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Injection molding of ceramic cutting tools for wood-based materials

F. Sommer*, F. Kern, R. Gadow

Institut für Fertigungstechnologie keramischer Bauteile, Universität Stuttgart (Institute for Manufacturing Technologies of Ceramic Components and Composites, University of Stuttgart), Allmandring 7b, D-70569 Stuttgart, Germany

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Abstract

In this study a mutable mold for ceramic cutting tools with inserts of different cutting angles and two different injection positions was designed. Three alumina-based ceramic feedstocks with different types and amount of second phases were developed. A mold filling study was carried out for both sprue positions in order to prove the molding behavior of the feedstock and the functionality of the mold. Debindering and sintering of molded green parts was arranged for each composition, respectively. Mechanical properties, microstructure and achieved cutting edge sharpness of produced tools were investigated. Results show that the mold design and injection molding process play a key role in order to manufacture cutting tools of best possible sharpness enabling a wood machining process. Feedstocks exhibit a good mold filling behavior resulting in comparatively sharp cutting edges of ≈10 μm after sintering. Mechanical properties show high potential for application of wood machining cutting tools.

Keywords: CIM; Injection molding; Ceramic composites; Cutting tools; Wood machining

1. Introduction

Cemented carbide tools for industrial wood cutting have become state of the art as they can provide a good ratio of hardness and fracture toughness.[1] Small cutting angles and sharp cutting edges with micrometer sized radii can be realized, which are mandatory for the cutting of wood and wood-based materials.[2] The wood cutting process itself is quite challenging as cutting speeds are normally ∼5 times faster compared to conventional metal cutting.[3] Moreover wood as a workpiece is anisotropic and inhomogeneous because it often contains knots and silicates.[4,5] Abrasive wear but also tannins in the wood, which chemically attack the binder phase of hard metals, frequently define the end of the lifetime for hard metal wood cutting tools.[6–9] When the radius of a cutting edge has become too large, blunted tools cannot cut wood fibers anymore, resulting in bad surface qualities of the machined product.

Wood machining technology of has dramatically improved during the last decades. Higher accuracy, feed rates and spindle rotations do not only have influence on process time but also surface qualities. In contrary, cutting tool materials were not studied such intensively. Spindle rotations for currently used hard metal tools are limited due to their high centrifugal forces and the clamping forces of the tool holder. The demands of improved wear behavior, the strong rise of the tungsten carbide price and limited rotation speeds of high specific density cemented carbides give rise to new investigations of cutting tool materials.

Promising materials are oxide ceramics as they exhibit high hardness, excellent wear resistance and no sensitivity to chemical attack. Moreover densities are approximately only one quarter of the density of tungsten carbide and do thus not limit the rotation speeds. First studies on alumina based cutting ceramics for wood machining were done by Gogolewski et al.[10] Chipping was the main problem but when grain sizes were reduced main failure mechanism was abrasive wear. Gel-casting and cold isostatic pressing of plates were chosen for defect-free processing of ceramic blanks. Tools were subsequently machined out of casted plates. Investigations on hot-pressed SiC particle reinforced Si_3N_4 ceramics showed outperforming properties compared to standard tungsten carbide tools.[11] However, also post-processing steps led to too high production costs for

* Corresponding author. Tel.: +49 711 68568234; fax: +49 711 68568301.
E-mail address: frank.sommer@ifkb.uni-stuttgart.de (F. Sommer).

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industrial scale cutting tools. A further approach was done by Strehler et al. Knive-shaped liquid phase Si_3N_4/SiC ceramics were uniaxially pressed and subsequently diamond-machined for the final shape.[12,13] Cutting tools were solidified by pressureless sintering and post-hipping. Results showed that final post-sintering heat treatment led to a partial crystallization of the intergranular phase, which was indispensable for good edge integrity. Compared to hot-pressed composites,[11] gas-pressure sintered samples displayed higher bending strength, lower hardness and toughness and larger grain sizes. Anyhow results showed twice as long lifecycles than standard tungsten carbide tools.[14]

Regarding the requirements for applicable ceramic cutting tools and industrial viability, ceramic injection molding (CIM) shows high potential as a processing technique. CIM offers the ability of economical mass production of three dimensional parts. Cost-intensive post-processing can frequently be avoided, because parts can be produced with tight dimensional tolerances.[15–19]

The aim of this study is to investigate if ceramic wood cutting tools can be manufactured by ceramic injection molding in sufficient quality. Tools must provide high hardness, fine microstructures and sharp cutting angles. In order to meet these requirements the use of sub-μm powders seems indispensable. However, the preparation of injection molding feedstocks from fine initial powders and the processing is quite challenging and needs careful selection of all processing parameters involved.

