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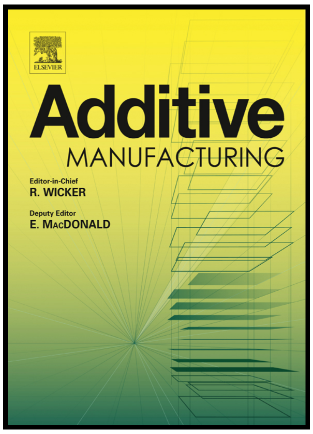

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Texture of inclined up-facing surfaces in laser powder bed fusion of metals

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Abstract

Considerable surface texture is one of the typical drawbacks of laser powder bed fusion (LPBF). Especially up-facing inclined surfaces suffer from insufficient quality, due to the combination of the staircase effect (also called stair-stepping effect), attached powder particles and elevated edges (edge effect). In this work, the contribution of the edge effect to the topography of up-facing inclined surfaces is investigated in detail for the first time. Moreover, the effect of contour scanning was evaluated on up-facing surfaces over the whole range of inclinations, from horizontal to vertical. The edge effect was found to play a dominant role for surfaces with a low inclination angle, especially when contour scanning is used. A suitable scanning strategy can thus be determined for each surface inclination. In the present study, an optimization of scanning strategy allowed a significant improvement of the inclined surface quality. The arithmetical mean height of the roughness profile R_a could be reduced up to 52% for low inclinations, 20% for high inclinations and 32% for vertical walls.

Keywords: laser powder bed fusion, surface quality, staircase effect, edge effect, maraging steel 300

1. Introduction

Laser powder bed fusion (LPBF) is among the most widely used additive manufacturing techniques. The component is built in a layer-by-layer manner, involving deposition of thin layers of metal powder, and their subsequent selective melting by a laser. Given its high freedom of design, this technology is able to produce complex customized parts (e.g. patient-specific implants) or components with a high performance-to-weight ratio (e.g. for aeronautic industry). Furthermore, LPBF enables a faster component production compared to the conventional manufacturing techniques which often require special tooling. On the other hand, LPBF often results in insufficient surface quality for the final application, and the components need to be further post-processed [1]. Surface quality is an important factor for mechanical properties of components. Components with high fatigue loading are especially sensitive to crack initiation because of high roughness [2].

Most of the previous studies on surface topography discuss cuboid LPBF parts with a focus on horizontal or vertical surfaces. Some authors have investigated up-facing inclined surfaces, but mostly for titanium alloys [3, 4, 5, 6, 7], some for stainless steels [8, 9], nickel-based [10, 11, 12, 13] or aluminum alloys [14]. To our best knowledge, the texture of inclined surfaces produced from maraging steel 300 has not yet been investigated in detail.

Compared to horizontal surfaces, up-facing inclined surfaces lead to a higher surface texture due to the combination of ”staircase effect”, powder particle attachment and ”edge effect”. Staircase effect (also called stair stepping effect) originates from part discretization into layers and is thus inherent to all additive manufacturing techniques [15]. However, the staircase effect alone does not explain the texture of inclined surfaces produced by LPBF. As a matter of fact, the texture is significantly higher than the geometrical model based on the stair-like profile first reported by Campbell et al. [15]. In a recent study, Newton et al. [16] showed that the amount of attached particles in powder bed fusion is increasing with increasing surface slope angle. The edge effect refers to elevated edges at the rim of the scanned area, mainly given by material’s surface tension, scanning strategy and in some cases material evaporation [17, 18]. In the context of inclined surfaces, the edge effect was mentioned in the literature [14], but its con-

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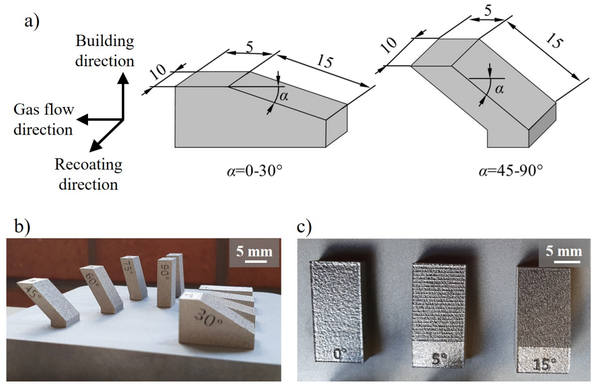

Figure 1: LPBF sample geometry, with (a) sample design for low and high inclination angle α, (b) samples overview and (c) a detailed view of the manufactured samples.

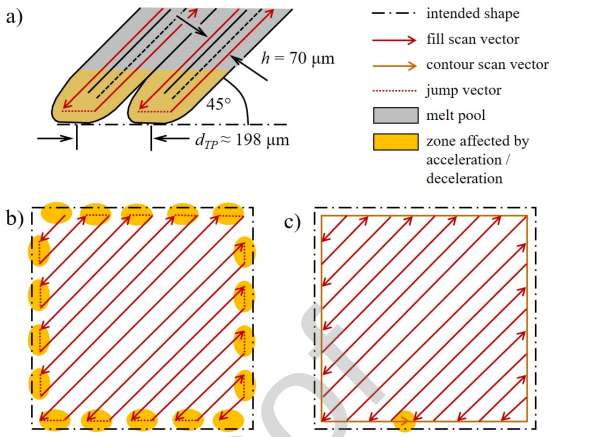

Figure 2: Illustration of the effect of acceleration-deceleration (a) in the bidirectional (zig-zag) strategy, and related possible overheating locations for scanning (b) without (NC) and (c) with contours (C).

tribution to the surface topography of these surfaces has not yet been quantified.

