Ductile behavior of optical glass in single point diamond turning

Comportamento dúctil de um vidro óptico no torneamento com ferramenta de diamante

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Abstract

Single point diamond turning tests were carried out on a B270 type glass. Submicrometer cutting conditions were applied in order to generate ductile response during single point machining. The profile generated by the rapid removal of the tool tip from the machined surface, analyzed by atomic force microscopy, showed that the brittle-to-ductile transition occurs at a few tenths of micrometers. According to the machining results, the maximum feed rate capable of generating a ductile mode machining behavior is of 0.9 micrometer/revolution. Furthermore, it was shown that with the cutting depth lower than 0.100 micrometer/revolution, the material removal mechanism is totally ductile. Ribbon-like chips were not observed when ductile machining was performed, as commonly seen during ductile machining of semiconductor crystals. The chips removed had a small needle-like shape. This material's fragile behavior during machining may be related to high densification during tool/material interaction with subsequent elastic recovery response.

Keywords: *soda-cal-silicates, diamond turning, Brittle-to-ductile transition, Atomic Force Microscope*

Resumo

Foram feitos testes com o vidro óptico B270® através do torneamento com ferramenta de diamante. Foram aplicadas condições submicrométricas de corte, a fim de se gerar uma resposta dúctil, para o vidro, durante a usinagem. O perfil gerado pela remoção rápida da ponta da ferramenta da superfície usinada, analisado através de um Microscópio de Força Atômica, mostrou que a transição frágil-dúctil, nesse tipo difícil de usinagem, ocorre abaixo de alguns décimos de micrômetros. De acordo com os resultados da usinagem, a máxima taxa de avanço capaz de gerar, na usinagem, um comportamento dúctil é de 0.9 µm/rev. Além disso, ficou demonstrado que, para profundidades de corte menores do que 0.1 µm/rev., o mecanismo de remoção de material é totalmente dúctil. Não foram observados cavacos em forma de fitas durante a usinagem dúctil, como pode ser visto comumente durante a usinagem dúctil de cristais semicondutores. Nesse caso, os cavacos removidos têm formato de pequenas agulhas. O comportamento frágil desse material, durante a usinagem, pode estar relacionado com a alta densificação na interface ferramenta/peça com subsequente recuperação elástica.

Palavras chave: *Vidros silicates com sódio e cálcio, torneamento com diamante, transição frágil-dúctil, Microscópio de Força Atômica.*

1. Introduction

Lapping and polishing are the most recalled processes for the machining of brittle materials. However, machining processes with defined tool geometry are currently being tested as an alternative to cutting optical glasses with low surface finish similar to those achieved by conventional processes. When a single point tool is applied to brittle materials, a serious constraint is to keep cutting conditions below critical values. This is done in order to prevent generating deleterious surface and subsurface damage such as microcracks. The ductile-to-brittle transition can be predicted by analyzing the onset of a fragile response when critical conditions are applied. The critical cutting depth for brittle materials is normally around values smaller than 1 micrometer. Consequently, the machine tool used to achieve such precise cutting conditions has to have special stiffness and precision characteristics in the positioning system (BLACKE, 1998).

Silicon, optical glasses and other typical brittle materials are known by their extreme fragility and low machinability when machined in the ductile mode. It has been postulated that ductile-regime machining requires post polishing processes, such as chemical polishing, in order to remove subsurface damage produced during single-point tool machining. The ductile-regime machining concept has been widely investigated since the early 1060s for semiconductors and amorphous materials such as glasses (HUNG & FU, 2000).

In order to achieve ductile response with typically brittle materials with single point tools, machine tools with special stiffness and precision characteristics in the positioning system are essential. Understanding the plastic response phenomenon of normally brittle materials is considered an important aspect in the investigation of their merchantability, and mechanical properties; hence the first parameters are used to predict the material's plastic behavior, correlating the experience with metal cutting theory. Machinability and the plastic response of intrinsically brittle materials are normally associated with their mechanical properties and compared with the metal cutting theory. It is conventionally established that the lower the material hardness, the higher the ductile response. According to this concept it can be inferred that brittle materials, irrespective of their intrinsic high hardness and fragility, may undergo a brittle-to-ductile transition when the dimensions of the cutting conditions are kept below a critical value (SREEJITH & NGOI, 2001).

