Chapter 2
Factors Influencing Machined Surface Quality

Abstract Ultra-precision diamond turning aims at producing advanced components with not only a high-dimensional accuracy but also a good surface roughness and form accuracy. Since the achievable machining accuracy is governed by the accuracy of the relative motion between the cutting edge and the workpiece, the performance of machine tools is of prime importance. Optimum conditions of factors such as machine tools, cutting tools, workpiece materials, cutting variables, cutting fluid, working environment, etc., need to be chosen to achieve a good result in diamond turning. This chapter elaborates all these key factors influencing the machined surface finish.

2.1 Machine Tools

In diamond turning, as in any metal cutting operation, the geometry of the cutting tool and the characteristics of the machine tool determine the achievable form accuracy and surface finish. Improvements in surface finish and form accuracy in diamond turning have depended mainly upon advances in the design of the machine tool. In the early stages of development of ultra-precision cutting, hydrostatic bearings (either gas or fluid) for machine tool spindles played a dominating role through their ability to operate at submicron rotational accuracy. The development of air bearing spindles in the 1960s most significantly affected progress in ultra-precision machining (Krauskopf 1984; Ikawa et al. 1991). The introduction of machine tools with high stiffness, laser position feedback, hydrostatic slideways, materials with high thermal stability and techniques to characterise machine tool errors have also improved the diamond turning process. Along with the refinement of conventional mechanical elements in machine tools, new designs have arisen; traction or friction drives for linear motion and positioning with nanometric resolution (Bryan 1979; Donaldson and Patterson 1983; Shimokohbe et al. 1989), piezoelectric microfeed devices for nanometric tool positioning (Patterson and Magrab 1985) and the error compensation of hydrostatic bearings (Kanai 1983; Shimokohbe et al. 1989).

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2.2 Vibration in Machining

For decades, vibration has been recognised in the force measurement of real cutting processes such as conventional machining, high-speed machining (HSM) and ultra-precision machining. Based on these vibration signals, a branch of research work focused on the sources of nonlinearities and chatter generation, in which the single-degree-of-freedom (SDOF) and the multi-degree-of-freedom (MDOF) dynamic models of cutting system are employed. Such models are capable of determining the stability of the cutting system, i.e. the transition between stable cutting and chatter vibration with regard to the change of cutting parameters, such as depth of cut and spindle speed (Wiercigroch and Budak 2001). The starting points of such dynamic models are the nonlinearities in metal cutting systems.

Early work in such area was done by Wu (1986) to model the shear angle oscillation in dynamic orthogonal cutting based on the work-hardening slip line field theory. Wiercigroch and Budak (2001) proposed a closed-loop model of dynamic and thermodynamic interaction in the metal cutting system. They investigated the four mechanisms of machining chatter: variable friction, regenerative cutting, mode coupling, and the thermomechanics of chip formation on the variation of shear angles in the course of machining. Moon and Kalmar-Nagy (2001) reviewed the prediction of complex, unsteady and chaotic dynamics associated with the material cutting process through nonlinear dynamical models. The developed dynamic models of cutting systems have been widely applied in the prediction and monitoring of system stability (Liu et al. 2004b; Schmitz et al. 2001; Khraisheh et al. 1995; Chae et al. 2006; Berger et al. 1998). Complex mathematical tools have been employed to establish the nonlinear models, such as Receptance Coupling Substructure Analysis (RCSA) (Schmitz et al. 2001), and wavelet decomposition (Berger et al. 1998). Khraisheh et al. (1995) used wavelet transform with the traditional Gaussian wavelet, phase plane, power spectrum, Poincaré map and fractal dimensions to analyse the experimental data to ascertain system stability and cutting status. Vela-Martinez et al. (2008) used a multiple degree of freedom model for chatter prediction in turning. Abouelatta and Madl (2001) used a regression method to find a correlation between surface roughness and cutting vibrations in turning, while Baker and Rough (2002) used the finite element method (FEM) to include both cutting tool and workpiece flexibility in the analysis.

