Sep 25th, 1:50 PM

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Stoeckel, Stefanie and Groeger, Sophie, "Investigation Of Topography Changes Of Blasted Surfaces: An Experimental Perspective Using Fiducial Markers" (2025). *15th International Conference on Shot Peening*. 1.
https://docs.lib.purdue.edu/icsp15/papers/industrial4/1

INVESTIGATION OF TOPOGRAPHY CHANGES OF BLASTED SURFACES: AN EXPERIMENTAL PERSPECTIVE USING FIDUCIAL MARKERS

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Abstract

Abrasive blasting is a process that intentionally modifies surface topography to meet specific functional requirements. The blast media is accelerated and interacts directly with the surface through impact. It is evident that the number of impacts and the overlap increase with time. This study aims to investigate these alterations to surface topography through repeated examinations of the same location. A methodology has been developed that employs the use of fiducial markers, which are protected during blasting by a custom 3D-printed cover. This method was used to observe changes in the topography of smooth and rough initial surfaces that had been blasted. Furthermore, the evolution over time has been analysed. It is evident that the developed method has enabled these alterations to be observed.

Keywords surface topography, fiducial markings, experimental analysis, wheel blasting

Introduction

Abrasive blasting is a process that can be used to modify the surface topography with a variety of objectives, such as cleaning, roughening, creating an optical appearance or inducing residual compressive stress, as in shot peening. The surface topography is subject to direct alteration as a consequence of the impact of the blast media. The term "surface topography" refers to the overall surface structure, including shape and surface texture [1]. Surface texture is defined as the remaining deviations after the removal of the nominal shape, often referred to as roughness [1]. The change in topography can be observed by surface measurements before and after the manufacturing process. The investigation focuses on areal surface topography, as the anisotropic surface generated by blasting is better represented by areal than profile measurement.

Surface measurement in general encompasses a limited portion of the surface in comparison to the total surface area of the workpiece. Consequently, it is not possible to locate the exact same spot without an unambiguous reference. In this context, fiducial markers can be utilised. These markers serve as reference points for the alignment of data sets from different stages of the manufacturing process. However, the challenge is that the markings must remain unchanged by the subsequent manufacturing process. The following review of literature explores two different aspects. First, the state of the art in markings for surface topography measurements is analysed. Secondly, studies examining the effect of time or coverage on surface topography for shot peening are presented.

Markings for surface topography measurements

Two different options for markings are generally available. The markers themselves can be utilised directly for image alignment. Alternatively, features of the surface topography can be employed. In the first case, different possibilities for markings are described. Hazeli et al. [2] conducted an investigation into the various stages of fatigue life, utilising indentations by a micro-indenter. Wei et al. [3] investigated material removal using three drilled craters. The craters were filled with glue during the manufacturing process of abrasive flow machining, so their bottom remained as an unchanged reference. This reference was utilised to overlay and position measured profiles. A similar approach was employed by Wang and Gao [4], who used milled slots in a triangular shape that were also covered with glue. Newton [5] used micro milled rectangles of 1 x 0.5 mm with rounded corners and a depth of 300 µm on an additively manufactured surface. This reference was utilised to observe various finishing processes, including shot peening. Nevertheless, the cover method is not the subject of further discussion. The utilisation of topographical features as markers, has also been explored by different scientists. Moretti et al. [6] developed algorithms based on the identification of landmarks on both the original and partly modified surface. This method is only capable of assessing partial changes, as it necessitates the utilisation of landmarks from the original surface. The relocation of the measurement area is conducted under a microscope through visual estimation. In a different approach, Leksycki and Królczyk [7] utilise fixed dimensions of the sample as an external reference point for positioning with optical measurement. They applied their method to compare different optical devices. In general the utilisation of markings and cover methods is not thoroughly documented, nor is it described in exhaustive detail. In the majority of cases, this is merely a minor component of the methodology section. Several methods exist; however, due to the unique characteristics of the manufacturing process, machine and materials, it is not possible to adopt one without modifications. Consequently, a methodology based on the existing approaches was developed for the investigation of blasting with a wheel blast machine and moving specimen.

