A Review of Partial Ductile Mode Machining for Brittle Materials

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Abstract. There is an increased trend in the usage of brittle materials for industrial applications. Most of these applications demand for a precise and accurate finishing which calls for new machining methods that can give a very good surface finish with proper control over surface integrity. These properties are significantly influenced by the material removal during machining. The mode of material removal during machining for brittle and ductile materials is completely different. Ductile materials plastically deform a significant amount before fracture when deformed in bulk. But in brittle materials there is no plastic deformation before fracture and the material removal is achieved by crack propagation. This results in poor surface finish and loss of surface integrity. To overcome these, a new mode of machining is developed. The application for this machining mode can be highly useful while machining glass, metallic carbides and nitrides etc. In this study, an overview of ductile mode machining mechanism in brittle materials with reference to grinding operation is presented.

Key words: brittle materials, plastic deformation, fracture, crack propagation

1. Introduction
Brittle materials have a wide range of applications as the use of ceramics, different types of glasses used for optical lenses and mirrors, craft components for optical communications, manufacture of automobile equipment, semiconductors, computers and other technological devices, in medical equipment and tools etc. Due to this increased demand for the use of brittle materials, it is very important that the machining processes for the brittle materials be very precise and easily replicable to exact and unique specifications.[1]

But usually, the machining of brittle materials is very difficult. When machined the brittle materials can deform through a variety of mechanisms and it is different from that taking place in ductile materials. In ductile materials, generally the material removal occurs by plastic flow of material in the form of severely sheared machining chips. But in brittle materials, initially median and lateral cracks are developed. The final material removal occurs through the propagation and intersection of...
cracks.[2] Due to this crack generation, the machining in brittle materials results in poor surface finish and loss of surface integrity. This becomes a major drawback for components used in applications requiring a high degree of precision.

Therefore to meet these challenges, a new mode of machining called ductile mode of machining is required to be developed to machine these brittle materials satisfactorily. Also called as partial ductile mode or ductile regime machining, these process involve the material removal through plastic deformation as compared to the crack formation and propagation in conventional machining of brittle materials. This method can be applied to many traditional machining processes like grinding, turning, drilling etc., thereby increasing the scope of applications.

2. Advances in Ductile mode grinding
Till date, a lot of progress is seen in the research on the ductile mode machining. In this paper, an attempt is made to consolidate the results of the various researchers on the ductile mode machining.

In a key note paper by Inasaki on ductile mode grinding of hard and brittle materials, the characteristic features of the brittle materials have been outlined and then a fundamental principal for grinding such materials has been presented. Also practical examples of advanced ceramic grinding are discussed and some remarks for attaining high efficiency grinding have been presented.[3]

Z.W.Zhong in his paper on ductile or partial ductile mode machining of brittle materials discussed the machining mode for silicon, glass, and some advanced ceramics. Scanned electron micrographs of the machined surfaces are used for evaluating the results of his work. The author used grinding and lapping operations on inexpensive machine tools and observed ductile streaks on the surfaces of the materials under good conditions after machining. A conclusion that this mode of machining is fast and economical is made and when applied for the manufacture of aspherical glass lenses, the method proved to be very economical. The important observations made in this work are improved surface quality and reduced polishing time.[4]

T.G Bifano and et.al. in their paper on ductile regime grinding showed that controlled grinding infeed rates as small as nanometers per grinding wheel revolution can result in grinding of brittle materials with plastic flow as the predominant material removal mechanism. They also showed that through this mechanism, surface finish similar to that of those achieved in polishing or lapping can be produced through grinding. Also it is possible to achieve controlled contour accuracy and complex shapes unlike in polishing and lapping. In their paper, a research apparatus and the required process parameters for this machining mode have been presented.[2]

From metallographic polishing published in asminternational.org, the chapter on brittle materials: principles provides an overview of the different chip fracture mechanisms, polishing mechanisms, abrasion mechanisms, and chip cutting mechanisms were discussed. The micrographs of the machined surfaces were used to study the effects of the different mechanisms after machining.[5]

