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Thermal effects in single point diamond turning: Analysis, modeling and experimental study

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ABSTRACT

Single Point Diamond Turning is one of the ultra precision methods to generate surface finish with highest possible dimensional accuracies. It involves material removal by shearing mechanism using a diamond tool tip, shearing of material results in generation of thermal energy which causes adverse impact on the tool wear, dimensional accuracy, and surface quality of work piece and on the cost of production. Thermal issues are generally taken care of by the application of coolant. Even after use of coolant, heat is transferred to workpiece while machining, which contributes to the residue of heat for next machining cycle. It deteriorates the surface quality of machined work piece to some extent. In this work, a mathematical model is proposed to compute the net residual heat transferred in the workpiece in terms of machining parameters. The equations describing temperature distribution inside cylindrical work piece, rate of heat transfer, net residual heat for a constant depth of cut are also computed and presented. The mathematical model is followed by the simulation model and the resultant parametric values through well designed sets of precision machining experiments using proper optimization technique to predict optimum machining combination that result in less distortion of surface quality.

1. Introduction

High precision finishing methods are important for present manufacturing scenario to improve quality control, interchangeability of components and longer fatigue life [1]. In SPDT a very thin chip or layer is machined under precisely controlled conditions by using single crystal diamond cutting tool [2]. SPDT is applicable to ductile materials that machine well rather than to hard brittle materials. However, by using a grinding head on a diamond-turning machine in place of the tool, hard brittle materials can also be finished [3]. A machining model using two parameters, the critical depth of cut and the subsurface damage depth, to characterize the ductile-regime material removal allows fracture-free grinding of glasses and ceramics as well as diamond turning of optical surfaces on materials such as germanium, Zinc Selenide, and Potassium di-Hydrogen Phosphate (KDP) [4]. SPDT can used to process many non-ferrous metals, like plastics and PMMA [5]. Performance of SPDT depends on number of factors which can be divided into two classes i.e. controllable and non-controllable parameters. Controllable parameters are those controllable by machinist (tool setting, spindle speed, tool feed, depth of cut and tool nose radius, tool rake angle etc). Non-controllable parameters are tool - workpiece vibration, thermal effects, scratches due to chips, tool wear and profile changes due to vacuum clamping.

Thermal effects have significant effect on machined components. The combined effect of material swelling and recovery affects the surface roughness in SPDT. Researchers have found that effect of material swelling for ductile materials would be high, when depth of cut is extremely small [6]. Surface roughness profile (Ra) is found to be different for different process parameters; a model-based simulation system is presented for the analysis of surface roughness generation in ultra-precision diamond turning. It means material and machine parameters also play some role in the resultant surface quality [7]. Metal cutting is very highly localized and non-linear, occurs at high temperatures, high pressures, involves shearing of work piece by overcoming its ultimate shear strength. This deformation at the shear plane takes at high strain rates and generates a large amount of heat. Heat is generally produced at three machining zones: primary, secondary and tertiary zones [8]. It is observed that 2% of the total work is converted into heat and much proportion of this heat is taken by chip (80–85%), tool (10–17%), and only (3–5%) is retained by the work piece [9]. Major part of heat that penetrates into the work piece is from primary zone. Most of the analytical studies use analytical models for the prediction of temperature and heat distribution on metal cutting process. The generated heat flux that enters the work piece can have a critical impact on dimensional accuracy and surface

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quality of the work piece. Thermal issues in SPDT are generally taken care by application of alcohol based coolant to ensure surface finish. The use of coolant in case of polycarbonates hampers the surface quality, so dry cutting is preferable. Temperature prediction is one of the most complex subjects in the metal cutting literature. It is difficult to develop a precise temperature prediction model in machining due to the complicated contact phenomenon. Therefore, accurate and repeatable temperature prediction still remains challenging due to the complexity involved [10]. Much work has been done to find contribution of primary zone's heat flux to heat partition in machining; an analytical model is used to evaluate the rise in chip temperature due to primary deformation heat zone [11].