Influence of blasting time or coverage on surface topography

A number of investigations into real surface topographies, predominantly in conjunction with simulation, have been conducted for shot peening. Abyaneh [8] investigated the general aspects of shot peening and coverage, with a particular focus on the overlap of shots. The researcher found and described by formula and diagram how the overlap increases with increasing process time. The author employed simulation [9], yet no empirical measurements were utilised. Zimmermann et al. [10] refer to developments in Abyaneh and show measurements of respective real topographies of 50%, 100% and 150% coverage. These measurements most likely do not refer to the same area, since there is no description of a reference. Zimmermann [10] contends that it is impossible to determine quantitative results of multiple overlap from surface images. Zhao [11] presents experimental results for areal surface topographies for five different peening times. In the related simulation, a greater number of peening times are evaluated. The impact of single new dimples in the same simulated area at four different stages is investigated, in order to examine sudden changes in Sp. Nordin and Alfredsson [12] present surface topographies for varying process times and intensities measured by confocal microscope. They analyse single indentations based on parameters like diameter, volume, and displaced material. Stöckel et al. [13] investigated areal blasted topographies for different times. The entirety of the experimental investigations do not present the change of topography on the same measurement area with an absolute reference. In the context of additively manufactured samples, the impact of blasting or shot peening on surface topography is examined as a post-processing method to finish and clean. Newton [5] presented the change of topography by shot peening of the same spot on an additively manufactured specimen using milled slots as reference. The specimen were build at inclination angle 0° and 90° and were shot peened to 200% coverage. It was found that the waviness was preserved and that no change in material ratio occurred for build angle 0°. A reduction in height was also observed in the 90° build angle. Krishna et al. [14] observed a greater number of angles and the post-processing by shot blasting. But no observations of the same area were recorded. However, as Newton does not provide any information regarding the surface coverage, it remains unknown how changes in the same area of additively manufactured specimen can be observed.

It is well established that shot peening exerts a significant influence on surface topography. A substantial number of experiments are conducted with the objective of analysing and quantifying the influence of process parameters, including shot velocity and shot material, amongst others. It is acknowledged that the initial topography and their roughness have a substantial impact. Furthermore, shot peening simulation has undergone substantial development, attaining the capacity to model multiple impacts and accurately replicate the resulting surface topography. However, it should be noted that the majority of these references pertain to nozzle systems and shot peening, and the interaction of the blast media with the surface is most likely different for wheel blast machines. Horowitz [15] writes that processes involving angular blast media that result in different topographies have not yet been explained. He also refers to Gay's theory that impacts from the same impact angle shift the material, resulting in folded material with similar slope angles.

The objective of this paper is to establish an experimental setup to locate and examine the topography in the same region and observe the change by the manufacturing process. Furthermore, the evolution of the blasted surface and the impact of blasting for an additively manufactured sample will be demonstrated. This development may serve as a foundation for further experimental investigation into the mechanisms of blasting by wheel blast machines.

Experimental Procedures or Computational Methods

Blasting and specimen

The machine applied for blasting is a wheel blast machine TWISTER, by BMF GmbH (Figure 1a). The system is a patented innovation that does not utilise compressed air. In this respect, it differs from other wheel blast machines. The blast media is provided and accelerated by an upstream, which is then distributed by a spin wheel in the middle. In addition, the workpieces are mounted on a workpiece carrier and move around the spin wheel and the carrier itself (Figure 1b). The manufacturing parameters that can be influenced include the speed of the spin wheel, the time, and the blast media. The speed here is always 9000 rpm. The blast media is a spherical steel shot S10 or a mixture of spherical and angular broken steel shots S/GM10. Both have a size range of 0.05 – 0.2 mm. The material of the milled or raw sheet specimen is steel 1.4301, with dimensions of 20x20x2 mm (Figure 1c). The additively manufactured specimen is composed of stainless steel (1.4404) with dimensions of the square of 20 x 20 x 2 mm (Figure 1d). The specimen was produced by laser powder bed fusion, with an inclination angle of 45°. Firstly, experiments were conducted to examine the initial state and the state after 10 minutes of blasting with S10. In a second experiment, the evolution of surface topography was observed over several times: 0 min (initial state), 1 min, 2 min, 4 min, 8 min, 12 min and 20 min with blast media S/GM10.

