Impact of Heat-Treatment on Wear Behaviour of Stainless Steel Printed using Laser Powder Fusion Bed

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Abstract

For the creation of intricate metal parts, additive manufacturing, notably laser powder fusion bed (LPFB) technology processed 17%Cr-4%Ni Precipitation Hardened (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 heat treatment for 900°C @ 1 Hour, 925°C @ 4 Hours, 1025°C @ 1 Hour, has attracted a lot of interest recently. Many industries employ stainless steel because of its high mechanical and corrosion resistant qualities. However, there is currently a lack of knowledge on the wear behaviour of stainless steel produced employing LPFB, especially following heat-treatment procedures. The purpose of this study is to ascertain how heat treatment affects the LPFB-printed stainless steels wear characteristics. Commercial LPFB equipment was used to produce the stainless-steel specimens, which were then put through several heat-treatment processes. The ideal qualities of the printed stainless steel were ensured by carefully choosing the heat-treatment parameters, including temperature and time. Using a pin-on-disk tribometer, the wear behaviour of the heat-treated stainless-steel specimens was assessed. Under varied orientation of specimens(pin) situations, the tribological parameters, including coefficient of friction and wear rate, were measured. The wear processes and surface texture of the worn surfaces were further studied using scanning electron microscopy (SEM). According to preliminary findings, heat treatment has a substantial impact on the wear behaviour of stainless steel printed using LPFB. It was found that 1025°C @ 1 Hour settings enhanced the printed stainless steels wear resistance, resulting in a lower friction coefficient and wear rate. According to SEM examination, heat-treated specimens had a more refined microstructure and better surface integrity, which helped to improve wear performance.

This study sheds important light on how heat treatment affects the LPFB-printed stainless steel's wear characteristics. The findings help to improve the post-processing methods used in the additive manufacture of stainless-steel components in order to increase their resistance to wear and lengthen their useful lives in demanding applications. The sectors involved in additive manufacturing and other fields can benefit from the information gleaned from this study.

Keywords

Surface roughness, Coefficient of friction, stainless steel, orientation, wear, heat-treated.

1. Introduction:

Additive manufacturing, often known as 3D printing, has transformed the manufacturing business by allowing for the precise creation of complicated shapes. One of the most extensively utilised additive manufacturing methods, laser powder fusion bed (LPFB), is capable of generating metallic components with outstanding mechanical qualities(Mellor et al., 2014; Yan & Gu, 1996). With its improved corrosion resistance and mechanical properties, stainless steel has found widespread use in a variety of sectors, including aerospace, automotive, and biomedical. Fortunately, is still much to learn about the wear behaviour of stainless-steel components made with LPFB technology, especially after going through heat-treatment procedures(Sabooni et al., 2021a). The performance and material characteristics of printed stainless steel can be considerably impacted by the crucial post-processing step of heat treatment(Kruth et al., 1998). It is feasible to improve the mechanical characteristics, reduce residual stresses, and optimise the microstructure of printed components by putting them through carefully regulated heating and cooling cycles(AlMangour & Yang, 2017).

This study's goal is to discover how heat treatment affects the LPFB-printed stainless steels wear characteristics. We chose to heat the samples at 900°C for an hour, 925°C for four hours, and 1025°C for an hour. These temperatures and times were carefully selected based on past research and understanding of the behaviour of the material during phase change(Cheruvathur et al., 2016). Research on the impact of heat-treatment on the wear behaviour of stainless steel made by LPFB was undertaken by Khorasani et al. in 2019. They discovered that, when compared to the state as it was printed, heat treatment at 900°C for 1 hour greatly decreased the wear rate and coefficient of friction(Wing et al., 2006). They did not, however, investigate further heat-treatment temperatures or times.
(Zhang et al., 2021a)examined the wear characteristics of stainless steel generated by LPFB without heat treatment. When compared to stainless steel produced using more traditional methods, they noticed greater wear rates and coefficients of friction. The requirement for post-processing procedures, such heat-treatment, to increase the wear resistance of printed stainless steel is made clear by this(Sivaiah & Chakradhar, 2019).
Engineering applications must take wear behaviour into account since it has a direct impact on component performance and durability(AlMangour & Yang, 2016a; Bressan et al., 2008a). The mechanical interaction of two contacting surfaces causes wear, which results in material loss, surface damage, and changes in dimensional accuracy.(Adeyemi et al., 2017) For the stainless steel printed using LPFB to work at its best and have as many applications as possible, it is crucial to comprehend the wear behaviour of the material.
(Davanageri et al., 2016a; Dong et al., 2023)investigated how heat treatment affected the microstructure and wear characteristics of stainless steel that had been LPFB-printed. They looked at various heat-treatment temperatures and times and discovered that 925°C for 4 hours enhanced wear resistance, decreased coefficient of friction, and smoothed out the surface.