Concerning the scanning strategy, in most of the reported studies either a bi-directional fill scanning is used or contour and fill scanning. But their choice seems to be based either on manufacturer's recommendations or on best practices.

The aim of this study is to provide a clear view on the effect of the contour scanning strategy in the context of inclined up-facing surfaces produced by laser powder bed fusion from maraging steel 300. Moreover, the contribution of the edge effect to the texture of these surfaces is investigated. This understanding can serve as a guidance for selection of a suitable scanning strategy depending on surface inclination.

2. Experimental setup and methodology

2.1. Manufacturing of the samples

The samples were manufactured in a modified LPBF machine from 3D Systems (DMP ProX320). The machine is equipped with a 500 W fiber laser with central wavelength of 1070 nm and a nominal focus size $d_{1/e^2} \approx$ 60 µm. The experiments took place in an inert argon gas atmosphere.

The sample geometry shown in Fig. 1a consists of a block with a 5 mm horizontal surface and 15 mm surface inclined by α=0-90°. All the pre-processing involving sample design, slicing and hatching was performed in the 3DXpert software from 3D Systems.

The material selected for this study is gas atomized maraging steel 300 with a nominal particle size distribution 15-45 µm. The powder particles morphology was investigated within a prior study [19] and the chemical composition is provided in Table 1.

The samples were built either using a simple "fill" scanning strategy (Fig. 2b) or "contours and fill" strategy (Fig. 2c). The fill was scanned in a bidirectional way, under 45° with respect to the sample edge, with a 90° rotation between layers. The process parameters applied to the bulk (fill) region were laser power P=150 W, scanning speed v=1100 mm/s, hatch spacing h=70 µm and layer thickness t=30 µm. This building strategy leads to fully dense parts. Considering a theoretical density of 8.1 g/cm^3, the measured density according to the Archimedes principle was 98.9% ± 0.1%.

The samples were named as a function of their geometry and scanning strategy, "NC" referring to a strategy without using contours (Fig. 2b) and "C" referring to a single contour strategy (Fig. 2c). For instance, 5°_{NC} stands for a sample scanned without contours and inclined by α=5°. The process parameters of the contours were identical to the bulk (fill), unless stated otherwise. The number of the contours varied between 0 and 4. The contours were always scanned before the fill (middle part) and their order of scanning was either "IN" (starting inwards, closer to the fill) or "OUT" (starting closer to the powder bed).

To investigate the single track behavior, a 30 µm powder layer was deposited on top of a surface remelted

Table 1: Chemical analysis of maraging steel 300 powder, as provided by powder manufacturer (Carpenter Additive).

Fe	bal.	Al	0.1 wt.%	C	<0.01 wt.%
Ni	18.8 wt.%	Cr	0.09 wt.%	N	<0.01 wt.%
Co	9.2 wt.%	Si	0.05 wt.%	P	<0.005 wt.%
Mo	4.7 wt.%	O	0.03 wt.%	S	0.002 wt.%
Ti	1.1 wt.%	Mn	0.02 wt.%		

with parameters equal to the building parameters. Consequently, 0.5 mm x 10 mm rectangles were scanned with various parameter combinations (P=130-190 W, v=600-1500 mm/s).

2.2. Characterization of the samples

The surface quality of the samples was characterized using a tactile profilometer Mitutoyo Formtracer CS3200 equipped with a 60° conical probe ended by a 2 µm tip radius. Samples were assessed based on 10 profiles measured perpendicular to the inclined surface stairs, 10 mm long and spaced by 60 µm. In order to remove the possible effect of the recoater, the long wavelength component (waviness) was removed from the measured data using a Gaussian regression filter according to ISO 16610-31 [20]. In this study a cut-off λ_c=2.5 mm was selected, as this value is widely reported in the literature for LPBF inclined surfaces [4, 5, 7, 12, 14]. An analysis of the dependence of the parameter values to the cut-off length revealed that most of the profile structure is captured for λ_c >2 mm. For the short wavelength cut-off length λ_s=2.5 µm was selected.

Several surface texture parameters were considered in this study. In the end, the surface assessment was done based on the R_a parameter according to ISO 4287 [21], being the arithmetical mean height of the absolute values of the roughness profile. Nevertheless, an analysis of other height parameters such as R_p, R_v, R_t or R_q showed a strong linear correlation with R_a in the case of as-built LPBF surfaces from maraging steel. The other parameters could have been used as well, but in this study the R_a parameter is more suitable in order to facilitate the comparison to the literature. To indicate the results and their dispersion, both mean value and standard deviation are given.

Selected surfaces were also measured with a confocal microscope Sensofar S-Neox over an area 3 mm x 3 mm. A 10x objective was used with a lateral pixel resolution of 1.29 µm. The areal measurements are presented leveled using least-square plane fitting, but otherwise unfiltered.

