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USE OF A VIBRATING BUILD PLATFORM DURING POWDER-BED FUSION OF METALS USING A LASER BEAM

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Abstract

Powder-bed fusion of metals using a laser beam (PBF-LB/M) is an additive manufacturing technique with rising interest in industry and academia. One major topic of current research is to optimize the performance of parts manufactured by PBF-LB/M. The use of vibrations during the solidification of metals to improve their mechanical properties is well-known for metal casting and directed energy deposition. In this work, a vibrating build platform was used during the PBF-LB/M process to influence the microstructure of parts. Analyses show an increase in sample hardness by up to 12.3 % for the same process parameters. Especially for process parameters that produce parts with lower relative densities, vibrations have an influence on part density. With an increase in part density, this effect gets less pronounced.

Introduction

Powder-bed fusion of metals using a laser beam (PBF-LB/M) is a widely used process for the direct additive manufacturing of metallic components. In this process, components are created layer upon layer by applying and melting individual layers of powder. An important field in the development and research of the PBF-LB/M process is to improve the quality and mechanical properties of PBF-LB/M parts. The mechanical properties of parts are mainly influenced by the microstructure. It is shown in the literature that the microstructure of PBF-LB/M parts can be influenced by the selected process parameters [1–3]. The present work investigates the influence of the use of a vibrating build platform during the PBF-LB/M process on the density, hardness, and microstructure of the manufactured components. For this purpose, samples were fabricated while varying selected process parameters (laser power and scanning speed) with and without the utilization of a vibrating build platform. While the use of vibrations during the solidification of molten metals has been investigated for other manufacturing processes [4–11], there are only few studies for the PBF-LB/M process [12,13]. In metal casting, a relatively large number of studies have been carried out on the use of vibration during solidification. Metal casting is not an additive manufacturing process. Here, significantly lower cooling rates occur compared to the PBF-LB/M process. The literature reports an increase in tensile strength, thermal fatigue strength, and impact toughness with the use of vibrations for the casting process [4,5]. These improvements in mechanical properties can be attributed to a change in microstructure. The microstructure changes from a long dendritic or columnar solidification to a finer microstructure with more equiaxed grains [4–6]. Laser welding is a manufacturing process, which has faster cooling rates than metal casting. In laser welding, a laser is used to melt a track surrounded by solid material. Thus, the solidification conditions and cooling rates, which are still slower than in the PBF-LB/M process, are more comparable to those of PBF-LB/M than is the case for metal casting. Experiments with and without the use of vibrations (789 and 1186 Hz) during laser welding have been conducted by Jin et al. showing a refinement of the microstructure, an increased penetration depth, and an increase in fatigue life with the use of vibrations [7]. They report that the degree of impact on the described properties differs for different vibration parameters. Tarasov et al. show increased tensile strength and micro-hardness when using vibrations with frequencies of 19.7 and 20.75 kHz, for which grain refinement has been suggested as a possible explanation [8]. When X5CrNiCuNb17-4-4 (17-4 PH) powder was processed by directed energy deposition using a laser beam (DED-LB/M/powder), Ning and Cong showed a reduction in the number of pores and micro-cracks, as well as a finer microstructure, higher tensile strength, higher yield strength, higher ductility, and higher toughness [9]. Similar to PBF-LB/M, in DED-LB/M/powder powders are melted by a laser in an additive manufacturing process. However, the powder is not present as a powder bed but is blown through one or more nozzle geometries onto the part surface during melting. Chen et al. achieved a finer microstructure and an increase in micro-hardness by using vibrations in the processing of Ti64 powder by DED-LB/M [10]. They applied vibrations with frequencies up to 30 Hz and showed that the microstructure became finer with increasing frequency. By applying vibrations at frequencies of 25-42 kHz to the build platform of a DED-LB/M/powder system when processing Inconel 718, Wang et al. achieved a reduced porosity, a reduced grain size, an increased micro-hardness, and an improved elasticity and wear resistance [11]. Although the application of vibrations always resulted in a decrease in porosity compared to samples produced without vibrations, it increased with increasing frequency. Tilita, Chen, Leung et al. and Tilita, Chen, Kwan et al. conducted studies on the use of a vibrating build platform for the PBF-LB/M process [12,13]. Tilita, Chen, Kwan et al. showed a refinement of the microstructure by using vibrations with a frequency of 50 kHz in the z-direction for the fabrication of X5CrNi18-10 (304L) single layers [12]. Tilita, Chen, Leung et al. reported an increase in nano-hardness but a decrease in micro-hardness by using a vibrating build platform for manufacturing samples with a height of 20 layers [13]. The results shown here are based on the investigations carried out in a previous publication [14].