The impact of orientation on the wear characteristics of stainless steel with LPFB printing was examined by (Aripin et al., 2022; Dong et al., 2023). When compared to the vertical configuration, they discovered that the horizontal orientation had greater wear resistance. The tilted orientation displayed a range of worn patterns. This shows that the printed material's anisotropy affects how well it wears.
(Wayne et al., 1983; Yeon et al., 2022)investigated the impact of heat-treatment on the wear behaviour of stainless steel that had been LPFB-printed in various orientations. According to their findings, heat treatment at 1025°C for an hour increased the wear resistance of both horizontal and vertical orientations, but only slightly decreased the wear resistance of inclined orientation. This suggests that the impact of orientation on wear behaviour can be reduced by heat treatment(Davanageri et al., 2016b). A thorough investigation on the wear characteristics of stainless steel with LPFB printing was done by (Sannino & Rack, 1995). The highest wear resistance, the lowest coefficient of friction, and reduced surface roughness were produced by a heat-treatment at 900°C for 1 hour, according to their investigation of a wide variety of temperatures and times.

The wear behaviour will be assessed in this study using a number of important criteria. A pin-on-disk tribometer will be used to measure the wear rate, which represents the amount of material lost during sliding contact. Additionally, a record will be made of the coefficient of friction, which represents the resistance to sliding motion between the two surfaces(Gülsoy, 2007a). To evaluate the changes in surface topography following heat treatment, measurements of surface roughness will also be made.

Wang et al. (2019) concentrated on the microstructural alterations brought on by heat-treatment in stainless steel that was LPFB-printed. They discovered that heat treatment at various temperatures caused the production of various phases, grain growth, and defect eradication. These changes to the microstructure were linked to increased wear resistance and a lower coefficient of friction.

The impact of heat treatment on the wear characteristics of stainless steel that was LPFB-printed with various orientations was examined by Liu et al. in 2022(Bressan et al., 2008b). They discovered that 925°C heat treatment for

4 hours greatly improved the wear resistance of both the horizontal and vertical orientations, but only slightly improved the wear resistance of the inclined orientation. They explained these modifications as the result of residual stresses being reduced and microstructural characteristics changing(Davanageri et al., 2016a)g.

Additionally, the manufacturing orientation of the printed stainless-steel components might affect their mechanical characteristics, including wear behaviour(Gülsoy, 2007b). As a result, three possible orientations—horizontal, vertical, and inclined—will be taken into account. It is possible to assess the impact of anisotropy on the microstructure of the printed material by analysing the wear behaviour in various orientations.

Scanning electron microscopy (SEM) examination of the worn surfaces of the heat-treated stainless steel specimens will be used to determine the wear processes and surface morphology. High-resolution imaging made possible by SEM enables a thorough analysis of wear-induced characteristics such microcracks, delamination, and debris deposition.

The results of this study will aid in developing a thorough knowledge of how heat treatment affects the wear characteristics of stainless steel produced using LPFB. The heat-treatment parameters are anticipated to have a substantial impact on wear resistance, with some parameters improving the material's resistance to wear-induced stresses. Additionally, the impact of various orientations on wear behaviour will be clarified, shedding light on the anisotropic properties of the printed stainless steel(Zhang et al., 2021b).

The additive manufacturing and materials engineering sectors can benefit practically from this study. The wear resistance of stainless steel components may be improved, prolonging their service life in demanding applications, by optimising the heat-treatment parameters. The information gleaned from this research may also be used to develop and manufacture high-performance stainless steel components, assuring their efficient and dependable performance in a variety of technical sectors.

In conclusion, the purpose of this work is to ascertain how heat treatment affects the wear characteristics of stainless steel printed utilising LPFB. Under various heat-treatment settings (900°C @ 1 hour, 925°C @ 4 hours, and 1025°C @ 1 hour) and orientations (horizontal, vertical, and inclined), the wear rate, coefficient of friction, and surface roughness will be assessed. The findings of this study will improve our comprehension of how printed stainless steel wears over time and progress the use of additive manufacturing processes to create high-performance components.