The edge morphology of sample 0°_{C} was assessed following the method described in detail in [18]. The sample top surface was contacted with the tactile probe 4 mm from the edge and a profile measurement was acquired in a direction perpendicular to the edge, containing both the horizontal surface and sample edge. In order to prevent probe damage, a gauge block was positioned about 1 mm below the investigated surface. The gauge block also serves as a reference plane for 2.5D data generation. The mean edge profile was created based on 150 profiles 6 mm long, spaced by 20 µm.

In order to examine the sample cross-section, selected samples were cut in half, embedded into resin and polished. Then a chemical etching using 10% nital solution was applied during 80 s. The microstructure was analyzed using a digital microscope Keyence VHX-6000. The same microscope was also used for a general assessment of the top view on the single tracks.

3. Results and discussion

3.1. Effect of scanning strategy

Improving the final quality of inclined up-facing surfaces starts with improving the as-built quality. For this purpose, the effect of scanning strategy was investigated, and more specifically the effect of contours scanning on the final texture of inclined surfaces.

Fig. 3 presents the influence of scanning strategy on surface texture, comparing a single contour scanning (C) and fill scanning without contours (NC). As shown in Table 2, the same scanning strategy was applied to various surface inclinations, ranging from α=0° (horizontal surface) till α=90° (vertical surface).

Parts built without contours (NC) show a symmetrical behavior of the arithmetical mean roughness R_a as a function of the inclination angle, following a second degree polynomial trend with a maximum at 43° (Fig. 3a). On the other hand, parts built with a single contour line (C) show very high R_a for low inclination angles, which is subsequently decreasing with a linear trend. The two trend lines cross at α_{th}=37°. Using contours is hence beneficial for manufacturing parts from maraging steel with inclinations higher than α_{th} and strongly detrimental for those lower than α_{th}. In order to better understand the origin of the surface texture of inclined surfaces, a distinction should be made between different

Table 2: Effect of the contours scanning strategy and surface inclination on the surface quality (tactile measurement, λ_c=2.5 mm). C: number of contours, α: surface inclination.

α / °	P / W	v / mm/s	R_a / µm (C=0)	R_a / µm (C=1)
0	150	1100	8.4 ± 0.8	9.3 ± 0.9
5	150	1100	11.9 ± 0.6	24.9 ± 2.2
15	150	1100	14.8 ± 1.1	20.8 ± 2.3
30	150	1100	17.2 ± 1.1	17.1 ± 1.5
45	150	1100	18.0 ± 1.7	16.6 ± 1.1
60	150	1100	16.2 ± 1.1	13.4 ± 1.2
75	150	1100	13.0 ± 0.6	10.4 ± 0.6
85	150	1100	11.2 ± 1.1	8.5 ± 0.5
90	150	1100	11.0 ± 0.6	7.4 ± 0.6

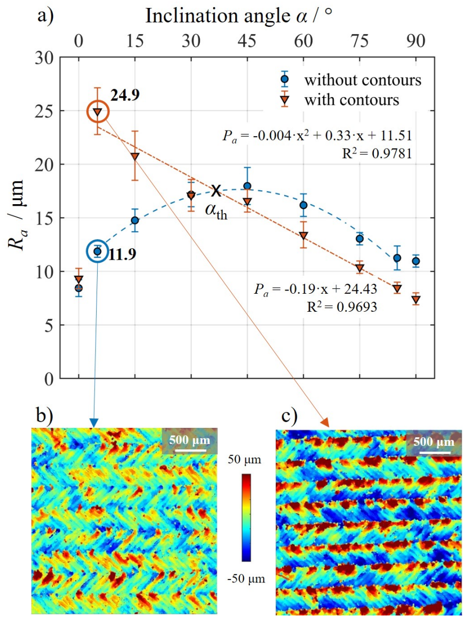

Figure 3: Effect of inclination angle α and scanning strategy on surface texture, with (a) plot based on the tactile roughness measurements (λ_c=2.5 mm), and height maps of samples (b) 5°_{NC} and (c) 5°_{C} acquired by confocal microscopy.

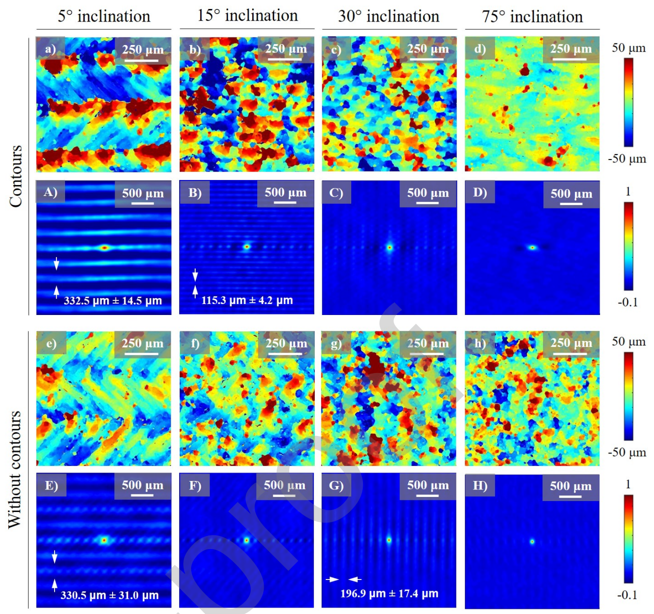

Figure 4: Surface texture variation with inclination angle and scanning strategy, with detail on height maps of samples (a-d) 5-75$^{\circ}_{C}$ and (e-h) 5-75$^{\circ}_{NC}$ acquired by confocal microscopy, and the corresponding normalized autocorrelation plots (A-D and E-H, respectively). Plots of the same kind have the same scaling. Feature repetition is indicated with arrows.

contributing factors, such as the staircase effect, edge effect, scanning strategy or random particles attachment.