Materials and methods

An AconityMIDI PBF-LB/M system (Aconity GmbH, Herzogenrath, Germany) equipped with a fiber laser with a wavelength of 1070 nm, a laser power of 400 W, and a nominal spot size of 110 µm was used for sample preparation. Two build processes were carried out under a nitrogen atmosphere with < 200 ppm residual oxygen while varying the exposure parameters. Both build processes were performed with the same sample setup under the same conditions and differed only in that one build process had an electric motor with an eccentric mass mounted on the build platform. This motor rotated at 9,000 rpm (150 s^{-1}) along the y-axis, introducing vibrations in the x-z plane of the build platform. Cube-shaped specimens with an edge length of 5 mm were fabricated using laser powers of 100-220 W and scan speeds of 500-1,500 $mm \cdot s^{-1}$. The laser power was varied in steps of 30 W and the scan speed in steps of 250 $mm \cdot s^{-1}$. A meandering scan strategy was used with a 90° rotation after each layer, with the scan vectors orientated parallel to the outer edges of the samples. The cube-shaped samples were rotated 45° along the z-axis, which caused the vibration plane to be rotated by 45° with respect to the scan vector direction. All samples were fabricated with a layer thickness of 30 µm and a hatch spacing of 90 µm. X2CrNiMo17-12-2 (1.4404) powder with a particle size distribution ranging from 15 µm to 45 µm was used for sample fabrication. Powder from the same batch was used for both build processes. During the build processes, specimens fabricated with a laser power of 100 W and scanning speeds of 1000 - 1500 $mm \cdot s^{-1}$ and 130 W and 1500 $mm \cdot s^{-1}$, respectively, had to be removed due to insufficient energy input, resulting in process failure. For the mounting of the vibration motor it was necessary to make a recess to the bottom of the build platform. In order to ensure the comparability of the two build processes, a build platform with the same recess was also used for the build process without vibrations.

The cross sections of the specimens were prepared by stepwise grinding and polishing of three specimen layers, each 1.25 mm apart, with the first layer 1.25 mm from the lateral surface of the specimen. Grinding was performed with SiC abrasive paper in mesh sizes of 320, 600, and 1000, and polishing was performed with diamond suspension in grain sizes of 3 µm and 1 µm. A VHX-6000 optical microscope (Keyence Corporation, Osaka, Japan) was used to determine the sample density. To measure the hardness in HV 1, five hardness indentations per prepared cross section were made with the Vickers hardness tester KB 30 S (KB Prüftechnik GmbH, Hochdorf-Addenheim, Germany) for the specimens that achieved a density above 99.9 % in at least one of the two build processes (with and without a vibrating build platform). From the 15 hardness values obtained per sample, the three hardest and softest values were removed to remove possible outliers and then the mean hardness and standard deviation of the hardness were calculated.

Results and discussion

Figure 1 a) and b) show the density of the samples produced with and without the use of a vibrating build platform plotted against the volumetric energy density (VED). In general, the trend is that as VED increases, the relative density of the samples increases and approaches a relative density of 100%. This trend is observable for both processes. A relative density of 99.90 %, which was set as the minimum density for the hardness test, is exceeded for the first time at a VED of 70.73 $J \cdot mm^{-3}$ for the specimens produced without a vibrating build platform, and at a VED of 81.48 $J \cdot mm^{-3}$ with the use of a vibrating build platform. All samples produced with a higher VED also have a density above 99.90 %. For both processes, a VED of 118.52 $J \cdot mm^{-3}$ is the lowest VED at which a relative density of 99.99% or higher is achieved. For the process using a non-vibrating build platform, the sample with the highest relative density reaches 99.997 % (SD 0.001). The densest sample produced with a vibrating build platform has a relative density of 99.996 % (SD 0.002). The highest densities achieved by the two processes are thus comparable. For both processes, the maximum density is achieved at the process parameters of 190 W laser power and 500 $mm \cdot s^{-1}$ (VED = 140.74 $J \cdot mm^{-3}$). In Figure 2, the difference in the relative density of the specimens manufactured in the two build processes is plotted against the density of the specimens from the build process with a non-vibrating build platform. Positive values mean that the specimens produced with a vibrating build platform have a higher relative density. For most specimens, the relative density decreases due to the use of a vibrating build platform, with this effect decreasing with increasing relative density. Outliers from this trend are represented by the specimens at 94.53 % and 98.26 % relative density. These outliers are likely due to process instabilities. For four of the parameter combinations considered, the use of a vibrating build platform does not result in a change in the measured relative density, with all four of these parameter combinations resulting in a relative density greater than 99.99 %. For four other parameter combinations, a slight increase in relative density is observed due to a vibrating build platform. However, these are only small increases, which are within the standard deviations of the measurements.

