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Research Paper

Experimental Study of the Effect of Different Spindle Speeds and Feed Rates in Dry Machining on a Brittle Material

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Abstract

Material removal modes in brittle material machining are divided into two categories: ductile modes and brittle modes. Many believe that there is a clear difference between energy costs in these two cases. Spindle speed (SS) and feed rate are the effective parameters in the material machining process. It is tried to conduct experimental studies on the effect of low spindle speeds and high feed rates on the turning of brittle material in this paper. Also, the tool geometry is an important factor in turning brittle materials; so the rake angle of the turning tool was changed for dry machining of a single-crystal workpiece. The results show that the surface roughness decreases by increasing the spindle speed and decreasing the feed rate, which reduces the surface damage significantly. The purpose of this experimental study is to investigate the effect of rotational speed and feed rate on surface roughness and surface texture in the lathe process of the workpiece using the ductile mode of machining and changes in the parameters of this process to control the configuration and dimensions of microstructures (micro craters, Surface pits, and micro-cracks).

Keywords

Machining, Spindle Speed, Feed Rate, Rake Angle, Surface Damage

1. Introduction

Reducing surface damage on machining of the workpiece in the shortest time to receive the final machining plays an essential role in the final surface quality of the product and reducing manufacturing costs. Due to the increasing demand for higher precision components, surface roughness and surface texture of a machined part are essential factors in the production process.

The material removal process in the machining of ductile materials occurs by plastic deformation which often creates a smooth surface without damage. Brittle regime machining (BRM) is characterized by the removal of material through the formation and diffusion of micro-cracks, micro craters, and surface pits at the workpiece surface. Therefore, brittle materials such as germanium, Silicon, Glass, and industrial ceramics can be a machine in ductile mode by changing the machining parameters and tool geometry.

Researchers have considered the tool feed rate as an effective operational parameter on brittle material machining and have stated that changes in the feed cause a position change in the critical chip thickness along with the tool nose [1]. Due to the complexity of interplaying between tool geometry, machining parameters, and material response, a significant fraction of material removal occurs by fracture even when ductile regime conditions are achieved[1]. The diamond turning process was initially developed for producing optical parts from non-ferrous metals such as aluminum and copper, which at the same time required the growth of infrared optical components (Ge and Si) to adapt the relevant technology for machining brittle materials [2].

On the contrary of intuition, the fact is that very brittle materials like Germanium and Silicon can machine without introducing fracture damage into the finished surface, while there is an extensive background on machining mechanisms for ductile metals [3]. Bifano et al. conducted an analytical and experimental study in 1991 on the feed rate required for Ductile-Regime grinding on brittle materials [4].

Blackley and Scattergood [5] conducted experimental study on the topography of chips in ductile mode machining of an 80 mm diameter germanium piece by single-edged machining through making cuts in the surface of the germanium piece. They observed a ductile to a brittle transition point in the topography of germanium chips. Morris et al. [6] investigated the ductile region by diamond turning on Germanium semiconductors. Leung et al. [7] investigated the direct machining of single-crystal Silicon in the ductile regime. They have stated that to produce a high-quality surface, the machining process needs to be ductile mode, and the chip thickness must be less than the critical value, which depends on the machining conditions, the parameters of the diamond tool, and the properties of the material.

Fang [8] studied the machinability of several brittle materials about the results of indentation, and he stated that plastic deformation is the predominant mechanism in material removal; when the shear stress in the direction of slip (more than the inherent critical value relative to the workpiece material) increases before Cleavage. Fang and Venkatesh [9] conducted experimental studies on the cutting of diamonds on Silicon with nanometric finish using different diamond tools at two negative rake angles and different cutting speeds. Zhong [10] investigated ductile mode machining or partial ducting on brittle materials such as silicon, glass, and some advanced ceramics.

Yan et al. [11] performed a research to expand the process of creating a microgroove on germanium monocrystal in ductile mode to make infrared Fresnel lenses. Yan et al. [12] conducted experimental research with high-precision machining properties on germanium polycrystals as lens substrates instead of single crystals. Cai et al. [13] studied the mechanism of groove abrasion of silicon monocrystals in Nano cutting ductile mode by diamond tools by using simulation of molecular dynamics. Özel et al. [14] considered the effects of cutting edge geometry, workpiece stiffness, feed rate, and cutting speed on surface roughness and forces in AISI H13 hardened steel turning. The effect of cutting edge geometry on the surface roughness was significant.

