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1		Effect of building directions on the surface roughness,
2	m	icrostructure, and tribological properties of selective laser
3		melted Inconel 625
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15 Abstract

16 To study the effect of the building directions on surface macro- / micro- structure and tribological properties of Inconel 625 samples manufactured by selective laser melting (SLM) 17 technology, parts were fabricated in three different building directions (0°, 45°, 90°). The 18 microstructure of SLM samples was characterized using optical microscope (OM) and 19 scanning electron microscopy (SEM). Only the γ -Ni phase was detected in the X-ray 20 diffraction (XRD) patterns of the SLM samples. The lattice constant of the γ -Ni phase in the 21 SLM 45°sample was the lowest among these SLM samples. The value of the surface 22 roughness of the SLM 45° specimen was the highest than other parts, while, the value of the 23 surface roughness of the SLM 0° sample was the lowest. The surface microstructure of the 24 25 SLM samples was primarily composed of columnar dendrites and equiaxed grains. Among these samples, the finest equiaxed grains (about $0.38-0.63 \mu m$) was evenly distributed in the 26 SLM 0° sample, while, the roughest equiaxed grains (approximately 0.73-1.26 µm) was 27 formed in the SLM 45° sample. Furthermore, the SLM 0° specimen showed the highest 28 microhardness value $(332 \text{ HV}_{0.2})$ and the best tribological performances, such as the lowest 29 average coefficient of friction (COF=0.31) and the wear rate $(57.2 \times 10^{-6} \text{ mm}^3 / (\text{N} \cdot \text{m}))$. 30 ^a These two authors contributed equally to this work.

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 evolution, Tribological performances.

33 **1 Introduction**

34 When it comes to the metal additive manufacturing (AM) technology, selective laser melting (SLM), the represent of sustainable metal production, is one of the most attracting 35 technologies employed in recent years, as stated by Chen et al. (2019) and Martin et al. (2017). 36 37 In the process of the SLM, metal powder is spread in thin layers and rapidly fused using 38 high-density laser beam in the layer-by-layer method in order to create object components with complex geometric shapes. This technique opens a wide field of possible applications for 39 many industrial sectors thanks to its eye-catching advantages, such as unlimited geometric 40 variability, design freedom and material flexibility, as revealed by Yan et al. (2019b) and Yan 41 42 et al. (2019a). Also, apart from the commonly used commercial pre-alloyed powder e.g., 43 nickel-based, cobalt-based, and iron-based alloy powder, this technique, due to the high energy density of the input laser beam, can also manufacture high melting point refractory 44 45 metals like molybdenum, tantalum, tungsten and their alloys. SLM technology can, therefore, be regarded as an emerging technology to produce metal components directly from the raw 46 47 material.

48 Inconel 625 is a nickel-based superalloy promoted by solid-solution hardening of various 49 elements like C, Cr, Mo, and Nb, which has been used in widespread applications such as 50 aerospace, marine, chemical and nuclear industries due to its outstanding yield, tensile and 51 creep strength at elevated temperature, as investigated by Paul et al. (2007). Inconel 625 52 components are generally manufactured by conventional manufacturing processes e.g., 53 casting, powder metallurgy and stir friction welding (Song and Nakata, 2010). With the 54 bombarding development of AM technology, manufacturing Inconel 625 components by AM 55 for industrial applications has steadily emerged as a promising approach. Currently, in the 56 review paper by Mumtaz and Hopkinson (2009), the SLM technology was reported to 57 successfully fabricate Inconel 625 parts. Compared to other AM techniques such as direct metal deposition (DMD) technology (Dinda et al., 2009), SLM, being able to efficiently 58 59 utilize material and achieve cost-effective processing, has obtained a great attention. The 60 investigations conducted by Frazier (2014), Yadollahi and Shamsaei (2017) and Yap et al. 61 (2015) showed that since the laser spot of SLM is focused in a tiny area of less than 100 µm 62 in diameter, extremely high temperature is generated in the center of the laser molten pool. Also, owing to energy distribution occurring in the laser spot, a great thermal gradient in the 63 Inconel 625 material is produced, which directly affects the microstructure and mechanical 64 65 performances of the processed parts.

To research the microstructure characteristics of the SLM Inconel 625 parts, recently,
some studies focusing on the microstructure features of this material have been published. Li

68 et al. (2017) found that fine columnar γ dendrite microstructure with strong texture was a significant feature of the SLM samples, and the heat treatment could recrystallize 69 70 microstructures, increase grain size, decrease dislocation density and diminish grain boundary 71 misorientation. Anam et al. (2014) investigated that cellular substructure grains with enriched zones of Nb and Mo in the inter-arm spacing were detected using SEM and EDS, and the 72 73 grains were also proved to grow preferentially in the build direction within the microstructure 74 of SLM Inconel 625 parts. Li et al. (2015) studied the microstructure evolution of SLM 75 Inconel 625 components and concluded that the microstructure was composed of elongated 76 columnar crystals. In addition, they reported that the effect of the applied heat treatment on 77 the microstructures of the SLM parts was not significant. Though many scholars have done 78 various experiments for describing the microstructure features of SLM Inconel 625 parts in 79 the different heat-treated states, the effect of the building directions on the microstructure of the surface and its evolution are still rarely analyzed. 80

