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Investigation of the Effects of Machining Parameters and Air Blowing on Surface Topography in High Speed End Milling of Silicon

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Abstract. Machining of silicon is an expensive affair because its inherent brittleness leads to subsurface crack generation. Research endeavours have therefore focused on ductile mode machining of silicon to obtain crack free machined surfaces with roughness as low as 0.22 μm or even below, hence eliminating the need for subsequent polishing/grinding operations. However, most of these research works utilized expensive ultraprecision machines and tools. This research aimed at determining the viability of using conventional milling machines with diamond coated tools, high speed attachments, and air blowing mechanisms in order to achieve ductile regime machining of silicon. Spindle speed, depth of cut, and feed rate, ranges: 60,000 to 80,000 rpm, 10 to 20 μm, and 5 to 15 mm/min respectively, were considered as the independent machining parameters. Compressed air at 0.35 MPa was also provided to prevent chip deposition on the finished surfaces. The resultant surfaces were analysed using Optical and Scanning Electron Microscopes. Then, the influence of each machining parameter on surface roughness was investigated. From the analyses it was concluded that all three machining parameters and air blowing had significant influence on the surface topography and integrity of silicon.

Introduction

Silicon is perennially used in the semiconductor and opto-electronics industries for its electrical properties. Such optical surfaces need to be free of damage or impurities [1]. But, the brittle nature of silicon leads to subsurface damage and crack propagation during most machining processes. Hence, many research works have focused on cutting parameters, surface roughness, chip formation, etc. that can lead to or indicate ductile mode machining of silicon. Sreejith [2] claimed that ductile machining of brittle materials was possible under controlled machining conditions. This was supported by Yan et al. [3] who stated that silicon was normally brittle but could be deformed plastically, yielding ductile chips and streaks, under the influence of high hydrostatic pressure. Siva et al. [4] concluded that ductile machining depended on tool geometry (large negative rake angle), process conditions, and workpiece material properties. Thimmaiah et al. [5] demonstrated that low feed, small tool tip radius, and high cutting speed, including certain pressure and temperature conditions, enabled ductile mode machining of silicon nitride. Rusnaldy et al. [6] achieved ductile mode machining of single crystal silicon using micro end milling. They used very small feed per tooth and diamond-coated tools with edge radius of 9 mm. Dali et al. [7] attained ductile mode machining in CNC end milling of silicon using diamond coated tools by using a combination of high speed spindle (60,000 to 80,000 rpm), low axial depth of cut (10 μm), and low feed (5 mm/min). They produced good surface finish (0.22 μm) and ductile streaks but, there was significant chip deposition on the machined silicon surface.

Also, most of these researchers employed expensive techniques, costly machineries, or unconventional approaches to obtain ductile mode cutting. This research utilized a simple conventional mill with a high speed attachment to end mill silicon. It focused on investigating the influence of three machining parameters (spindle speed, depth of cut, and feed) along with compressed air flow on the machined surface quality. The resultant surfaces were analysed using Optical and Scanning Electron Microscopes. The results showed that conventional milling could be used economically to machine silicon with diamond coated tools and air blowing, in the ductile regime, and generate crack free and mirror finished surfaces. The current work aims at determining the influence of cutting parameters and airblowing on surface roughness in machining of Si.

Experimental Details

Machining was conducted on a Universal Milling Machine Deckel FP4M with a 4 kW motor and maximum spindle speed of 2500 rpm. A NSK Planet 850 was then attached to the spindle and connected to the air supply via the Nakanishi AL-0201 Air Line Kit, which controlled the high speed attachment by regulating the compressed air flow. The set-up consisted of another air supply for the blower and air gun. Fig. 1 shows the experimental set for end milling of single crystal silicon wafer with a diamond coated end mill. Diamond coated tools of diameter 2 mm were used in the experiments. Spindle speed, depth of cut, and feed rate were chosen as the machining parameters. These parameters were varied within fixed ranges (60,000-80,000 rpm, 10-20 µm, and 6-18 mm/min respectively) and their individual effect on surface roughness (µm) and surface integrity was observed. The air pressure was kept constant at 0.35 MPa.

