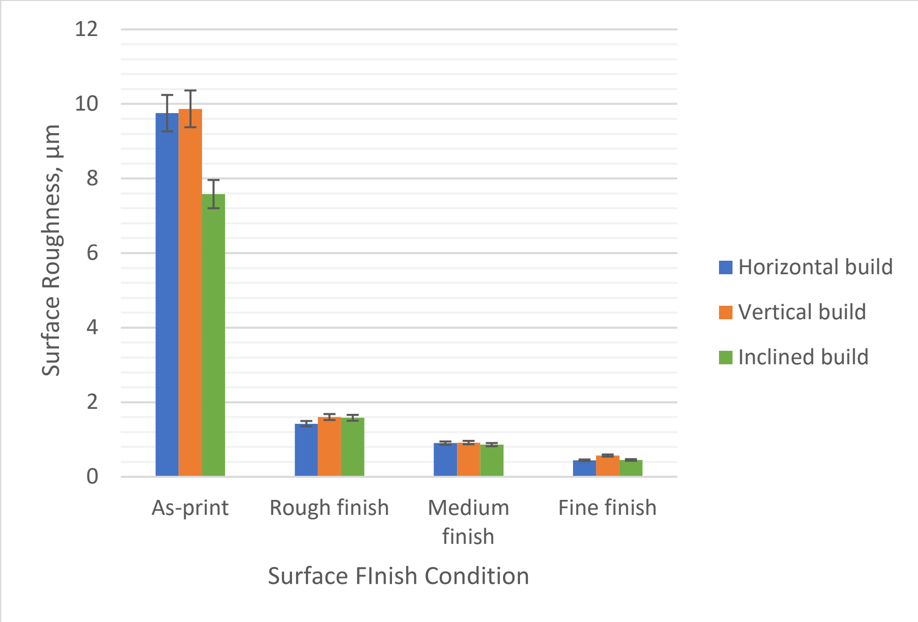

Figure 2. variation of surface roughness w.r.t. surface finish conditions

2.2 Characterization

Testing for surface roughness was performed on the printed 17-4-PH SS alloy with a completed surface. The completed surfaces were evaluated using a Mitutoyo surface roughness SJ 210. Similar to this, the pin-on-disc as shown in Fig 1 c, Ducom POD 4.0 was used to evaluate the wear characteristics of polished 17-4-PH SS alloy. As process parameters, a 10N applied stress, a 1000m sliding distance, a 30min rubbing period, and an ambient working temperature were used.2T engine oil was used as the lubricant to evaluate the wear behaviour under lubricated conditions. Additionally, the optical microscope Moticam 20 in China was used to examine the microstructure of worn surfaces for changes in grain structure both before and after abrasion. Similarly, the HITACHI, S1500, JAPAN scanning electron microscope was used to analyse the worn surface fractograph.

3. Results and Discussion

3.1 Wear Behavior

3.1.1 COF

Figure 3 shows the coefficient of friction values of various build direction performed on printed17-4 PH SS alloy. It is noted that the as-printed17-4 PH SS alloy gives a COF of 0.53, 0.52 and 0.52. For all three orientations of the 17-4 PH SS alloy, a rise in COF was seen. This notable difference is really what causes the layer interference effect in the build position and material solidification [14]. However the polished surfaces of the printed 17-4 PH SS alloy cause a significant COF reduction. For finely finished 17-4 PH SS alloy that was printed horizontally and vertically, reductions of 43 and 51.9% were found. The cause of the increased sliding velocity of the fine polished surface is the decrease in COF. Zai, Le et.al 2020.

However, the COF decreased from rough to medium finish while selecting 240grit size for fine finishing. This reduction is the reason of the molecules of the 17-4 PH SS alloy having a higher surface affinity and less subsurface hardening.

Thus, better high adhesion wear loss and thermal erosion of base material result from increased adhesion with the wear disc. Asaduzzaman Chowdhury et.al. It has been found that the worn surface with better finish raised the COF, indicating that exceptionally smooth surfaces have a high surface energy and a high adhesive nature. As a result, there is more friction between the work piece and the abrasion wheel. This outcome was caused by the high surface tension and surface energy of a highly smoothed surface. It is also noted that the inclined built, fine finished17-4 PH SS alloy shows lesser COF of 0.22 among all build directions. This shows that there is less surface adhesion. This is a result of the melted 17-4 PH SS alloy's homogeneous filling, solidification, and cavitations effects at the moment of printing Zhang 2020,J. A. Slotwinski 2014.