In Ductile Mode Machining Simulation of Glass Material Using MATLAB by Bhagwat Vishal B.,and Dr. R. Manu, Sreenath efforts are made to study the crack propagation in brittle materials.FE simulations are carried out to analyze the maximum stressed regions in the work piece during machining which leads to cracks. Finally the effect of depth of cut (DOC) on brittle fracture mechanism is analyzed and a transition from brittle mode to ductile mode machining is discussed from the view point of size effect. The effect of rake angles is also studied on the chip formation process of brittle material. Cutting forces are studied for different rake angles considering its importance for selecting cutting conditions and parameters.[6]
A.M. Kovalchenko in his studies on ductile cutting of brittle materials considered different theoretical and experimental studies on ductile cutting of brittle materials. This mode of cutting is based on the high pressure induced phase transformation of the machined material followed by the cutting of the amorphous transformed material which makes it possible to avoid cracking. The different decisive factors for implementing this method have been studied.

3. Mechanism and Factors involved in ductile mode machining

The setup for ductile mode grinding should be designed taking the high rigidity and low infeed requirements as primary considerations.

There are a number of factors which result in the high hardness of the brittle materials which is the main reason for the difficulty to machine. Generally brittle materials are characterized mostly by covalent bond which has a higher thermal conductivity and a low coefficient of thermal expansion. The ratio of covalent bonding to ionic bonding in brittle materials is very high resulting in higher hardness and lower values of Young’s Modulus. But in ductile material hardness is low and they have higher Young’s Modulus. These factors can be attributed to low density, low mobility of dislocations, large inter atomic distances and low surface energy. All the above mentioned factors result in brittleness and eventually in the difficulty to machine.

The material removal energy can become the main consideration involved in the transition of brittle to ductile material removal at smaller depth of cuts. Plastic flow is energetically more favorable than fracture for smaller depth of cuts. Ductile chips are controlled by depth of cuts. There exists a critical depth of cut which marks the transition from ductile to brittle machining. In ductile mode machining, the critical depth of cut is around 50nm to 1μm. When the depth of cut employed in the machining process is less than the critical depth of cut, then the material removal can occur through plastic flow rather than by fracture.

Another factor impacting the transition from brittle to ductile mechanism while machining is the size of the indenter. While the indenter size has no impact on the plastic flow while machining in ductile mode, this becomes an important factor for brittle machining. A large tip size produces a cone crack and a small size results in plastic deformation while applied with less pressure. But with large pressure and small tip lateral and median cracks are induced in the material.

From the theory of fracture mechanics it is observed that the growth of a crack, the extension of the surfaces on either side of the crack, requires an increase in the surface energy. Griffith suggested a crack propagation parameter which can be taken as the material property characterizing the resistance to fracture. Irwin suggested a strategy to resolve the energy required for the crack initiation and propagation into two components: stored elastic strain energy released during crack propagation and the dissipated energy which includes the plastic deformation and surface energy. The strain energy acts as the thermodynamic driving force for fracture whereas the dissipated energy provides the thermodynamic resistance to fracture. Then the total energy is

\[ G = 2\gamma + G_p \]

where \( \gamma \) is the surface energy and \( G_p \) is the plastic dissipation (and dissipation from other sources) per unit area of crack growth. For brittle materials such as glass, the surface energy term dominates and \( G \approx 2\gamma \). For ductile materials such as steel, the plastic dissipation term dominates and \( G \approx G_p \). For polymers close to the glass transition temperature, we have intermediate values of \( G \) between 2 and 1000 J/m\(^2\).
4. Conclusion
The following are some of the conclusions made from the above study:

- The material removal mechanism in brittle materials is observed to be through micro brittle fracture while in ductile materials it is through plastic deformation.

- The grinding force required for material removal is high for ductile materials compared to that required for brittle materials due to the higher hardness of the materials.

- Compared to ductile materials, brittle materials require low specific grinding energy.

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