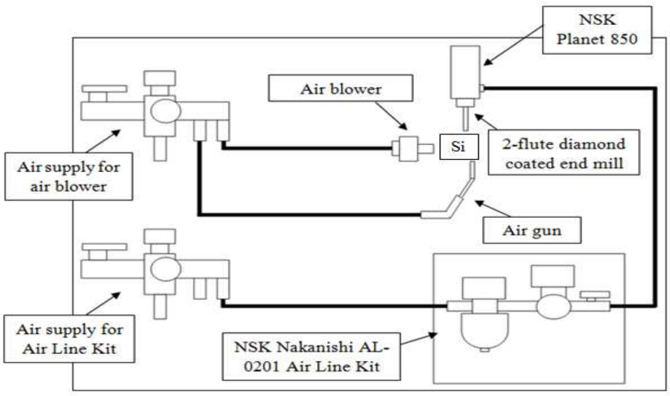

Fig. 1: Experimental set-up with high speed attachment and air blowing system

Results and Discussions

Fig. 2(a-b) demonstrates the effect of air blower on surface integrity in silicon end milling. It was observed that the application of air blower (Fig. 2b) led to a surface with lesser or no chip deposition compared to the surface obtained, under similar machining conditions, by Dali et al. [7] (Fig. 2a), where no air blower was used.

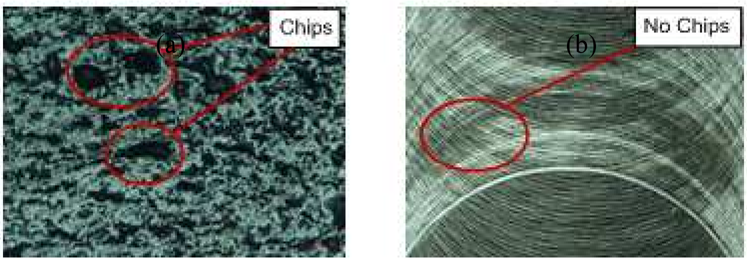

Fig. 2: Optical microscope images of silicon surfaces (20X magnification): (a) CNC milling (v = 60,000 rpm, DOC = 15 µm, f = 10 mm/min) (b) Conventional milling (v = 60,000 rpm, DOC = 10 µm, f = 5 mm/min, P = 0.35 MPa).

Fig. 3 illustrates the optical and SEM images for two silicon surfaces obtained using two different spinde speeds while the other machining parameters were kept constrant. It was noticed that the higher spindle speed of 80,000 rpm (Fig. 3(c-d)) produced larger ductile streaks and almost no chip deposition on the silicon surface compared to that at the 60,000 rpm (Fig. 3(a-b)) case.

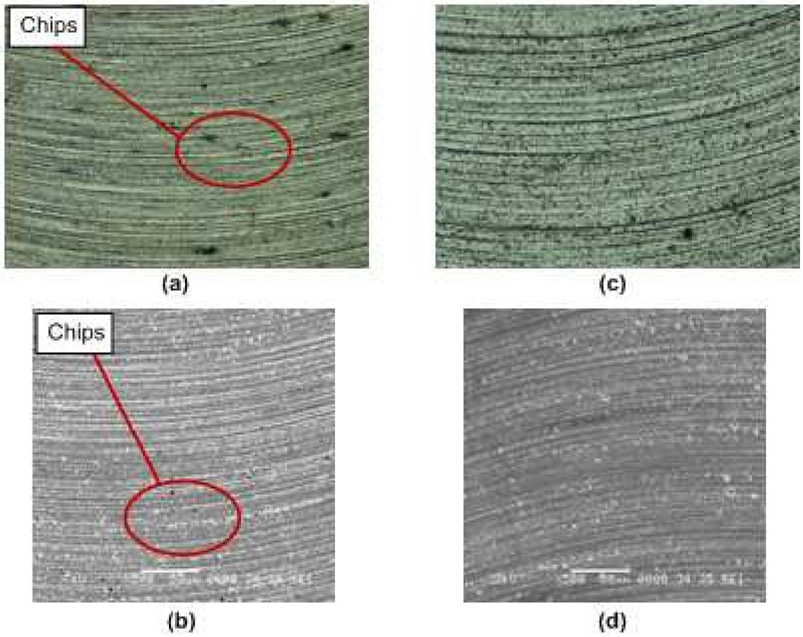

Fig. 3: Images of machined silicon surfaces (d = 15 µm, f = 12 mm/min, P = 0.35 MPa): (a) Optical image (v = 60,000 rpm), (b) SEM image (v = 60,000 rpm), (c) Optical image (v = 80,000 rpm), and (d) SEM image (v = 80,000 rpm).

Fig. 4 illustrates the optical and SEM images for another two silicon surfaces obtained using different depth of cut while keeping the other machining parameters constrant. It was noted that the higher DOC of 20 µm (Fig. 4 c-d) produced more chip deposition as well as fracture on the silicon surface compared to the DOC of 10 µm (Fig. 4 a-b).