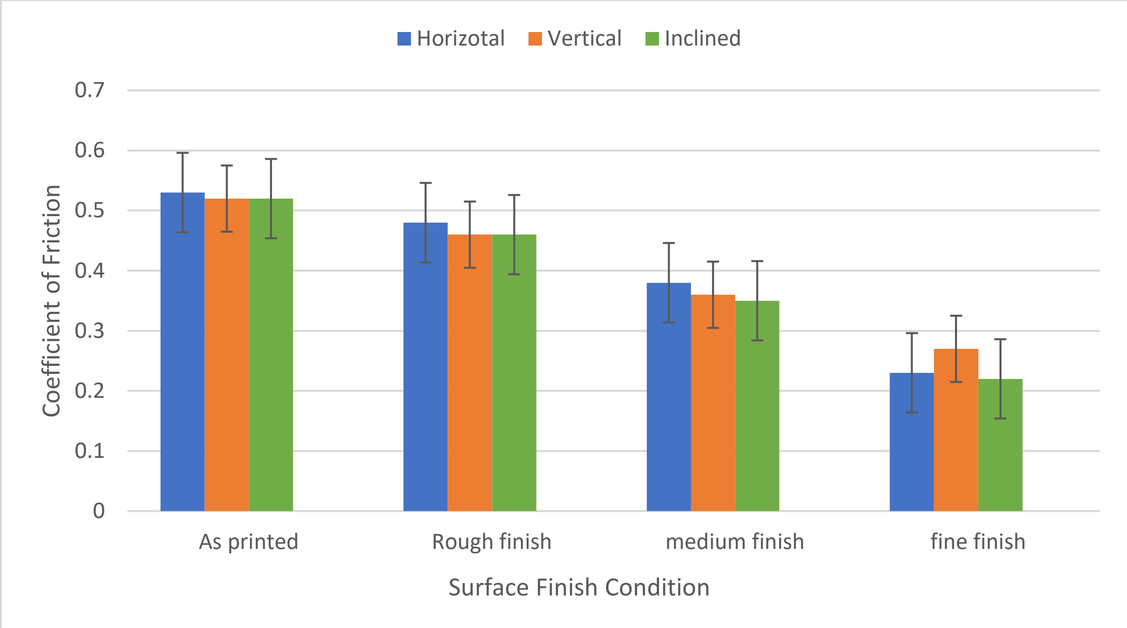

Figure 3: coefficient of friction values

3.1.2 Wear Rate

Figure 4 shows the specific wear rate of various build direction of 17-4- PH SS alloy. It is noted that the as-printed 17-4- PH SS alloy using LPBF method gives a notable wear loss% of10.99, 6.41, 3.52 for as-printed 17-4- PH SS alloy via horizontally, vertically and inclined direction. The horizontal built 17-4- PH SS alloy giving higher wear loss than the vertically and inclined. This is because of creation of high rough surface during the printing time. It is further noted that the polished surfaces of printed17-4- PH SS alloy as rough, medium and fine format giving substantial improvement in wear resistance. A wear loss % of 6.33, 2.39, 1.99 in rough finish, 6.92, 1.44, 1.39 in medium finish, 0.63, 0.89, 0.8 in fine finish respectively. Among all the build directions, the inclined printed 17-4- PH SS alloy possesses lesser wear loss %. This is an outcome of the material being filled uniformly and solidifying at a faster rate due to the large surface area. Because of the homogeneous layering and smooth surface, there is less wear loss throughout the abrasion process. The wear resistance is increased by this occurrence. The 17-4-PH SS alloy has a higher degree of finish due to excellent finishing, which results in a higher coefficient of friction between the sliding surfaces. As a result, adhesion and thermal erosion are more likely to occur, which eventually makes the two- and three-body abrasion phenomenon stronger. The highly polished surface's high surface energy increased the adhesion between the sliding surface and the abrasion disc, which raised the adhesion wear loss. Through three body wear mechanisms, this debris during abrasion adhered between the sliding surfaces and created additional wear loss. Barthelmie, R.J. et.al 2020, Nitesh Vashishthaet.al 2014.