As well known, manufacturing methods have a great impact on the microstructure and 81 82 mechanical performances of the SLM Inconel 625 parts. Therefore, some other researchers 83 have also studied the impact of applying different SLM manufacturing strategies on the 84 microstructure and mechanical properties of the SLM Inconel 625 parts. Yadroitsev et al. 85 (2009) investigated the effect of the different building directions on the mechanical properties of the SLM Inconel 625 parts, and the results displayed that the Young's modulus value for 86 the "horizontal" samples was by 1.5 times higher than that for the "vertical" specimens and 87 was close to that of wrought Inconel 625 component (about 200 GPa). However, the yield 88 89 strength and ultimate strength of the samples were not significantly affected by the change in the building directions. Yadroitsev and Smurov (2010) also found that elongation of the SLM 90 Inconel 625 parts was only 8-10 % compared to 40 % for conventionally cast and wrought 91 components. Moreover, Gonzalez et al. (2019) compared the microstructures and mechanical 92 93 properties of Inconel 625 parts produced by different AM techniques. The results illustrated 94 that SLM specimens had potential to display outstanding mechanical properties as compared 95 to ones fabricated using other technologies. As described above, the majority of the current 96 studies were primarily concentrated on the effect of laser processing parameters and building 97 directions on the microstructure and mechanical properties of SLM parts.

98 In summary, building directions can be adjusted to modify the microstructure of the 99 SLM components, as demonstrated by Rashid et al. (2018). However, to date, the impact of the building directions upon the surface microstructure of the SLM Inconel 625 components, 100 101 particularly the diverse microstructure caused by the complex thermal history and 102 micro-reaction occurring in the SLM process, has not been explored in depth. Besides, 103 relationships existing between the printing orientations and the tribological behavior of the 104 SLM Inconel 625 parts have not been systematically studied, either. Obviously, there is still a 105 research gap about the effect of SLM building directions on the wear performance of the SLM 106 Inconel 625 samples.

Hence, this problem should be of great interest to researchers as it not only helps to dig in the depth of the wear mechanism of SLM parts but also is deemed to be useful for the design and fabricating strategy of SLM components for generating high wear-resistant surfaces. Thus, the influence of the building directions on the macrostructure characteristics such as surface roughness, the surface microstructure evolution, and the wear mechanism of the SLM Inconel 625 parts are discussed and analyzed in detail within this work.

113 2 Experimental details

114 **2.1. Manufacturing procedure**

In this work, Inconel 625 powder (EOS GmbH, Germany) with a spherical shape was 115 used as the raw material. The chemical composition of this used powder is shown in Table 1. 116 117 The overview and magnified surface morphology of the used Inconel 625 powder are displayed in Fig. 1a. The particle size distribution (d_{10} =23.3 µm, d_{50} =34.3 µm, and d_{90} =49.6 118 µm) of the powder, measured by the laser diffraction powder sizer (Mastersizer 2000, 119 120 Malvern Instruments Ltd., UK), is given in Fig. 1b. As described in Fig. 1c, the laser scanning strategy was chosen as zigzag pattern with 67° rotation between the neighboring layers. These 121 122 specimens were built up in three different orientations by SLM using an EOS M290 (EOS 123 GmbH, Germany) system. As shown in Fig. 1d, the different category of the processed samples is marked as 0°, 45°, 90°. After conducting a systematic investigation, laser spot of 124 100 µm, laser power of 280 W, layer thickness of 30 µm, hatch distance of 110 µm and 125 126 scanning speed of 950 mm/s were used to process these samples. In order to avoid oxidation, 127 the chamber of the SLM machine was filled with high purity nitrogen (99.99 %) to maintain the residual oxygen content below 0.13 %. 128



129

Figure 1. (a) Macroscopic morphology of the raw material; (b) particle size distribution; (c)
SLM scanning strategy used to process the samples; (d) SLM Inconel 625 samples produced
by applying different building directions.

133

Table 1: Chemical composition of the Inconel 625 raw powder

Element	Ni	Cr	Mo	Nb	Fe	Со	Al	С
wt.%	Balance	20.00-23.00	8.40-10.00	3.15-4.15	≤5.00	≤1.00	≤0.40	≤0.10

134 **2.2. Material characterization**

The surface roughnesses of these SLM parts were evaluated by a DektakXT profilometer 135 (Bruker, American). The surface area of 1000 μ m×1000 μ m of the each SLM sample at 136 different building directions was selected as the surface roughness test plane. The surface 137 138 microstructure characteristics of the SLM Inconel 625 samples were observed using an 139 optical microscope (OM, Leica Dmi5000m) and a scanning electron microscopy (FEI Nova Nano SEM 450). Before conducting the metallographic analyses, all the samples were 140 polished by SiC grinding papers with different grits and then etched for 20 s in aqua regia 141 142 solution containing 100 ml HNO3 and 300 ml HCl. Phase composition of the SLM parts was 143 utilized by X-ray diffraction (XRD, Siemens, Germany) at 40 kV and 40 mA in a 20 range of 30-100°. 144

145 **2.3. Mechanical performances**

The Vickers microhardness was measured using a microhardness tester (Leitz-Wetzlar,
Germany) with a load of 200 g and an indentation time of 25 s. Before testing the

microhardness, surface roughness of the testing plane of the each SLM sample were polished
to below 0.15 µm. The microhardness values were recorded after measuring different
locations on each surface of the SLM specimens, and then the average value of 10 times
measurements was calculated.