The 3-D temperature field is determined on the chip, tool and work piece during machining. Temperature fields can affect other properties such as residual stresses and tool wear, and thus tool life and fatigue life of finished parts. The finite difference method (FDM) [12,13], finite element method (FEM) [14,15] based models are proposed. A numerical method based on finite difference method is also presented that combines the steady-state temperature prediction in continuous machining with transient temperature evaluation in continuous machining [16,17]. Impact of temperature generated at tip of micro-cutting tool on surface integrity of commonly used optical materials using fiber Bragg grating sensor [18] and it is concluded that at higher temperature included on cutting tool tip during machining results in poor surface integrity. Apart from the temperature prediction, temperature measurement at the tool edge – work piece interface is even more challenging. It is important to accurately measure the thermal energy generated and propagated. These temperatures are used in two ways. The measured temperature data can be used to validate models predicting temperature and the thermal data may be used as input into machining models. There are several techniques available for performing this measurement, thermal imaging [19,20] fiber Bragg grating [18], thermocouple techniques [21,22,16] are some of the methods to measure temperature while machining process.

Residual heat in workpiece raises the need for over-tolerant specifications on the parts or requires post-processing in order to remove residual thermal stresses. It may reduce the fatigue life of the machined components as a result of residual stress [22]. It is very critical to find a fast and precise solution to predict residual heat in a machined component given the process parameters and material properties. Analytical modeling of residual heat penetrating into the work piece may be a solution of this critical problem. This modeling can help in compensating for the material swelling and recovery, which may arise as a result of residual heat contained in work piece after completion of machining cycles. Polycarbonate material is a particular group of durable thermoplastic polymers. Although it has high impact-resistance, it has low scratch-resistance and low thermal conductivity (0.19–0.22 W/(m K) at 23°). Unlike most thermoplastics, polycarbonate can undergo large plastic deformations without cracking or breaking. Application areas of these materials include medical applications including normal and high-speed projectile-resistant eye protection and lighting applications that would normally indicate the use of glass. Many kinds of lenses are manufactured from polycarbonate, including automotive headlamp lenses, lighting lenses, sunglass/eyeglass lenses, swimming goggles and SCUBA masks, and safety glasses/goggles/visors including visors in sporting helmets/masks and police riot gear.

The work is dedicated to machining of polycarbonate lenses. The profile of polycarbonate lenses is very important for reducing optical aberrations in optical systems. During machining due to thermal effects the profile of finished product (polycarbonate lenses) may get distorted. This paper focuses on development of a mathematical model to predict temperature distribution in workpiece during machining process and amount of residual heat remaining after a certain number of machining cycles. The obtained theoretical results are then verified through some set of simulation and experimental results. It was analyzed that temperature of successive machining layers increases due to transfer of heat residue from one machining layer to another machining layer affecting surface profile and roughness.

Table 2.1
List of input parameters.

Parameters	Symbols	Units
Spindle speed	ω	rev/min
Cutting speed	V	mm/min
Depth of cut	Z_0	mm
Feed	f	mm/rev
Thermal conductivity	k	W/m K
Thermal diffusivity	α	m^2/s

Table 2.2
List of output parameters.

Parameters	Symbols	Units
Amplitude parameter	R_a	µm
Profile error parameter	P_t	µm

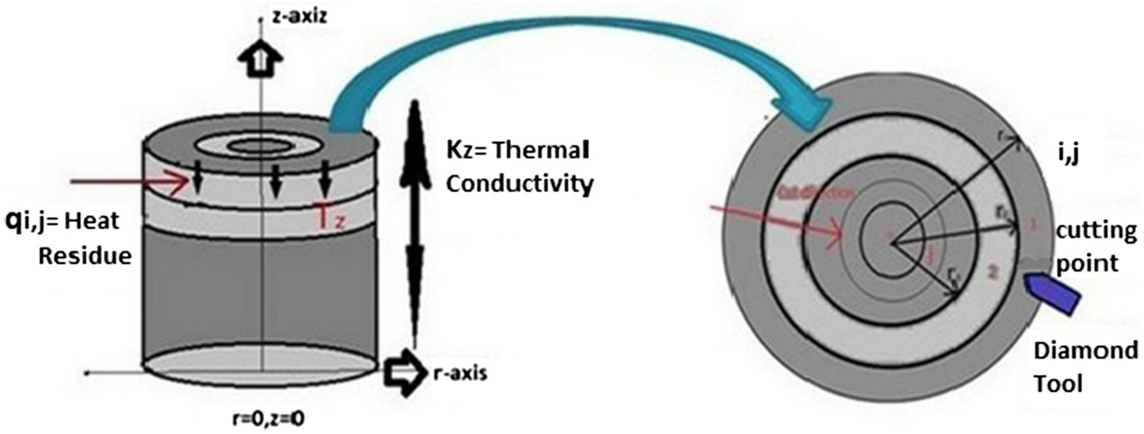

Fig. 2.1. Single Point Diamond Turning of Cylindrical Work piece.