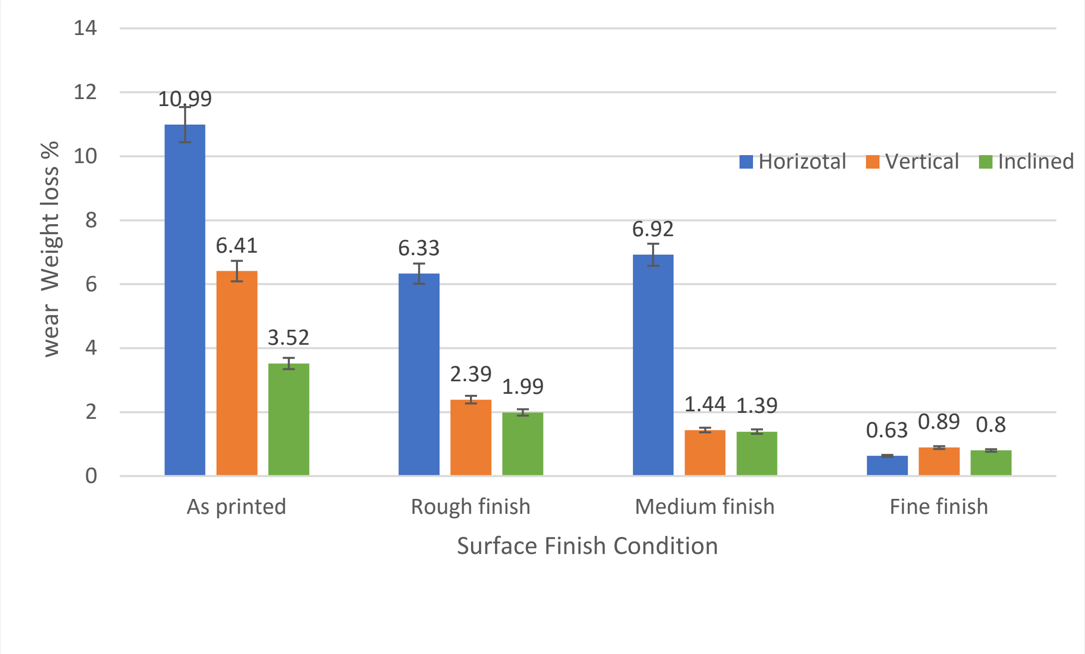

Figure 4: Wear weight loss % of printed 17-4 PH SS alloy

3.2 Microstructural characterization:

Fig. 5a–c shows the SEM microstructure of the additively manufactured (AM) 17-4 PH specimens in all the build directions. The as-received 17-4 PH microstructure features lath martensite, residual austenite, and fine dispersion of NbC carbides in the matrix. Columnar grains that have grown and oriented themselves along the melt pool's temperature gradient would be seen in the as-printed 17-4 PH alloy. In a face-centered cubic (fcc) or body-centered cubic (bcc), this epitaxial growth takes place in the easy-growth direction, i.e., 100>, because the four close-packed (111) planes are symmetrically located around the 100> axes, which require the longest time to solidify, and as an outcome, serve both to drag and guide the solidifying grain. Some of these columnar grains have lengths of over 100 m and have stretched from one melt-pool to the other. Some inclusions are also observed in the microstructure as shown by arrow in Fig. 5a-c.

The reduction of surface roughnesses via polishing process possesses fine microstructure. There is no debris formation indicating strong harder surface after the sufficient runs. The SEM micrographs of worn surface of horizontally build Figure 6a-b, Material flaking occurs throughout the abrasion process because of this rough finish. The adhesion and erosive wear phenomenon dominate on the fine polished surface because it has higher surface tension, which makes for easier high material removal. More scars are visible, most likely as a result of three different body abrasion mechanisms. Sınmazçeliket.al 2020. The Horizontal printed and medium finishes figure 6a, 17-4 PH SS alloy shows higher scar on the worn track whereas the rough and fine finished surfaces show reasonably higher wear resistance and structural stability. Moreover, in all surface finished conditions the inclined build direction of build direction gives remarkably less grooves and debris than others. This phenomenon is the reason for highly homogeneous build mechanism, which produces harder and stronger build interface between layers Sınmazçeliket.al 2020. Thus gives lesser wear loss and COF. Moreover, it has been reported in other studies that samples fabricated vertically typically contain more porosity compared to those built horizontally. Zai, Le.et.al 2020.