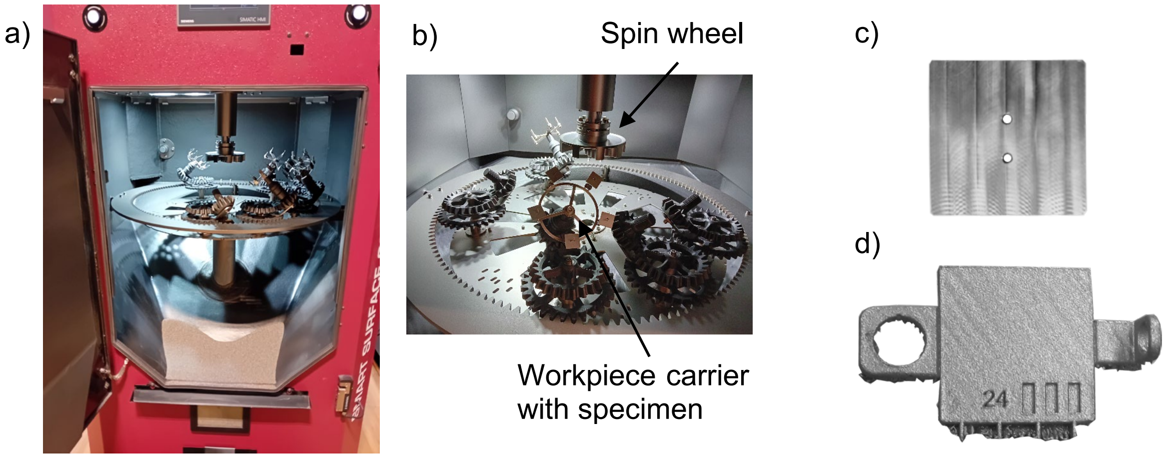


Figure 1. a) Wheel blast machine TWISTER, b) detail of the machine, c) milled specimen and d) additively manufactured specimen

Measurement

The measurement is conducted using the Confovis DUO Vario, which incorporates both structured illumination mode (SIM) and focus variation. The first of these is applied for surface texture measurements. An objective 20x/NA0.6 has been used and a measurement area of 630x630 µm recorded. In order to create larger measurement areas four or six measurements are stitched in a row. The surface data is processed with MountainsMap®10.2. The general pre-processing of data involves the following steps: alignment to the LS-plane and removal of noise with a Gaussian filter and cut-off 2.5 µm. Roughness parameter were calculated after applying Gaussian filter with a cut-off of 0.25 mm. The colocalisation function of MountainsMap® is employed for digital image correlation. The specimens are prepared by ethanol cleaning to remove dirt and, in particular, residues from the blasting process. In the topographies the non measured points (NM) are not filled and indicated with white colour.

Development of cover and markings

The manufacturing process as well as the measurement provide the requirements for the marking. The marking must:

- be recognised by the measurement system and located visually,
- be protected during the process and adhere to the moving specimen,
- be easy to use and cost-effective, and
- be permanent and not removed by cleaning or covering.

Therefore, a combination of marking and a cover was used, as known from the state of the art. A 3D-printed cover was designed individually for each specimen. The first cover was developed for the milled specimen. Four distinct shapes were designed and printed: a U-shape, an edge, an L-shape and an H-shape as shown in Figure 2. It is crucial that all covers are securely fastened to ensure an optimal fit, which is accomplished by applying pressure. They also provide a fit by the shape, especially the U-shape. In the case of the H-shape, the length of the bridges in the middle was intended to determine the pressing force. The edge of all the covers is sloped in the direction of the specimen with the intention of minimising the shadowing effect and providing access of the blast media to the surface near the cover.