It is well established that glasses may present a viscoplastic deformation when the temperature is higher than the transition temperature. The material removal mechanisms generally observed for glass are brittle fracture and plastic deformation. It is believed that the energy required for the generation and propagation of microcracks is larger than that required for plastic response.

In this work, soda-cal silicate glass samples were machined in an ultraprecision machine tool. Single point diamond turning tests with submicrometer cutting conditions (depth of cut and feed rate) were carried out. The interrupted cutting test is performed to analyze the cutting tool profile left on the machining surface. This is done by the rapid removal of the cutting tool nose from the cutting surface. The surface and the profile of the tool left on the surface are then analyzed by atomic force microscopy to accurately estimate the depth at which the brittle-to-ductile transition takes place. The surface roughness of the ductile mode machining with single point diamond tool was measured. The chips removed from the machined surface were observed by means of scanning electron microscope to evaluate the material removal mechanism during ductile mode machining.

2. Experimental Procedure

In these experiments, the glass type B270 workpiece was fixed on a mounting plate, which was then fixed at the center of the spindle. The workpiece surface was slightly tilted to the spindle axis so that the cutting depth varied continuously from 0 to 10 mm (Fig. 1a) when the tool cut the surface from the center to the periphery of the workpiece, as described elsewhere. Figure 1b shows schematically the shape of the cut surface in this experiment. The quality of the machined surface was observed and analyzed with a Zeiss optical microscope and a scanning electronic microscope (SEM). Figures (2a) and (2b) illustrate the areas with ductile and brittle machining, respectively. The region in Figure (2b) shows regular feed marks without fracture. It is apparent that ductile machining takes place. A few small fractures, shown as dark spots, appear when the cut depth is around 2 micrometer in the brittle-mode region, evidencing very irregular fractures. The surface quality of a ductile machining part in the ductile-mode region of Figure (2b) was examined with an atomic force microscope (Digital Nanoscope III). Figure (3) shows the 3D plot of the surface near the transition area. The measured area is of approximately 50μm.

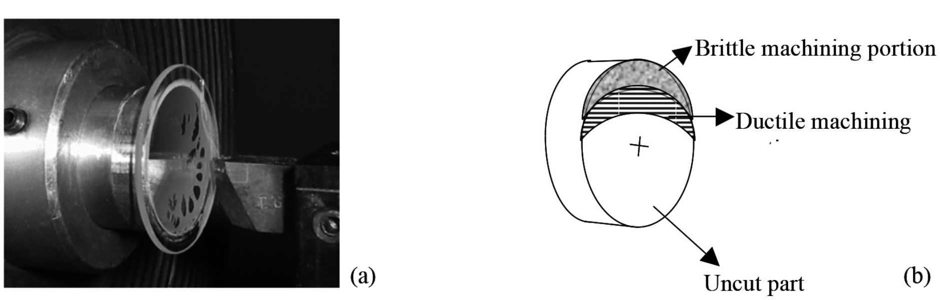


Figure 1
a) Mounted on the machine tool vacuum chuck, b) a schematic diagram of the shape of the machined surface.

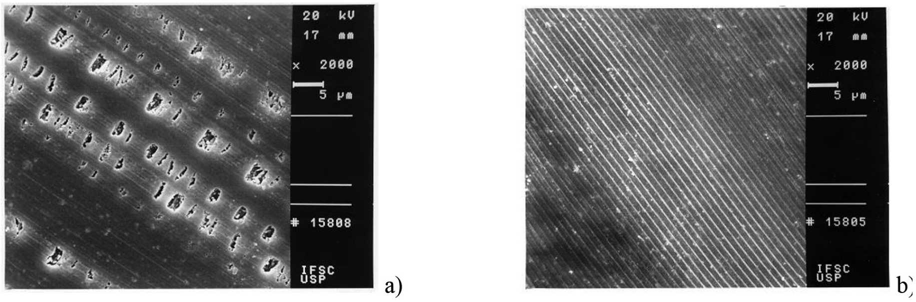


Figure 2
a) Machined surface cut in the ductile mode and, b) machined surface cut in the brittle mode.