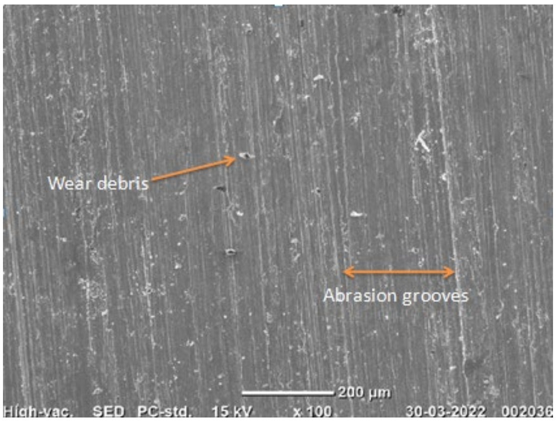

Figure 5a: As built-H

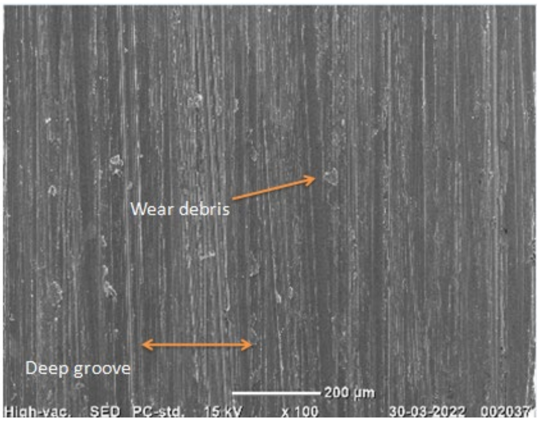

Figure 5b: As built-I

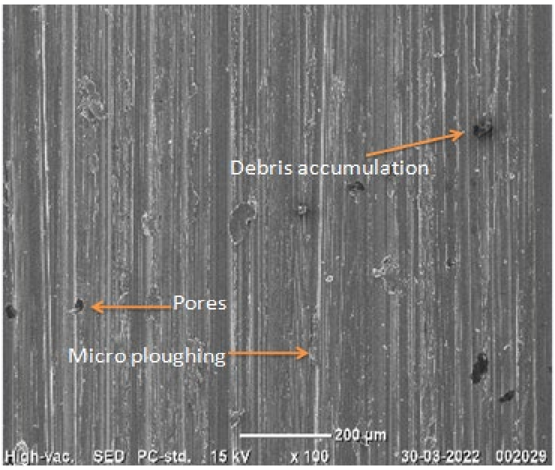

Figure 5c: As built-V

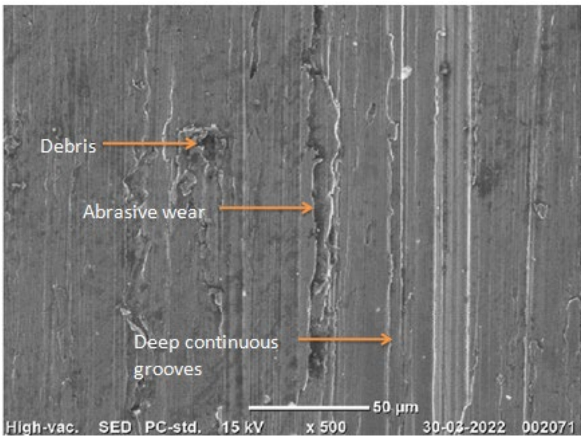

Figure 6a: Medium finish- Horizontal built

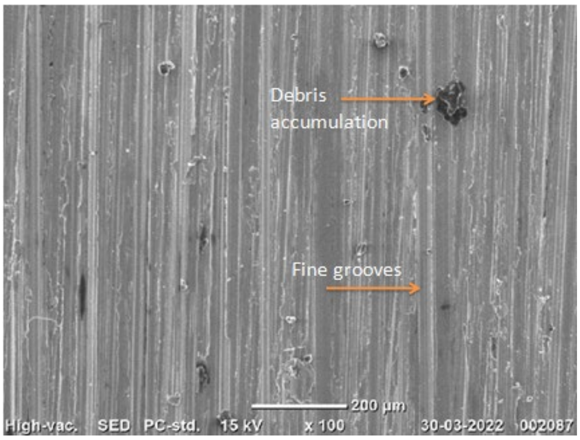

Figure 6b: Fine Finish –Horizontal built

4. Conclusion:

This study investigated the tribology behavior of additively manufactured 17-4 PH SS specimens via LB-PBF process subjected to different polishing conditions. The results obtained from a ball on disk tribometer experiment were used to evaluate the friction and wear properties in lubricated conditions. The following conclusions can be drawn based on the experimental results and observation:

1. LB-PBF 17-4 PH SS as-built specimens have high wear rate as compared to polished conditions. This is probably due to the higher hardness of LB-PBF 17-4 PH SS.

2. Medium finish- Horizontal built LB-PBF 17-4 PH SS possesses higher wear rate as compared to rough and fine finished samples. This is attributed to the lath martensite and austenite formed on the surface result of higher surface roughness of LB-PBF specimens.
3. Fine Finish –Horizontal built specimens showed least wear loss, but on an average the inclined built specimens in all polishing conditions showed least wear loss.
3. Adhesion was the dominant wear mechanism, while abrasion and surface fatigue were the wear mechanisms.

In closing, the findings of this study indicate that as-built samples show more wear loss, and hence cannot be used directly in application without polishing. Wang, T et.al. 2015.

Acknowledgement:
The authors would like to thank **Dr.T.Ram Prabhu**, Scientist F, DRDO Bangalore, for his technical support in conducting wear testing and microstructural study.

Conflict of interest:
Authors hereby confirmed that there is no conflict of interest.

Funding:
There is no funding received for this research.

Data availability
There is no data availability for this research. The data is private.

References:
A. Gaard, P. Krakhmalev, and J. Bergstrom, Microstructural Characterization and Wear Behavior of (Fe, Ni)-TiCMMc Prepared by DMLS, *J Alloys Compd*., 2006, 421, p 166–171.

A. Meyveci, I. Karacan, U. Caligulu, and H. Durmus, Pin-on Disc Characterization of 2xxx and 6xxxAluminum Alloys Aged Precipitation Age Hardening, *J. Alloys Compd.,* 2010, 491, p 278–283

Adeyemi, A., Akinlabi, E.T. and Mahamood, R.M., 2018. Powder bed based laser additive manufacturing process of stainless steel: A review. *Materials Today: Proceedings*, 5(9), pp.18510-18517.

Amanov, Auezhan (2021). Advancement of tribological properties of Tiâ“6Alâ“4V alloy fabricated by selective laser melting. *Tribology International, 155(), 106806–.* doi:10.1016/j.triboint.2020.106806

Amarendra H. J.a* ,Prathap M. S.b , Karthik S.c , Darshan B. M.d , Devaraj d , Girish P. C. d , Aruna V. T. d. Combined Slurry and Cavitation Erosion Resistance of Hvof Thermal Spray Coated Stainless Steel, *5th International Conference of Materials Processing and Characterization (ICMPC 2016).*Amarendra H. J et al./ Materials Today: Proceedings 4 (2017) 465–470

Asaduzzaman Chowdhury, Mohammad (2019). *Friction, Lubrication and Wear* || Tribological and Wear Behavior of Metal Alloys Produced by Laser Powder Bed Fusion (LPBF). *, 10.5772/intechopen.77584(Chapter 6), –.* doi:10.5772/intechopen.85167

