LASER SINTERING OF TUNGSTEN CARBIDE CUTTER SHAFTS WITH INTERGRATED COOLING CHANNELS

TOMAS J.[1], SCHUBERT T.[2], BERNTHALER T.[2], MERKEL M.[1], SCHNEIDER G.[2], SELLMER D[3]

1. *Institute for Virtual Product Development, Aalen University of Applied Science, Beethovenstr. 1, Aalen, 73430, Germany*
2. *Materials Research Institute Aalen, Aalen University of Applied Science, Beethovenstr. 1 Aalen, 73430, Germany*
3. *MAPAL Dr. Kress KG, Obere Bahnstraße 13, Aalen, 73431, Germany*

ABSTRACT: Long lifetime, low wear and high dimensional accuracy are essential requirements for tools in the metal processing industry. High temperatures in the interaction zone between tool and component are harmful and lead to premature malfunction and imprecise processing results. To counteract these, cemented carbides are utilized with suitable properties in terms of stiffness and strength. Furthermore, the lubricants and coolants are used to reduce the temperature to a tolerable degree and to create suitable conditions for the machining. To guarantee an efficient fluid transport, tools include transport channels. These are difficult to achieve with conventional manufacturing methods. Additive manufacturing opens up new possibilities for implementing cavities with almost any shape. This paper presents the design of carbide cutter shafts and their manufacturing. The course and cross-section of channels are optimally designed for the requirements of the process zones to be cooled. The additive production by powder bed based laser sintering required a definition of the process parameters scanning speed, layer thickness and hatch distance that was adapted to the cemented carbide. This is supported by extensive materials characterization methods such as light and electron microscopy, qualitative and quantitative microstructure analysis and mechanical tests (bending strength, Young's modulus, hardness, fracture toughness). The results are used to correlate process parameters, microstructure development and properties. The objective is to create a parameter set suitable to manufacture tungsten carbide cobalt hard metal parts with similar properties than conventionally produced hard metals. The cutter shafts produced by the additive process have a diameter of 16 mm and will be equipped with brazed cutting inserts in a further process step.

KEYWORDS: cemented carbide, transport channels, additive manufacturing, 3D printing

Introduction

In comparison to steel, hard metals and especially those of tungsten-carbide with cobalt as a binder material offer excellent properties with regard to hardness, Young's modulus and wear resistance and thus provide superior stiffness and dimensional accuracy as tool shafts for high performance machining. It is due to these properties that the conventional manufacturing of tool shafts from hard metals via powder processing, compacting, sintering and machining is very time and cost intensive and limited with regard to geometrical freedom. With the help of additive manufacturing restrictions in design can be overcome and distinct reduction of production time can be expected by the reduction of time consuming machining. Besides that, no higher raw material costs incur as conventional hard metal powders can be used and must not be specially produced like for additive

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manufacturing of steel components. Compared to conventional manufacturing of hard metal components via compacting and sintering, the microstructure in additive manufacturing via laser based powder bed fusion is formed in the very short time span of laser irradiation on the powder and the rapid cooling after irradiation. Much higher temperatures are reached than during conventional sintering and cooling and solidification is also very rapid due to process characteristics. These characteristics crucially affect phase formation and mechanical properties of the manufactured components. For these reasons extensive research has to be conducted with regard to the general manufacturability of tungsten-carbide cobalt hard metals via powder bed fusion and correlations of process parameters and microstructure/property formation before parts can be designed and manufactured. The present work shows the material development process from powder characterization, parameter studies and property determination to design and manufacturing of tool shafts.

METHODOLOGY

The cutting shafts with cooling channels were fabricated with a SLM 280HL machine (SLM Solutions GmbH, Lübeck, Germany). The used method is further referred to as laser powder bed fusion (L-PBF) (Hitzler et al. 2018). The features of SLM are a 400 W Yb-fiber-laser with a minimum spot diameter of ca. 80 µm and a cylindrical build space with a diameter of 90 mm and height of 100 mm. Nitrogen and argon were used as process gases. The temperature of the mounting plate was kept constant at 650 °C throughout the entire manufacturing process.