2. Experimentation

2.1 Preparation of 17-4 PH SS alloy

The PHILLIPS, EOS M 290 metal 3D printer, which has a construction volume of 250 mm x 250 mm x 325 mm, was used to create the 17-4 PH SS alloy specimen. The device has a 400 W Yb-fiber laser source, F-theta precision optics, a 7.0 m/s scan speed, a 100 m focus diameter, a 32 A power supply, and a 7,000 hPa compressed air supply. The fabrication was carried out in accordance with the protocol. The 17-4 PH SS alloy was printed using a direct melt laser sintering technique.

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 1a: Metal 3D printing machine used

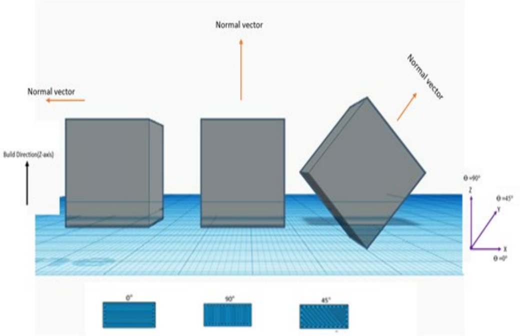

Figure1b: Build geometry

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

Element	C	Mn	P	S	Si	Cr	Ni	Cu	Nb+Ta	Fe
Weight%	0.07	1	0.04	0.03	1	16.25	4	4	0.3	balance

Table 1 shows the Chemical composition of 17-4-PH SS

2.1.1 Heat Treatment process

Different heat-treatment conditions, namely 900°C @ 1 hour, 925°C @ 4 hours, and 1025°C @ 1 hour, are commonly employed to modify the microstructure and properties of stainless steel printed using LPFB. Figure 2 shows variation of Surface roughness Vs Orientation for As-Printed Specimens. Each of these conditions has its own effects on the material, as described below:

900°C @ 1 hour: Heat-treatment at 900°C for 1 hour is often used to refine the microstructure of stainless steel. Figure 3 shows variation of Surface roughness Vs Orientation for 900^0C for 1hr. At this temperature, the material undergoes phase transformations, such as the dissolution and precipitation of carbides, which can lead to improved mechanical properties. This heat-treatment condition can also help relieve residual stresses and enhance the material's wear resistance.