Benarji, K., Ravi Kumar, Y., Jinoop, A.N. et al. Effect of Heat-Treatment on the Microstructure, Mechanical Properties and Corrosion Behaviour of SS 316 Structures Built by Laser Directed Energy Deposition Based Additive Manufacturing. *Met. Mater. Int.* **27,** 488–499 (2021). https://doi.org/10.1007/s12540-020-00838-y

Benarji, Koyilada; kumar, Yennam Ravi; Ashwin, Pawar (2020). Numerical simulation and experimental study on austenitic stainless steel by laser assisted metal deposition (L-MD*). Materials Today: Proceedings, (), S2214785320340402–.* doi:10.1016/j.matpr.2020.05.460

Barthelmie, R.J.; Letson, F.W.; Ahsan, S.N.; Barbaria, D.K.; Barrera, C.S.; Crear, A.; Dudley, L.C.C.; Garell, M.; La Spisa, E.J.; Li, S.; Mishr, A.; Paranjape, A.R.; Rambaran, S.; Shah, A.; Singh, A.; Hu, W.; Pryor, S.C. (2020). Wind turbine blade leading-edge erosion: laboratory experiments and image processing under an engaged learning experience. *Journal of Physics: Conference Series*, 1452(), 012046–. doi:10.1088/1742-6596/1452/1/012046

C.A.SchuhT.G.NiehT.Yamasaki,Hall–Petch breakdown manifested in abrasive wear resistance of nanocrystalline nickel. *Scripta Materialia* ,Volume 46 Issue 10.

Cherry, J. A.; Davies, H. M.; Mehmood, S.; Lavery, N. P.; Brown, S. G. R.; Sienz, J. (2015). Investigation into the effect of process parameters on microstructural and physical properties of 316L stainless steel parts by selective laser melting. *The International Journal of Advanced Manufacturing Technology*, 76(5-8), 869–879. doi:10.1007/s00170-014-6297-2

Cheruvathur, Sudha; Lass, Eric A.; Campbell, Carelyn E. (2016). Additive Manufacturing of 17-4 PH Stainless Steel: Post-processing Heat Treatment to Achieve Uniform Reproducible Microstructure*. JOM, 68(3), 930–942.* doi:10.1007/s11837-015-1754-4

D.H. Jeong, U. Erb, K.T. Aust, and G. Palumbo, The Relationship Between Hardness and Abrasive Wear Resistance of Electrodeposited Nanocrystalline Ni–P Coatings, *Scr. Mater*., 2003, 48, p 1067–1072.

Dawei Guo, Chi Tat Kwok, Lap Mou Tam, Dawei Zhang, Xiaogang Li, Hardness, microstructure and texture of friction surfaced 17-4PH precipitation hardening stainless steel coatings with and without subsequent aging, *Surface and Coatings Technology,* Volume 402, 2020, 126302, ISSN 0257-8972, https://doi.org/10.1016/j.surfcoat.2020.126302

Ebara, Ryuichiro (2016). The influence of metallurgical factors on corrosion fatigue strength of stainless steels. *Procedia Structural Integrity*, 2(), 517–524. doi:10.1016/j.prostr.2016.06.067

Facchini, Luca & Vicente, Nerio&Lonardelli, Ivan &Magalini, Emanuele &Pierfrancesco, Robotti& Molinari, Alberto. (2010). Metastable Austenite in 17–4 Precipitation-Hardening Stainless Steel Produced by Selective Laser Melting. *Advanced Engineering Materials*. 12. 184-188. 10.1002/adem.200900259.

Godec, Damir; Cano, Santiago; Holzer, Clemens; Gonzalez-Gutierrez, Joamin (2020). Optimization of the 3D Printing Parameters for Tensile Properties of Specimens Produced by Fused Filament Fabrication of 17-4PH Stainless Steel. *Materials,* 13(3), 774–. doi:10.3390/ma13030774

González, M.A.; Rodríguez, E.; Mojardín, E.; Jiménez, O.; Guillen, H.; Ibarra, J. (2017). Study of the erosive wear behaviour of cryogenically and tempered WC-CoCr coating deposited by HVOF. *Wear*, 376-377(), 595–607. doi:10.1016/j.wear.2016.12.061

Gorsse, Stéphane; Hutchinson, Christopher; Gouné, Mohamed; Banerjee, Rajarshi (2017). Additive manufacturing of metals: a brief review of the characteristic microstructures and properties of steels, Ti-6Al-4V and high-entropy alloys. *Science and Technology of Advanced Materials*, 18(1), 584–610. doi:10.1080/14686996.2017.1361305

Gratton, Alexander. (2012). Comparison of Mechanical, Metallurgical Properties of 17-4PH Stainless Steel between Direct Metal Laser Sintering (DMLS) and Traditional Manufacturing Methods.

Gu, Hengfeng& Gong, Haijun& Pal, Deepankar& Rafi, H. & Starr, Thomas & Stucker, Brent. (2013). Influences of Energy Density on Porosity and Microstructure of Selective Laser Melted 17-4PH Stainless Steel. 24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013.

Gu, Hengfeng& Gong, Haijun& Pal, Deepankar& Rafi, H. & Starr, Thomas & Stucker, Brent. (2013). Influences of Energy Density on Porosity and Microstructure of Selective Laser Melted 17-4PH Stainless Steel. *24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013*.