Cutter Shafts

The cutter shafts under investigation differ in diameter and length. The structure for all shafts is the same. A basic part is cylindrical and takes roughly the half of the length. There is no complex geometry in this section. Another part has axis-symmetric segments each covering caves with a few millimeters in depth. The additively manufactured cutter shafts will be equipped with brazed cutting inserts in a further process step. In Figure 1 a CAD-model of a cutter shaft with a diameter of 16 mm is shown including cross section and cooling channel. The section with complex geometry has a length of about 40 mm.

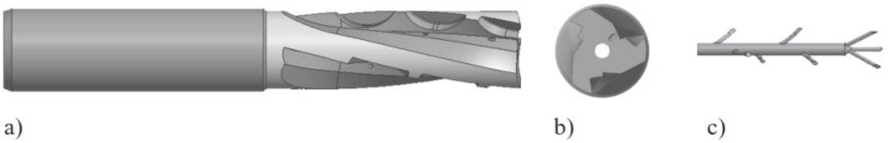

Figure 1. a) CAD-model of cutting shaft; b) cross section; c) cooling channel

Powder

For all samples, a commercially available WC-Co powder Amperit 526 (H.C. Starck) with a Co-content of 17 wt-% was used. The intrinsic purpose of the used powder is wear resistant coatings applied via flame or plasma spraying. This kind of powder was used because it provides morphology and a grain size distribution suitable for the additive manufacturing process. Flame and plasma spraying requires round powder particles with a good flowability which are the same characteristics required in additive manufacturing via L-PBF. The used powder comes in an agglomerated and partially sintered state which provides good flowability and stable particles. The powder grain size distribution was determined by microscopic image analysis. The maximum powder grain size (D99) was approx. 25 µm. The mean grain size (D50) was approx. 10 µm. Figure 2a shows a SEM image of the round powder morphology. Figure 2b shows the particle size distribution for the used powder, the particle size is represented by the equivalent circle diameter (ECD).

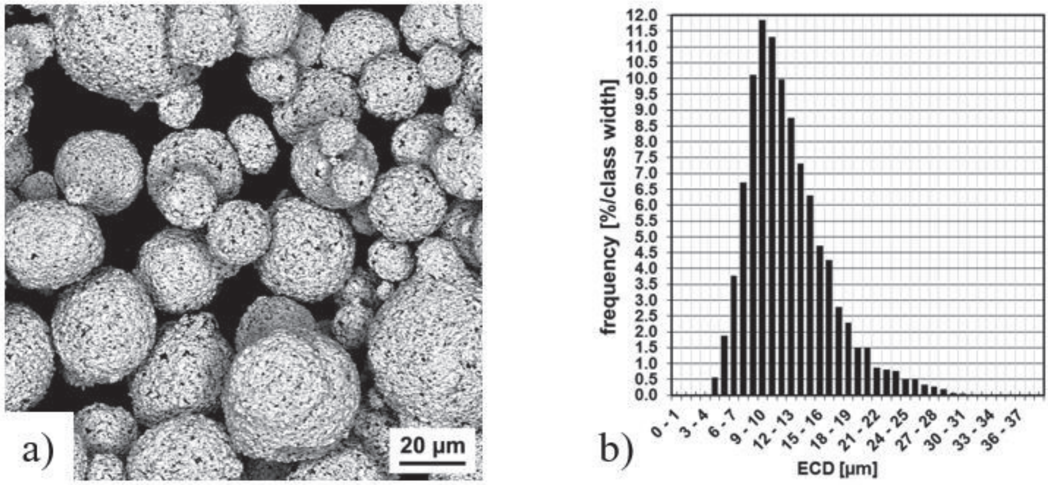

Figure 2. a) Amperit 526 agglomerates used in AM experiments, SEM BSE; 450x; b) powder particle size distribution, size classes = equivalent circle diameter (ECD) (Schubert et. al. 2017)

As the powders intrinsic purpose is wear resistant coatings, no additives found in conventional hard metals for cutting tools such as Vanadium-carbide or Chromium-carbide to oppress growth of the WC-phase or the formation of unwanted η-phase are present in the used powder.