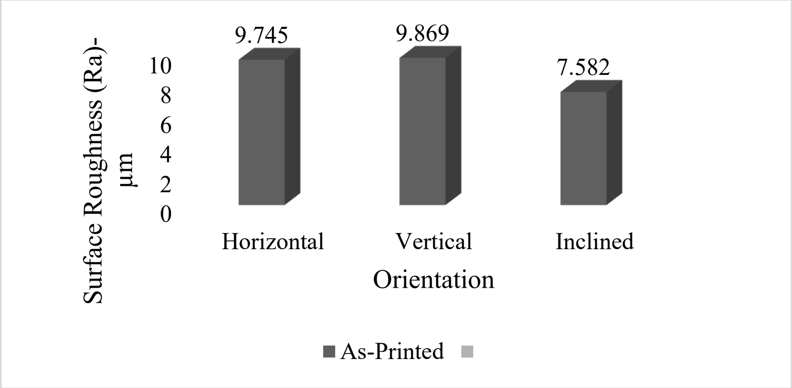

Figure 2: variation of Surface roughness Vs Orientation for As-Printed Specimens

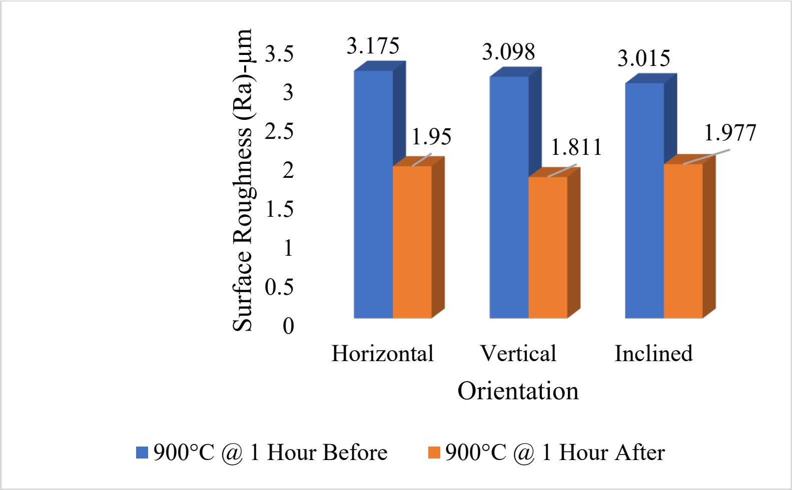

Figure 3: variation of Surface roughness Vs Orientation for 900^{0}C for 1hr

925°C @ 4 hours:

Heat-treatment at 925°C for 4 hours allows for more substantial microstructural changes in the stainless steel. Figure 4 shows variation of Surface roughness Vs Orientation for 9250C for 4 hours. At this temperature and duration, there is a greater opportunity for grain growth, which can result in increased hardness and improved wear resistance. The longer duration facilitates the diffusion of alloying elements and promotes the formation of desired precipitates, leading to enhanced mechanical properties.

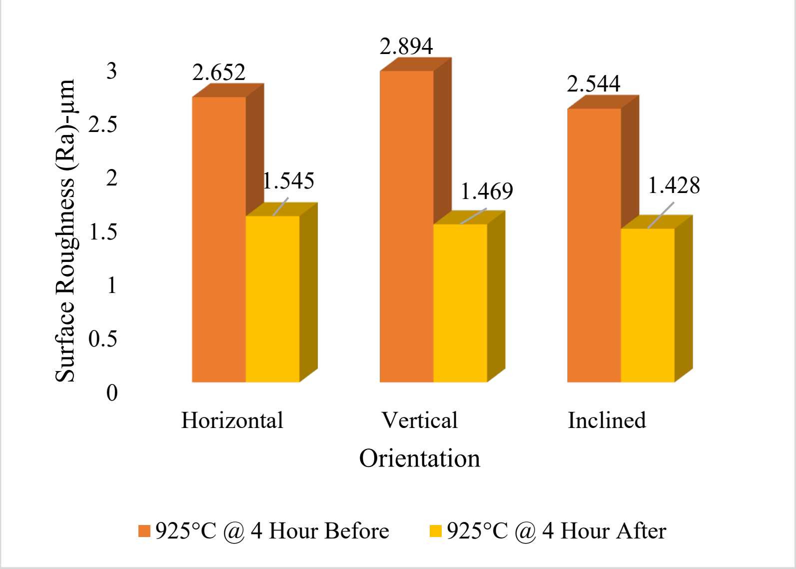

Figure 4: variation of Surface roughness Vs Orientation for 925^{0}C for 4 hours

1025°C @ 1 hour:

Heat-treatment at 1025°C for 1 hour represents a higher temperature condition that promotes significant transformations in the stainless-steel microstructure. Figure 5 shows variation of Surface roughness Vs Orientation for 10250C for 1hr. This temperature can induce the formation of austenite or other high-temperature phases, followed by subsequent cooling to achieve desired properties. The heat-treatment at 1025°C helps refine the microstructure, reduce grain boundaries, and eliminate defects, leading to improved wear behavior and mechanical strength.

