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Modelling the abrasive flow machining process on advanced ceramic materials

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ABSTRACT

Abrasive flow machining (AFM) is a unique machining method used to achieve high surface quality on inner, difficult-to-access and on outside contours. Using AFM, it is possible to realise predefined edge rounding on any brittle or hard material. AFM is easy to integrate in an automated manufacturing environment. The abrasive medium applied during AFM is a fluid consisting of a polymer which carries silicon carbide or super-abrasive grains. With a specified pressure and temperature, this fluid flows in alternating directions along the contours of the workpiece resulting in an abrasive effect. AFM is also well suited to process advanced ceramic materials. Especially advanced ceramics are playing increasingly a significant role as a substitute for metals. However the high costs for the inevitable finishing process on ceramics prevent a more frequent use. This paper represents the technological results of a research-project discovering the fundamental principles of AFM on advanced ceramic materials such as a correlation between flow processes, surface formation and edge rounding. Furthermore an insight into a process model is given, which was developed using modern simulation techniques. The overall objective of this approach is to anticipate work results like surface quality and edge rounding on any user-defined geometry.

1. Introduction

Components from high-performance ceramics have gained importance over the last few years. Because of their outstanding characteristic properties like excellent hardness, wear- and temperature-resistance these components are increasingly applied in automotive industry, in medical technology and manufacturing (Helml, 2005). In industrial applications ceramic cutting inserts for turning and milling are the state of the art. Building upon these results, prototypical fully ceramic end milling cutters were developed that hold high potentials in new fields of application. Somehow there are reasons against the implementation like low fracture toughness of ceramic materials and high costs as a result of a time-consuming finishing process.

Abrasive flow machining is an innovative fine grinding procedure with gentle material removal mechanisms. In contrast to other machining methods for deburring and polishing, it is possible to machine difficult-to-access cavities, inner contours and undercuts in a reproducible manner (Spur et al., 1997). Hence 90% of industrial applications of AFM are finishing in mould and die making. Typical components machined by AFM include extrusion moulding dies for aluminium profiles as well as crimping and stamping tools (Fig. 1). In industrial applications residues of any kind on compression moulds could be removed by abrasive machining (Ramchandran et al., 1999). Within 2 min processing time an improvement of the surface roughness from $Ra = 2\ \mu m$ to $Ra = 0.2\ \mu m$ could be achieved.

AFM has high potentials in processing ceramic materials, due to its characteristic as material removal layer by layer of sintered skins and defined edge rounding. A correlation between flow processes and surface formation on ceramic materials has not yet been discovered. In industry, the process is normally implemented in costly and time-consuming preliminary investigations that have to be carried out by trained staff (Uhlmann and Szulczynski, 2001). The aim of the research-project is to elaborate the fundamentals of the process and to detect functional correlations between setting parameters, process and work result.

2. Process technology

The largest effort in AFM development was put into the carrier material. This material consists of a visco-elastic polymer of high viscosity, which keeps the abrasive grains almost homogeneously distributed. Depending on the impact velocity, this material can show a flowing behaviour, or – under quick impact – offer the mechanical resistance needed for the grains to cut the workpieces surface (Uhlmann and Szulczynski, 2005). The material has to be temperature-resistant and needs to show a good wearing behaviour.

Prior to machining, the grinding medium is inserted into the lower cylinder. The workpiece is positioned in the specifically designed workpiece-holder and clamped between the cylinders (Fig. 2a). The two main functions of the workpiece-holder are to

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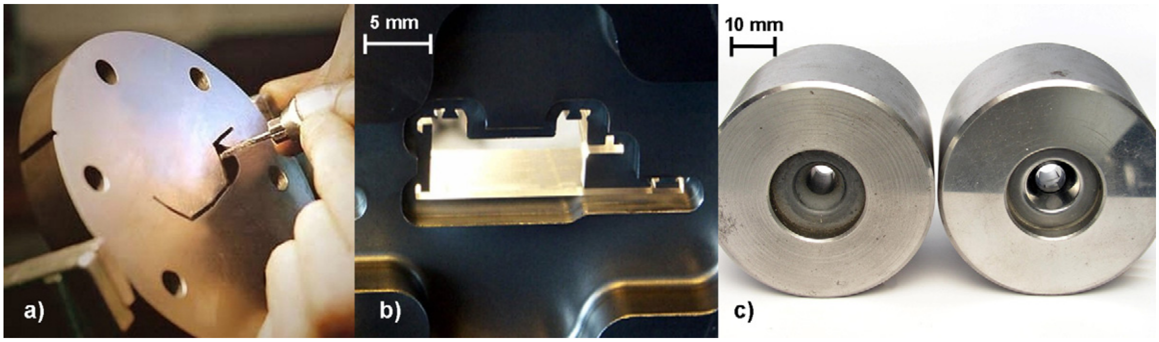

Fig. 1. (a) Polishing by hand of an extrusion moulding die. (b) A cavity of an extrusion moulding die finished by AFM. (c) A tool for the deformation of wires before and after AFM.