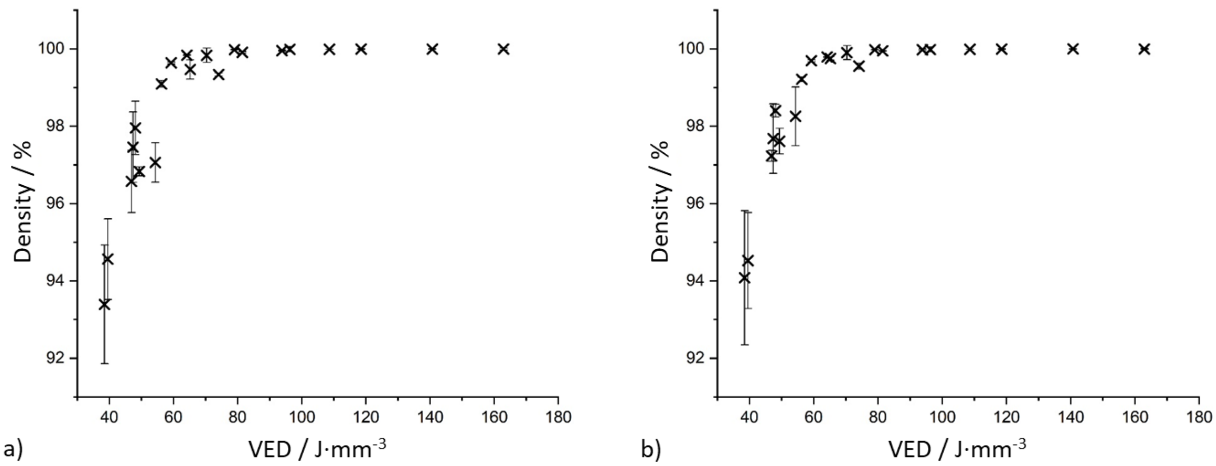

Figure 1: Relative density with standard deviation plotted over volumetric energy density a) without using a vibrating build platform, b) using a vibrating build platform.

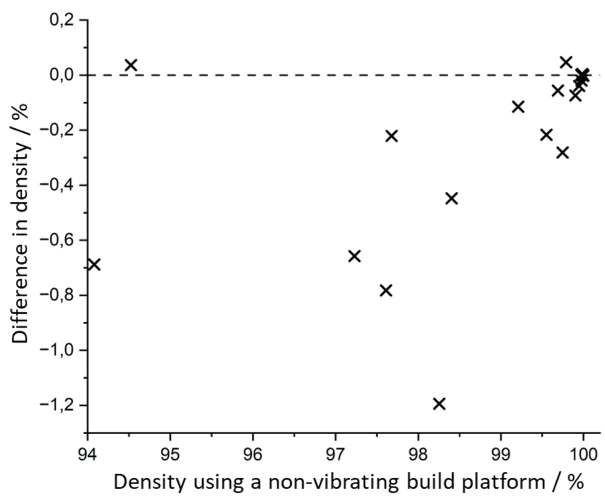

Figure 2: Difference in relative density (density using a vibrating build platform – density using a non-vibrating build platform) plotted over relative density of samples manufactured using a non-vibrating build platform.