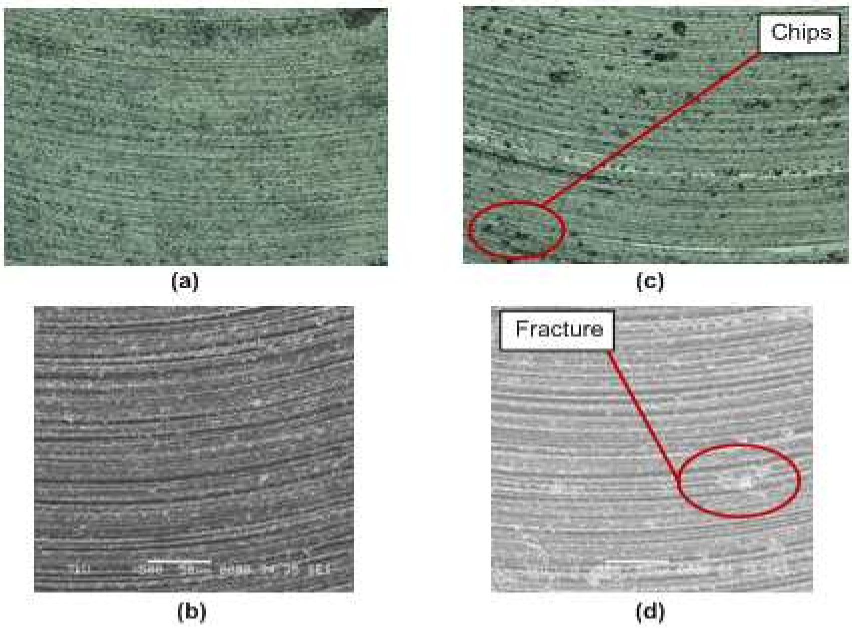

Fig. 4: Images of machined silicon surfaces (v = 70,000 rpm, f = 12 mm/min, P = 0.35 MPa): (a) Optical (d = 10 µm), (b) SEM image (d = 10 µm), (c) Optical image (d = 20 µm), and (d) SEM image (d = 20 µm).

Fig. 5 illustrates the optical and SEM images for another set of two silicon surfaces obtained using different feed while keeping the other machining parameters constrant. It was noted that at the lower feed rate of 6 mm/min (Fig. 5 a-b) there were higher amount of ductile streaks compared to that at the higher feed rate of 18 mm/min (Fig. 5 c-d).

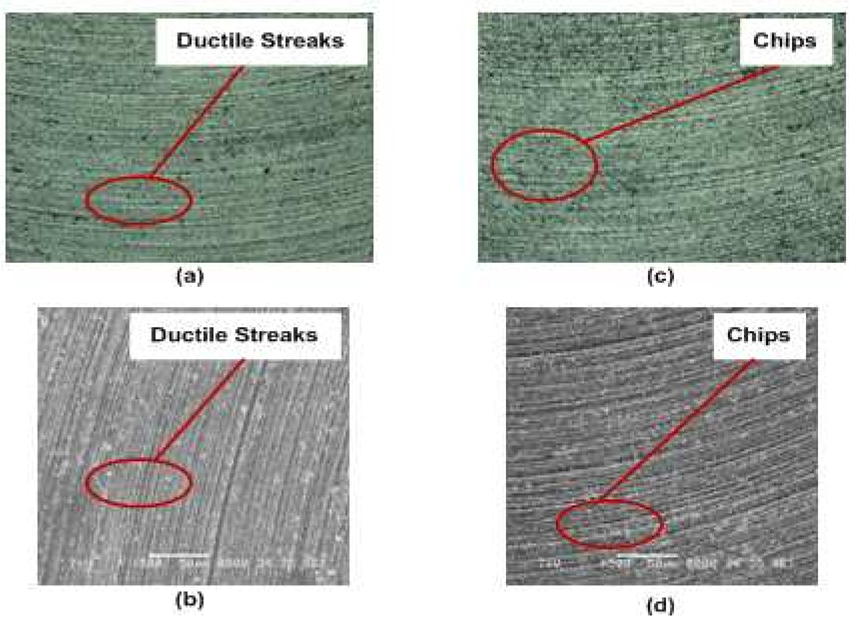

Fig. 5: Images of machined silicon surfaces (v = 70,000 rpm, d = 15 µm, P = 0.35 MPa): (a) Optical image (f = 6 mm/min), (b) SEM image (f = 6 mm/min), (c) Optical image (f = 18 mm/min), and (d) SEM image (f = 18 mm/min).

Conclusions

The analyses showed that conventional milling machine with high speed attachment, diamond coated tools, and air blower could be used to machine single crystal silicon in the ductile regime to produce machined surfaces with good surface topography. Also, it can be concluded (from the ductile streaks and lower chip deposition) that the combination of higher spindle speed, lower depth of cut, and lower feed rate enables ductile mode machining.

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