Periodic features present on the surface can be detected using a Fourrier analysis or autocorrelation. In this case the autocorrelation function was calculated on areal confocal measurement data and subsequently normalized by the central peak value. The advantage of the autocorrelation is that it indicates the spacing and orientation of the features repeated on the surface, but the exact measurement location on the sample does not affect the final outcome. In order to improve the signal-to-noise ratio, a mean autocorrelation was calculated from four measurements on different locations on the surface. The detected periodicity is indicated with arrows.

As shown in Fig. 4, the sample with α=5° built without contours (5°_{NC}), and especially its counterpart built with a contour (5°_{C}), show a strong periodicity related to the staircase effect. The main detected phase shift is very close to the theoretical stair width (343 µm). Sample 15°_{C} shows a moderate degree of periodicity, as well comparable to the stair width for this inclination (112 µm). The same slope but without using contours (15°_{NC}) did not lead to any significant periodicity.

Most of the samples with $\alpha > 15°$ show a random texture due to powder particles attachment to the surface. Newton et al. [16] observed that the coverage of powder particles on additively manufactured inclined surfaces is increasing with increasing surface inclination. However, as shown in Fig. 4g,G, some of the samples scanned without contours manifest a slight pattern in the direction perpendicular to the stair edge. As a bi-directional (zig-zag) scanning strategy is used, this surface feature corresponds to the distance between the turning points of the melt pool (d_{TP}), occurring every second scan track (illustrated in Fig. 2a). It can be hence determined as double the hatch spacing h projected to the measurement plane. It can be calculated with Eq. 1, considering the scanning direction at 45° with respect to the side surface and h=70 µm.

$$d_{TP} = 2 \cdot h/\sin(45°) \approx 198\,\mu\text{m} \tag{1}$$

At α=30°, the surface texture of parts produced with and without contours appears to be comparable (Figs. 3a,4c,g). This inclination leads to a stair width of 52 µm, which is smaller than a single track width (≈80 µm). The edge effect thus seems to dominate the surface texture for a stair width significantly larger than the melt pool width.

For higher inclinations with even smaller stair width, the presence of contours is consistently improving the inclined surface quality (Fig. 3a). As the low distance

Table 3: Effect of contours process parameters on the surface quality of 5°_C (tactile measurement, λ_c=2.5 mm). C: number of contours, contour spacing h=70 µm.

Sample	P / W	v / mm/s	C	R_a / µm
1	100	1300	1	26.6 ± 4.1
2	125	1300	1	31.6 ± 4.1
3	150	1300	1	27.4 ± 2.9
4	175	1300	1	25.3 ± 1.2
5	200	1300	1	25.0 ± 1.2
6	100	1100	1	30.9 ± 3.7
7	125	1100	1	25.8 ± 2.4
8 (reference)	150	1100	1	24.9 ± 2.2
9	175	1100	1	26.1 ± 2.5
10	200	1100	1	24.4 ± 2.1
11	100	900	1	23.4 ± 2.7
12	125	900	1	23.9 ± 3.1
13 (minimal)	150	900	1	22.8 ± 2.3
14	175	900	1	26.6 ± 2.9
15	200	900	1	23.2 ± 2.4

between consecutive stairs does not allow the edge to protrude significantly, it does not deteriorate the side surface quality anymore. On the contrary, when no contours are used, a higher amount of particles attached to the side surface can be observed (Fig. 4h). This is related to the zone of vector ends, as illustrated in yellow in Fig. 2. Tian et al. [12] showed that acceleration and deceleration of the scanning mirrors can significantly hinder the surface quality. However, despite a compensation with the "skywriting" method, these zones can easily lead to higher temperatures. Using only fill scanning without contours leads to a scanning field fully surrounded by vectors ends (Fig. 2b). Contrarily, when contours are used, there is only a single location of acceleration/deceleration around each scanning field (Fig. 2c), leading to the overall improved quality of steep surfaces (Fig. 4d). Moreover, as discussed above, additional features originating from the scanning pattern (such as the turning points of the melt pools) can further hinder the surface quality if contours are not used (Fig. 4g).

The maximal distance of the detected periodic features is about 330 µm for a stair width and about 200 µm for the turning points of the scanning pattern (Fig. 4). Using a cutoff length λ_c=2.5 mm to filter the profile data presented in Fig. 3a appears to be appropriate in order to capture information about the overall surface quality including these features.

