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Internal reinforced domains by intermediate deep rolling in additive manufacturing

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A R T I C L E I N F O

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Process-integrated deep rolling

A B S T R A C T

This paper presents a new concept to integrate mechanical surface treatment into the build process of additive manufacturing (AM). The layer-based build process during Selective Laser Melting (SLM) allows for accessing the single layers before continuing the addition of further layers above the mechanically treated surfaces. Deep rolling is applied to enhance the Surface Integrity into depths of several SLM-layers (450 µm) before the part is re-integrated into the SLM-process. The hardness alterations and increased full-width-half-maximum (FWHM) are preserved after continuing the AM-process. The results reveal the potential to generate material-internal reinforced domains and thus enhance the Material Integrity after AM.

1. Introduction and motivation

Additive Manufacturing (AM) [1,2] opens up new options regarding the design [3] of highly complex parts made of a wide range of materials [4]. Techniques based on powder beds such as Selective Laser Melting (SLM) lead to a layer-by-layer generation of parts. Due to the high temperature gradients and rapid cooling during the SLM-process, complex residual stress distributions after re-solidification of the material are observed.

The Surface Integrity [5] of SLM-components has been discussed e.g. by Brinksmeier et al. [6] indicating that the layer-orientation has a significant influence on the residual stresses even after post-processing of samples made of AISI 52100. Li et al. [7] pointed out that in metals, elevated temperatures of the whole part during the SLM-process as well as suitable post-processing beneficially influence the residual stress state of additively manufactured parts. Post-processing by mechanical surface treatment such as shot peening, hammering or deep rolling [8] has been successfully applied to enhance the Surface Integrity of casted metal components by means of hardness alterations and induction of compressive residual stresses in the past. Consequently, Breidenstein et al. [9] analyzed the influence of the temperature as well as the effects of milling and deep rolling on the Surface Integrity of AM-parts made of H13-steel. They revealed advantageous surface and subsurface properties after deep rolling based on microstructural transformations, hardness alterations and compressive residual stresses. Dumas et al. [10] observed a significantly lower fatigue strength of Ti-6Al-4V parts produced by SLM and traced this effect back to the porosity and brittle phases. Mechanical surface treatment, despite of its positive effects on the fatigue strength, was not considered. Le Coz et al. [11] analyzed the specific influence of the layer-based material properties after SLM in orthogonal micro cutting. Due to the comparably low mechanical loads during the process, the subsurface properties of the SLM-parts remained unaffected.

The publications dealing with improving the surface and subsurface properties of additively manufactured parts are limited to the AM-process itself and post-processing. Comprehensive post processing by machining or/and mechanical surface treatment is mandatory to meet required Surface Integrity of e.g. functional surfaces. This is a considerable drawback regarding the potential advantages of process chains including AM. Furthermore, post-processing is limited to well accessible areas. The bulk material as well as surfaces of parts with a complex design have to remain in the as-printed state.

Thus, this paper presents a new approach to take advantage of the temporary accessibility of the single layers during AM (here SLM) by locally reinforcing the material in an intermediate deep rolling step. Repeating the process steps of deep rolling and continuation of the addition of layers allows for a stepwise generation of material-internal reinforced domains with a high degree of freedom regarding their design (see Fig. 1).

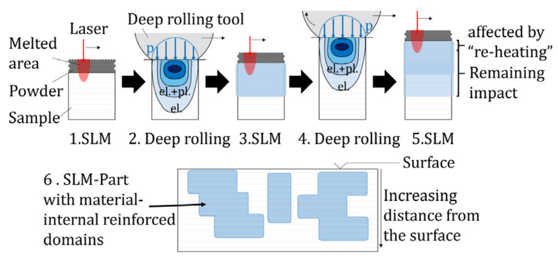

Fig. 1. Generation of material-internal reinforced domains by intermediate deep rolling during the SLM build process.