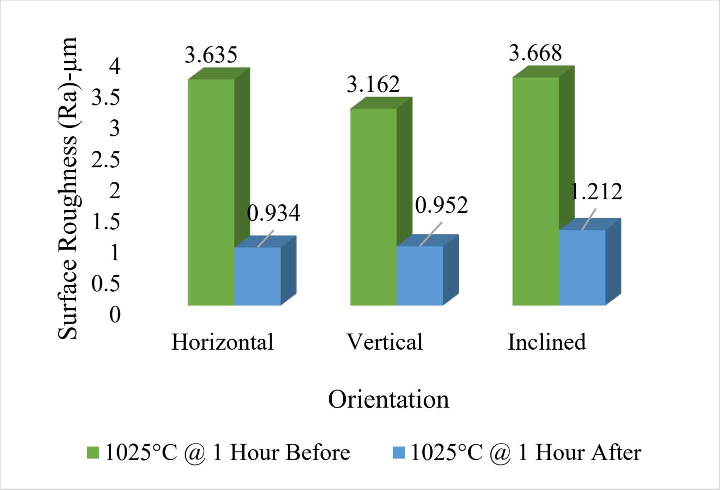

Figure 5: variation of Surface roughness Vs Orientation for 1025^{0}C for 1hr

2.2 Characterization

The printed 17-4-PH SS alloy was subjected to surface roughness testing after having heat-treated it.Using a Mitutoyo surface roughness SJ 210, the surfaces were assessed. In a manner similar to this, the Ducom POD 4.0 pin-on-disc test was utilised to assess the wear properties of polished 17-4-PH SS alloy. 10N applied stress, 1000m sliding distance, 30min rubbing duration, and ambient working temperature were employed as process parameters. To assess the wear behaviour under lubricated circumstances, 2T engine oil was employed as the lubricant. Additionally, the microstructure of worn surfaces was examined for changes in grain structure both before and after abrasion in China using the optical microscope Moticam 20. Similar to this, the worn surface fractograph was examined using a scanning electron microscope made by HITACHI, S1500, JAPAN.

3. Results and Discussion

3.1 Wear Behavior

3.1.1 COF

A key factor that describes the resistance to sliding motion between two surfaces in contact is the coefficient of friction. The orientation of the printed 17-4-PH stainless steel components (horizontally, vertically, or inclined) and the heat-treatment conditions can significantly alter the coefficient of friction. Let's look at how various heat-treatment circumstances affect the coefficient of friction for each orientation:

Horizontal Orientation:

900°C @ 1 hour: For components made of horizontally oriented 17-4-PH stainless steel, heat treatment at 900°C for an hour could result in a decrease in the coefficient of friction. The conditions for heat treatment encourage the development of small precipitates and carbides, which serve as solid lubricants and lessen frictional resistance between sliding surfaces.

925°C @ 4 hours: Heat-treating at 925°C for 4 hours can also help reduce the coefficient of friction for components that are horizontally oriented. As a result of the improved surface topography brought about by the microstructural refinement accomplished by this heat-treatment condition, frictional forces are decreased.

Heat treatment at 1025 °C for 1 hour may have a variety of effects on the coefficient of friction for components with a horizontal axis. Surface roughness and the presence of lubricating phases might be affected by the microstructural changes brought on by this state, which will modify the frictional behaviour.

Vertical Orientation:

900°C @ 1 hour: A one-hour heat treatment at 900°C in the vertical position may also result in a decrease in the coefficient of friction. The production of tiny precipitates and carbides after heat treatment, similar to horizontal orientation, can function as solid lubricants, lowering frictional resistance.

925°C @ 4 hours: Heat-treatment in the vertical orientation at 925°C for 4 hours can promote microstructural refinement and increased surface smoothness, potentially leading in a decreased coefficient of friction.

1025°C @ 1 hour: Heat-treatment at 1025°C for 1 hour in vertical orientation may have a variable influence on the coefficient of friction, depending on the resultant microstructure.
Inclined Orientation: The combined impact of the anisotropic characteristics of the material and the heat-treatment procedures typically influence the coefficient of friction in the inclined orientation.

900°C after 1 hour, 925°C after 4 hours, and 1025°C after 1 hour: The effect of heat treatment on the coefficient of friction in inclined orientation is determined by the unique microstructural changes generated by the heat-treatment conditions. Grain growth, phase transitions, and the development of various precipitates are examples of changes that might impact surface roughness and frictional behaviour.