3.2. Texture of surfaces with low inclinations

As given in Fig. 3, the case of α=5° represents the highest difference in texture by changing the scanning strategy: 5°_C led to R_a=24.9 µm ± 2.2 µm compared to 11.9 µm ± 0.6 µm for 5°_{NC}, corresponding to a reduction

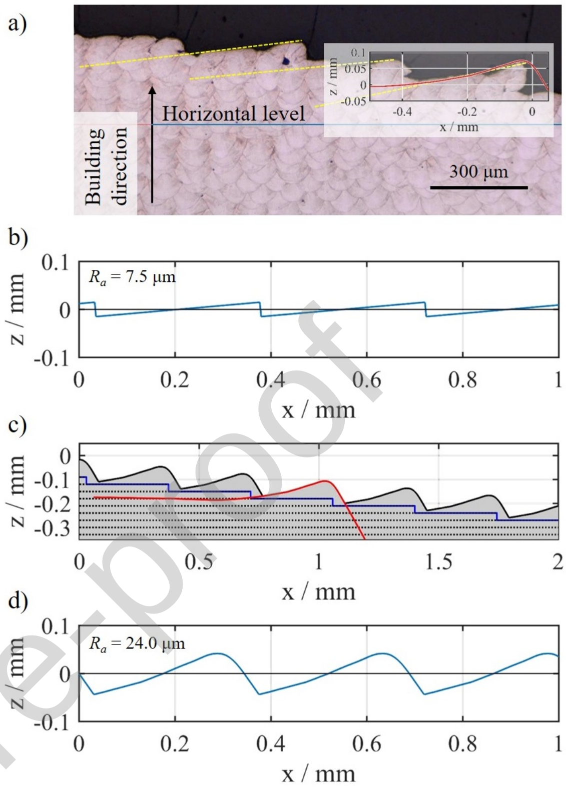

Figure 5: Contribution of the edge effect to the texture of low inclination surfaces, with (a) comparison of the mean edge profile of a cuboid (0°_C) and a single stair of a 5°_C, the horizontal reference line corresponds to a least square fitting of the MP deepest points, (b) theoretical profile of the stairs considering α=5° and t=30 µm, (c) superposition of the theoretical stairs and mean edge profile of a cuboid, (d) calculated profile resulting from the stair and cuboid edge superposition.

by 52%. The origin of the high surface texture for 5°_C can be explained by a strong contribution of the edge effect, meaning elevated edges forming at the rim of each stair (Figs. 3c,4a). Fig. 5a shows a high degree of similarity between a single stair of a 5°_C inclined surface and an edge of a simple cuboid (0°_C). Moreover, note that the intended horizontal stairs are in reality not perpendicular to the building direction but inclined up to 11° (Fig. 5a). This relatively counter-intuitive observation is in a good agreement with the mean edge profile, calculated according to the method provided in [18].

The theoretical surface texture given by the staircase effect can be determined analytically using Eq. 2. It was first reported by Campbell et al. [15], estimating the arithmetical mean height of a staircase profile with a stair height (layer thickness) t and surface slope α.

Table 4: Effect of number of contours (C) and order of scanning (OS) on surface quality of 5°_C (tactile measurement, λ_c=2.5 mm). Contour spacing h=70 µm.

P / W	v / mm/s	C	R_a / µm (OS: IN)	R_a / µm (OS: OUT)
150	900	2	24.5 ± 1.5	28.6 ± 1.9
150	900	3	23.8 ± 1.7	28.2 ± 1.0
150	900	4	21.7 ± 2.2	24.7 ± 1.5

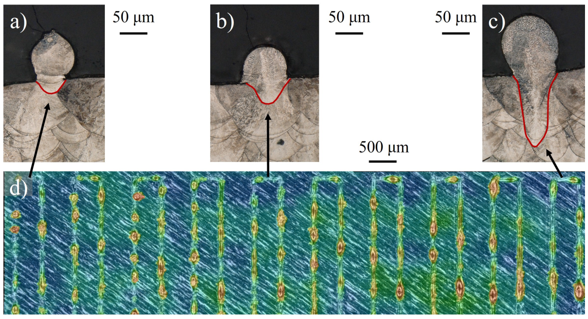

Figure 6: Single tracks with layer thickness t=30 µm and P=150 W, v=1500-600 mm/s (from left to right). Cross-sections at (a) v=1500 mm/s, (b) v=1100 mm/s, (c) v=600 mm/s and (d) top view.

$$R_a = \frac{t \cdot \sin\alpha}{4 \cdot \tan\alpha} \tag{2}$$

As illustrated in Fig. 5b, the theoretical surface texture for 5°_C given by the staircase effect (R_a=7.5 µm) is significantly lower than the measured one (R_a=24.9 µm ± 2.2 µm). On the other hand, a superposition of the theoretical stairs and mean edge shape (Fig. 5c) results in a calculated R_a=24.0 µm (Fig. 5d), being very close to the measured value. This further confirms the above mentioned strong contribution of the edge effect to the texture of 5°_C.

Table 3 gives the effect of P and v variation of the contour vector on the surface quality of 5° inclined parts. Only a minor improvement was observed when decreasing v of the contour scan, but P did not seem to have a strong influence on R_a. The lowest R_a was observed with P=150 W and v=900 mm/s, but the surface texture dropped only slightly, to 22.8 µm ± 2.3 µm.