Figure 2. Design of four different covers

The U-shape was found to be the most effective configuration for this specimen. The cover was optimised with brackets and cut-outs on the inner edges, ensuring a precise fit. As markers, multiple indentations are created by a Vickers hardness indenter in form of a pyramid, resulting in a square of 55 µm with a depth of 13 µm. This allows for the same area to be measured multiple times. The presence of several indentations serves as an indication of both rotation and direction. At least one indentation is therefore required to be out of line, and three or four indentations are generally employed. They are implemented in the initial state, after which an initial measurement is carried out. The markings are not easily discernible by the naked eye. Therefore, they have been positioned in line with the bottom hole in the middle of the specimen as an additional reference. Figure 3 illustrates the processing of the specimen.

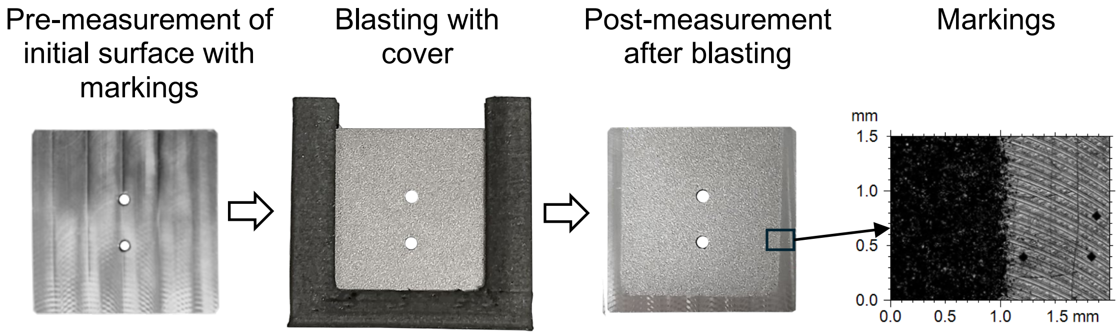


Figure 3. Processing of the milled specimen

The cover of the additive specimen had to be redesigned due to its differing shape. As a U-shape is not possible in this instance, a cover with two arms on the back that clamp onto the specimen like a lever was employed. First experiments with hardness indentations revealed that these were difficult to discern from the extremely uneven surface. The depth of the indentation is 13 µm, which is nearly equivalent to the height of the protruding particles, characterised by a mean height of local hills (Shh) of 13.2 µm. However, the features present on the surface itself proved to be sufficient for the overlay of images. A marking is still necessary for the positioning of the measurement area. Therefore, two crossing lines of a height marker needle are utilised. These are clearly visible to the naked eye and can also be distinguished by the measurement device, yet they were not included in the measurement. Several specimens were blasted with the process in Figure 4. Determining the extent of the cover proved to be a challenging task. Unfortunately, only one specimen was successful, allowing the pre- and post-measurements to be superimposed. Thus further refinement is required, for instance by incorporating the height marker lines into the measurement.

