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Size effects in finish machining of porous powdered metal for engineered surface quality

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ABSTRACT

Porous tungsten is conventionally machined with the aid of a plastic infiltrant to achieve acceptable surface finish. For dispenser cathode application, both high surface porosity and low surface roughness are necessary. Cryogenic machining has already been demonstrated to be capable of eliminating the need for plastic infiltration by greatly reducing smearing of pores. In order to address the problem of undesirable brittle fracture during cryogenic machining, the importance of uncut chip geometry is investigated. The value of critical chip thickness, beyond which brittle fracture occurs, is found to be closely linked to the microstructure of the workpiece material. While machining with very low uncut chip thickness leads to ploughing and spalling of the workpiece surface, ductile mode machining of porous tungsten with cryogenic cooling is found to yield excellent surface quality. When the maximum uncut chip thickness is approximately equal to the average ligament diameter of 80% density porous tungsten ($d \approx 8$–$9\,\mu$m), ductile mode machining is possible under both dry and cryogenic conditions. Changes in shock compaction behavior of the workpiece material, leading to altered physical properties, is hypothesized to be the underlying mechanism of ductile mode machining of porous tungsten.

1. Introduction

Cryogenic machining of porous tungsten is used to produce highly porous emitting surfaces for application in dispenser cathodes [1]. Rather than using a plastic infiltrant to ensure open surface porosity, cryogenic machining relies on the cooling effect of pressurized liquid nitrogen to alter machining mechanisms and limit tool wear [2,3]. Previous work of the authors has shown that nose wear of cermet cutting tools was reduced by more than 50% compared to dry machining [2,4]. While cermet tools were capable of producing acceptable surface quality at low cutting speeds, tool wear increased dramatically with cutting speed [2]. Cryogenic machining with polycrystalline diamond tools (PCD) has been shown to lead to minimal tool wear and very low surface roughness when limited cryogenic pre-cooling of the workpiece to −90 °C was used along with a slight negative rake angle of $\gamma = -5°$ [5].

Cryogenic flood cooling reduces the cutting temperature below the ductile to brittle transition temperature of tungsten, resulting in brittle fracture. Likewise, large negative rake angles and large cutting edge radii (i.e., large negative effective rake angles) increase the severity of brittle fracture. Since fracture machining results in deep pits and small chips that easily adhere to the cutting edge, surface quality with this mode of machining is poor. The problem of adhesion and built-up edge (BUE) during brittle fracture machining of porous tungsten was addressed in a previous study by employing modified PCD cutting tools [5]. Reduced cutting edge roughness and slightly increased cutting edge radius compared to upsharp ground tools led to significantly increased cutting edge strength and improved chip flow, reducing BUE. Cryogenic high speed cutting at speeds up to $v_c = 400$ m/min with acceptable tool wear can be achieved with lightly honed PCD tools.

Beyond a critical cutting speed of approximately 250 m/min, ductile mode machining of porous tungsten is possible. Along with brittle fracture, BUE is eliminated at high cutting speeds, allowing for surface roughness as low as $R_a = 0.4\,\mu$m to be achieved. However, the relatively large cutting edge radius necessary to prevent catastrophic edge chipping of PCD tools at high speeds also causes severe smearing. While smearing of pores may be desirable under certain circumstances, most applications of porous tungsten require high levels of surface porosity to permit gas or liquid to be transported through the component. In the specific case of dispenser cathode emitting surfaces, a barium compound needs to be dispensed from the porous bulk (or a reservoir) to counter the

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Nomenclature

$\dot{\varepsilon}$	Strain rate
a_p	Depth of cut
d	Grain/ligament size
f	Feed
h	Uncut chip thickness
h_c	Critical uncut chip thickness
$h_{\max}$	Maximum uncut chip thickness
$h_{\min}$	Minimum chip thickness
h_s	Steady state chip thickness
K_1	Fracture toughness (mode 1)
$k_{c\,(c)}$	Specific cutting force at $h_{\max} = h_c$
$k_{c\,(s)}$	Specific cutting force at $h_{\max} = h_s$
N	Nose wear (retract of cutting edge)
$R_{a\,(c)}$	Surface roughness at $h_{\max} = h_c$
$R_{a\,(kinematic)}$	Kinematic (theoretical) surface roughness
$R_{a\,(s)}$	Average surface roughness for $h_{\max} \geq h_s$
r_c	Tool radius (nose radius in turning)
r_β	Cutting edge radius (uniformly rounded)
T_c	Cutting temperature
$T_{c\,(c)}$	Cutting temperature at $h_{\max} = h_c$
$T_{c\,(s)}$	Cutting temperature at $h_{\max} = h_s$
VB_C	Flank wear at the nose region
v_c	Cutting speed
γ	Rake angle

rate of evaporation at the surface [6,7]. Ductile mode cryogenic high speed machining of porous tungsten with modified PCD cutting tools is therefore not suitable for finish machining of porous tungsten in dispenser cathode applications.

