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Residual stresses in additive manufactured precision cemented carbide parts

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Abstract

Due to the good strength properties and high hardness, components made of cemented carbide are used in various industrial sectors as key components, e.g. mould making and matrices. Precision cemented carbide parts are mainly machined by milling and electrical discharge machining (EDM). Nevertheless, long machining times and excessive tool wear are remaining challenges at the state of the art. A promising approach to overcome these challenges is the machining of precise cemented carbide parts using a process chain consisting of near-net-shape laser powder bed fusion (LPBF) and subsequent finishing using a dedicate diamond slide burnishing process. Within previous investigations a geometrical accuracy of $a_g \leq 10$ µm and a reduction of the surface roughness by Ra = 89 % could be achieved. Within this work plastic deformation induced by the diamond slide burnishing and the effects on the material properties in the surface area were investigated, e.g. residual stresses. For this purpose, the lattice distortion of the metallic cobalt phase was measured by X-ray diffraction using high-energy synchrotron radiation. In addition, the height profile of the residual stresses was also recorded in distances of d = 3 µm to obtain information about the depth effect of the diamond slide burnishing process. Based on the investigations an increase of the residual compressive stresses could be obtained. This shows a particularly positive effect especially for additively manufactured components, as these often show a slight porosity and higher surface roughness as conventional manufactured components. In this way, crack propagation can be prevented and the fatigue strength can be increased.

keywords: additive manufacturing, diamond slide burnishing, residual stresses, X-ray diffraction

1. Introduction

Additive manufacturing (AM) processes enable lightweight designs of highly complex metallic workpieces and ensure an increasingly important saving of resources and energies. Nevertheless, AM processes are limited regarding the achievable surface roughness values 5 µm ≤ Ra ≤ 15 µm, the geometrical accuracies a_g as well as the occurring residual stresses σ_R. Due to increasing demands on the properties of additively manufactured workpieces, the development of innovative process chains is essential [1]. For this purpose, a dedicated process chain composed of near-net-shape AM followed by the diamond slide burnishing (DSB) as a precision finishing technology was developed in previous investigations [2]. This allowed to drastically improve the surface roughness values as well as the geometrical accuracies a_g in a single digit micrometer range. Based on these results, an extensive analysis of the material properties of AM manufactured as well as post processed parts with regard to the occurring residual stresses σ_R was carried out in this study.

2. Experimental Setup

For manufacturing of precision cemented carbide parts a dedicated process chain and sequence composed of near net shape AM by LPBF followed by DSB as a precision finishing process was used. For better comprehensibility, the process sequence is schematically illustrated in Figure 1. The used part material was a cemented carbide with a cobalt percentage of 17 % and a grain size in a range of 23 µm ≤ g_s ≤ 40 µm.

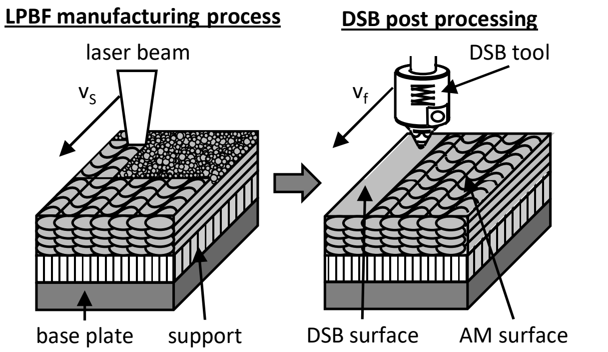

Figure 1. AM process sequence with DSB as post process

Table 1 shows the used initial sets of LPBF process parameters.

Table 1. Investigated LPBF process parameters

Process parameters	Part 1	Part 2
Pre-heating h_p	500 °C	500 °C
Laser power p_L	80 W	310 W
Energy density ρ_E	222 J/mm³	1,722 J/mm³
Speed v_L	0.4 m/s	0.2 m/s
Pulsation p_u	Const.	Const.
Point distance l_P	8 µm	4 µm
Exposure time t_E	20 µs	20 µs

For the LPBF process the machine tool RenAM 500 Q HT of the Renishaw GmbH, Pliezhausen, Germany, was used. The DSB of the near-net-shape AM parts were carried out on the 5-axis-high-precision-machine tool HSC MP7/5 of the company exeron GmbH, Oberndorf, Germany, with a dedicated DSB tool made of single crystal diamond with a radius of r = 1.5 mm from the company BAUBLIES AG, Renningen-Malmsheim, Germany. For post processing of the surface, a process force f_P = 140 N was applied. The measurements of the surface roughness values were carried out with the surface roughness measurement device nanoscan 855 of the company JENOPTIK AG, Jena, Germany. To measure the residual stresses σ_R of the additively manufactured parts as well as the post processed parts, transverse sections with a thickness d_S = 1 mm were prepared. Diffraction measurements were subsequently carried out at the "DEUTSCHES ELEKTRONEN-SYNCHROTRON" (DESY), Hamburg, Germany. The measurement points (MP) were realised at distances of d_M = 3 µm, d_M = 6 µm and d_M = 9 µm from the surface with a beam energy of E_B = 66.6 keV and a probe distance of a_P = 1.15 m. The evaluation was based on the lattice distortion of the cobalt phase, which enables a calculation of the occurring residual stresses σ_R [3].