The correlation between vibration and surface roughness has become another focus of research. Abouelatta and Madl (2001) employed a mathematical tool to analyse the vibration and surface roughness data obtained in a series of cutting experiments. The proposed correlation model did not take account of the material removal mechanism in metal cutting process; therefore, no physical model was sought to explain the vibration effect on surface roughness of the machined surface. Cheung and Lee (2000a, b) proposed a surface roughness simulation model which considered the effect of process parameters, tool geometry and relative vibration between the tool and the workpiece. The authors assumed that the relative vibration between the tool and the workpiece was a steady simple harmonic motion with small amplitude and a low frequency. The same low frequency range has also been investigated by Sze et al. (2006), Lee et al. (2002), among others. Moreover, only the relative vibration in the infeed cutting direction was considered which was adopted from the assumptions made by Takasu et al. (1985) and Bispink (1992), while the influences of self-excited chatter and tool wear were neglected. Their investigated vibration frequency range belonged to a very low part of the entire spectrum. Those frequencies above 10 kHz were neglected in both the experimental work (Liu et al. 2004b) and the simulation models (Takasu et al. 1985). In addition to the common understanding that the relative vibration in the infeed (thrust force) cutting direction (Cheung and Lee 2000b) was regarded as a predominant factor in the generation of good surface finish, the effect of relative vibration in the cutting direction also significantly contributes to surface generation which was featured by high-frequency tool-tip vibration (HFTTV) (Wang et al. 2010b).

In light of the fact that materials behave differently in material removal due to their mechanical and thermal properties, work material also plays a critical role in the study of machining processes. Material swelling and recovery have attracted a lot of attention due to its influence on surface roughness in the micro-cutting process. To et al. (2001) clarified the concept of material swelling, and elaborated on the influence of material swelling based on the measured surface profile in diamond turning of single crystal materials. The plastically deformed material underwent an elastic recovery behind the cutting edge (on the clearance face of the cutting tools) to form the freshly cut surface. Liu et al. (2004a) reviewed such elastoplastic deformation in the micromachining process, and proposed two mechanisms—chip removal and ploughing/rubbing. The ploughing effect, which is induced by the cutting edge radius and tool wear, is of great importance in the analysis of cutting mechanism and chip formation. Guo and Chou (2004) studied the ploughing force based on the data of cutting forces acquired in the metal cutting experiments with a large uncut chip thickness ranging from 0.03 to 0.2 mm, and at very slow (0.073 m/s) and medium (1 m/s) cutting speeds. The induced elasticity and the swelling/recovery effects in work materials were pronounced, so that the ploughing force could be clearly observed in their experiments. In the research by Shawky and Elbestawi (1997), the ploughing force was regarded as the source of process damping embedded in their dynamic model of tool vibration in the conventional turning process. In single point diamond turning (SPDT), a large strain rate and a small depth of cut are guaranteed by the accuracy of ultra-precision machine tools, which in turn results in the ploughing effect being less pronounced in SPDT than that in conventional machining.

2.3 Cutting Conditions

It is well known that the machined surface finish and form accuracy are produced as a result of the transfer of the tool profile onto a workpiece; hence, the level of the roughness is governed by the controllability of the relative motion between the cutting tool and workpiece. The state and dynamic behaviour of an ultra-precision machine is a dominant parameter for attaining a high surface quality (Weck and Hartel 1986; Weck and Modemann 1987, 1988; Takasu et al. 1985). The machined surface roughness of non-ferrous metals using diamond tools was found to be larger than the theoretical geometrical surface roughness derived from the tool geometry and the feed rate (Kobayshi 1978). A reason for this phenomenon was that the steady, small amplitude vibration between the cutting tool and the workpiece surface caused the deterioration of the machined surface (Takasu et al. 1985). In many practical setups for ultra-precision machining, a few tens of nm peak-to-valley (P–V) roughness might be a practically achievable limit due to the combined effects of a variety of error sources.