Ceramic cutting tools of three different alumina-based developed feedstocks were injection molded. Debindering and sintering of molded green parts was tailored for each composition, respectively. Mechanical properties, microstructure and achieved cutting edge sharpness of produced tools were investigated. Further investigations will focus on wear behavior of ceramic tools in wood machining but are not part of this study.

2. Experimental

2.1. Materials processing

Three alumina-based feedstocks were developed from commercially available ceramic powders and thermoplastic binder. Composites recipes are shown in Table 1. Starting powders chosen were Al_2O_3 APA0.5 (Ceralox, USA, particle size $d_{50} = 300$ nm, $S_{BET} = 8$ m^2/g) and Al_2O_3 SPA0.5 (Ceralox, USA, particle size $d_{50} = 400$ nm, $S_{BET} = 8$ m^2/g). Powders used for the reinforcing dispersion were SiC C25 (Ceram GmbH, $d_{50} = 400$ nm, $S_{BET} = 25$ m^2/g) and $YCrO_3$ (synthesized acc.[20]). Sintering additives added to Al_2O_3–SiC composites were $MgAl_2O_4$ (99%, S30CR, Baikowski, France, particle size $d_{50} = 200$ nm, $S_{BET} = 30 \pm 5$ m^2/g) and yttria (99.9%, Alfa Aesar, Karlsruhe, Germany, $d_{50} = 3.39$ μm, surface by mercury porosimety $S_{Hg} = 9.16$ m^2/g). An aqueous suspension of each composition was prepared and subsequently bead milled (Dispermat SL, VMA Getzmann, Germany) at 3000 rpm. The deagglomerated suspension was then blended with a polyethylene wax and polyethylene glycole based commercial binder (Licomont EK 583 G, eMBe Products, Germany). Mixing in a sigma-blade kneader (Hermann Linden Maschinenfabrik, Germany) was carried out at 140 °C until the solvent was evaporated and a thermoplastic compound was formed. The amount of thermoplastic binder was chosen between 40.7 vol.% and 39.5 vol.% with regard to the nanopowder content of each composition (Table 2). Feedstocks were subsequently granulated and mixed in a twin screw extruder ($d = 16$ mm, $l/d = 25$, Thermo Fisher Scientific, Germany). The homogenizing step was carried out for two times at 140 °C at 250 rpm to improve homogeneity by introducing high shear forces. After extrusion through a $d = 3$ mm die, the cold feedstocks were crushed for further processing.

Table 1
Powder compositions used for feedstocks.

Feedstock	Matrix [vol.%]	Second phase	Dopants
Al_2O_3	100 Al_2O_3 (APA0.5)		1500 ppm $MgAl_2O_4$
ACY	97.9 Al_2O_3 (APA0.5)	2.1 vol.% $YCrO_3$	
AS	95 Al_2O_3 (SPA0.5)	5 vol.% SiC (C25)	3000 ppm $MgAl_2O_4$/ 3000 ppm Y_2O_3

Table 2
Powder loadings of feedstocks developed.

Feedstock	Powder loading [vol.%]
Al_2O_3	60.5
ACY	60.5
AS	59.3

2.2. Mold design

A mutable mold was designed for the manufacturing of ceramic cutting tools. Angles of blades are variable due to mold inserts of different angles. By changing the length of ejector pins, holes can be created in the blades, enabling a secure locking during milling by metal pins of the tool holder. Sprue position and geometry are changeable by assembling the sprue orientated mold part to an upper or lower position. Injection is thus either possible by a pin gate of $d = 3.5$ mm in central position or film gate from the end of the cutting blade ($b \times h = 11 \times 0.6$ mm). In order to assist complete filling the mold was prepared for optional vacuumizing. Fig. 1 shows a 3D image of a cutting tool with 55° cutting angle and optional pin or film gate.

2.3. Injection molding and heat treatment

Injection molding was carried out on a hydraulic machine (Allrounder 270C 400-100, Arburg, Germany) with an 18 mm screw. The machine was equipped with position regulated screw and CIM cylinder assembly. Injection molding parameters were optimized for each feedstock. Green parts were debindered in a two-step process. First the water soluble binder part was