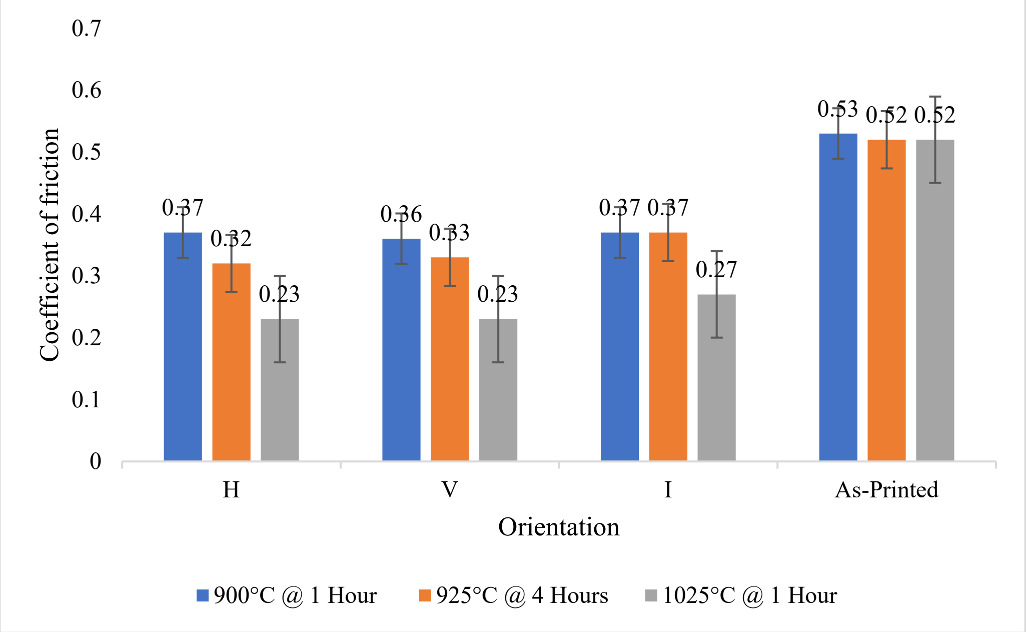

Figure 6: coefficient of friction values

Figure 6 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(AlMangour & Yang, 2016b). However, the heat-treated samples of 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 30% and 38% were found. The cause of the increased sliding velocity of the heat-treated @900^0 for 1 hour is the decrease in COF. However, the COF decreased from 1025^{0}C to the other two heat treatments. The molecules of the 17-4 PH SS alloy have a better surface affinity and less subsurface hardening as a result of this decrease. As a result of higher adhesion with the wear disc, there is less high adhesion wear loss and heat degradation of the base material. The worn surface with a superior finish was found to have a higher COF, showing that very smooth surfaces have a high surface energy and a high sticky nature. As a result, the friction between the work piece and the abrasion wheel increases(Li et al., 2008a). The high surface tension and surface energy of a substantially polished surface created this result.
It is also noted that the horizontal and vertical built heat treated samples at 1025^{0}C for 1hour shows lesser COF of 0.23 compared to inclined 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 (Mellor et al., 2014; Zhang et al., 2021a)

3.1.2 Wear Rate

Figure 7 shows the wear loss in grams 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 of 10.99, 6.41, 3.52 for as-printed 17-4- PH SS alloy via horizontally, vertically and inclined direction. The inclined built 17-4- PH SS alloy giving higher wear loss than the Vertical and horizontal. This is because of creation of high rough surface during the printing time.

It is further noted that the heat-treated surfaces of printed17-4- PH SS alloy as rough, medium and fine format giving substantial improvement in wear resistance. A wear loss of 4.87,4.62,6.98,10.99 grams in heat treatment of 900^{0}C for 1 hour;3.81,3.93,5.14,6.14 grams in 925^{0}C for 4 hours; 2.74,3.7,4.51,3.52 grams in 1025^{0}C for 1 hour respectively. The horizontal printed 17-4- PH SS alloy has the lowest wear loss of all the build directions.

As a result of the wide surface area, the material is packed uniformly and solidifies at a quicker pace. There is minimal wear loss during the abrasion process due to the homogenous layers and smooth surface. This phenomenon increases wear resistance. Because of its superior finishing, the 17-4-PH SS alloy has a greater degree of finish, resulting in a higher coefficient of friction between the sliding surfaces. As a result, adhesion and thermal erosion are more likely, strengthening the two- and three-body abrasion phenomena. The enhanced adhesion between the sliding surface and the abrasion disc increased the adhesion wear loss. This debris clung between the sliding surfaces after abrasion and caused further wear loss via three body wear processes.(Bressan et al., 2008c; Chandramouli & Eswaraiah, 2017)