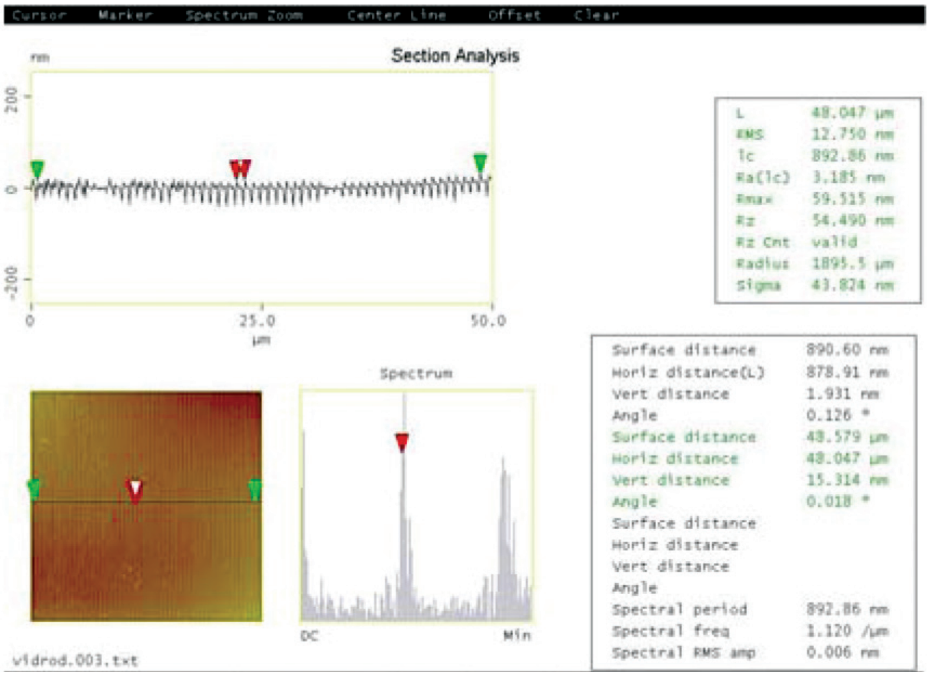


Figure 3
Three dimensional image generated by AFM of the ductile portion of the sample.

The properties of the B-270 glass are highlighted in Table (1). The code B270 is used by the manufacturers for a silicate modified glass known as "window glass" which is composed of % in weight of 72% SiO_2, 1% Al_2O_3, 10% CaO, 14% Na_2O, 2% MgO.

Softening Temperature	Linear expansion coefficient	Density	Elastic Modulus
521°C	8.2 µm/m°C	2.55 g/cm^3	71.5 GPa

Table 1
Proprieties of B270 glass

The glass bulk samples are fixed to the vacuum chuck of an ultraprecision machine tool (ASG 2500) as shown in Fig. (1a) and the interrupted cutting test (described elsewhere) is carried out using facing cuts. The cross feed direction was from the outside to inside. These conditions provided ductile and brittle modes during machining, with mirror-like and opaque surface finish. This procedure generates a surface path as described schematically in Figure (1b). Alkalisol 900 (synthetic water soluble oil made from a complex mixture of organic and chloride solvents developed by ALKALIS BRASIL was used as the lubricant and coolant during turning. The cutting fluid is positioned in the cutting zone by continuous spray and the spindle is kept at a constant speed of 100 revolutions per minute (RPM). The varying cutting parameters are feed rate and cutting depth.

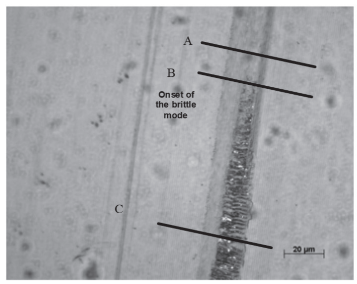
The cutting tool used in the tests was a single point diamond tool fabricated by Contour Fine Tooling® (CO45NG** nose radius 1.13665 mm, rake angle –5° and clearance angle 12°). An Optical Microscope and a Digital Scanning Microscope, Zeiss model DSM 960, operated at 20 kV were used to conduct the observation of the chips and surface. Metallization coating provided enhanced visualization of the surface details at high magnifications. The atomic force microscope (AFM) was a Digital Nanoscope IIIa. It was operated with a standard 50-60° conical silicon nitride stylus of 5 nanometer radius tip, with cantilever spring constant of ~ 0.06 N/m. A conventional contact mode was used in a raster scanning mode over the stylus, and in contact with the surface by contact forces of typically 10-100 nanometer. The inspection process consisted of measuring the surface roughness and obtaining images of the uncut shoulder in order to determine precisely the brittle-to-ductile transition depth. Table 2 presents the cutting parameters used in the cutting tests.