Proper selection of cutting variables not only increases the manufacturing efficiency but also influences the surface roughness of the workpiece. Optimum conditions such as cutting speed, feed rate and depth of cut are essential in order to achieve a good surface finish. In general, the surface roughness of a workpiece is of small value when the cutting speed is either very high or low. If the cutting speed is within a range that produces a built-up edge (BUE), the machined surface roughness is always comparatively large. Machined surface roughness is closely related to an even rotational speed of every machine tool at each designated speed. It is suggested that the best way for precision cutting is to select the optimum cutting speed in an assumed range by testing the roughness obtained for every rotational speed of the spindle. As a general rule, the smaller the feed rate, the smaller the machined surface roughness. However, in precision and ultra-precision cutting, whether a diamond tool or carbide tool is used, the machined surface roughness will again increase if the feed rate is smaller than a certain critical value. This is because at a too slow feed rate the feeding mechanism of the machine tool is apt to produce stick-slip motion. Therefore, there is an optimum value for feed, and this can be determined individually by experimental methods (Zhang 1986). With the increase of depth of cut, the contact length of the cutting edge with the workpiece being cut increases, thus increasing the cutting force. The temperature in the cutting zone shows little change, because the dissipation of heat from the cutting edge is improved with an increase in depth of cut. As the depth of cut decreases to a certain value, the machined surface roughness starts to increase. This is because the metal layer being cut becomes too thin to be cut off; the squeezing action on the workpiece by the rounded portion of the cutting edge (tool edge radius) is intensified, thus increasing the friction, deformation volume, and the machined surface roughness accordingly. The fine depths of cut (submicrometre), finite edge radius of the tool, low ratio of depth of cut to the edge radius, quality of cutting edge, and even minute amounts of wear on the clearance face of the tool add to the complexity of the ultra-precision machining process.

Arcona (1996) summarised the studies on the tool force, chip formation, and surface finish in diamond turning. The measured tool force contains useful information on cutting parameters and tool condition which influences the finish of the machined surface. An empirical tool force model was developed by Arcona and

Dow (1998) for tool force feedback. The important material-related data such as the coefficient of friction and shear angle have to be determined experimentally and a truly predictive theory was not yet attempted in these early works.

2.4 Single Point Diamond Tools

Cutting tools directly affect machining quality and manufacturing efficiency. The sharpness of a cutting edge is a primary factor which determines the minimum depth of cut. The sharper the cutting edge, the smaller the minimum depth of cut and hence lower surface roughness (Ikawa et al. 1987; Zhang 1986). High-quality cutting tools that can produce very fine chips are essential for machining components to a high-dimensional accuracy and surface quality. Natural single point diamond tools are exclusively used in micro-cutting for their nanometric edge sharpness, form reproducibility and wear resistance. They are recognised to be ideal ultra-precision cutting tools. The design, manufacturing and proper use of diamond tools are among the key elements of the single point diamond turning (SPDT) technique.

The cutting tool in ultra-precision machining systems must have the capability of stable cutting in the submicron/nanometre region, e.g. in diamond cutting aluminium substrates for X-ray telescope optics. The surface finish and form accuracy are influenced by the tool sharpness and its stability. Small increases in the temperature of the tool shank due to tool wear and the associated increase in the specific cutting energy affect the machining accuracy (Moriwaki et al. 1990). Tool sharpness has a further effect on diamond-turned surfaces through the minimum chip thickness, or the depth of cut at which no chip forms due to the finite edge radius of the tool. The rounded cutting edge radius of diamond tools may be as small as 0.01 μm, but cutting tools made of other materials cannot be sharpened to such an extent due to their structural restriction, and their cutting edge roughness is also limited for the same reason. Therefore, the performance of other tool materials on the machined surface finish cannot be as good as a diamond tool. There may be a physical limitation in the radius of the cutting edge or the cutting edge sharpness. Based on the energy balance between the surface and elastic strain energies at the cutting edge, the critical edge radius of diamond tools was calculated to be about 2 nm. From these observations, it is considered that the cutting edge of diamond tools can be polished to a radius less than a few nanometres, and the possible minimum depth of cut can be of the same order.