H.R. Lashgari, C. Kong, E. Adabifiroozjaei, S. Li, Microstructure, post thermal treatment response, and tribological properties of 3D printed 17-4 PH stainless steel, *Wear,* Volumes 456–457, 2020, 203367, ISSN 0043-1648, https://doi.org/10.1016/j.wear.2020.203367

H.R. Lashgari, Y. Xue, C. Onggowarsito, C. Kong, S. Li, Microstructure, Tribological Properties and Corrosion Behaviour of Additively Manufactured 17-4PH Stainless Steel: Effects of Scanning Pattern, Build Orientation, and Single vs. Double scan, *Materials Today Communications*, Volume 25, 2020, 101535, ISSN 2352-4928, https://doi.org/10.1016/j.mtcomm.2020.101535.

Haghdadi, Nima; Laleh, Majid; Moyle, Maxwell; Primig, Sophie (2020). Additive manufacturing of steels: a review of achievements and challenges. *Journal of Materials Science*, (), –. doi:10.1007/s10853-020-05109-0

Haghdadi, Nima; Laleh, Majid; Moyle, Maxwell; Primig, Sophie (2020). Additive manufacturing of steels: a review of achievements and challenges. *Journal of Materials*

I. MathohobE. T. Akinlabi, N. Arthur, M. Tlotleng, N.W. Makoana, The effects of LENS Process parameters on the behaviour of 17-4 PH stainless steel, *TMS 2020 149th Annual Meeting and Exhibition Supplemental Proceedings.*

J. A. Slotwinski, E. J. Garboczi, P. E. Stutzman, C. F. Ferraris, S. S. Watson, and M. A. Peltz(2014). Characterization of Metal Powders Used for Additive Manufacturing. *Journal of Research of the National Institute of Standards and Technology*, 119(), 460–. doi:10.6028/jres.119.018

J. Tacq, L-PBF and Heat Treatment of 17-4PH steel, Sirris (2021) *INSIDE Metal AM project"*

J Justin Maria Hillary[3,1], R Ramamoorthi[2] and Samson Jerold Samuel Chelladurai[2], Dry sliding wear behaviour of Al6061–5%SiC—TiB_2 hybrid metal matrix composites synthesized by stir casting process,*Materials Research Express*, Volume 7, Number 12Citation J Justin Maria Hillary *et al* 2020 *Mater. Res. Express* 7 126519

K. Niranjan and P.R. Lakshminarayanan, Dry Sliding Wear Behaviour of In Situ Al–TiB2 Composites, Mater. Design, 2013, 47, p 167–173.

Kumar, Sandeep; Manani, Sunil; Nikunj, Patel; Pradhan, Ajaya Kumar (2020). Synthesis and air jet erosion wear behavior of aluminum â" Al3Ti In-Situ composite. *Materials Today: Proceedings*, (), S2214785320343133–. doi:10.1016/j.matpr.2020.05.701

Li, Ping; Zhao, Yanjie; Wang, Libo (2019). *Research on Erosion-Corrosion Rate of 304* Stainless Steel in Acidic Slurry via Experimental Design Method*. Materials, 12(14), 2330–.* doi:10.3390/ma12142330

Mahmoudi, M., Elwany, A., Yadollahi, A., Thompson, S.M., Bian, L. and Shamsaei, N. (2017), "Mechanical properties and microstructural characterization of selective laser melted 17-4 PH stainless steel", *Rapid Prototyping Journal,* Vol. 23 No. 2, pp. 280-294. https://doi.org/10.1108/RPJ-12-2015-0192

Murr, Lawrence E.; Martinez, Edwin; Hernandez, Jennifer; Collins, Shane; Amato, Krista N.; Gaytan, Sara M.; Shindo, Patrick W. (2012). Microstructures and Properties of 17-4 PH Stainless Steel Fabricated by Selective Laser Melting. *Journal of Materials Research and Technology, 1(3), 167–177.* doi:10.1016/S2238-7854(12)70029-7

Nitesh Vashishtha, R.K. Khatirkar, S.G. Sapate, Tribological behaviour of HVOF sprayed WC-12Co, WC-10Co-4Cr and Cr3C2−25NiCr coatings, *Tribology International*, Volume 105, 2017, Pages 55-68, ISSN 0301-679X, https://doi.org/10.1016/j.triboint.2016.09.025

Otto, M., Pilz, S., Gebert, A., Kühn, U., &Hufenbach, J. (2021). Effect of Build Orientation on the Microstructure, Mechanical and Corrosion Properties of a Biodegradable High Manganese Steel Processed by Laser Powder Bed Fusion. *Metals*, *11(6), 944.* doi:10.3390/met11060944

Pal, Snehashis; Tiyyagura, Hanuma Reddy; Drstvenšek, Igor; Kumar, Cheruvu Siva (2016). The Effect of Post-processing and Machining Process Parameters on Properties of Stainless Steel PH1 Product Produced by Direct Metal Laser Sintering. *Procedia Engineering,* 149(), 359–365. doi:10.1016/j.proeng.2016.06.679

Patrick Köhnen, Simon Ewald, Johannes Henrich Schleifenbaum, Andrey Belyakov, Christian Haase, Controlling microstructure and mechanical properties of additively manufactured high-strength steels by tailored solidification, *Additive Manufacturing*, Volume 35, 2020, 101389, ISSN 2214-8604, https://doi.org/10.1016/j.addma.2020.101389.