Cutting parameters	Values
Depth of cut (µm)	0.2 to 3.0
Feed Rate (µm/revolucion)	0.5 to 1.0

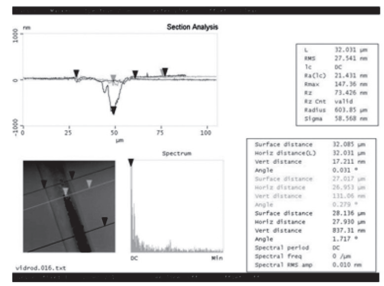
Table 2
Cutting parameters used in the machining experiments

3. Results

Figure (4) shows an optical microscope image of the uncut shoulder generated on the glass sample. The uncut shoulder is composed of two parts representing the ductile (region A) and the onset of the brittle regime (region B). The morphology of the cutting grooves in Fig. (4a) shows tooling marks according to the feed rate condition applied. No sign of cutting edge defect is found within the primary surface roughness structure. Figure (4b) shows the tridimensional image of the uncut shoulder in the ductile-to-brittle transition portion. Although a smooth surface finish is presented it should be noted that the surface does present micro cracks when the transition takes place, meaning that the micro cracks were not deep enough to cause damage to the surface finish. The cross section analysis of the uncut shoulder showed different depths. The depth at which the ductile mode is achieved is a bit higher than 17 nanometers. The brittle mode takes place very near a depth greater than 130 nanometers, which is shown by the formation of microcracks perpendicular to the cutting direction. As the cutting tool advances, the cutting depth increases, clearly showing the brittle mode at the depth of 837 nanometers. The cutting depth value can be also estimated by using an equation proposed by JASINEVICIUS (1998), for round nose tools, as shown in Table 3.



a)



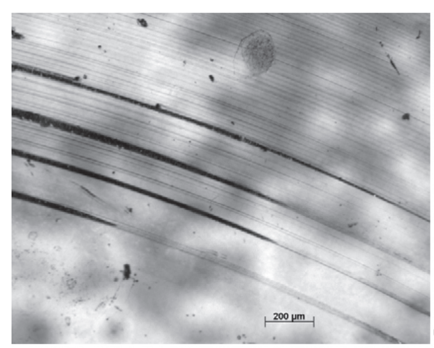
b)

Figure 4
a) Uncut shoulder of B270 glass in three different regions and cutting widths, b) MFA of the uncut shoulder analyzed

Table 3
Estimated cutting depth achieved as a function of the width of the uncut shoulder of the B270 glass, for round nose tools ($W^2 = 2.a_p.r$) (JASINEVICIUS, 1998).

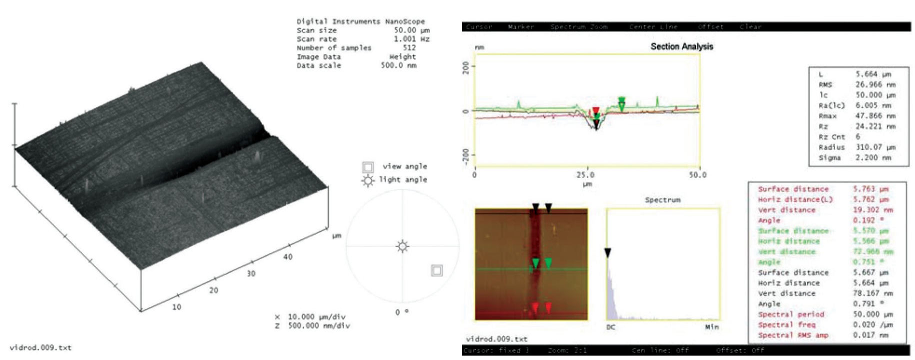
Uncut shoulder width W (µm))	Estimated depth of cut a_p (µm)
6.2	0.017
17	0.131
43	0.84

Figure (5b) shows a 3D image of the tool in the piece. The analysis of the section displayed in this figure shows that a permanent deformation is produced in the glass at depths of a few tenths of nanometers. This plastic behavior corroborates with what has been observed in glass for very small loads of indentations (i.g,10g). This plastic glass behavior is interesting to study the material removal mechanism. It is known that the depths where the glass begins the plastic recovery are only a few tenths of nanometer. Therefore, the material removal under ductile behavior for glass depends heavily on the type of turning tool. The lower the distance to the lower edge, the more critical the depth of the brittle-to-ductile transition.