Dry sliding ball-on-disk wear tests were evaluated at room temperature with a CSEM 152 tribometer equipment. Before testing the friction and wear performance, the surface 153 roughness (Ra) of all SLM specimens were polished to below 0.15 µm. Si₃N₄ balls with a 4 154 mm diameter, cleaned with ethanol before performing the tests, were chosen as the 155 counterpart material sliding on the produced samples. The wear test conditions included a 156 testing load of 500 g, a rotational speed of 100 mm/s, a sliding distance of 200 m, and a 157 rotation radius of 3 mm. The coefficient of friction (COF) was automatically recorded by the 158 machine during the sliding tests. The worn surface of each sample was observed and analyzed 159 by SEM after finishing the wear tests. The macroscopic morphology of the worn tracks was 160 measured by the 3D surface profilometer. The wear rate (ω) of the samples was calculated via 161 162 the formula as follows and counted the mean value after three measurements:

163
$$\omega = \frac{2\pi rS}{W \times L}$$

where r is the radius of the wear track, mm; S is the cross-sectional area of the worn tracks,
mm²; W is the testing load, N; and L is the sliding distance, m.

166 **3 Results and discussion**

167 **3.1 X-ray diffraction analysis**



168

Figure 2. (a) XRD diffractograms of the SLM specimens fabricated in different building
directions; (b) the magnified view of the (111) crystal plane

171 According to the X-ray diffraction patterns of the SLM samples printed in different 172 building directions, as shown in Fig. 2a, only peaks related to γ -Ni (fcc) phase was found. 173 From the phase diagram of the Fe-Cr-Ni ternary alloy, it can be further concluded that the 174 matrix is γ phase with the rather high solubility of Fe in γ -(Cr, Ni) based on the study of Yen 175 et al. (2008).

The diffraction peaks of some intermetallic phases like γ " phase (Ni₃Nb), Ni₂ (Cr, Mo), 176 Laves phase (NbCr₂), etc., were not detected, although these intermetallic compounds may 177 have been formed at elevated temperature. The reasons of that may be explained below: as the 178 laser scanning speed (950 mm/s) and the cooling rate of the molten pool (10^{5} K/s- 10^{6} K/s (Yan 179 180 et al., 2020b, 2020a)) were extremely high, these features would cause the velocity of the atomic reconstruction at the front of the solid-liquid interface is quite higher than the diffusion 181 velocity. Hence, the solution atoms were trapped in the solid-liquid interface leading to the 182 occurrence of the so called "solution trapping" phenomenon. Because of this, metallic solute 183 atoms such as Cr, Nb, Mo, and etc., which were enriched at the front of the solid-liquid 184 interface, did not have much chance to form intermetallic compounds and these solute atoms, 185 therefore, were captured in the γ -Ni matrix. As a result, other phases were hard to observe in 186 the XRD patterns of the SLM parts printed in various building directions. Note that a small 187 188 number of intermetallic compounds might have been formed in the SLM parts, however, 189 probably because of the low content and the small sizes of these precipitates, they were still not presented in the XRD diffractograms (Dinda et al., 2009). 190

191

Table 2: Lattice constants of the γ -Ni phase formed in the SLM Inconel 625 parts.

Sample	Lattice constant (Å)	Fitting error	
Standard y-Ni phase measured by	3 5011	/	
Graulis et al. (2009)	5.5911		
SLM 0° part	3.59474	≤10.33	
SLM 45° part	3.59204	≤10.07	
SLM 90° part	3.59353	≤10.11	

The lattice constants of SLM Inconel 625 parts fabricated in the various building
directions were calculated using the Rietveld Refinement method proposed by Alexander and
Klue (1989) and Materials Information Company (1991) and are listed in Table 2.

As shown in Fig. 2b, the diffraction peaks of the SLM samples were shifted to a 195 low-angle direction as compared to the (111) crystal plane of the standard γ -Ni phase. 196 Amongst all the printed samples, the offset value of the SLM 45° sample was the lowest. 197 According to Table 2, the measured lattice constants of γ -Ni phase in the SLM parts were 198 larger than the standard lattice constant of γ -Ni phase (a=3.5911 Å), which further led to the 199 200 occurrence of lattice distortion of the γ -Ni phase. Additionally, the lattice constant measured 201 in the SLM 0° sample was larger than that of the SLM 45° and SLM 90° sample, while, the 202 lattice constant was the lowest in the SLM 45° sample.