Contrary to these observations, Artzt et al. [22] reported roughness improvement with laser power decrease and scanning speed decrease. This difference in behavior and sensitivity to process parameters can be explained by the used material, but more likely by different features dominating the surface texture. The work of Artzt et al. [22] focuses on vertical walls, which are sensitive to powder particles attachment (see Section 3.1). The simple fact of using contours, decreasing P or increasing v of the contour vectors reduces the heat

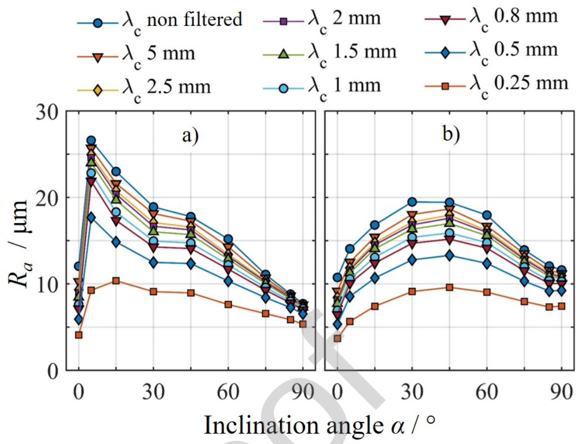

Figure 7: Effect of the cut-off length λ_c on the R_a value as a function of surface inclination α (a) when contours are used, (b) when no contours are used.

input, which consequently decreases the amount of attached particles and R_a. However, as described above, the texture of surfaces with a low inclination is driven by different phenomena: the staircase effect, but especially the edge effect. Further insights on the edge effect sensitivity to P and v variation can be acquired through a study of single line scan behavior.

As shown in Fig. 6, maraging steel has a high tendency for "balling". This refers to formation of discontinuous tracks due to high surface tension and capillary instability. The balling phenomenon is often associated with low heat input or high scanning speed [23]. More scan track discontinuities at high v would hence explain the increase of R_a with increasing v of contours, in case of 5° samples. Balling can be also material related, as illustrated by the following experiment: a thin layer of maraging steel powder (t=30 µm) was scanned with a wide range of combinations of laser power (130-190 W) and scanning speed (600-1500 mm/s). The melt pool morphology given in Fig. 6 shows shallow melt pools in the conduction melting mode (Fig. 6a,b) as well as melt pools in the keyhole melting mode with a high depth-to-width ratio (Fig. 6c). Although the deep melt pools were implying overheating, all the tracks showed signs of balling (Fig. 6d).

High surface tension of the material, together with a small laser spot diameter (d_{1/e^2} ≈60 µm) lead to relatively narrow tracks, further promoting the tendency for balling. In the literature, this material is often processed with larger laser spot sizes, at the expense of reduced surface quality and geometrical precision. Among the references from a recently published review by Mooney and Kourousis [24], only about 30% of the authors reported using a laser spot diameter below 100 µm.

Increasing the number of contours, so that the whole stair width is covered by them, also brought only a slight improvement. Table 4 shows that scanning four contours with scanning strategy "IN" (starting with the contour closer to the fill) resulted in R_a=21.7 µm ± 2.2 µm.

As reported by Yadroitsev et al. [25], the first scanned track is often built higher than the following tracks. This is related to a phenomenon called denudation driven by complex physics described by Matthews et al. [26]. Denudation refers to powder-free zones along the scan track, as the surrounding powder particles were attracted to the melt pool. The first scanned track has hence a sufficient powder supply on both sides, but the following scan track has only a single-sided powder supply leading to its lower height. When scanning multiple contour tracks, it is hence beneficial to start scanning closer to the fill, in order to avoid a high edge effect at the stair rim.

The results presented in this section thus clearly show that the scanning strategy without contours remains the most convenient one for the 5° samples.

3.3. Comparison to the state-of-the-art

Various quality of inclined surfaces has been reported in the literature (Fig. 8). As discussed by Leach et al. [27], the ISO standards developed for conventional manufacturing techniques are not particularly suitable for evaluation of surfaces produced by additive manufacturing, especially the recommendations of cut-off lengths by ISO 4288 [28]. As a consequence, different cut-off lengths λ_c have been used for data filtering in the reported studies. Considering arithmetical mean height of the roughness data R_a as a function of surface inclination, the general trend line is expected to be maintained if λ_c is reasonably long. Fig. 7 provides such an example based on the data from Fig. 3a. A shorter λ_c causes a downward shift of the curve and a slight change of its slope as the curve tends to flatten. However, using $\lambda_c < 0.8$ mm does not seem to reflect anymore the overall surface texture as it focuses on the presence of spatter and attached powder particles. For $\lambda_c \geq 0.8$ mm, the general trend is maintained, as is the crossing point of both trend lines determining α_{th}. Also for this reason, studies using $\lambda_c < 0.8$ mm were not considered. In order to provide complete information about the reported studies, the legend of Fig. 8 includes the used material, but also the measurement method (tactile or optical) and cut-off length used for filtering. The information about the scanning strategy (C or NC) can be also found in the legend, even though some authors [4, 5, 7, 8, 10, 14] do