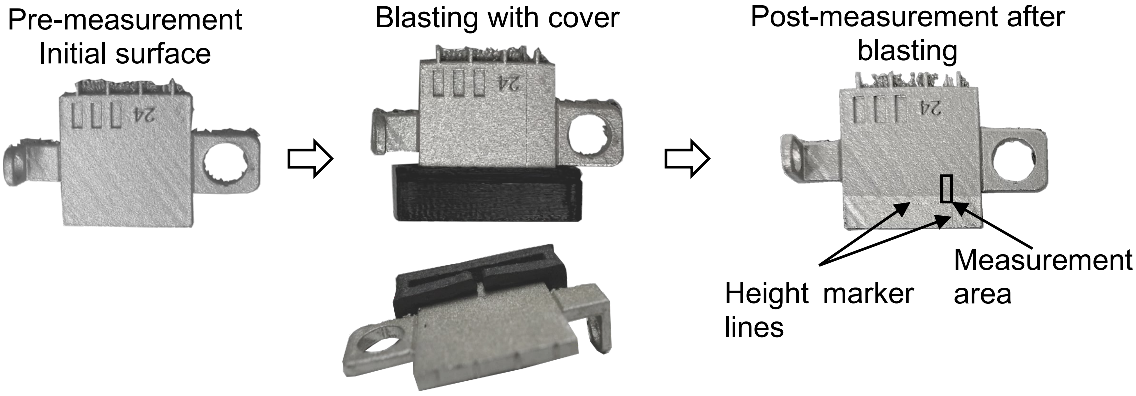


Figure 4. Processing of the additively manufactured specimen Nr. 24-III

Results and discussion

Milled specimen

The milled surface has an Sa of 0.23 µm. This is smooth in contrast to the surface after blasting with an Sa of 3.54 µm. The surface was measured in its initial state and after 10 minutes of blasting, as illustrated in Figure 5a and b. The deepest points of all four of the fiducial markers were selected manually to colocalise the surfaces and adjust height, position and rotation. The result is shown in Figure 5c. The positioning of the measurement area differed between the measurements, visible by the shifted position of the hardness indentations. As a result of this shift, a significant proportion of data is unable to be utilised for the colocalisation, resulting in its loss. Hence the positioning of the measurement area must be optimised for future experiments.

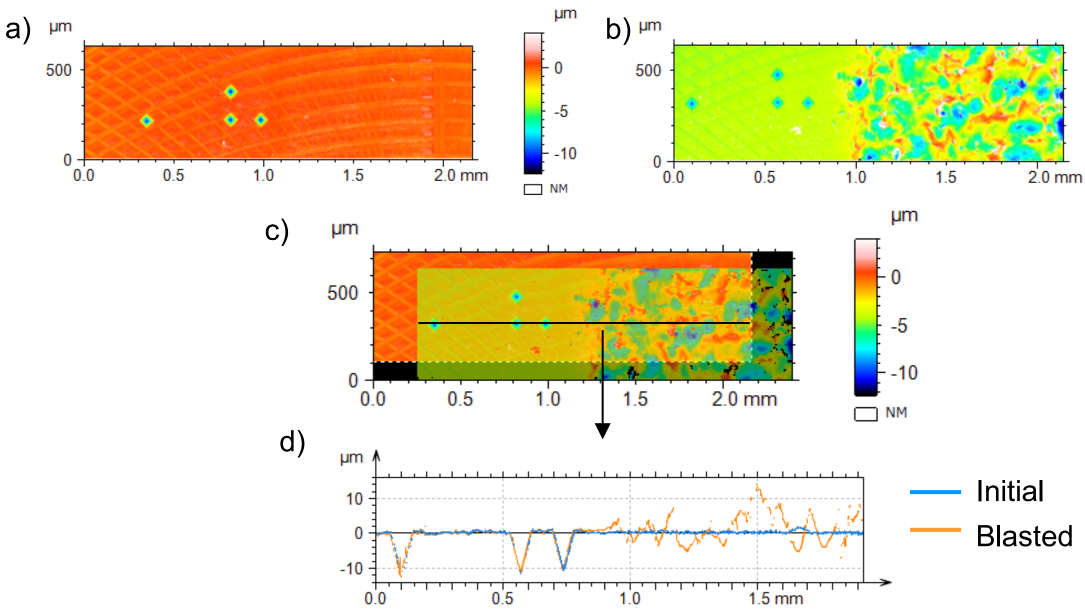
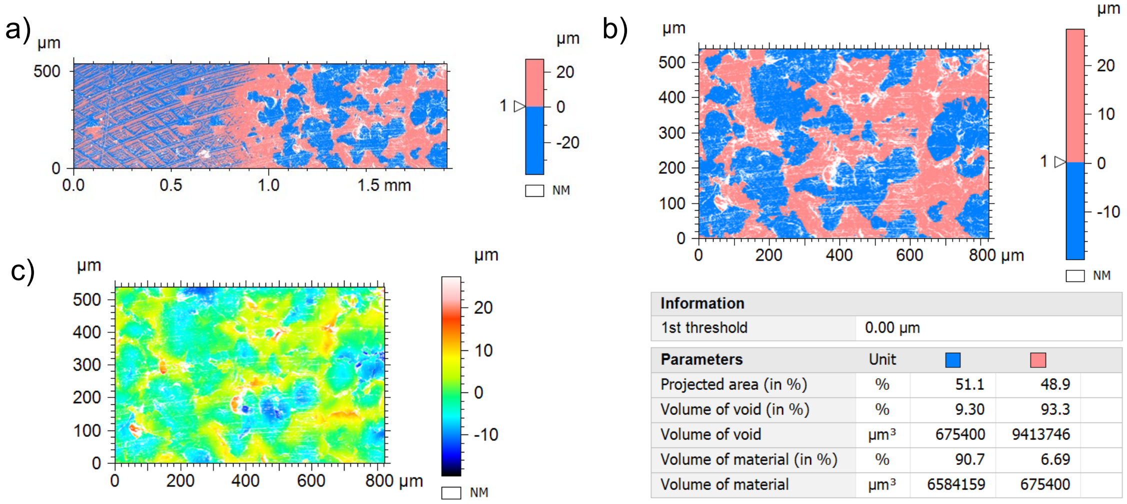