Numerous factors such as element solid solution, surface stress, and etc. will lead to the
 diffraction peak shift and the lattice distortion. As the laser scanning strategy was the same for
 fabricating these SLM samples, it is estimated that the surface stress was not significantly

206 different among these SLM specimens. Thus, the difference of the above phenomenon that occurred in the SLM parts could be primarily attributed to the difference existing in the 207 amount of the multi-element solid-solution γ -Ni phase of the printed parts. This situation 208 might be explained by the fact that the solid solubility of the alloying elements was high 209 within the fine microstructure of the SLM 0° sample due to the extremely rapid solidification 210 rate. In contrast, as the cooling rate might be relatively slower during the solidification 211 process of the SLM 45° and the SLM 90° samples, there might have been enough time for the 212 213 diffusion process of the alloying elements in these samples. As such, it is thought that a supersaturated solid-solution y-Ni phase with slightly lower solid solubility was produced in 214 215 the mentioned samples as compared to that of the SLM 0° sample.

After considering the above results and researching the analysis of Aliofkhazraei (2015) and Cieslak et al. (1988), the formation sequence of the phases after solidification of the molten pool can be proposed as follows:

 $L \rightarrow L + \gamma - (Cr, Ni) \rightarrow \gamma - (Cr, Ni) + intermetallic phases$

220

3.2 Macro- / Micro-structure characteristics

221 3.3.1 Surface roughness



222

Figure 3. SEM macroscopic morphology of the SLM samples: (a) 0° ; (b) 45° ; (c) 90° ;

- three-dimensional surface topographies of the SLM specimens: (d) 0° ; (e) 45° ; (f) 90° ;
- surface roughness formation mechanism of the SLM parts: (g) 0° ; (h) 45° ; (l) 90° .

226 To investigate the impact of applying different building directions on the surface roughness, the surface morphology of the SLM Inconel 625 samples processed in different 227 228 printing directions is shown in Fig. 3. The SLM 0° sample showed a relatively smooth surface 229 having only a small number of partially melted powder particles within the borders between 230 the neighboring tracks (Fig. 3a). Whereas, in the SLM 45° sample, plenty of partially melted 231 particles were noticeable on the interfaces between the adjacent layers, which are thought to be essentially caused by the prominent stair steps (Fig. 3b). Similarly, multiple partially 232 233 melted powder particles were found in the SLM 90° sample (Fig. 3c). However, it is noted that these small stair steps were no longer present in the SLM 90° sample compared to that in 234 235 the SLM 45° sample. Moreover, the above macrostructure characteristics (Fig. 3a-c) were quantitatively analyzed by the Ra measurement of these samples (Fig. 3d-f). The SLM 0° 236 sample had the smoothest surface (Ra=5.706 µm), while the SLM 45° sample exhibited the 237 roughest surface (Ra=31.397 µm). 238

To further understand the influence of the building orientations on the surface roughness 239 240 of the printed parts, the forming mechanism of the observed macroscopic morphology is 241 presented in Fig. 3g-1. It is known that the balling phenomenon (Gu and Shen, 2009) and the 242 stair stepping effect (Strano et al., 2013), also promoting the occurrence of the balling 243 phenomenon, are the essential factors affecting the surface roughness of the SLM parts 244 produced under the different building orientations. With regard to the balling phenomenon, 245 the micro-sized balls and large-sized balls can be assumed as the two major types of balling 246 phenomenon. When the preset powder bed is irradiated by the laser beam, the molten pool 247 having heterogeneous surface tension is produced, owing to the different volumes of different elements existing in the molten pool based on the study of Steen and Mazumder (2010). The 248 partial kinetic energy of the laser beam is converted into the surface energy of the molten 249 250 metal, due to a high scanning velocity producing some smaller metal droplets of alloy 251 material. To ensure that these droplets have a minimum surface energy, a variety of 252 micro-sized balls will be formed under the joint influence of the surface tension and gravity. 253 Besides, a small quantity of metal droplets also tend to splash from the surface of the molten 254 pool and then solidify into the micro-sized balls on the surface of the SLM parts.

In general, the phenomenon of forming the micro-sized balls is uncommon due to the limited kinetic energy created by the high scanning velocity. The relatively smooth surface observed on the macro-surface appearance of the SLM 0° sample (Fig. 3a and Fig. 3g) is an evidence for this claim. Additionally, the laser remelting process existing in these overlapping regions is beneficial for inhibiting the balling phenomenon and improving the surface finish of SLM parts (Yasa and Kruth, 2011). Consequently, the smoothest macroscopic surface could be obtained on the SLM 0° sample.