The profile of a machined surface is basically composed of the repetition of the tool profile transferred in the plane normal to the cutting direction; therefore, the geometrical accuracy of the cutting edge and its stability have a great influence on the machined surface roughness. The process of profile transfer will be disturbed due to the complicated and unidentified interfacial phenomena between the cutting edges and workpiece materials, such as interfacial affinity. As diamond has little affinity for a variety of materials, a diamond cutting edge is considered to have high transfer fidelity, which is the ability to transfer the profile of a cutting edge to a work surface.

Even when machining soft materials such as non-ferrous metal, the wear on the cutting edge grows substantially as the cutting length increases (Ko and Cho 1992; Taminiau and Dautzenberg 1991; Keen 1971; Hara 1988). It is generally recognised that the tool wear has a great influence on the cutting force and the quality of the machined surface. A less sharp tool will lead to higher cutting forces, and hence more power dissipation in the cutting process and more heat development (Lucca et al. 1990; Komanduri and Shaw 1975; 1976; Evans 1991). Cutting with a blunt tool therefore decreases the machining accuracy.

Ultra-precision diamond tools, which are used to produce high-precision optical components, should be not only sharp but also highly accurate in regard to cutting edge geometry. Accurate measurement of the cutting edge radius is needed in the manufacture and assessment of diamond tools. Edge structure is said to be preferably evaluated by an SEM (Scanning Electron Microscope) in terms both of topography and in establishing the cutting edge radius down to a few tens of nm (Asai et al. 1990). The profile accuracy of the cutting edge also has a great influence on the machine surface quality. With natural and synthetic single crystal diamonds, diamond tools are manufactured with various geometries for different applications like diffractive tools, milling tools, half-radius tools, etc. (Fig. 2.1)

2.5 Environmental Conditions

The achievable surface finish and form accuracy are dependent upon the stability of the machining environment. Any minute changes in the machining environment may cause a considerable variation in the machining accuracy. Variations in the temperature and delivery of the coolant can lead to form errors. The surface can be degraded through any motion that affects the relative position of the tool and workpiece. The sources of such disturbances can be acoustic vibrations, electrical noise, spindle runout, slideway vibration or inhomogeneity of the workpiece

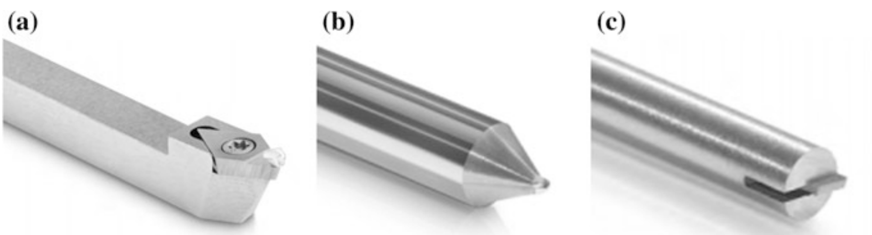

Fig. 2.1 Typical diamond tools for **(a)** diamond turning (lens tool), (**b**) ball end milling, and **(c)** toric milling tool. *Courtesy* Contour Fine Tooling Company

material that produces high-frequency variations in the cutting forces and tool vibration. The stiffness of the machine tool also influences the characteristics of the machine surface. The currently available ultra-precision diamond turning machines are usually installed in large air-conditioned and vibration-isolated rooms to control the vibration, temperature, moisture and also cleanliness. A completely stable diamond turning environment is often difficult and costly to maintain. In an extended period of time required for a specific manufacturing operation, thermal deformation of the whole ultraprecision cutting system will have an adverse effect on the achievable machining accuracy (Moriwaki 1990).

In the study of the changing environment in the cutting process, power spectrum analysis is becoming a powerful tool to identify degenerating manufacturing conditions either due to process faults (such as tool wear) or machine tool problems (such as vibration, slideway error, etc.) (Whitehouse 1994). From the spectral information below the feed frequency, a tremendous amount of information about the process and machine tool is available, such as bearing chatter, slideway error and vibration external to the machine. Some of the longer wavelengths occurring in the subharmonic region of the power spectrum are illustrated in Fig. 2.2.