Figure 5. Milled Specimen a) Pre-measurement of initial surface (A) b) Post-measurement after blasting (B) c) superimposition of surfaces A and B d) extracted profile

The extracted profile in Figure 5d is a representation of the shift in material, highlighting both the dents and the significant bulging. Subsequent analysis of the material shift was conducted to assess whether the dents and hills have the same volume. The initial surface was utilised as a reference and to determine the threshold to separate dents and hills (see Figure 6a). The threshold is equivalent to the mean level, with a value of zero. Thereafter, the blasted area is extracted, and the same threshold is applied (Figure 6b). The volume of void material in the blue region is a representation of the dents. The respective hills by bulging result in the volume of material of the red area. The absolute number for both parameters is precisely 675400 µm³.



Information			
1st threshold	0.00 µm		

Parameters	Unit	🟦	🟥
Projected area (in %)	%	51.1	48.9
Volume of void (in %)	%	9.30	93.3
Volume of void	µm³	675400	9413746
Volume of material (in %)	%	90.7	6.69
Volume of material	µm³	6584159	675400

Figure 6. a) threshold on entire surface b) threshold and analysis of the blasted surface on extracted area c) corresponding topography of the extracted area

This phenomenon indicates that the material from the dents is redistributed to the hills. With reference to the geometry and microscopic deviations presented, it appears that no material removal or compression occurs during the blasting process. Further research is required into material properties such as hardness and stress, in order to consolidate the hypothesis.

Several iterations

A raw sheet steel specimen was subjected to different blasting times and measured every time. The objective of the study was to observe the changes in topography that result from blasting. In anticipation of exponential behaviour, the experiment begins with a minimal time interval of 1 min, which is then increased to 2 min, 4 min and 8 min, respectively. Figure 7 provides a synopsis of the respective blasting times and measured topography. The extracted and enhanced area from the far left of the full measurement area is shown on the right.