Moreover, the formation of the large-sized balls on the macroscopic surface is rather typical, which can be marked as a wetting problem between the molten metal and the surface of the solidified SLM parts. The equilibrium of interfacial free energies existing among the 265 molten metal, the solidified printed samples and the ambient air can be governed by (Das,266 2003):

267

 $S=\gamma_{sg}-\gamma_{sl}-\gamma_{lg}$

where S is the spreading coefficient and γ_{sg} , γ_{sl} and γ_{lg} are the interfacial energies of the 268 solid-gas, the solid-liquid and the liquid-gas, respectively. According to the above equation, 269 270 the value of the S reflects the degree of spontaneous liquid spreading. The molten pool of the SLM Inconel 625 parts is inevitably susceptible to oxidation during the rapid solidification 271 272 process, due to the existence of some active elements (e.g., Ni, Cr, etc.) prone to oxidation in the composition of these samples (Das, 2003). However, the γ_{sg} of these metal oxides are 273 quite lower than the corresponding γ_{lg} (Bunnell et al., 1995) causing a negative S. Hence, 274 275 under this condition, the molten metal tends to diminish surface energy by forming dozens of large-sized balls, instead of wetting the metal oxide films. Furthermore, owing to the 276 277 extremely short dwelling time of the laser beam (normally less than 4 ms, as demonstrated by Simchi (2006) and Simchi and Pohl (2004)) and the exceedingly high solidification rate of the 278 279 molten pool (up to 30 m/s, as reported by Gholipour et al. (2011) and Rack and Kalish, 280 (1974)), the molten metal cannot perfectly wet the surface. This phenomenon, therefore, 281 facilitates the formation of the large-sized balls on the surface of the printed samples.

As a result, the large-sized balls were detected on the macroscopic surfaces of the SLM 282 45° sample (Fig. 3b) and the SLM 90° sample (Fig. 3c). Moreover, the macro-surface 283 appearance of the SLM 45° sample (i.e., the study plane shown in Fig. 3h) was composed of 284 multiple micro-sized stair steps. Since there doesn't exit the remelting process in the regions 285 286 of the stair steps, therefore, the balling effect produced on the surface of the previous cladding layer cannot be eliminated. Consequently, under the combined effect of the balling effect and 287 stair stepping effect, the value of the surface roughness of the SLM 45° sample is the largest. 288 As for the surface of the SLM 90° sample, it is noted that, thanks to the remelting 289 290 phenomenon occurred between the neighboring layers, a relatively fine surface finish is 291 obtained. However, the balling phenomenon especially the large-sized balls was also evident 292 (Fig. 3c and Fig. 3l) in the sample prepared under this condition.

293 **3.3.2 Microstructure evolution**



294

Figure 4. Microstructures of the SLM parts: (a) the SLM 0° sample; (b) enlarged view of
region 1 in a; (c) enlarged view of region 2 in a; (d) the SLM 45° specimen; (e) enlarged view
of region 3 in d; (f) enlarged view of region 4 in d; (g) the SLM 90° part; (h) enlarged view of
region 5 in g; (i) enlarged view of region 2 in g.

299 Fig. 4 presents the microstructures of the SLM parts, manufactured in different building directions (0°, 45°, 90°) using OM and SEM. As for the microstructure of the SLM 0° sample, 300 301 the width of the laser track shown in Fig. 4a was approximately 86-108 μ m, which was 302 basically equal to the laser spot size (100 μ m). The microstructure close to the overlapping line (region 1) was mainly composed of columnar dendrites (near the overlapping line) and 303 equiaxed grains (near the middle of the laser tracks), as depicted in Fig. 4b. In contrast, 304 305 basically only fine equiaxed grains with a size of about 0.38-0.63 μ m (region 2) existed in the middle of the laser tracks as displayed in Fig. 4c. Fig. 4d shows the large fish-scale shape 306 molten pool distributed within the microstructure of the SLM 45° sample. The coarse 307 columnar structures and equiaxed grains were still observed next to the overlapping line 308 (region 3) between these two adjacent layers (Fig. 4e). Fig. 4f illustrates that the columnar 309 structures were grown on the surfaces of the equiaxed grains with a size of approximately 310 0.73-1.26 µm (in the region 4). The fish-scale morphology with the size of 21-45 µm in 311 height, formed in the SLM 90° specimen, was roughly equal to the powder layer thickness (30 312 μm). In addition, the distance between the neighboring tracks (about 105-129 μm), measured 313 from the Fig. 4g, was substantially equivalent to the hatch space. As displayed in Fig. 4h and 314

Fig. 4i, the columnar dendrites and equiaxed grains (about $0.45-0.91 \ \mu m$). Interestingly, both existed in the overlapping regions between the adjacent laser layers (region 5) and in the molten pool (region 6).

In short, after observing and analyzing the microstructures of the SLM parts in different
building directions, it is found that the microstructures, regardless of the building orientations,
are primarily made up of columnar dendrites and equiaxed grains.