3. Experimental investigations

Within the investigation of the dedicated process chain for manufacturing of precision cemented carbide parts composed of AM and the DSB two different LPBF parameter sets were evaluated, see Table 1. To gain extensive knowledge about the influence of the material part conditions regarding the DSB, two different parts with high and low relative densities ρ_{rel} were analysed. As a result of the investigations the cemented carbide parts showed different specific properties regarding the surface roughness as well as the residual stresses σ_R. Correlating to Table 1 specimens of class 'part 1' showed a surface roughness of Ra = 11.43 µm paired with a relative density ρ_{rel} = 78.27 % and specimens of class 'part 2' of Ra = 13.41 µm paired with ρ_{rel} = 89.94 % after the LPBF. Figure 2 illustrates the findings of the measurements of the residual stresses σ_R.

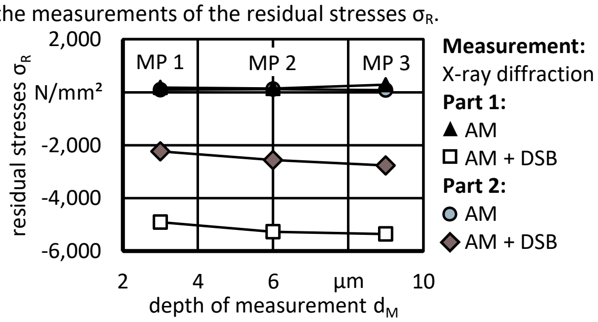

Figure 2. Results of the measurements of residual stresses σ_R

Both investigated parts show slight residual tensile stresses in the range of 103 N/mm² ≤ $\sigma_{R,t}$ ≤ 201 N/mm² in the initial state after LPBF. The results of the investigations show a great influence of the initial part conditions after LPBF on the DSB. The DSB enables a transformation of the existing residual tensile stresses $\sigma_{R,t}$ into residual compressive stresses $\sigma_{R,c}$. The development of the residual compressive stresses $\sigma_{R,c}$ as a function of the measuring depth d_M shows a slightly decreasing development for both parts. Using the DSB for specimens of class 'part 1' residual compressive stresses of $\sigma_{R,c}$ = -5.364 N/mm² could be obtained, which correlates to an increase of 2,600 %. In general, specimens with lower relative density ρ_{rel} and higher porosity after LBPF result in higher residual compressive stresses $\sigma_{R,c}$ and enable a more effecitive post-processing by DSB. Furthermore, the initial specimen conditions after LBPF also show an influence on the post-processing concerning the achievable surface roughness. The DSB enables a reduction of the surface roughness value of 'part 1' from Ra = 13.41 µm to Ra = 1.48 µm and of 'part 2' from Ra = 11.43 µm to Ra = 2.87 µm. Due to a higher porosity after LBPF, the cobalt phase in the micro-structure could be significantly more deformed. This leads to a higher density ρ, which correlates to higher residual compressive stresses $\sigma_{R,c}$ compared to a lower achievable surface roughness. To show the deformation mechanisms during the post processing by DSB, the specimens of 'part 1' and 'part 2' after LBPF as well as after DSB are visualised in Figure 3.

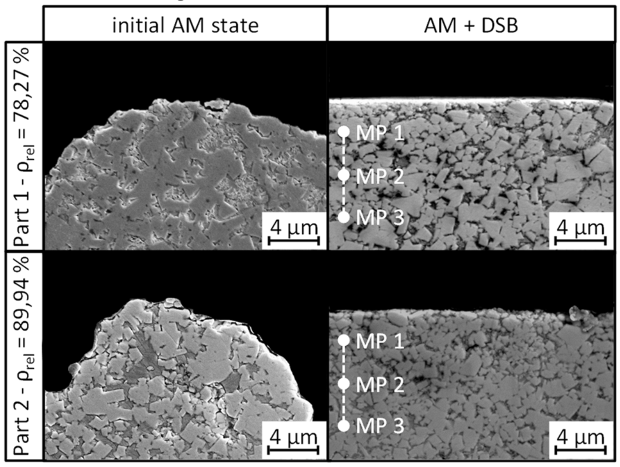

Figure 3. Cross section of AM parts in initial state and after DSB

In detail, the forming mechanism depends on the near-surface porosity after LBPF as well as the micro-scale fractures of the tungsten carbide particles during DSB. Based on the results, a dedicated process chain for the manufacturing of precision cemented carbide parts with industrial needed compressive residual stress states $\sigma_{R,c}$ could be proven.

4. Conclusion and further investigations

The findings indicate the interdependency of the LPBF process parameters and the related DSB concerning the achievable material properties. It could be proven that the initial specimen conditions after LPBF influence the achievable residual compressive stresses $\sigma_{R,c}$ and surface roughness values. AM parts with lower densities ρ enable a more effective deformation behaviour of the cemented carbide parts. The DSB enables a unique transformation of residual tensile stresses $\sigma_{R,t}$ into residual compressive stresses $\sigma_{R,c}$. According to the results, residual compressive stresses of $\sigma_{R,c}$ = -5.364 N/mm could be identified, which correlates to an increase of 2,600 % to the initial state. Furthermore, the surface roughness could be reduced to Ra = 1.48 µm, which leads to an improvement of 89 %. As a result, a dedicated process chain was successfully developed, which enables the production of application-specific additively manufactured parts made of cemented carbide. Further investigations address the Additive Manufacturing of a dedicated material micro-structure with a high-density ρ core and a low-density ρ surface area to optimize the material strength and the achievable residual stress state σ_R and surface roughness (Figure 4).

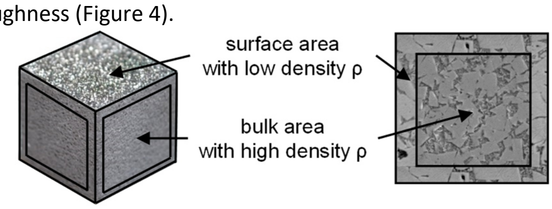

Figure 4. Dedicated material micro-struture for precise AM carbide parts

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