Influence of laser beam scanning strategy in the selective laser melting of 316L steel powder on macrostress

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Abstract. The use of selective laser melting (SLM) leads to the formation of a complex material structure with high residual elastic stresses. The work investigates the distribution of macrostresses in SLM samples using five different scanning strategies. The stresses were measured by X-ray method and by recording the change in the shape of the specimens as a result of their separation from the platform using digital correlation image method. The combined use of the two methods provides more reliable results for SLM samples. It is shown that depending on the scanning strategy, the nature and magnitude of macrostresses change which are distributed more isotropically and have a smaller value when using scanning strategies with different directions of the laser beam movement.

1. Introduction
The selective laser melting method (SLM) is an additive manufacturing method in which the metallic part is formed layer-by-layer from metal powder. The advantage of this method is that it is possible to produce parts with complex shapes, with inner cavities [1]. The powder is melted by laser radiation and a melt pool is formed in which the material re-solidified again after shifting the laser beam to another area. This determines the formation conditions of the material - crystallization at a temperature gradient, the sequence of heating and cooling of the material. These, in turn, lead to the formation of high thermal stresses [2] and anisotropy of mechanical properties due to the complex structure of the material [3]. SLM samples contain overlapping areas of individual tracks [4] from successive laser passes filled with column grains with close crystallographic orientations [5, 6].

The high level of residual macro stresses is a negative feature of the SLM method, as it can cause the part to warp after separation from the construction platform due to stress relaxation. Optimization of the laser beam scanning strategy, scanning speed and laser power [7, 8], as well as heat treatment for stress relief before separation of parts from the construction platform can be considered to reduce this phenomenon. But, all these methods require monitoring the level of macrostress in a sample to determine their effectiveness.

Various calculation and experimental methods are used to estimate the value of macrostress in samples manufactured by additive manufacturing methods. For example, stress fields near the melting pool when applying a separate track can be calculated analytically [9] and measured in-situ using...
synchrotron radiation [10]. The distribution of residual macrostresses in a sample can be measured experimentally using the X-ray method [11] and neutron diffraction [12], or calculated by numerical simulation as a superposition of stresses from multiple tracks [7, 8].

All these methods of determining macrostress have their advantages and disadvantages, and therefore it seems reasonable to use a combination of different methods. Therefore, the purpose of this work is to reveal the influence of the scanning strategy on the residual macrostress by combining two methods of determining the macrostress - X-ray and by changing the shape of the sample at stress relaxation. Specimen shape change was determined by digital image correlation method [13].

2. Samples and research methods

Samples of 316L steel produced by SLM on MeltMaster3D-550 with ytterbium fiber laser of maximum power of 1 KW and working area of 550×450×450 mm, layer thickness of 20-250 microns were studied in this work. To print samples, the following SLM-process parameters were used: laser power 320 W, scanning speed 850 mm/s, scanning step 80 µm, layer thickness 50 µm. For each of the five manufactured samples, different scanning strategies were used, as shown in Figure 1. The sample size is 10×10×50mm. For the simplicity of further presentation, let's introduce a coordinate system: the Z-axis is selected along the direction of sample growth, the Y-axis along the long side of the sample, and the X-axis along the short side of the sample.

The samples were printed on a 22 mm thick construction platform. For easier separation of the sample from the platform, a supporting structure in the form of a grid of mutually perpendicular edges 0.3 mm thick and 1 mm step was printed below them. At the first step, the specimens were examined directly on the construction platform in the state after printing (figure 2-a). In the second step, the supporting structure was cut off, except for a small section of one rib in the center of the sample, which allowed for stress relaxation by changing the shape of the sample (figure 2-b). The keeping of a small segment of the supporting structure was due to the comfort of measurements. At each of these steps, the macrostresses in the sample were measured by X-ray method and the surface profile was recorded by digital images correlation.
The measurement of residual elastic macrostresses was performed by $\sin^2 \psi$ method on Bruker D8 Discover X-ray diffractometer using filtered Cu radiation. For this purpose, a line (400) in the range of angles $2\Theta$ 115-122.5° and angles $\psi$=0, 10, 20, 30, 40, 50° was recorded. To exclude the influence of the sample surface roughness (measurements were made without additional surface preparation after printing), the geometry with parallel beam (i.e. Goebel mirror) was used. When measuring, the sample was set so that the beam would get into its central part. The macrostresses were determined in the X and Y directions.

Detection of the sample surface profile was carried out by the method of digital images correlation. Measurements were carried out on the upper surface of the sample, on which chaotically distributed marks-stains (speckle structure) were applied. Then, the spatial location of the applied marks was identified by optical system to determine the surface profile of the sample. Additional markings were made on the specimen surface in advance to align the coordinates of the surface points before and after removing the supports. Polynomial approximations of the upper surface profile along the midline in the initial state ($F_1(y)$) and after removal of supports ($F_2(y)$) were used for quantitative description of the sample shape change. Stresses from the sample shape change were calculated using the finite element method (FEM). The two-dimensional beam bending problem (representing the investigated sample) was solved, where the upper surface movement was set by function $-(F_2(y) - F_1(y))$, as shown in Figure 2c.

3. Results and discussion

3.1. Experimental results

Figure 3 shows graphs of X-ray measured macrostresses in investigated samples in initial state (figure 3-a) and after removal of supporting structure (figure 3-b) in two directions. Macrostresses in the initial state are mainly tensile, significant compressive stresses were found only in sample 3 in the direction Y. In samples 1 and 2, the stresses along X and Y directions respectively (directions perpendicular to the scanning direction) are close to zero. After removing the Y-axis supports, the sign changes to the opposite, and for the X-axis stresses only the value changes.