It should be noted that in these specimens the finest microstructure and the largest 321 322 number of equiaxed grains were distributed in the SLM 0° sample, while, the SLM 45° 323 sample possessed the coarsest microstructure and the least quantity of equiaxed grains. In 324 order to explain the above phenomenon, the influence of the building directions on the surface microstructure evolution process is analyzed. The microstructure features in Fig. 4 can be 325 characterized and analyzed by considering the surface microstructure evolution process of 326 327 multi-tracks (region A) and multi-layers (region B) of the SLM Inconel 625 parts, as depicted in Fig. 5. The heat input (Q_s) distribution in the molten pool can be estimated by the Gaussian 328 329 heat source and thus the corresponding Q_s is expressed below (Luo et al., 2018):

$$Q_s = Q_m exp(-\frac{2r^2}{R^2})$$

where Q_m is the maximum heat flux density; r is the radial distance between the observing 331 point and the laser spot center and R is the laser spot radius. Therefore, in the same plane 332 irradiated by the laser beam, as r gradually increases, the heat input amount will gradually 333 334 decrease. This trend will result in the temperature in the middle of the molten pool to be much higher than that in the boundary region of the molten pool. In the central area of the molten 335 pool, the convective heat transfer process occurs mainly in two directions, i.e., from the center 336 337 to the periphery of the molten pool, and from the surface of the molten pool to the ambient 338 environment. This phenomenon will make the actual temperature (T_q) gradient in the liquid 339 metal at the central region of the molten pool much lower than the liquidus temperature (T_1) gradient. Consequently, the resulted large degree of constitutional undercooling ($\Delta T = T_L - T_L$) 340 T_{α}) satisfies the nucleation conditions of the equiaxed grains. Hence, a heterogeneous crystal 341 342 nucleation process in the central region of the molten pool will occur, and they will gradually 343 grow into polyhedral grains, i.e., stage 1 (as shown in Fig. 5b).

344 Based upon the requirement for the minimum Gibbs free energy, crystal interfaces are 345 often composed of crystal planes with lower interfacial energy. Therefore, the polyhedral surfaces formed are the interfaces with low interfacial energies, while, the "corner" regions 346 347 are crystal planes with high interfacial energies. According to the XRD spectrums (as displayed in Fig. 2), it can be interpreted that the crystal plane of the minimum interfacial 348 349 energy of the γ phase grains in the SLM Inconel 625 component is {111} crystal plane. In a 350 non-equilibrium solidification process of the molten pool, a solute concentration gradient in 351 the liquid metal at the front of the polyhedron is high and thus the diffusion speed is quite 352 large. It is owing to this reason that the growth morphology of the polyhedral grains is shown in stage 2. When the equiaxed grains rapidly grow larger and approach each other, the grain boundaries tend to have equal angles and the intersecting interface of three grains will be preferentially formed (remarked in stage 3). To meet a requirement of the minimum grain boundary energy, as displayed by Callister and Rethwisch. (2015) among these grains, the following equation can be presented:

358 $\frac{\gamma_{1-2}}{\sin\alpha_3} = \frac{\gamma_{2-3}}{\sin\alpha_1} = \frac{\gamma_{3-1}}{\sin\alpha_2}$

where γ_{1-2} , γ_{2-3} , and γ_{3-1} are interfacial tensions; α_1 , α_2 , α_3 are interface angle between adjacent 359 grains. Thus, in the final stage, the interface angles between adjacent grains will be prone to 360 361 be 120° and also be substantially equal. Finally, the equiaxed grains at the center of the 362 molten pool exhibit hexagonal structures (as shown in stage 4). Besides, since the marginal 363 area of the molten pool is surrounded by the powder bed, the temperature gradient at the edge of the molten pool will be much greater than that at the center of the molten pool. 364 365 Additionally, there is little difference in the solidification rate between the center area and the boundary area of the molten pool. Under such conditions, the columnar dendrites will form 366 367 and distribute along the margin of the molten pool.





Figure 5. (a) Surface microstructure characteristics of the multi-tracks and the multi-layers
regions of the SLM parts; (b) equiaxed grains formation mechanism diagram; (c) schematic
profile illustrating the effects of temperature gradient G and growth rate R on the morphology
of solidification microstructure described by Liu et al. (2016).

373 Combining the above analysis and Fig. 5c, the microstructure of the SLM 0° sample is
374 the one with the multi-tracks overlapping region (as depicted in region A of Fig. 5a). The

microstructure evolution from the boundary of the laser track to the middle of that consist of separately coarse columnar dendrites, fine columnar dendrites, coarse equiaxed grains and fine equiaxed grains. This microstructure features denote that the columnar dendrites primarily grew along the laser tracks (as shown in Fig. 4b), while, the equiaxed grains were distributed in the center of that (as displayed in Fig. 4c).