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2. Approach and experimental set-up

To gain a general understanding regarding the potential of deep rolling to enhance the **Surface Integrity** of SLM parts by reinforcing the material, the achievable surface and subsurface properties after deep rolling an as-printed state of the material (AISI 316L) was investigated in a first step (Section 3.1). For this purpose, SLM-generated parts with varied porosity were deep-rolled after the AM-process and the hardness alterations and the surface roughness were investigated. Based on these findings, a deep rolled part was re-integrated into the SLM-process to apply additional layers to the deep rolled area (Section 3.2). It was expected that the high temperatures during continued SLM affect the surface and subsurface properties observed after deep rolling. However, in case that the reinforcement remains after continuation of the SLM-process, the internal local properties of the material (**Material Integrity**) would be affected in a beneficial way and differ from the properties of the bulk material. The modification of the **Material Integrity** in certain areas will lead to a stepwise generation of domains (Section 3.3) of locally specific material properties (Fig. 2).

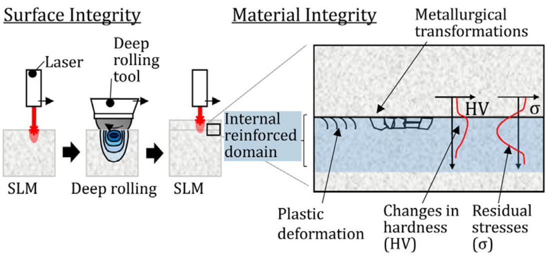

Fig. 2. Modification of the Material Integrity in material-internal domains.

2.1. Generation of SLM-samples with varied properties

Within this study, AISI 316L samples generated by Selective Laser Melting were investigated. For the initial analysis of the Surface Integrity resulting from deep rolling as-printed SLM-surfaces, the microstructure and porosity of simple cubes with an edge length of 50 mm were varied by utilizing different hatch distances h_d of 150 µm and 120 µm. Since the latter resulted in a lower porosity, a hatch distance of 120 µm was chosen for the experiments aiming at re-integration of the part and analyzing the Material Integrity. The layer thickness of 50 µm as well as the utilized laser power of 235 W were kept constant for all samples.

2.2. Deep rolling of the surface of SLM-parts

Deep rolling was performed utilizing a hydrostatically supported ceramic tool (Ecoroll HG6) with a ball diameter of 6 mm at a conventional CNC milling machine tool. The deep rolling pressure p_r was varied to apply different mechanical loads by means of the rolling force F_r to the surfaces (cf. Fig. 3a). By a translatory motion, a contact between tool and workpiece is achieved resulting in a plastic deformation of surface and subsurface layers. With a feed f of 0.1 mm, areas measuring 10 mm × 10 mm are deep rolled on the top face and the lateral face of the cubes varying the relation between the deep rolling direction and the layer orientation (Fig. 3b). Table 1 summarizes the applied process parameters.

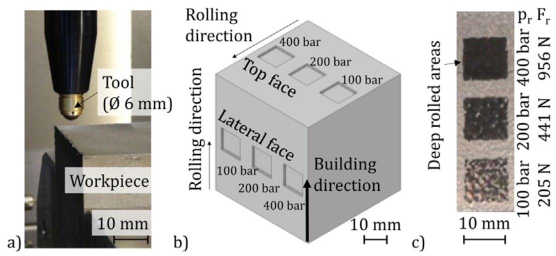

Fig. 3. Experimental set-up for the analysis of the Surface Integrity after deep rolling SLM-parts under varied conditions.

Table 1
Process parameters of the deep rolling process.