The hardness in HV 1 was determined for parameter combinations that achieved a relative density above 99.90 % in at least one of the two build processes. The measured hardness values for the samples from the two build processes are shown in Figure 3. At a laser power of 160 W and a scanning speed of 500 mm·s^{-1}, the process without a vibrating build platform achieved the highest hardness of 251.78 ± 6.46 HV 1. The highest observed hardness using a vibrating build platform was 279.44 ± 5.90 HV 1, which is 27.66 HV 1 harder than the maximum measured hardness with the non-vibrating build platform. Figure 4 shows the difference in hardness of the specimens from the two build processes plotted against VED. Positive values represent an increase in hardness with the use of a vibrating build platform. There is an increase in hardness for all parameter combinations, with the average hardness increase being 21.04 HV 1 and the maximum hardness increase being 30.67 HV 1 at the highest applied VED, representing a hardness increase of 12.3 %. No trend between hardness difference and VED is observed. It can be assumed that the hardness increase is due to finer microstructure, which will be investigated in future. Tilita et al. [12] observed a refinement of the microstructure in the PBF-LB/M process due to the use of vibrations.

According to Hall [15] and Petch [16], the yield strength increases due to a finer microstructure, which in turn leads to higher hardness values [17].

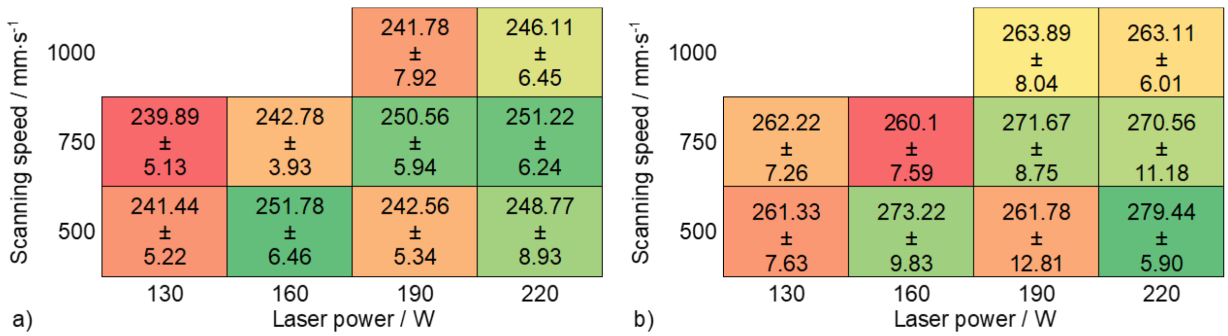

Figure 3: Hardness with standard deviation in HV 1 of samples manufactured a) using a non-vibrating build platform and b) using a vibrating build platform.

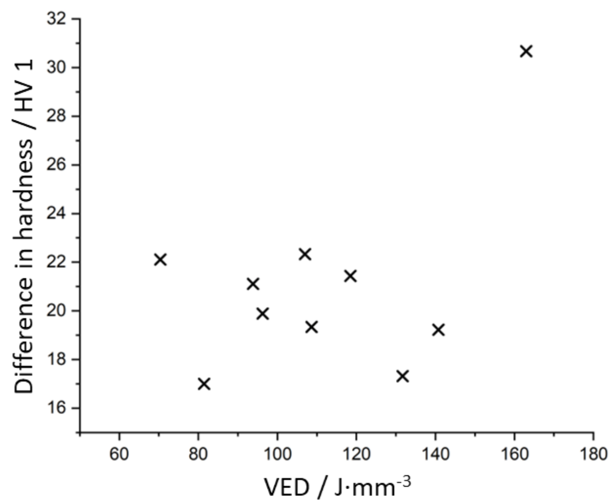

Figure 4:Difference in hardness (hardness using a vibrating build platform – hardness using a non-vibrating build platform) plotted over volumetric energy density.

Conclusion

This work shows the influence of a vibrating build platform on the relative density and hardness of samples made of X2CrNiMo17-12-2 by PBF-LB/M. For the generation of vibrations, a motor with an eccentric mass was used, which was mounted on the bottom of the build platform and introduced vibrations with a frequency of 150 Hz (9,000 rpm) into the build platform. The use of a vibrating build platform resulted in a reduction in relative density for most samples, although this effect is less pronounced at high relative sample densities. All specimens for which hardness measurements were carried out showed an increase in hardness with the use of a vibrating build platform. The average increase in sample hardness was 21.04 HV 1. The maximum hardness increase for specimens produced with the same process parameters with and without the use of vibrating build platform was 30.67 HV 1 (12.3 %)

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