2.6 Workpiece Materials

The material removal process is not governed solely by the cutting tool but also critically by the material of the workpiece. The proper selection of work materials gives acceptable machinability which results in the desired nanometric surface finish. At present, typical materials that can be successfully machined are copper alloys, aluminium alloys, nickel alloys, silver, gold, electroless nickel, PMMA plastics and some of the infrared materials such as silicon and germanium. Ferrous materials such as steels cannot be diamond turned due to the rapid tool wear caused by the chemical affinity between the diamond tool and workpiece. Silicon and germanium are brittle materials and machining has to be done in the ductile regime, i.e. below a critical depth of cut to avoid crack propagation.

The crystallography of the workpiece substrate has also drawn much interest in order to optimise the surface finish (Koenig and Spermath 1991; Lee and Zhou 1993). In general, a material with fine grain size is preferred to eliminate the grain boundary effect. An amorphous material is most desirable as it is considered to possess a high degree of homogeneity and can give a superfinish with diamond turning. Single crystals and polycrystals, which exhibit strong crystallographic textures (i.e. highly directional properties), are to be avoided in coaxial machining processes such as turning operations. But for non-coaxial machining processes such as fly cutting, the best crystallographic cutting direction should be selected (e.g. the cutting of KDP single crystals used in laser optics). Despite the importance of the effect of material crystallography and anisotropy on the diamond turning process, there is still no scientific model or quantitative theory to predict the optimum crystallography cutting direction and our knowledge in this area is still largely empirical.

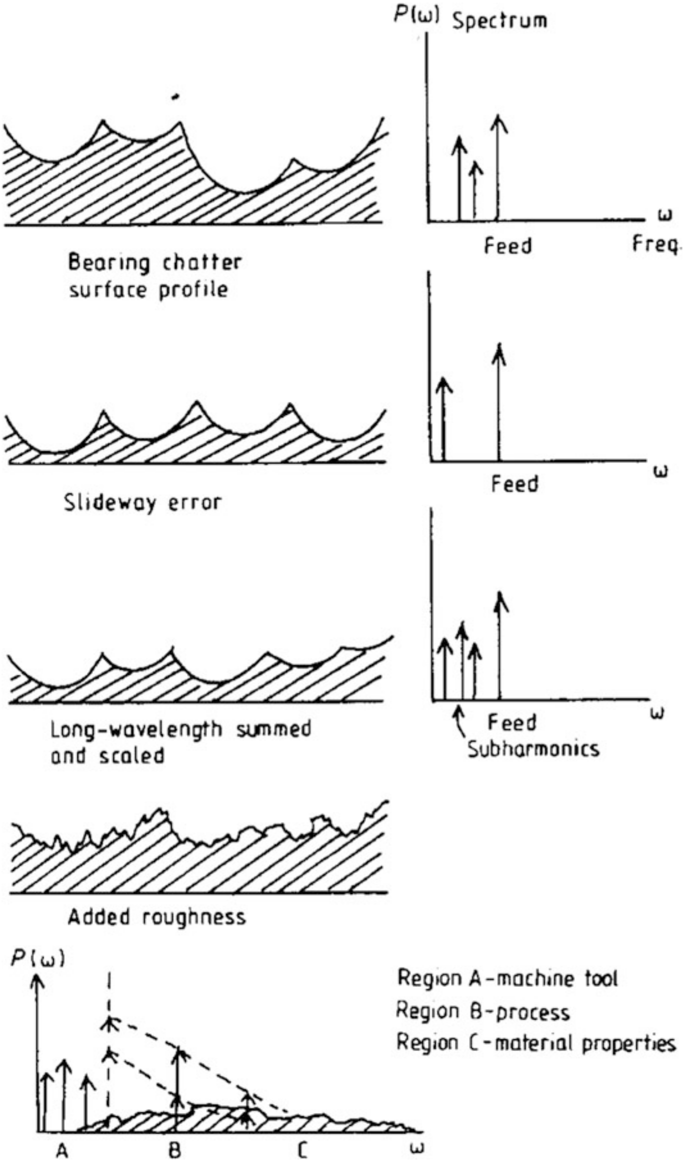

Fig. 2.2 Long-wavelength effect and total signature. *A*, subharmonic machine tool; *B*, harmonic tool wear; *C*, high-frequency material process parameters. From Whitehouse (1994)