Parameter	Values
Ball diameter d_b/mm	6
Deep rolling pressure p_r/bar	100, 200, 400
Deep rolling force (measured) F_r/N	205, 441, 956
Rolling speed v_r/mm/min	100
Feed f/mm	0.1

2.3. Re-integration of deep rolled parts into the SLM-process

Based on the findings regarding the achievable Surface Integrity, parameters for re-integration of a deep rolled sample into the SLM-process were defined. A deep rolling pressure of 400 bar (F_r = 956 N) was chosen for two reasons: i) high hardness alterations are expected and might be preserved even after continuation of the SLM-process and ii) with higher deep rolling pressures the resulting surface roughness decreases. Smoother surfaces are considered to potentially affect the attachment of additional layers in the SLM-process in a detrimental way. Thus, it had to be examined, if re-integration leads to undesired effects such as increased porosity or even hollow cavities. As shown in Fig. 4, an area of 10 mm x 15 mm was deep rolled with the parameters indicated in Table 1 (p_r = 400 bar; F_r = 956 N). The deep rolling direction was set parallel to the layer orientation. Deep rolling was performed at a DMG turning lathe after dismounting the sample from the SLM-printer (AconityLAB). Without an additional cleaning step, the deep rolled part was re-mounted into the SLM-printer to continue the SLM-process.

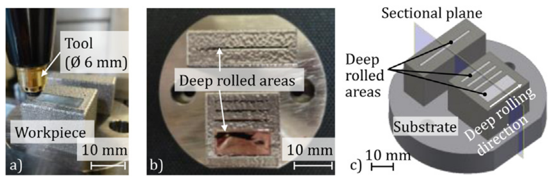

Fig. 4. Deep rolling set-up (a) and deep rolled area (b) which was re-integrated into the SLM-process. The sectional plane indicates the location of the cross sections and measurements (c).

3. Results

3.1. Surface integrity after deep rolling of as-printed surfaces

The arithmetic mean roughness values Ra (tactile measurements) as well as the arithmetical mean height of the surface Sa (area of 865 µm × 600 µm, Talysurf CCI HD+ Software SPIP 6.7.4) were measured and significantly decreased by deep rolling. With higher deep rolling pressures, lower Ra- and Sa-values were obtained (Table 2). As visible in Fig. 3c, especially the as-printed surface as well as the surface after deep rolling with low deep rolling pressures show a significant waviness. To limit the effect of the waviness and to analyze a potential influence of very smooth

Table 2
Sa-values (ISO 25178, applying a form operator and ISO 16610 Gaussian filter) and Ra-values before (L_c = 2.5 mm, L_s = 0.008 mm) and after deep rolling (L_c = 0.8 mm, L_s = 0.0025 mm); ± standard deviation.

	h_d [mm]		as-printed	Deep rolling force F_r [N]		
				205	441	956
Top face	150	Sa	4.61	0.29	0.18	0.10
		Ra [µm]	*18.7 ± 2.6*	*1.6 ± 0.65*	*0.6 ± 0.02*	*0.5 ± 0.04*
	120		3.72	0.39	0.15	0.06
			14.9 ± 2.2	*1.4 ± 0.35*	*0.6 ± 0.12*	*0.3 ± 0.02*
Lateral face	150		8.91	0.46	0.24	0.23
			12.4 ± 0.3	*1.5 ± 0.79*	*0.4 ± 0.03*	*0.3 ± 0.15*
	120		11.50	0.55	0.24	0.25
			14.0 ± 1.0	*0.8 ± 0.15*	*0.5 ± 0.14*	*0.3 ± 0.05*

surfaces on the attachment-behavior of additional layers in the continued SLM-process, a hatch distance of $h_d = 120\,\mu m$ is chosen for the subsequent experiments.