Figure 4 shows the results of measuring the shape change of the sample as a result of removing the supporting structure: the surface height maps in the initial state (figure 4-a) and after removing the supports (figure 4-b), obtained by the digital images correlation. We can see that there is some bending of the sample in the initial state - the edges are located above the central part. After removing the supports, the bend along the long side of the sample (Y-axis) becomes stronger, and along the short side, the shape changes less.

Figure 4-c shows an example of the stress distribution calculated with the help of FEM on the data on changing the shape of the sample. It should be noted that the obtained character of stress changes
by height of the sample well corresponds to that obtained in [11] - compressive stresses are observed in the lower part of the sample and tensile stresses in the upper part. We will compare the results of stress calculations for different samples by the value of stresses in the center of the upper surface - in the area of X-ray stress measurement. Figure 4-g shows a graph of the calculated stresses along the Y-axis in the central part of the upper surface of the samples. All stresses have the tensile nature.

3.2. Comparison of X-ray macrostress with shape change data

Comparing change of measured value of residual elastic stresses at removal of supporting structure (figure 3) with change of sample shape (figure 4-a, b), it can be noted that significant change of X-ray macrostresses and sample shape occurs only along Y direction. It follows that both methods register the same nature of stress relaxation and there is a good quality coincidence of results.

Figure 4. Evaluation results of the sample shape change: a - surface profile shape in initial state; b - surface profile shape after removal of supports; c - stress distribution calculated by FEM; d - calculated values of stresses along the Y axis in the central part of the upper surface of the sample.

On the graph shown in the figure 5, a quantitative comparison of the results of macrostress determination by the methods used was made. The graph shows that the best match of results is observed for samples 4 and 5 - with the scanning strategies in the form of strips with change of direction and chess. The worst match was found for samples 2 and 3, with a single-pass scan strategy.
along X and with a change of direction. Sample 1 occupies an intermediate position for matching the results.

It should be noted that in X-ray measurements, information about the state of the material is obtained only from the uppermost layer applied in the printing process, which is caused by the small depth of penetration of X-rays (~10-20 microns) relative to the track depth (~100 microns) [4]. This will explain the differences in quality of the results obtained for different printing modes. Thus, in samples 4 and 5 all used laser beam directions are presented in one layer, therefore the value of stresses in the layer is closest to the value of stresses in the sample as a whole. In sample 3, on the contrary, the scanning direction in the layers is alternating and the situation is opposite to that observed in samples 4 and 5.

Figure 5. Comparison of results of determination of macrostresses by X-ray method and by change of sample shape

To explain the differences in the results in sample 2, where scanning was performed in the X direction in all layers, it should be taken into account that according to the results [9], when applying a single track, tensile stresses of greater magnitude are formed along the scanning direction. Thus, in sample 2, local stresses along the Y-axis in a small area under the X-ray beam are small, but due to the elongated shape of the sample along the Y-axis, they were sufficient to bend the sample.

3.3. Effect of scanning strategy on residual stresses.

We will analyze the impact of the scanning strategy on the value of macrostress in samples with different scanning strategies based on the data of both used methods. As we have shown in 3.2, although these methods may produce inaccurate results in some cases, the combination of these methods allows us to overcome this problem.

In samples 1 and 2, which were printed with laser beam scanning in one direction in all layers, a high level of macrostress along the scanning direction and a lower level perpendicular to it are detected (figure 3-a, figure 4-g). The reason for this is elongation of the melt bath at track application along the laser beam direction. Consequently, due to the longer length of the heated section, compression of the material during cooling leads to higher tensile stresses along the track. This is confirmed by the higher stress value in sample 1 relative to sample 2 (and the highest among all samples) - here the scanning was carried out along the long side of the sample and the tracks are longer.

In samples 4 and 5, in which at printing of each layer a part of the area of horizontal section of the sample was scanned by a laser beam along X axis, and the other along Y axis, a close level of macrostresses in these directions is observed (figure 3-a). There is no reason to suppose that in this case the character of stresses arising at application of a separate track changes. Then we can conclude that due to the mutual influence of regions with different scanning directions, the leveling of macrostress levels along different directions occurs. Here, there is a difference in the distribution of macrostresses in layers with different scanning directions, as evidenced by the differences in the results of the X-ray method and measurements of changes in the shape of the sample. However, the
alignment of the overall macrostress level in the sample is achieved by interaction of neighboring layers with each other rather than different parts of the same layer.

Thus, a more uniform distribution of stresses and a decrease in their overall level is observed when using scanning strategies that combine different scanning directions in one layer or in different layers. This is consistent with the results of macrostress simulation [7], where the minimum value and most uniform distribution of macrostresses is obtained for a strategy with frequent changes in the scanning direction.

4. Conclusions
The distribution of macrostresses formed in the samples manufactured by the method of selective laser melting (SLM) with the use of different laser beam scanning strategies, by X-ray method of measuring macrostresses and by changing the shape of the sample after separation from the construction platform is studied. It is shown that due to the specific features of SLM samples - the possibility of stress gradients formation between different layers, stress anisotropy - to obtain reliable results it is necessary to compare data of different stress measurement methods. Through the joint analysis of X-ray data and changes in the shape of the samples, it has been established that the scanning strategy has a strong influence on the distribution of macrostresses: when scanning in one direction, the distribution of stresses is anisotropic, while when combining different directions of scanning in successive neighboring layers or in one layer, the anisotropy and the stress value decreases. The results are in good agreement with the literature on experimental, analytical and numerical determination of macrostresses.

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