Because sharp edged cutting tools are necessary to ensure open surface porosity, relatively low cutting speeds need to be used for finish machining of porous tungsten. Upsharp cutting tools are highly susceptible to shock loading, which prevents such tools from being used at high cutting speeds for porous tungsten. As mentioned earlier, achieving acceptable surface porosity and surface roughness at low cutting speeds has already been shown to be feasible when upsharp cutting tools and limited cryogenic pre-cooling to a bulk workpiece temperature of −90 °C are used. Limited pre-cooling is difficult and time-consuming to implement reliably in an industrial environment when batch sizes are small and workpiece geometries vary widely, as is the case for dispenser cathodes. Since cryogenic flood cooling (high flow rate, no pre-cooling) is significantly easier to implement in an industrial setting (and the ultimate goal of this study is to achieve industrial implementation), the present study seeks to determine a novel method for avoiding undesirable brittle fracture while simultaneously achieving open surface porosity and low surface roughness with cryogenic flood cooling. It was hypothesized that there is a critical chip thickness beyond which brittle fracture takes place and below which ductile mode machining is possible with limited smearing, provided that a sufficiently sharp cutting tools are used.

Critical chip thickness effects have been widely studied for very brittle materials. In the early 1990s, Bifano et al. and Blackley et al. [8–12] developed the technique of ductile mode machining of extremely brittle substances such as germanium and glass in diamond turning and creep-feed grinding. Motivated by experimental observations of ductile deformation occurring at very low tool feed, Bifano et al. [9,10] developed a model for ductile mode material removal below a critical depth of cut and/or chip thickness based on the theory of indentation for brittle materials. A variety of theoretical models for ductile material removal in brittle materials have been developed, though no single mechanism appears to be solely responsible for the phenomenon. Rather, achieving fracture free machining depends on many variables such as the cutting edge radius, rake angle, cutting speed and most importantly, uncut chip thickness [13–15].

Liu et al. [16] developed a comprehensive analytical model for the prediction of critical chip thickness based on the assumption that large compressive stress at small values of undeformed chip thickness and/or cutting edge radius suppresses crack formation. More specifically, the researchers hypothesized that the critical chip thickness is equivalent to the condition of the local stress intensity being equal or less than the fracture toughness of a given brittle material. Yan et al. [15] developed a method of ductile mode diamond turning of single crystal silicon at large tool feed to reduce tool wear. Large feed turning was achieved with a very sharp ($r_\beta \approx 50$ nm) single crystal diamond cutting tools at highly negative rake angle ($\gamma = -40°$) and very low depth of cut ($a_p < 58$ nm) to induce a hydrostatic stress state ahead of the cutting edge. The researchers experimentally measured the value of critical chip thickness by dynamically varying tool feed and measuring surface roughness as a function of maximum uncut chip thickness; the current study will use a similar approach to determine h_c. Both Liu and Yan et al. [15,16] hypothesized that when the uncut chip thickness is larger than a critical value, approximately the same order of magnitude as the cutting edge radius, a tensile stress state ahead of the cutting edge leads to brittle fracture. Below the critical chip thickness, the material in the primary deformation zone was hypothesized to be under sufficient compressive (hydrostatic) stress to shield crack formation at flaws within the workpiece microstructure, allowing for severe plastic deformation even at low temperatures.

Arif et al. [17,18] performed numerous experimental and theoretical studies on determining the critical chip thickness in milling and turning of materials ranging from tungsten carbide to single crystal silicon and *BK7* glass. By computing both the ductile mode and brittle mode energies as a function of undeformed chip thickness, Arif et al. [18] were able to accurately predict critical chip thickness for single crystal silicon and *BK7* glass by finding the intercept between ductile and brittle mode material removal. Additionally, the researchers also provided a semi-quantitative explanation for the increase in specific cutting force as very small uncut chip thickness (i.e., a size effect) by citing the importance of elastic springback (ploughing) and a lower number of total defects within the primary deformation zone to aid in plastic deformation.

Size effects are of particular importance in finish machining operations, where uncut chip thickness is on the same order of magnitude as cutting edge radius [13,19–21]. A precise definition the term 'size effect' was provided by Vollertsen [20]: "*Size effects are deviations from intensize or proportional extrapolated extensive values of a process which occur, when scaling the geometrical dimensions.*" He further distinguished between three categories of size effects, namely density, shape and microstructure effects, respectively. In this scheme, Vollertsen categorized the commonly observed increase in specific cutting energy at decreasing uncut chip thickness as a microgeometry effect, which is a subgroup of the category of microstructure [20]. Subsequent work by Vollertsen et al. [22] explored the size effect in manufacturing of metallic components in greater detail, particularly size effects in metal cutting. In the case of porous metals, Tutunea-Fatan et al. [23] demonstrated that workpiece porosity has a direct effect on measured cutting forces. However, the average pore size of the porous titanium foams investigated by the researchers was on the order of millimeters, rather than microns, as in porous tungsten. Therefore, several convoluted size effects are to be expected when machining porous tungsten. In addition to the microgeometry effect that arises from the finite size of the cutting edge, density effects that occur due to the uniformly distributed pores are also likely. Critical chip