Besides the effects on surface roughness, even low deep rolling pressures affect the subsurface properties in a beneficial way. This can be deduced from the hardness depth profiles shown in Fig. 5 (left) for the sample with a hatch distance of 120 µm (top face). Compared to the bulk hardness of about 240 HV0.5, an increase to 350 HV0.5 is achieved for all pressures. Comparable values are observed for the lateral face (Fig. 5 (right)). Increasing the deep rolling pressure results in an increase of the depth effect of the reinforcement. A pressure of 400 bar results in an increased hardness up to a surface distance of 400–450 µm. The red lines in Fig. 5 represent the strain hardening severity for a deep rolling pressure of $p_r = 400$ bar. At a layer thickness of 50 µm during the SLM-process, the strain hardening effect covers a range of ca. 8–9 layers which are reinforced by the mechanical surface treatment. The strain hardening is accompanied as expected by high compressive residual stresses into depths of 1 mm starting with −500 to −600 MPa at the surface near layers as X-ray-diffraction measurements revealed.

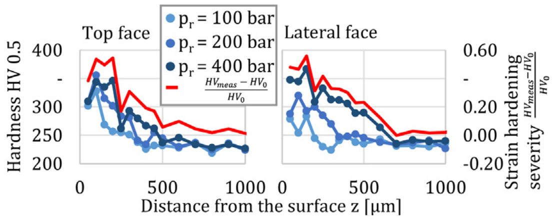

Fig. 5. Hardness depth profiles after deep rolling.

3.2. Material integrity after re-integration of deep rolled parts

To analyze the influence of re-integrating deep rolled surfaces into the SLM-process on the strain hardening effects, additional SLM-layers were added to the deep rolled part shown in Fig. 4. The investigations were performed based on generating a cross-section of the re-integrated part (Fig. 6 (left)) covering areas which were deep rolled prior to re-integration and areas which remained in the as-printed state before re-integration (Fig. 6 (right). In the cross section (Fig. 6 (middle)) a small lateral offset between the SLM-layers generated initially and those added after deep rolling is observed. It results from reclamping of the component and is helpful when it comes to the localization of the initial surface. As can be seen in the cross section, the attachment of the layers added after re-integration of the deep rolled sample into the SLM-process appears to be accurate. No porosity or imperfections were observed in the surrounding material. Regarding the density of the material, no difference between the initially deep rolled surface and the as-printed state is observed (Fig. 6 (right)). Thus, neither the fact that the continued printing took place on non-preheated material nor the fact that the sample has left the evacuated building space in between caused any problems. The reduction of the surface roughness by deep rolling (Ra after deep rolling = 0.3 µm) did not affect the attachment of additional layers.

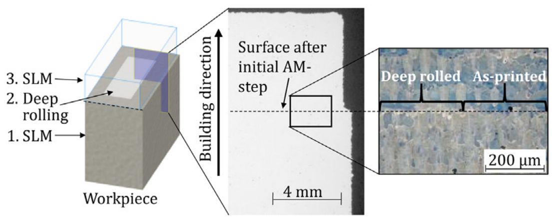

Fig. 6. Cross-sections indicating the good material attachment after re-integration of deep rolled samples into the SLM-process.

The analysis of the Surface Integrity after deep rolling indicated that a deep rolling pressure of 400 bar may lead to a maximum hardness of 350 HV0.5 and a depth effect of 400–450 µm. Due to the high thermal impact during the continuation of the SLM-process, a

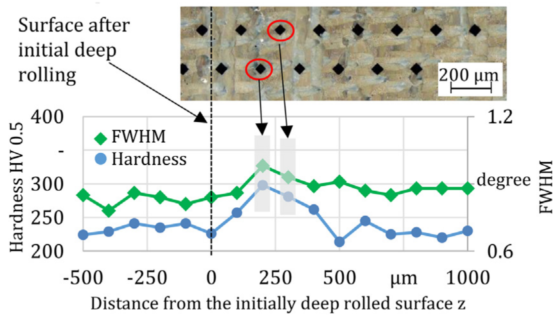

Fig. 7. Hardness depth profile after re-integrating a deep rolled part into the SLM-process.