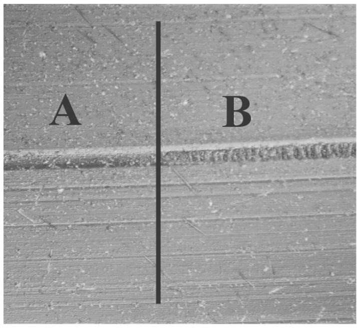
(a)

Figure 5(a)
Map view of B270 glass showing brittle-to-ductile regions,



(b)

Figure 5 (b)
MFA of the tool entry into the piece showing that the glass undergoes plastic deformation with small machining depths.



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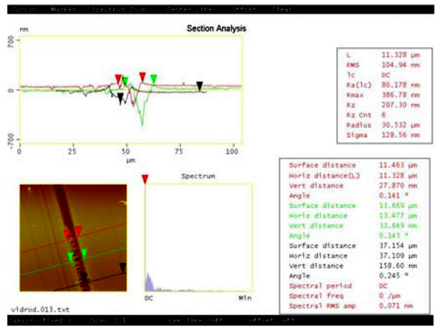


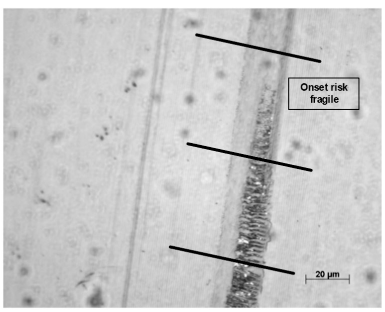
b)

Figure 6
a) Optical Microscopy of the uncut shoulder in the britlle machining showing the brittle-to- ductile behavior due to the change in cutting depth, b) MFA analysis of the cross section of brittle-to- ductile transition.

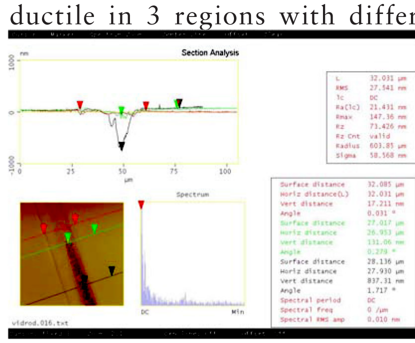
Figure (6a) Part A means ductile machining and part B is the means brittle behavior. According to JASINEVICIUS (1998), this is measuring the cutting width of this uncut shoulder (W), using equation $W^2 = 2a_p.r$, where r is the radius of the tool tip; there is a value to approximate the depth of cut used in the experiment.

The value estimated by MFA in Fig. (6b) for the cut width in the brittle-to-ductile transition was 13.67 micrometers and these values amount to a machining depth of 0.157 microns, which is validated by the brittle-to-ductile transition in this image. This value confirms the cutting edge radius of commercially sold diamond tools.

Figure (7a) shows the shoulder ductile in 3 regions with different widths (W) and, through Jasinevicius equation the cut depths will be determined. The first is the region where the brittle-to-ductile region of the B270 glass is probably situated. Table IV shows the depths of cut of the shoulder widths (W) in Fig. (7b). The cut depths cut in the figure are measured from top (first line) to bottom (third line) - smaller W for larger W.



(a)



(b)

Figure 7
a) Uncut shoulder of B270 glass showing three different regions and cutting widths, b) MFA of the shoulder analyzed.

Shoulder width W (µm)	Depth of cut a_p (µm)
20	0.100
21	0.131
21	0.84

Table 4
Depth of cur calculated for B270 glass

The table above illustrate that the brittle cracks shown in the shoulder (Fig. 7a) begin in a narrow range of 0.13 micrometer. It can be stated that for the B270 glass studied in this work, the ductile-to-brittle transition, according to Jasinevicius equation, the cut depth is probably around ap = 0.13 µm for a feed rate of f = 0.9 micrometer / rev. Thus, for a feed rate of f = 0.9 µm / rev., there is a cutting ductile for somewhat larger cut depths as shown in Fig. (7b). However, it is possible that for the ductile diamond turning of glass, the cutting conditions will be greatly reduced.