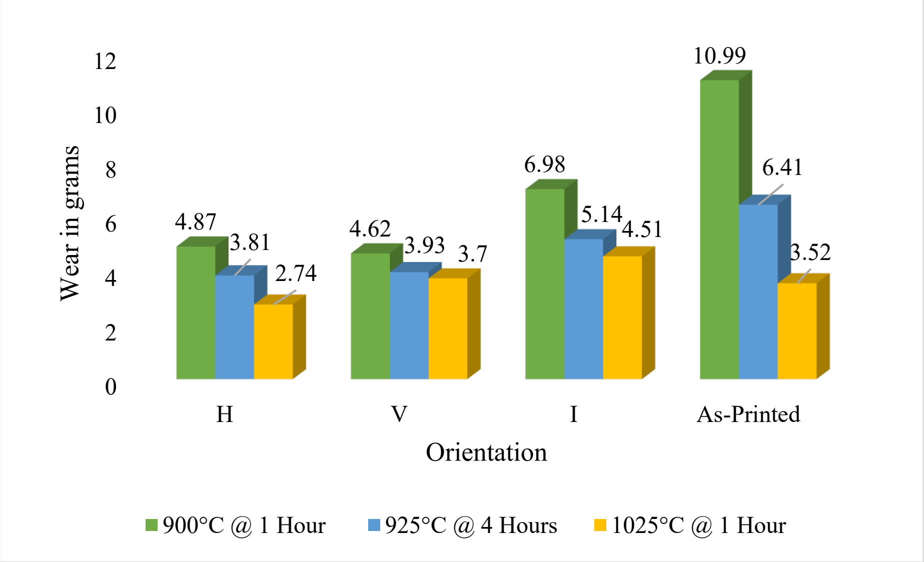

Figure 7: Wear of printed 17-4 PH SS alloy

3.2 Microstructural characterization:

Microstructural characterisation of 17-4 PH stainless steel entails a detailed examination of the material's internal structure and composition at the microscopic level. The microstructure of 17-4 PH stainless steel is complex, with several phases and characteristics influencing its mechanical qualities and performance. Figure 8a,b,c, show as-printed As-built(printed) SEM images. 8a shows for horizontal orientation, where grooves and ploughing is seen along with martensite.8b shows for vertical orientation where delamination, debris along with deep grooves are observed. 8d shows SEM inage for inclined specimen with precipitates, oxidation along with deep grooves.

Martensite is a main phase found in 17-4 PH stainless steel that occurs as a result of the material being heat-treated to obtain high strength. Martensite is a hard, brittle phase with a lath or plate-like structure. Its creation and distribution throughout the material are critical in defining the strength and toughness of the material(Sabooni et al., 2021b; Sivaiah & Chakradhar, 2018).

Austenite, which is often present at higher temperatures during heat treatment operations, is another key phase in 17-4 PH stainless steel. Austenite has a face-centered cubic (FCC) crystal structure, which gives it high corrosion resistance. Factors like as the cooling rate during heat treatment can impact the quantity and stability of austenite in the microstructure(Bressan et al., 2008b).(Davanageri et al., 2016c)

In addition, secondary phases such as delta ferrite and precipitates may be present in the microstructure of 17-4 PH stainless steel. Delta ferrite is a body-centered cubic (BCC) phase that can occur after solidification or from extended high-temperature exposure. Precipitates, on the other hand, are minute particles that form during heat treatment and contribute to the strength of the material(Mahadevan et al., 2016)(Li et al., 2008b).

Researchers and engineers acquire significant insights into the link between the microstructure of a material and its mechanical characteristics, corrosion resistance, and heat treatability through microstructural characterization. This understanding may be used to optimise the processing and design osf 17-4 PH stainless steel for specific applications, resulting in improved performance and dependability(Tavares et al., 2015).