2.7 Deformation Behaviour of Materials in Machining

The chip removal process in diamond turning can be classified into two types. One is due to plastic deformation on the dislocation slip planes and the other is due to cleavage fracture on the cleavage plane. Ductile region machining is possible in brittle materials at a critical depth of cut where the energy in propagating cracks equals the energy of plastic deformation. A better understanding of the basic plastic behaviour at the micrometre and submicrometre underformed chip thickness is vital for understanding the formation of the chip model at this level of cut. The plastic behaviour and properties that were thought important in influencing the metal cutting process have been summarised by Shaw (1984). A mechanism for large strain plastic flow was proposed by Shaw et al. (1953) which was considered as an add-on to dislocation theory (Taylor 1938). Crystal imperfections were reckoned to be reasons for the inhomogeneous strain. In metal cutting, the shear planes were thought to be very closely spaced corresponding to the closeness of spacing of the "weak spots" in the metal. Figure 2.3 shows a specimen with a uniform distribution of weak points with a spacing of *a*. The amount of slip on a given shear plane is determined by the shear strain (γ):

$$[X = \frac{a^2 \sin\phi}{t}\gamma] \tag{2.1}$$

The relationship in Eq. (2.1) was then used by Shaw to estimate the shear stress on shear plane with $[(\gamma \sin\theta)/2t]$. The model, although grossly oversimplified, served to explain the change in specific cutting energy with undeformed chip thickness (t) and the backs of thin chips showing inhomogeneous strain. The shear front-lamellar structure in metal cutting chips has been studied by Black (1971, 1972) in detail using transmission electron microscopy. The shear plane was thought to be a dislocated glide plane (i.e. {111} <110> in FCC metals). When the primary slip system does not coincide with the direction of maximum strain,

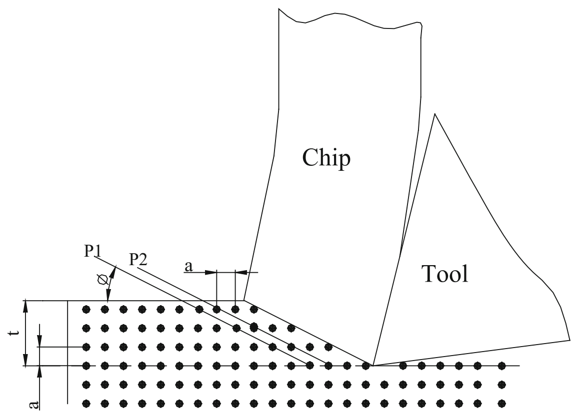

Fig. 2.3 Specimen with uniform distribution of points of stress concentration (weak points). After Shaw (1950)