Pierre Auguste1 , Arnold Mauduit1 , Lionel Fouquet1 , Sébastien Pillot1. Tudy On 17-4 Ph Stainless Steel Produced By Selective Laser Melting. *U.P.B. Sci. Bull., Series B, Vol*. 80, Iss. 4, 2018 ISSN 1454-2331

Pooja Angolkar, Manzoor Hussian Effect of build direction and surface finish on wear behavior of AlSi10Mg alloy casted by laser powder bed fusion, , *Metall. Res. Technol.* 119 (4) 409 (2022) DOI: 10.1051/metal/2022048

Rebecca F. Schaller, Jason M. Taylor, Jeffrey Rodelas, Eric J. Schindelholz; Alex of Powder Bed Fusion Additively Manufactured 17-4 PH Stainless Steel. *CORROSION* 1 July 2017; 73 (7): 796–807. doi: https://doi.org/10.5006/2365

S. Jacobson and N. Axen, Transition in the Abrasive Wear Resistance of Fiber- and Particles-Reinforced Aluminium*, Wear,* 1994, 178, p 1–7.

S. Suresh, N.S.V. Moorthi, S.C. Vettivel, and N. Selvakumar, Mechanical Behavior and Wear Prediction of Stir Cast Al–TiB2 Composites Using Response Surface Methodology, *Mater. Design*, 2014, 59, p 383–396.

S.C. Tjong, S.Q. Wu, and H.G. Zhu, Wear Behavior of In Situ TiB2Al2O3/Al and TiB2Al2O3/Al-Cu Composites, Compos. *Sci. Tehcnol*., 1999, 59, p 1341–1347 .

Saboori, A., Gallo, D., Biamino, S., Fino, P. and Lombardi, M., 2017. An overview of additive manufacturing of titanium components by directed energy deposition: microstructure and mechanical properties. *Applied Sciences*, *7*(9), p.883.

Sanjeev KC, P.D. Nezhadfar, C. Phillips, M.S. Kennedy, N. Shamsaei, R.L. Jackson, Tribological behavior of 17–4 PH stainless steel fabricated by traditional manufacturing and laser-based additive manufacturing methods, *Wear*, Volumes 440–441, 2019, 203100, ISSN 0043-1648, https://doi.org/10.1016/j.wear.2019.203100

Satish R.; Bhatt, Dhananjay V.; Menghani, Jyoti V. (2017). Recent Research Status on Erosion Wear – An Overview. *Materials Today: Proceedings, 4(2), 257–266.* doi:10.1016/j.matpr.2017.01.020

Shrestha, Rakish, Amanda Sterling, Brandon Lessel, Nam Phan, Mohammad Reza VaziriSereshk, and NimaShamsaei. "Mechanical Behavior of Additively Manufactured 17-4 PH Stainless Steel Schoen Gyroid Lattice Structure*." Solid Free. Fabr* (2018): 716-723

Sima Ahmad Alidokht, Phuong Vo, Steve Yue, Richard R. Chromik,Erosive wear behavior of Cold-Sprayed Ni-WC composite coating, *Wear*, Volumes 376–377, Part A, 2017, Pages 566-577, ISSN 0043-1648, https://doi.org/10.1016/j.wear.2017.01.052

Sınmazçelik, Tamer; Fidan, Sinan; Ürgün, Satılmış (2020). Effects of 3D printed surface texture on erosive wear. *Tribology International, 144(), 106110–.* doi:10.1016/j.triboint.2019.106110

Soltani-Tehrani, Arash; Pegues, Jonathan; Shamsaei, Nima (2020). Fatigue Behavior of Additively Manufactured 17-4 PH Stainless Steel: The Effects of Part Location and Powder Re-use. *Additive Manufacturing, (), 101398–.* doi:10.1016/j.addma.2020.101398

T.S. Eyre, Wear Characteristic of Metals, *Tribology International,* 1976, 10, p 203–212

Townsend, A.; Senin, N.; Blunt, L.; Leach, R.K.; Taylor, J.S. (2016). Surface Texture Metrology For Metal Additive Manufacturing: A Review. *Precision Engineering, (), S0141635916300721–* . doi:10.1016/j.precisioneng.2016.06.001

W.C. Oliver and G.M. Phar, An Improved Technique for Determining Hardness and Elastic Modulus Using Load and Displacement Sensing Indentation Experiments, *J. Mater. Res.,* 1992, 7, p 1564–1583

W.E. Frazier, Metal Additive Manufacturing: A Review, *J. Mater. Eng. Perform*., 2014, 23, p 1917–1928.

Wang, T., Zhu, Y.Y., Zhang, S.Q., Tang, H.B. and Wang, H.M., 2015. Grain morphology evolution behavior of titanium alloy components during laser melting deposition additive manufacturing. *Journal of Alloys and Compounds*, *632*, pp.505-513.