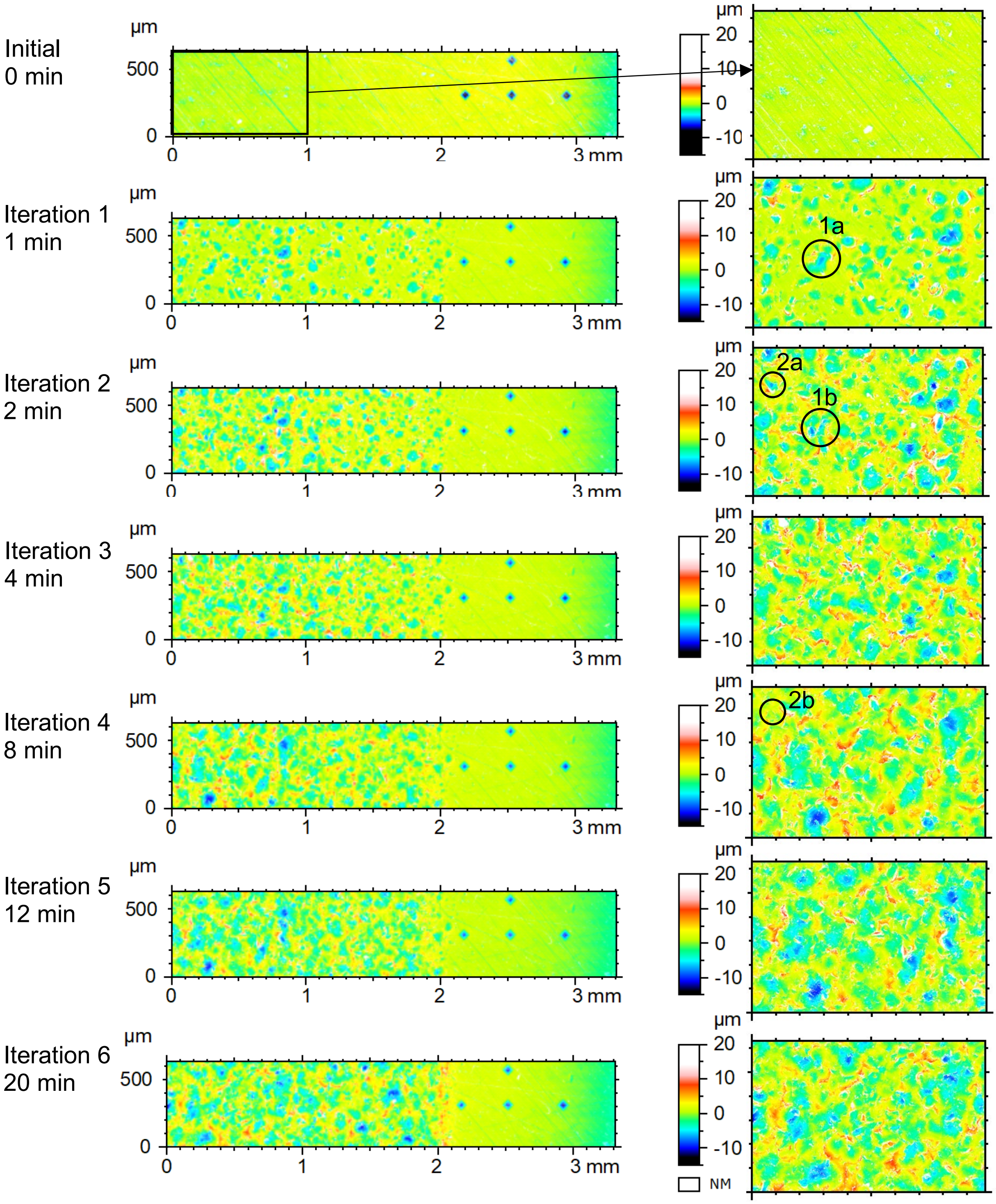


Figure 7. Change of the surface topography on the same spot for different times of blasting

In the first iteration, a significant proportion of the sample still showed the original surface. The variation in shot sizes and shapes is evident from the presence of smaller and larger indentations, as well as rounder and more elongated forms. Due to the non-spherical nature of the impacts, it is challenging to ascertain overlap. However, it appears that some overlap was already present from the beginning, which is consistent with Abyaneh's theory. During the second iteration, the increase in impacts, especially bulging is visible. The new impacts can also affect the dales with the bulging. An example of this is highlighted in the extracted areas numbered 1a and 1b, where the dale is partly separated by additional impacts. The initial surface in this iteration is still clearly visible. From iterations 3 to 4, several large impacts, as well as a lot of bulging, transform the surface significantly. In terms of the dales and hills, this is the biggest shift in material and topography. Some dales vanish completely, as can be seen in the highlighted example from 2a to 2b. This may be a coincidence, as the subsequent iterations show less change. The extracted area does not show significant changes in the subsequent iterations. Most of the large dales remain. However, in the complete measurement area, the area near the cover shows greater change. Perhaps the shadowing effect caused by the cover results in slower and delayed progress of blasting. From iteration 5 to 6, significant impacts appear in this area of the surface, as well as concentrated bulging near the cover. The latter could resemble the blasting process near the edges.

Overall, the process appears to be highly stochastic in this wheel blast machine. Since the workpieces move around, the impact angles of the media vary, making the process even more stochastic. It may be easier to first observe changes using a more regular blast medium with fewer diverging diameters and one consistent shape; therefore, this could be the next step. Additionally, it appears that significant material displacement is occurring, with the same material becoming dented and bulged multiple times. This raises questions about the impact on other material parameters, such as hardness or stress.