Regarding the SLM 45° specimen, its microstructure is substantially equivalent to the 380 microstructure of the SLM 90° sample being intercepted at a 45° angle. The microstructure of 381 382 the SLM 90° sample is the one with the multi-layers region (as illustrated in region B of Fig. 383 5a). Hence, the microstructure formation mechanism of both samples can be depicted by region B of Fig. 5a and the microstructure evolution of these two specimens can be 384 principally determined using the heat dissipation direction, the preferred orientation of the 385 dendrites, and the ratio of the temperature gradient (G) to the solidification rate (R) (Fig. 5c). 386 At the bottom of the molten pool, since G, close to the substrate, is rather small and R is quite 387 large, therefore, a typical characteristic of epitaxial columnar growth perpendicular to the 388 389 interface of the molten pool will occur. In the middle of the molten pool, due to the further reduction of G/R, fine dendritic structures are distributed on the surface of the coarse 390 columnar dendrites. Moreover, since the heat dissipation direction of the solidification 391 392 microstructure is mainly through the multi-layers region and powder bed, the growth orientation of the dendrites is only in the opposite direction of the heat dissipation direction. 393 This results in the directional growth of the columnar structures (as shown in Fig. 4e and Fig. 394 395 4h). Ascending from the middle of the molten pool, the G is the lowest and the R is the largest, 396 so the value of G/R is the smallest. Consequently, in addition to the formation of the fine dendrites, the fine equiaxed grains can be also formed at the top of the molten pool (as 397 demonstrated in Fig. 4f and Fig. 4i.). As for the remelting areas, the microstructure will 398 399 maintain the growth direction of the microstructure in the previous layers and continue to 400 grow because of the phenomenon of structural inheritance. This feature not only ensures the 401 bonding strength between the adjacent layers but also makes the epitaxial structure have 402 continuity in the growth direction (Fig. 4e). Another interesting phenomenon in the remelting 403 zone is that the melt flow will produce a scouring effect on the solute-rich layer at the front of 404 the columnar dendrites. This makes the columnar dendrites grow obliquely just like Fig. 4h.





Figure 6. Microhardness of the SLM parts built in different building directions

As presented in Fig. 6, the average microhardness of the SLM 0° sample, the SLM 45° 408 409 sample and the SLM 90° sample is 332 HV_{0.2}, 314 HV_{0.2} and 322 HV_{0.2}, respectively. The 410 mechanical performances of the SLM samples have a strong correlation to their 411 microstructure characteristics. Comparing these three types of the SLM samples built in 412 different orientations, the massive fine equiaxed grains distributed within the surface microstructure of the SLM 0° sample have a significant effect on the improvement of its 413 414 hardness. In contrast, the comparably coarse columnar dendrites and equiaxed grains formed in the surface of the SLM 45° and the SLM 90° samples will induce lower hardness values in 415 these samples as compared to the SLM 0° one. Additionally, the average microhardness of the 416 SLM 45° part is the lowest among these specimens by the cause of having the coarsest 417 microstructure. 418

419 **3.4** Anisotropy in tribological properties



420 **3.5.1** Coefficient of friction and wear rate

Figure 7. (a) COF - distance profiles and (b) wear rate of the SLM samples fabricated in the
different building directions.

424 Fig. 7 displays the effect of the building directions on the tribological properties including the COF and wear rate of the SLM specimens. The corresponding statistical results 425 426 are listed in Table 3. As for the SLM 0° sample, the average COF of the stable stage of friction (i.e., the wear distance from 50 m to 200 m) is 0.31 and the average wear rate is only 427 57.2×10^{-6} mm³/(N•m). In contrast, the average COF and the wear rate of the SLM 45° sample 428 and the SLM 90° sample are relatively higher, as compared to the SLM 0° one. These can be 429 attributed to the coarser columnar dendrites and equiaxed grains dispersed within the surface 430 431 of these specimens as compared to the SLM 0° one. As a result, amongst these parts, the SLM 45° sample exhibits the worst tribological performance, as it contains the coarsest surface 432 microstructure. 433

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Table 3: Tribological properties of SLM Inconel 625 specimens produced in different building orientations

Sample	Average COF	Average wear rate (×10 ⁻⁶ mm ³ /(N•m))		
SLM 0° part	0.31	57.2±3		
SLM 45° part	0.38	87.8±2.5		
SLM 90° part	0.35	62.2±3.8		

436 **3.5.2** Worn track morphology and mechanism



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Figure 8. Worn surface morphology of (a) SLM 0° sample; (b) magnified view of region 1 in
a; (c) 3D surface topography of a; (d) SLM 45° sample; (e) magnified view of region 2 in d; (f)
3D surface topography of d; (g) SLM 90° sample; (h) magnified view of region 3 in g; (l) 3D
surface topography of g.

Details about the worn surface morphology of the SLM Inconel 625 parts are revealed in 442 Fig. 8. For the SLM 0° specimen, the average width of the worn track was about 531.6 µm. 443 Numerous grooves and furrows were scattered on the surface of the worn track, illustrating 444 that the main wear mechanism causing damage during the test was abrasive. A small quantity 445 of micro craters and cracks could also be presented in region 1 (Fig. 8b), which demonstrate 446 the occurrence of delamination in the worn surface. The 3D surface topography of the SLM 0° 447 sample after experiencing the friction stage was relatively smooth (Fig. 8c). While, as for the 448 SLM 45° part, the width of the worn track was 646.5 µm (Fig. 8d). As depicted in Fig. 8d-e, a 449 great number of cracks and parallel deep grooves were presented on the worn surface of this 450 sample which is indicative of delamination and deformation phenomenon occurring on the 451 worn surface. Thus, the 3D surface topography of the SLM 45° part was comparably rougher 452 than that of the SLM 0° part (Fig. 8f). As seen in Fig. 8g, the width of the wear track for the 453 SLM 90° sample was 602.6 μ m. In addition, a small number of cracks and craters were 454 455 produced due to the plowing effect. This indicated that the ploughing were also another primary wear mechanism damaging this sample. It is noted that the 3D surface of the wear 456 trace of the SLM 90° sample was rather smoother than that of the SLM 45° part. 457

458 In short, the abrasive and micro-ploughing wear mechanisms are the main wear

459 mechanism damaging these SLM Inconel 625 parts. Moreover, it is concluded that the effect 460 of the building directions on the tribological performances of these samples (such as average 461 COF, wear rate and worn track morphology) cannot be neglected. Hence, the influence of the 462 printing orientations upon the wear performance and the friction behavior of the samples are 463 discussed below.