certain reduction of the hardness in the strain hardened areas can be expected. This is confirmed by the hardness depth profile presented in Fig. 7. Compared to Fig. 5, a drop of the hardness from 350 HV0.5 to the bulk hardness is observed in the range of the very first layer added after deep rolling. The thermal load during SLM furthermore reduced the hardness into depths of up to 230 µm below the initially deep rolled surface. Below this depth, the hardness alterations remain unchanged by the SLM-process. This indicates that the chosen deep rolling parameters are suitable to induce plastic deformation and strain hardening which persistently affects the Material Integrity. This is supported by the analysis of the full-width-half-maximum (FWHM) assessed by X-ray diffraction. The FWHM is an indicator for the distortion of the crystal lattice e.g. due to plastic deformation (dislocation slip, twinning effects, and other effects). It is deduced directly from the shape of the peaks measured in X-ray diffraction. The depth profile in Fig. 7 shows a maximum in accordance with the measured hardness. The highest FWHM was obtained at a depth of 230 µm below the initially deep rolled surface. Here as well, the thermal impact of the continued SLM-process leads to a reduction of the FWHM in the first 230 µm below the deep rolled surface to a level comparable to the bulk material.

3.3. Material-internal reinforced domains

The microstructural properties of the material-internal reinforced domains were analyzed using the Electron Backscatter Diffraction (EBSD) technique in a scanning electron microscope (SEM). For this purpose, a cross section was prepared. The EBSD measurements was used to analyze the rotation angles of the (grain) boundaries (Fig. 8) as an indication of different alterations of the microstructure. Comparably high rotation angles as observed in the first 230 µm below the initially deep rolled surface indicate that the heat of the continued SLM-process causes recrystallization effects. The rotation angles >5° are indicated by green and blue lines and are more pronounced in the strain hardened and re-heated layers compared to the layers additionally applied during the continuation

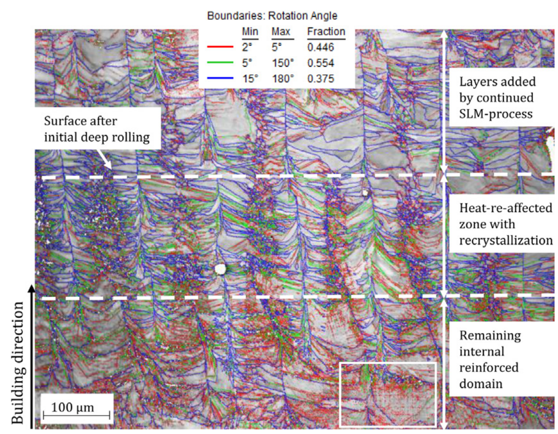

Fig. 8. Microstructure of the remaining internal reinforced domain (bottom), the initially deep rolled but heat re-affected zone (middle), and the additionally applied SLM-layers (top) including the rotation angles of the boundaries indicating dislocation slip and twinning (red) as well as recrystallization (blue and green).

of the SLM-process. Below the heat-re-affected zone, remaining strain hardening (small rotation angles <5°, red lines) is observed in a domain with reinforced material.

As for the hardness depth profile shown in Fig. 7, the depth of the area with remaining signs of plastic deformation is about 250 μm. Within this internal reinforced domain, dislocation slip and twinning effects are observed and emphasized in Fig. 9. In the etched cross section (Fig. 9 left) as well as in the combined SEM/EBSD image (Fig. 9 right) the remaining plastic deformation can be observed. The location of the detail presented at the right hand side is indicated by the small white frame in Fig. 8. The analysis of the rotation angles reveals that not all deformation lines visible in the SEM-image (Fig. 9 (right)) are mapped and depicted by red lines. As a consequence, the remaining strain hardening effects in the internal reinforced domain likely are more pronounced than implied by the color code in Fig. 8.

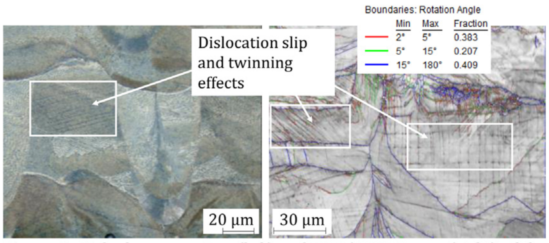

Figure 9. Etched cross section (left) and SEM/EBSD image (right) of the microstructure within the remaining internal reinforced domain.