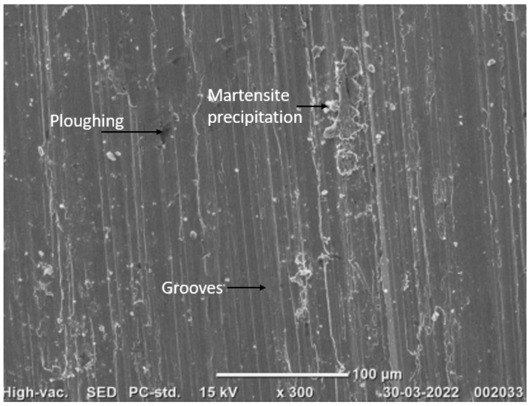

Figure 8a: As built-H

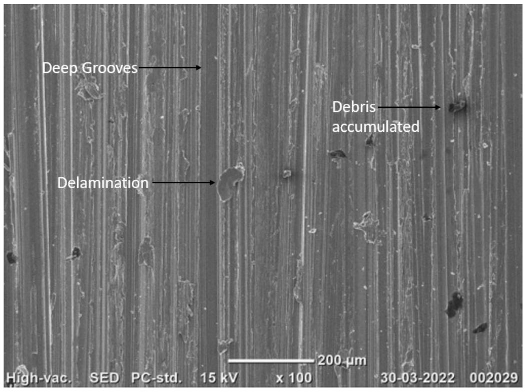

Figure 8b : As built-V

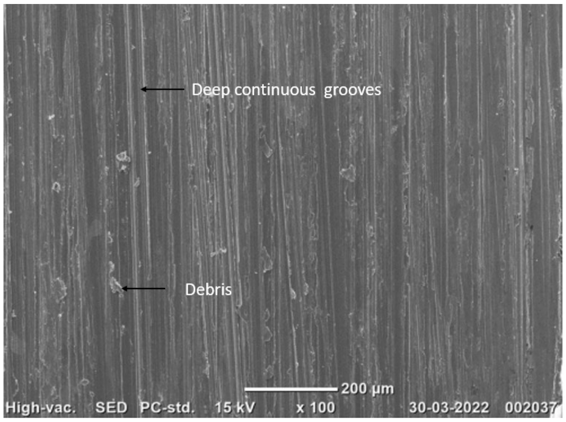

Figure 8c: As built-I

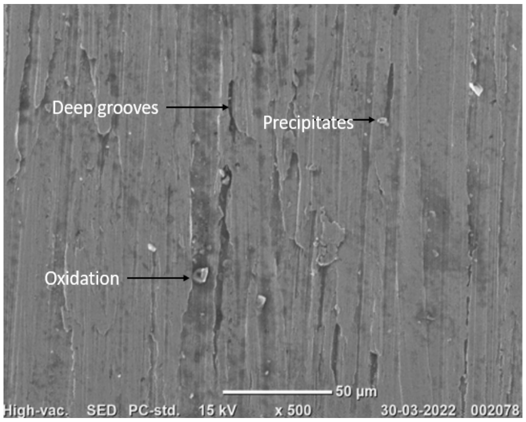

Figure 8d: Inclined specimen at 900^0C for 1 hr

4. Conclusion

In conclusion, the impact of heat-treatment on the wear behavior of stainless steel printed using Laser Powder Fusion Bed (LPFB) in different orientations (horizontal, vertical, and inclined) has been investigated at various heat-treatment conditions, including 900°C @ 1 hour, 925°C @ 4 hours, and 1025°C @ 1 hour. Based on the available literature and research findings, the following conclusions can be drawn:

Wear Behavior: Heat-treatment plays a crucial role in improving the wear resistance of the printed stainless steel components. Heat-treatment at 900°C @ 1 hour and 925°C @ 4 hours generally lead to improved wear resistance compared to the as-printed condition. The formation of fine precipitates, carbides, and the refinement of the microstructure contribute to the enhanced wear resistance.

Coefficient of Friction: Heat-treatment also affects the coefficient of friction of the printed stainless steel. Generally, heat-treatment at 900°C @ 1 hour and 925°C @ 4 hours tends to reduce the coefficient of friction. The formation of solid lubricants, microstructural refinement, and improved surface smoothness contribute to the decrease in frictional resistance.

Surface Roughness: Heat-treatment can influence the surface roughness of the printed stainless steel components. In some cases, heat-treatment at 900°C @ 1 hour and 925°C @ 4 hours leads to improved surface roughness, which can further contribute to reduced wear and friction.

Orientation Effects: The orientation of the printed stainless steel components, whether horizontal, vertical, or inclined, can have an impact on their wear behavior. Horizontal orientations generally exhibit better wear resistance compared to vertical orientations. The inclined orientation often shows intermediate wear behavior. However, the effect of heat-treatment on wear behavior may vary depending on the orientation.

Overall, heat-treatment at 900°C @ 1 hour and 925°C @ 4 hours has shown promising results in terms of improving wear resistance, reducing the coefficient of friction, and enhancing surface roughness of the stainless steel printed using LPFB. However, the effects of heat-treatment can depend on various factors, including the specific heat-treatment parameters, the composition of the stainless steel, and the intended application.

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 post processing.Wang, T et.al. 2015.

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Conflict of interest:

Authors hereby confirmed that there is no conflict of interest.

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Data availability

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

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