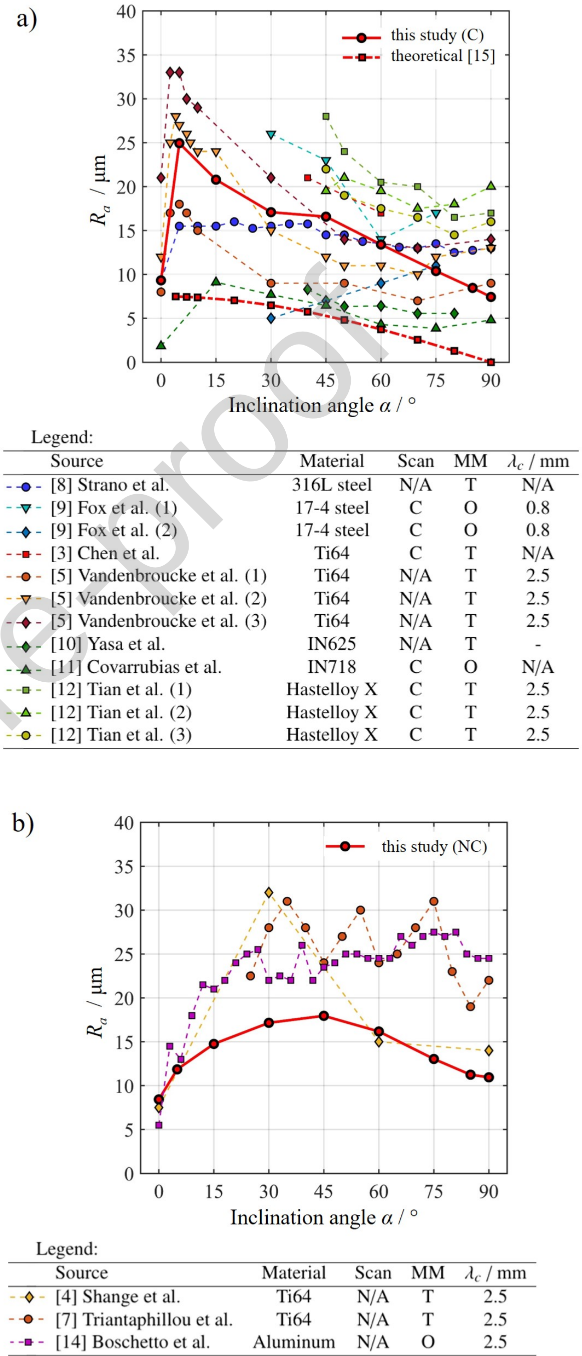

Figure 8: Arithmetical mean height R_a of the inclined surfaces texture from this study and reported in literature, (a) descending trend associated to using contour scanning (C), (b) ascending trend associated with scanning without contours (NC). Cut-off length λ_c, scanning strategy (Scan.), measurement method (MM): tactile (T) or optical (O), N/A: information not available. (1-3) refer to various processing parameters.

not give all the details about the used strategy. Moreover, in order to compare the data trend lines, only studies containing more than three surface inclinations were considered.

Generally, two distinct trends can be distinguished among the collected data: a descending or an ascending trend of R_a as a function of surface inclination. Despite the differences in used material and data processing, a similar behavior can be observed for all the surfaces built using contours (Fig. 8a). At low slope angles, many authors [5, 8, 11] observed a significant surface deterioration compared to horizontal surfaces, and a gradually improving quality with increasing slope angle [3, 5, 8, 10, 11, 12]. To our knowledge, the only exception was reported by Fox et al. [9], where a different behavior was observed for different process parameters, depending on the heat input. However, they used a short λ_c, which shifted the attention more towards the short wave features. Moreover, Tian [12] investigated a large range of contours process parameters for various surface inclinations, noticing that all parameter sets followed a very similar trend. When using contours, the comparison to the state-of-the-art is rather consistent with the present study. In spite of the evident difference in magnitude, the general trend does not seem to be very sensitive to the change of material and filtering methods.

Fig. 8a also gives a visual comparison of the data to the theoretical R_a prediction based on the analytical model (Eq. 2), consistent with the reported data. However, some of the curves [5] including this study present a steeper of slope for $\alpha < 30°$. As determined in Section 3.1, in this inclination range the edge effect is dominant, and further deteriorates the surface quality.

Conversely, some authors [4, 14] reported an ascending trend for low inclinations (Fig. 8b). This behavior would suggest a dominant influence of the powder particles attachment, as the general trend line is in a good agreement with the particle coverage observed by Newton et al. [16]. For higher inclination angles, some authors observed stagnation [7, 14] and others a decrease [4]. As discussed in Section 3.1, when scanning strategy without contours is used, the surface is strongly marked by the acceleration and deceleration of the scanning mirrors illustrated in Fig. 2c. Combined to the specific morphological and thermophysical properties of the powder, the observed behavior might be then relatively sensitive to the used material and equipment.

Besides the scanning strategy, lower layer thickness [5] as well as lower powder particle size [29] were also found to play an important role in inclined surface texture. Nevertheless, the general trend lines of R_a as a function of surface inclination seem to be conserved when varying these factors.

4. Conclusions

Surface quality is an important factor influencing mechanical properties of the produced part. Understanding the origins of surface features helps optimizing the manufacturing process in order to reach a better surface texture, and thus improve mechanical properties of the final component. This study determines the effect of scanning strategy on the quality of up-facing inclined surfaces produced by laser powder bed fusion from maraging steel 300. Depending on the surface inclination and used scanning strategy, surface texture was found to be dominated by features originating from different sources.