Fig. 9. Etched cross section (left) and SEM/EBSD image (right) of the microstructure within the remaining internal reinforced domain.

4. Conclusions and outlook

This paper presents the new approach to combine deep rolling and SLM to generate material-internal reinforced domains. Based on the characterization of the Surface Integrity of SLM-parts after deep rolling, a deep rolled surface was re-integrated into the SLM-process. The resulting Material Integrity is characterized by:

- an imperfection-free attachment of the additionally applied layers. Re-integration of a deep rolled surface into the SLM-process does not seem to cause any incompatibilities.
- a heat-re-affected zone with a depth of ca. 230 μm (4 layers) which shows a microstructure indicating recrystallization-effects. The hardness of this layer is only slightly increased compared to the bulk material. The depth of this layer is strongly influenced by the SLM-parameters and may be reduced by varying e.g. the laser power.
- a remaining material-internal reinforced domain exhibiting hardness alterations with a thickness of 200–250 μm (4–5 layers). The local Material Integrity in these domains can be influenced by intermediate deep rolling and is characterized by dislocation slip and twinning effects. Due to its determined depth effect, deep rolling of every single layer is not necessary to generate an internal reinforced domain.

The presented findings reveal the potential to generate internal reinforced domains by intermediate deep rolling in additive manufacturing. Integrating a mechanical surface treatment into the SLM-process makes use of a specific feature of additive manufacturing: the temporary accessibility of all regions of a part. The modification of the local mechanical material properties (Material Integrity) of additively manufactured parts carries the potential to improve the functional performance of e.g. highly stressed components. The properties of local and conventionally inaccessible areas can be enhanced combining the advantages of additive manufacturing and mechanical surface treatment. For example, the inner structures of 3D-printed cooling lubricant nozzles, which are subject to abrasive wear, can be reinforced using this approach. Considering the assumed positive effects already in the design phase might allow for engineering resource efficient lightweight components capable of tolerating loads comparable or superior to conventionally manufactured parts.

The thermal effects during the continuation of the SLM-process reduce the hardness alterations as expected. However, the layers with remaining strain hardening have a depth of 250 μm which indicates that for alternating deep rolling and addition of only a few supplementary SLM-layers, consistent internal domains with high geometrical flexibility (c.f. Fig. 1) may be generated.

To produce SLM-parts with enhanced Material Integrity in domains which are inaccessible after SLM, dismounting of the workpiece from the SLM-machine and performing the deep rolling process at a separate machine tool is proven to be possible but comparably inefficient. Based on the findings presented and further research, the set-up of new hybrid machines would improve productivity and pave the way for integrating the mechanical surface treatment into the build process during additive manufacturing. For an SLM-process, a deep rolling portal could be installed into the chamber of an SLM-machine. Alternating selective exposure and deep rolling would lead to the desired generation of parts with material-internal reinforced domains. In this set-up, the part would not leave the atmosphere in the SLM-chamber until the part is finished. It is of high interest, how the heat re-affected zones react to the alternating procedure as in the presented work, only one deep rolling step was performed. Analysis of the Material Integrity of those parts as well as their functional properties (fatigue strength, wear resistance, etc.) will reveal the potential to simplify the process chain of highly loaded AM-parts. The potential elimination of the often applied step of hot isostatic pressing (HIP) would be one example for the beneficial effects of improving the Material Integrity already during the build process.

The general approach of integrating the mechanical surface treatment into the build process in additive manufacturing is not limited to SLM. Hybrid machines combining laser deposit welding and machining can be used to integrate deep rolling or machine hammer peening into additive manufacturing, as well. A transfer to wire-based laser metal deposition is conceivable.

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