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465 466

Figure 9. Schematic diagrams of sliding wear mechanism on the surface of the SLM Inconel 625 parts manufactured at different printing directions: (a) 0°; (b) 45°; (c) 90°.

Fig. 9 illuminates the relationship between the surface microstructure and the wear mechanism of the SLM Inconel 625 samples manufactured in different building orientations. Compared with the columnar dendrites, the fine equiaxed grains are easier to accommodate large strains announced by Martin et al. (2017). During the sliding wear process, thus, the columnar dendrites are liable to break up under the tangential force (F_T) resulting in a poor wear resistance performance.

Among these specimens, the finest microstructure (e.g., columnar dendrites and 473 equiaxed grains) were primarily formed in the surface of the SLM 0° specimen (Fig. 4a-c). 474 475 Therefore, under the illustration of Fig. 9a, as the columnar structures are peeled off during 476 the wear process, the equiaxed grains will be also gradually peeled off. Then, upon the 477 influence of this process, some inconspicuous plows (Fig. 8a), a small quantity of micro craters, and some micro cracks (Fig. 8b) were progressively formed on the worn track surface. 478 As mentioned, this phenomenon produced the smoothest worn surface with the narrowest 479 480 average width of the worn track (Fig. 8c) in SLM 0° sample. On the contrary, according to the 481 surface microstructure analysis of the SLM 45° specimen (Fig. 4d-f), the roughest columnar dendrites and the smallest number of equiaxed grains were dispersed within the 482 microstructure of the SLM 45° component. Consequently, according to Fig. 9b, after a large 483 quantity of rough columnar dendrites are peeled off in the process of the sliding wear, a huge 484 485 number of craters and cracks are produced in the damaged areas. As the wear process is further performed, these numerous micro craters and cracks will connect to each other, and 486 then produce the massive larger cracks. This phenomenon could be observed in Fig. 8e. 487

488 Hence, the roughest worn trace surface with the largest average width of the worn track was obtained in this sample, as displayed in Fig. 8f. As for the SLM 90° component, under the 489 490 description of Fig. 4g-l, the surface microstructure of the SLM 90° sample was finer than that 491 of the SLM 45° part and the proportion of the equiaxed grains in the microstructure was more 492 than that of the SLM 45° specimen. Therefore, under the illumination of Fig. 9c, only a small quantity of columnar structures within the surface of the SLM 90° specimen will begin to 493 break up and generate some tiny craters and cracks during the dry sliding wear process. As 494 495 compared to the SLM 45° part, these craters and cracks were not joined together but only scattered on the worn surface of the SLM 90° specimen (Fig. 8g-h). Finally, as seen in Fig. 8l, 496 497 a relatively rough worn surface was obtained.

498 **4** Conclusion

In summary, a variety of SLM Inconel 625 samples were successfully fabricated by SLM technology to study the effect of the building directions upon the performances of the SLM parts. In this work, experiments were conducted to investigate the impact of the building orientations on the surface roughness, microstructure evolutions, and tribological properties of the selective laser melted Inconel 625 parts. Primary conclusions drawn from this work were listed as follows:

1. The phase structure of the SLM Inconel 625 specimens was predominately composed of the γ -Ni (fcc) phase. The lattice constant of the γ -Ni phase in the SLM 45° sample (3.59204 Å) was lowest than other SLM samples. The microstructure of the SLM parts was composed of the columnar structures and the equiaxed grains. Among these samples, the finest microstructure and the largest number of equiaxed grains (0.38-0.63 µm) were distributed in the SLM 0° sample, while, the SLM 45° sample possessed the coarsest microstructure and the least quantity of equiaxed grains (0.73-1.26 µm).

512 2. The value of the surface roughness of the SLM 45° sample (31.397 µm) was the 513 roughest owing to the balling phenomenon and the stair stepping effect. On the contrary, the 514 value of the surface finish of the SLM 0° specimen (5.706 µm) was the smoothest due to the 515 remelting phenomenon.

516 3. For the SLM 0° specimen, the average COF and the wear rate was 0.31 and 517 $57.2 \times 10^{-6} \text{ mm}^3 / (\text{N} \cdot \text{m})$, respectively. In contrast, for the SLM 45° sample, the average COF 518 and the wear rate was respectively 0.38 and $87.8 \times 10^{-6} \text{ mm}^3 / (\text{N} \cdot \text{m})$.

The present work demonstrates that the SLM building direction has an obvious influence on the surface macro- / micro- structure and tribological properties of the Inconel 625 parts. This paper will attract the attention of the engineering community for designing a proper building direction to obtain a desirable surface with better tribological performances.

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