Parameter studies on AM-process

WC-Co and hard metals in general neither are largely unexplored with regard to the L-PBF process so no basic parameter sets for AM of hard metals are commercially available nor published in scientific literature. Therefore fundamental test series were required before actual tools can be additively manufactured from hard metals via L-PBF. To find suitable parameters such as laser power, scan speed, line distance etc., and screening tests in form of parameter matrices were set up and extensively investigated. A set of parameters is considered suitable when built up samples provide low residual porosity, a homogeneous microstructure and no macroscopic failures such as thermally induced cracks. For a parameter study, small volume samples (10 mm x 10 mm x 10 mm) are arranged in a matrix and for every line a specific parameter is changed in fixed increments.

To narrow down a suitable parameter window for the additive manufacturing of WC-Co hard metals, a large amount of samples containing different parameters were examined. For a better comparability, the volumetric energy density (VED [J/mm^3]) (VDI 2013) is calculated from laser power, scanning speed, line distance and layer thickness. Figure 3 shows selected light microscopic images along the parameter studies longitudinal to the build direction with corresponding VED.

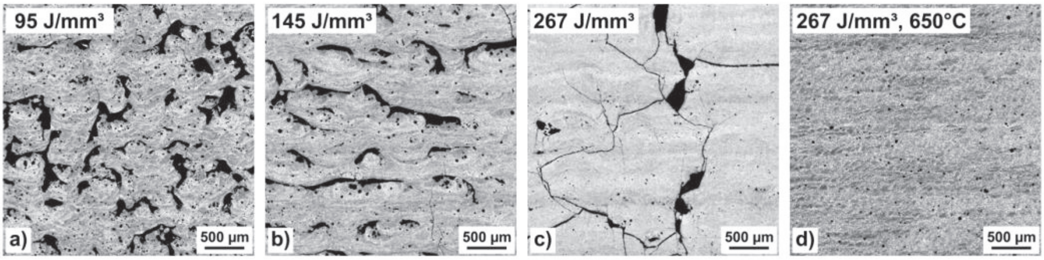

Figure 3. Selected cross sections from the parameter studies, light microscope images, 100x, tile images, a) VED = 95 J/mm³; numerous pores; b) VED = 145 J/mm³; lower porosity cracks; c) VED = 267 J/mm³; platform heating 200 °C, low porosity, numerous cracks; d) VED = 267 J/mm³; platform heating 650 °C, low porosity, no cracks

For a VED of 95 J/mm³ irregular pores along with round pores can be observed which result from insufficient compaction due to low energy input. When VED is increased to 145 J/mm³ the overall sample density rises significantly and the amount of irregular shaped pores decreases whereas cracks occur. Further increase of the VED to 267 J/mm³ leads to a further decrease of porosity but more and more cracks occur. Coming across increasing numbers of thermally induces cracks, the build in heating system of the SLM 280HL was used (Berger et al. 2016). Figure 3d shows a sample with 267 J/mm³ VED and a heated build platform of 650°C. Qualitatively the appearance of round pores increases but crack formation is completely suppressed. Due to low residual porosity and the non-formation of cracks, the parameter set of the sample in Figure 3d is the set of choice for further sample and the final tool shaft build.

The essential process parameters are: Scan speed 360 mm/s, Laser power 200 W, hatch distance 0.045 resp. 0.1 for core resp. final layer. Based on the selected set of parameters, samples with 45 mm x 7 mm x 7 mm (H x W x D) were built to determine mechanical properties and investigate microstructure formation.

To determine phase formation during the L-PBF process, at first X-ray diffraction analysis (XRD) was carried out on the samples in the as-build state. Measurements showed the WC phase and the cubic cobalt binder phase as well as the brittle and undesired η-phase. To reduce η-phase, different heat treatment experiments were carried out. A 20 h heat treatment at 1350 °C under inert atmosphere showed the best results. The brittle η-phase could significantly be reduced as shown in Figure 4a. As the η-phase is very critical with regard to mechanical properties, all further testing was carried out on heat treated samples.