Williams Ch., Mistree F., Rosen D., A Functional Classification Framework for the Conceptual Design of Additive Manufacturing Technologies, *Journal of Mechanical Design,* 133 12 (2011)

Wu, Ming-Wei; Huang, Zeng-Kai; Tseng, Chun-Feng; Hwang, Kuen-Shyang (2015). Microstructures, mechanical properties, and fracture behaviors of metal-injection molded 17-4PH stainless steel. *Metals and Materials International*, 21(3), 531–537. doi:10.1007/s12540-015-4369-y

Yu Sun, Rainer J. Hebert, Mark Aindow , Effect of heat treatments on microstructural evolution of additively manufactured and wrought 17-4PH stainless steel. *Jmade* (2018), doi:10.1016/j.matdes.2018.07.015

Zafar, Sunny; Sharma, Apurbba Kumar (2016). Abrasive and erosive wear behaviour of nanometric WC–12Co microwave clads. *Wear*, 346-347(), 29–45. doi:10.1016/j.wear.2015.11.003

Zai, Le; Zhang, Chaoqun; Wang, Yiqiang; Guo, Wei; Wellmann, Daniel; Tong, Xin; Tian, Yingtao (2020). Laser Powder Bed Fusion of Precipitation-Hardened Martensitic Stainless Steels: A Review. *Metals,* 10(2), 255–. doi:10.3390/met10020255

Zai, Le; Zhang, Chaoqun; Wang, Yiqiang; Guo, Wei; Wellmann, Daniel; Tong, Xin; Tian, Yingtao (2020). Laser Powder Bed Fusion of Precipitation-Hardened Martensitic Stainless Steels: A Review. *Metals*, 10(2), 255–. doi:10.3390/met10020255

Zhang, Ying Yang, Sheng Zhao, Yaoyao Fiona, 2020 Manufacturability analysis of metal laser-based powder bed fusion additive manufacturing—a survey 1433-3015, https://doi.org/10.1007/s00170-020-05825-6

Zitelli, ;Folgarait, ; Di Schino, (2019). Laser Powder Bed Fusion of Stainless Steel Grades: A Review. *Metals,* 9(7), 731–. doi:10.3390/met9070731

Zhiheng Hu, Haihong Zhu, Hu Zhang, Xiaoyan Zeng, Experimental investigation on selective laser melting of 17-4PH stainless steel, *Optics & Laser Technology*, Volume 87, 2017, Pages 17-25, ISSN 0030-3992, https://doi.org/10.1016/j.optlastec.2016.07.012

Zhu, Y.Y., Tang, H.B., Li, Z., Xu, C. and He, B., 2019. Solidification behavior and grain morphology of laser additive manufacturing titanium alloys. *Journal of Alloys and Compounds*, *777*, pp.712-716.

Bibliographies

Mrs. Pooja. Angolkar, Research Scholar, JNTU-Hyderabad, has been in the teaching profession with 12 years of experience. She has received Bachelor of Engineering (Mechanical Engineering) from Visvesvariah Technological University, Karnataka in 2009, M.Tech (CAD/CAM) from JNTU Hyderabad in 2013 and pursuing Ph.D in Mechanical Engineering from JNTU Hyderabad. She has taught various subjects at under graduate level and as a supervisor; she has guided two M.Tech and more than twenty-two B.Tech projects. She has participated more than 40 Seminars, Conferences and Workshops of Regional, National and International importance. She has published 15 research articles in peer reviewed journals.

Dr. M. Manzoor Hussain is presently Registrar of Jawaharlal Nehru Technological University, Hyderabad and Professor in Mechanical Engineering Department. Earlier he has served as Director of Admissions for three years, and the founder Principal of constituent college of JNTUH at Sultanpur, Sangareddy District. He was the chairman of Board of Studies of JNTU in Mechatronics Engineering and Automobile Engineering. He has guided over 50 post graduate thesis and supervised 21 PhD scholars and currently 7 research scholars are working under his supervision. His areas of research include composite materials, manufacturing, additive manufacturing, air-conditioning, welding and industrial engineering. He has over 26 years of experience in teaching and administration in various capacities. He has published over 65 papers in peer reviewed journals and National and International conferences. He was awarded the best teacher award by Telangana State Government in the year 2016.

Dr.Qutubuddin S.M., working as Associate Professor, Industrial and Production Engineering Department, P.D.A.College of Engineering, Kalaburagi. He has more than 30 years experience in teaching and research and has published more than 40 papers in International and National journals and Conferences. Under his supervision 01 research scholar has completed PhD and 02 are undergoing. His research interest include Human Factors and Ergonomics, Occupational Health and Safety; Production/Operations Management. He was actively involved in getting NBA accreditation for the department. He is a life member of ISTE, IIPE, IAENG and IEOM Society USA. He is the Faculty Advisor of IEOM Student Chapter at PDACEK. The chapter was awarded the best student chapter three times in various IEOM Annual Conferences at Bangkok 2019, Dubai 2020, and Istanbul 2022. He is serving regularly in various capacities as a Reviewer, Track Chair, Session Chair and Technical Committee member in IEOM International conferences since 2015. He is assigned as Director of IEOM Operations in India. He has been awarded with Best Faculty Advisor Award, Teaching Excellence Award and Distinguished Service Award at IEOM Conferences.