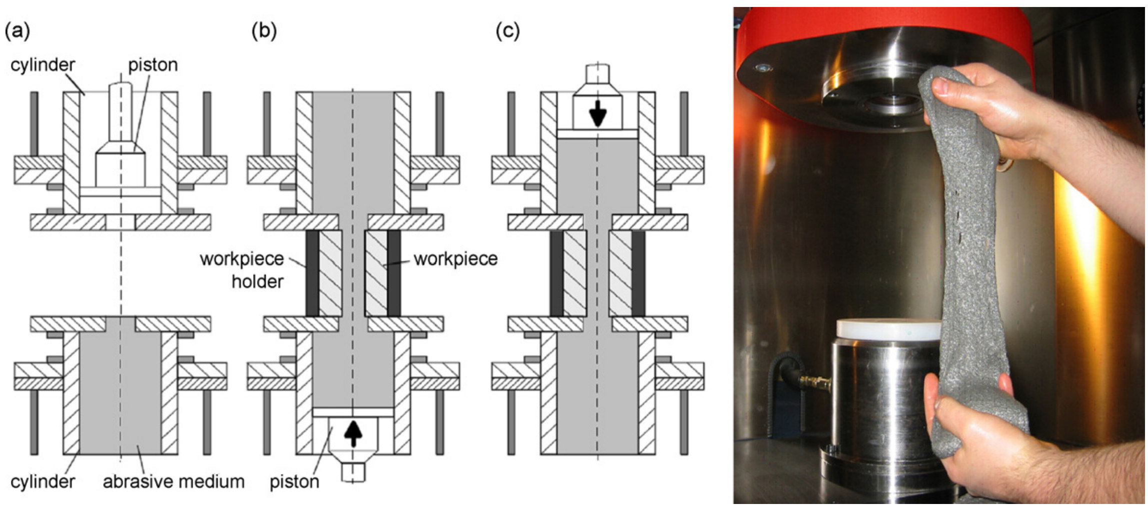

Fig. 2. Process principle during abrasive flow machining (AFM).

clamp the workpiece and to assure a controlled media flow in a closed system. Inside the fixture the medium flows through a narrowing channel before reaching the workpieces cavities. Initially, the grinding medium is heated to working temperature by the heater/cooler. Then the grinding medium is pressed upwards into the workpiece-holder along the machined workpiece shapes (Fig. 2b). After that, the process is repeated in the opposite direction (Fig. 2c). This machining cycle is repeated until the desired work result is obtained.

Adjustable machining parameters are the system pressure inside the hydraulic cylinder, which controls the flow velocity, then the processing temperature, which determines the character of the polymer carrier, and naturally the processing time. Even the grinding medium could be diversified in its viscosity as well as the specification of the used abrasive grain and the grain size.

3. Experimental set-up

The experiments were carried out on a Delta Towers MF100 type abrasive flow machine from MICRO Technica Technologies, Kornwestheim. Commercially available oxide ceramics (ZTA ceramic with >90% Al_2O_3 by vol.), non-oxide ceramics (>98% β-Si_3N_4 by vol.) and mixed ceramics (Al_2O_3 with <30% TiC by vol.) of the company Ceramtec AG, Plochingen, Germany, have been used. For investigations of the material removal mechanism and surface formation on ceramic materials, workpieces with simple-shaped geometries like planar surfaces have been machined during the first project period. On the base of these experiences complex-shaped workpieces like thread guides have been used in the following project period (Fig. 3). All simple-shaped surfaces had been lapped to remove drag-marks of hard machining and to achieve the same initial surface quality (Ra = 0.34 μm; Rz = 2.8 μm).

For the machining of advanced ceramic materials polycrystalline diamond PDA311 of the company Element Six Ltd., Shannon, Ireland, has been used as abrasive grain. A grinding medium with specification MF10-D46-200 was used. The first term indicates the viscosity of the polymeric carrier material (silicone-basis), which is a specification given by the manufacturer. The second term specifies the grain size of the used abrasive, like D 46 for a diameter of 44.5 μm according to DIN 69101. The last term describes a weight ratio of 1:2 between the carrier medium and the abrasive grains. Two different grain sizes have been used: D 46 and D 181 with a diameter of 185 μm. Under the conditions of constant cross-section the machining parameters shown in Table 1 were determined in a series of preliminary tests.

4. Results of the technological investigations

4.1. Surface formation on simple structures

To achieve the same initial surface quality all ceramic workpieces have been lapped. Afterwards the surface texture was

Table 1
Machining parameters.

Temperature, T (°C)	Pressure, p (bar)	Processing time, t (min)
30–40	20–30	1–20