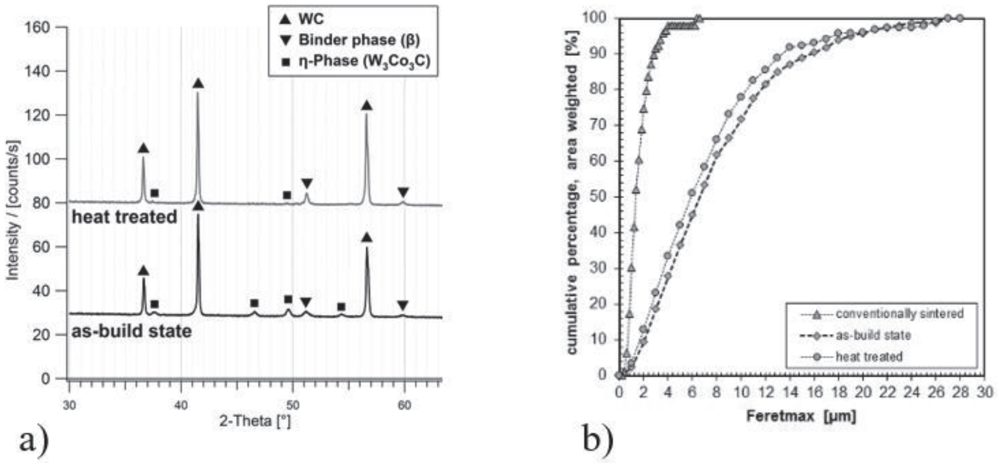

Figure 4. a) XRD analysis results for as-build and heat treated state, phase reflexes marked; b) grain size distribution of the WC phase in different sample states (Schubert et. al. 2017)

Another critical factor with regard to mechanical properties of WC-Co hard metals is the grain size of the WC phase. Because of similar gray values of the occurring phases and difficulties in grain boundary etching of the WC phase, a conventional image analysis to determine grain size is not suitable for the investigated material. To overcome this issue, WC grain size was measured via electron backscatter diffraction (EBSD). The results of the grain size distribution are shown in Figure 4b. For comparison and to show the severe grain growth during additive manufacturing, a sample of the used powder was conventionally sintered and analysed similar to the AM samples. The conventional sample shows a max. grain size (D99) of approx. 5.8 µm whereas the as-build sample shows a max. grain size of approx. 24.1 µm. The heat treatment shows no significant effect on the grain size (D99 = 24.7 µm).

Mechanical properties

The samples were heat treated and precisely ground and polished to match the requirements for bending strength (DIN EN ISO 3327:2009), Young's modulus (DIN EN 843-2:2007) and fracture toughness testing (DIN CEN/TS 14425-5:2004). Vickers hardness (DIN EN ISO 6507-1:2006) was also tested on the ground and polished samples. The results of mechanical testing are shown in Table 1.

The Young's modulus is determined by the four-point bending test (Roell/Zwick 100, Zwick GmbH Ulm, Germany). The Young's modulus out of five tests results in an average value of 400.8 GPa with a standard deviation of 4.8 GPa. This value is in the range from 300 GPa to 500 GPa (Kieffer et. al. 1965) which are achieved by conventional production methods.

Table 1. Mechanical properties

	Value	σ
Vickers Hardness [HV10]	1015	46
Bending strength [MPa]	1517	135
Young's modulus [GPa]	400.8	4.8
Fracture toughness	16.9	0.8

Figure 5. Additively manufactured cutter shafts

Figure 5 shows a set of additively manufactured cutter shafts.

CONCLUSION

The conducted experiments show that it is possible to produce WC-Co hard metals via laser powder bed fusion and that mechanical properties similar to those of conventionally produced hard metals can be achieved. However further research is required to improve mechanical properties , especially the bending strength, to reduce foreign phases and get an overall more stable and controlled manufacturing process. Geometrical accuracy and the manufacturability of small structures like cooling channels in general have to be investigated and developed.

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