Surfaces with low inclination angles are strongly marked by the staircase effect combined to the edge effect, especially if contours scanning is applied. Contour scanning is detrimental for slightly inclined surfaces of maraging steel components, as both the edge effect and the balling phenomenon hinder the surface quality. The contribution of the edge effect was proved by superposing the theoretical staircase profile and a mean edge profile of a simple cuboid. The calculated R_a (24.0 µm) was found to be very close to the measured one (24.9 µm ± 2.2 µm). The impact of the edge effect was found to be limited to the inclinations with an inter-layer stair width significantly larger than the melt pool size (typically $\alpha < 30°$).

Contrarily, the quality of surfaces with high inclination angles ($\alpha > 42°$) is enhanced by contour scanning. Using contour scanning decreases the amount of overheated locations in contact with the surrounding powder bed. As a consequence, the quantity of attached particles is noticeably reduced, as are other features originating from the fill scanning pattern. It is thus advised to produce these surfaces using a scanning strategy with one or multiple contours.

Moreover, an appropriate cut-off length λ_c can also help understanding the origins of surface topography. In order to investigate the presence of spatters or attached powder particles, using $\lambda_c < 0.8$ mm seems to be a suitable solution. However, to capture the overall surface topography, longer cut-off ($\lambda_c \geq 0.8$ mm) is required.

This knowledge can be used to select a suitable scanning strategy for each surface inclination. For instance, the surface texture of samples inclined by $\alpha = 5°$ can be improved by 52% if no contours are used. On the other hand, using contours improved the quality of samples with $\alpha = 75°$ by 20% and of vertical walls by 32%.

As a consequence, these findings can be implemented in the phase of build file preparation. This would lead to a considerable improvement of the as-built quality of inclined surfaces.

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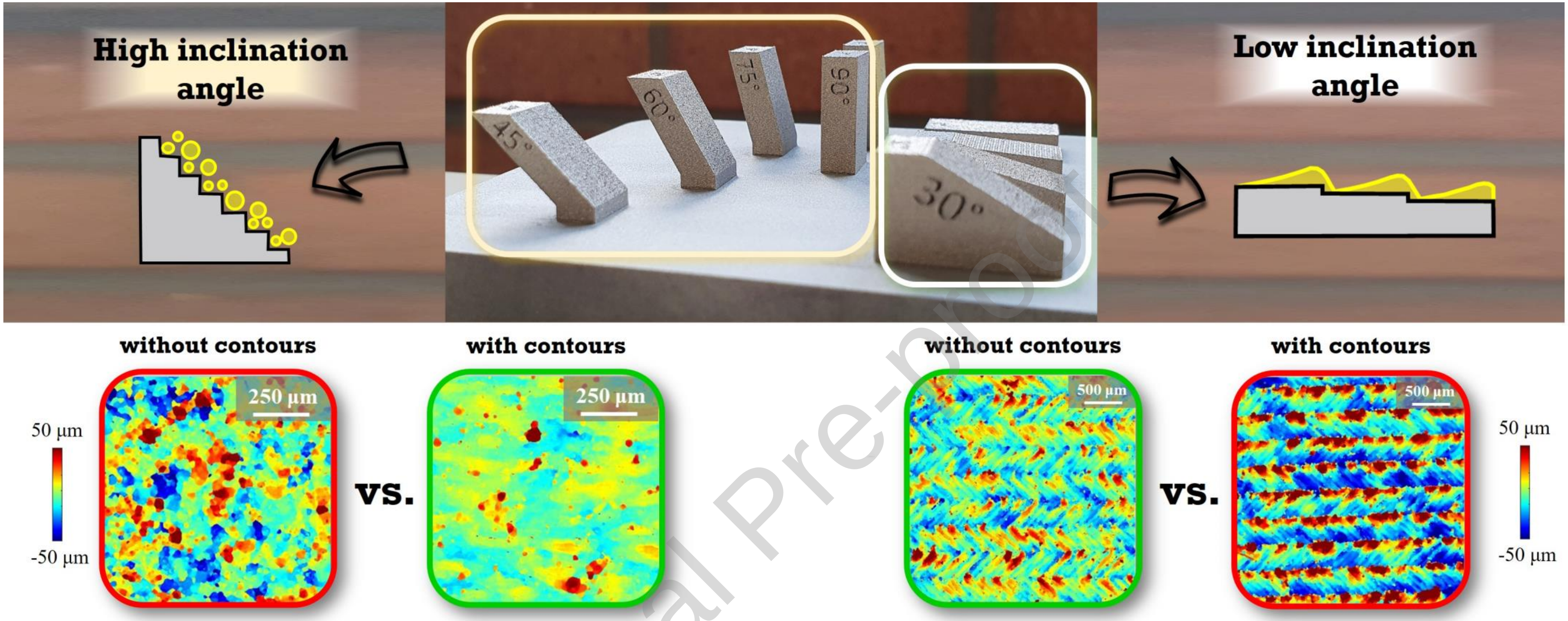
High inclination angle
45°
60°
75°
90°
30°
Low inclination angle
without contours
with contours
without contours
with contours
50 µm
-50 µm
250 µm
vs.
250 µm
500 µm
vs.
500 µm
50 µm
-50 µm

Credit Author Statement

Jitka Metelkova: Conceptualization, Investigation, Writing - Original Draft, **Lars Vanmunster**: Methodology, Investigation, Writing - Review & Editing, **Han Haitjema**: Investigation, Writing - Review & Editing, **Brecht Van Hooreweder**: Supervision, Writing - Review & Editing.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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