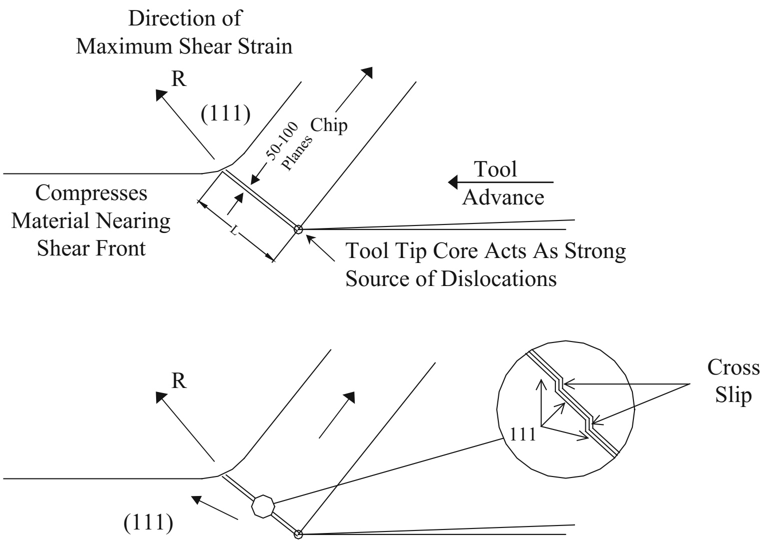

Fig. 2.4 The effect of cross slipping of the dislocations form one parallel (111) plane to another when the direction of maximum strain does no coincide well with the {111} plane. From Black (1971)

cross-slipping of the dislocation from one parallel (111) plane to another will then occur (Fig. 2.4). Most researchers since the 70s have thought that (111) planes played a dominant role in the formation of the shear plane in metal cutting, although it was also recognised by Williams and Gare (1977) that other planes with a less favourable orientation also serve as shear planes. The possibility of a simple model to predict the shear angle was ruled out by Shaw (1984).

Although the crystallographic aspect of the deformation process was well recognised, it was not until the widespread use of ultra-precision diamond turning technology that the importance of the material imperfection and crystal plasticity emerged once again. The role of imperfections in diamond turning was discussed by Hashimoto (1989). Figure 2.5 shows the imperfections in materials that influence micromachining.

As the cutting proceeds, the material will be plastically deformed, triggered by microscopic defects such as precipitates, the generation of dislocations, voids, etc. It can be seen from Fig. 2.5 that the cutting process leads to a multiplication of defects, a considerable number of which will remain in the subsurface layer and will thus influence the integrity of the surface (Iwata and Ueda 1974, 1976; Brown and Luong 1976; LeMaitre and Bizeul 1974). These defects include not only dislocations but also fine cracks, cavities, delamination and cracked particles which may have lost their binding power to the base material.

The crystallographic orientation of the substrate material being cut exerts a great influence on the micromachining process (Koenig and Spenrath 1991; Sato et al. 1978, 1983; Stadler et al. 1987; Ohmori and Takada 1982). As the depth of cut in

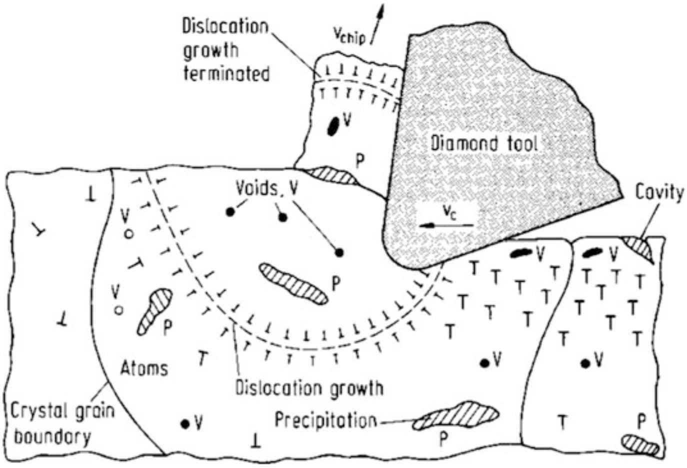

Fig. 2.5 Imperfections in materials that influence micromachining. From Hashimoto (1989)

ultra-precision cutting is usually less than the average grain size of a polycrystalline aggregate, cutting is generally performed within a grain. The polycrystalline workpiece material, which may be considered to be an isotropic and homogeneous continuum in conventional analysis, must be treated as a series of single crystals which usually have quite random orientations and anisotropic properties. Therefore, the machined surface quality and the mechanism of chip formation depend very much on the crystallographic orientation of the material being cut (Whitehouse 1994). The effect of crystallographic orientation on the surface quality cannot be avoided in the cutting of polycrystalline materials.

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