Additively manufactured surface

Next, the effect of blasting on a rougher additively manufactured surface that has a Sa of 7,3 µm and Sq of 9,4 µm is shown. Figure 7a and b show the measurements before and after blasting. On the left side of the measured area the covered and unchanged initial surface is still visible after blasting. The scales are all the same.

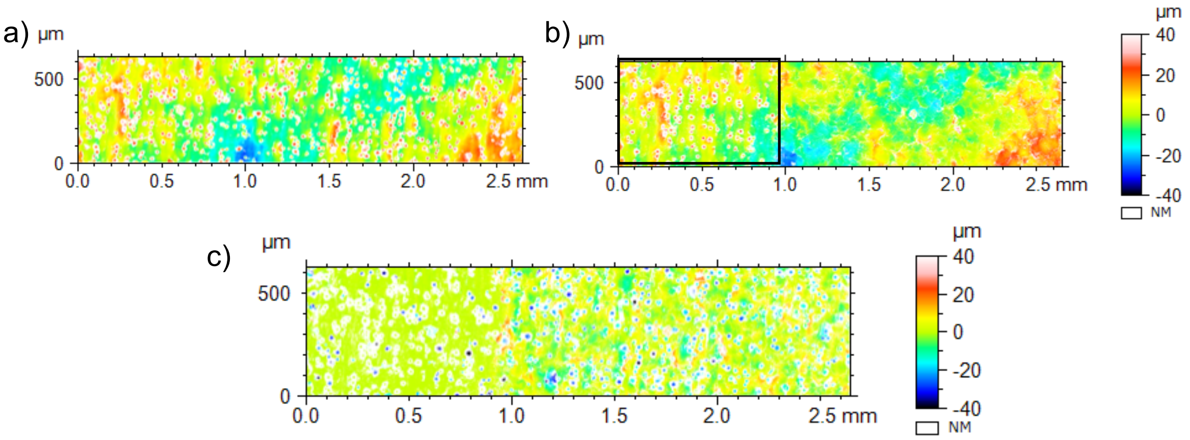


Figure 8. Specimen 24-III a) Pre-measurement of initial surface (A) b) Post-measurement after blasting (B) c) difference of surfaces (B-A)

Figure 8c displays the difference between the two measurements. The blue colouration indicates less material in comparison to the initial surface. The numerous blue dots indicate that the adherent particles from the powder have been effectively removed by the blasting process. Additionally, particles have been removed from the covered section. This phenomenon may be attributed to the act of adding the cover. Since it has to sit firm some force is needed and leads to the removal of some particles during attachment. Furthermore, the impact of the blast media creates notable dents, characterised by a dark green hue, along with elevated red areas. It is evident that larger form deviations are observable in the initial and pre-measurement surfaces. This investigation demonstrates the applicability of blasting as a post-process for surfaces manufactured by additive processes, since it can remove adherent particles. Nevertheless, it has been demonstrated that bigger deviations are not impacted, as was also found by Newton. Further investigations with other inclination angles and more patterned initial surface structures can be conducted. In addition a variety of blast media, particularly larger sizes and alternative materials, are to be considered.

Conclusions

In summary, this paper presents a methodology that employs fiducial markers and a 3D-printed cover. This methodology can be used to experimentally investigate changes in topography resulting from manufacturing processes. The markings fulfil two functions: firstly, they align the data set after measurement, and secondly, they enable the measurement area to be relocated for measurement. Therefore, different types of marking are used, including hardness indentations and inscribed lines.

This method has been used to observe the blasting process on smooth surfaces in one or more iterations, as well as on additively manufactured surfaces. This procedure may be useful for experimental investigations into the influence of surface topography on multiple impacts. However, more observations of the blasting process, especially of additional parameters such as shot velocity, are needed to investigate impact mechanics. Including a camera during the process could be beneficial. Furthermore, investigating the impact angles of the media is recommended. It is highly probable that there will be discrepancies, which can affect and interact with the topography.

In conclusion, this method has proved to be a valuable tool for gaining insight into the blasting process and the interaction with surface topography. This methodology can be adapted for use with other processes or machines.

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