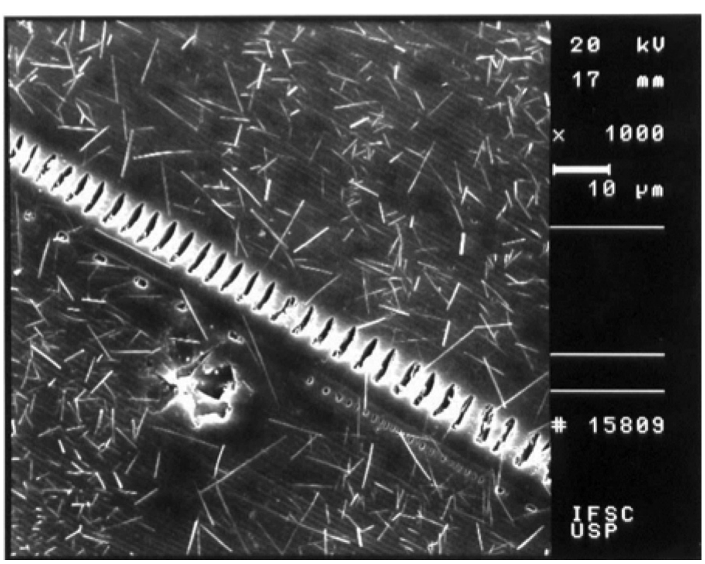


Figure 8
Needle-shaped chip of the B270 glass over the region machined with brittle uncut shoulder at the center of the figure.

Figure 8 shows the uncut shoulder and small fragments of needle-like material resulting from the removed material, that is, chip fragments that were not removed. Figure 9 shows the MFA image of the shoulder shown in Fig 8. You can see the estimated cut depth and the depth of the micro cracks that formed in the shoulder toward cross-cutting to the cut. This kind of micro crack can be attributed to compressive stresses generated during the cut by the interaction between the tool and the material. However, it should be noted that stress must be generated over the uncut shoulder that may have generated on the layers below the surface, showing average cracks as in the indentation model.

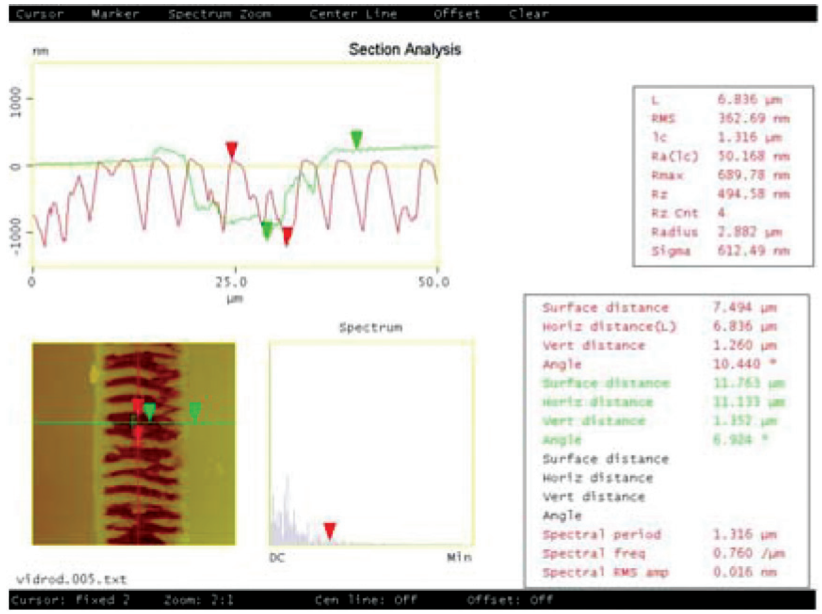


Figure 9
MFA of the uncut shoulder showing height of the shoulder and the depth of the cracks formed in the cross-section to the direction of the cut.

4. Conclusions

Despite showing some ductility during single point diamond turning, it should be noted that the depth range is very low. This indicates very uneconomical cutting conditions in terms of the material removal rate. However the value of 131-209 nanometer depth for the brittle-to-ductile transition is quite similar to those observed in the case of semiconductor crystal machining with diamond tools. It is worth mentioning that the rake angle of the tool is not sufficiently negative to assert that it is hindering the mechanism of brittle failure. More negative tools can present better results in terms of critical depth of cut.

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