Tanaka et al. [15] reviewed a guideline for ductile mode machining based on the analysis of single-crystal silicon deformation by molecular dynamics simulations. The results show that increasing the temperature in the chip formation region can soften the material, and also the hydrostatic pressure in the chip formation region can lead to the transfer of the material phase from single crystal to amorphous. Pawase et al. [16] studied spherical germanium lenses with diamond tools in the precise form and desired dimensions; Also, the effect of machining parameters (effect of feed and cutting depth on surface roughness) and tool conditions on the quality of the produced lens has been studied.

Kovalchenko and Milman [17] analyzed the mechanism of self-healing cracks in ductile mode cutting and also the anisotropy effect of silicon material on the mechanism of chip formation. They have shown that the self-healing property of microcracks, microfractures, and micro-chips by filling the defects, due to the Silicon metallic phase can achieve easily in the partial ductile mode. Zhang et al. [18] reviewed surface roughness production in ultra-precision machining. Gupta et al. [19] examined the roughness of the machined surface using a single-point diamond tool at a negative rake angle on a single-crystal germanium substrate. Bai et al. [20] studied experimentally on ductile mode machining of silicon monocrystals by polycrystalline diamond tools, then they concluded that the cross-sectional shape and amplitude structure are directly related to the surface morphology and the cut surface during the single crystal micromachining process of Silicon, and also, creating a continuous and stable cross-force strengthens ductile mode machining.

Feifei et al. [21] studied analytically the effects of improvement and lateral flow on surface production, as well as the static region and phase transition in nano-cutting of single-crystalline Silicon. They have stated that the lateral flow of the material increases the roughness of the produced surface. Safavipour and Farahnakian [22] have conducted an experimental study of germanium dry machining with various rake angles and different feed rates of the tool. They have performed several experiments with different rake angles and feed rates on germanium material by keeping the cutting depth and spindle speed constant.

The aim of the present work is an experimental study of the turning of germanium material in dry machining by changing the tool rake angle as a constant parameter with high feed rates, low spindle speeds, and its effect on surface roughness and surface damage.

2. Experimental

2.1 Testing equipment and procedures

Workpiece material and dimensions

Ge is a brittle material and is used as an optical material for producing lenses and substrates in IR technology in the form of single-crystal or polycrystal. In this experiment, A germanium optical piece with a diameter of 32 mm and a thickness of 2.5 mm was used, Ge piece embedded on an aluminum fixture made according to Figure1 using a heat-softened adhesive.

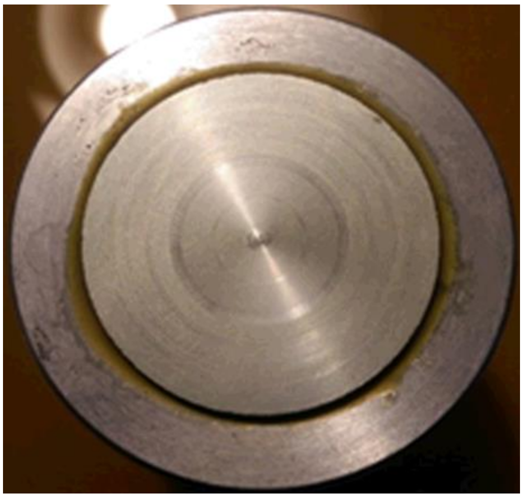

Figure 1. Sample of machined germanium and embedded in the relevant fixture

Cutting tool material and dimensions

Making the tools used in diamond turning is by using different types of diamonds. The cutting tool used in the desired tests of insert type, lathe with polycrystalline diamond, and nose radius of 0.47 mm. Natural or synthetic single-crystal and polycrystalline diamond tools are used in many machining applications due to their strength and abrasion resistance, depending on the type of workpiece and the relevant machining parameters.

The experiments were performed by changing the rake angle of the tool in a negative direction with a clearance angle of approximately 14.5 degrees for all tests according to Figure 2a, and Table3 with different rotational speeds and feed rates.

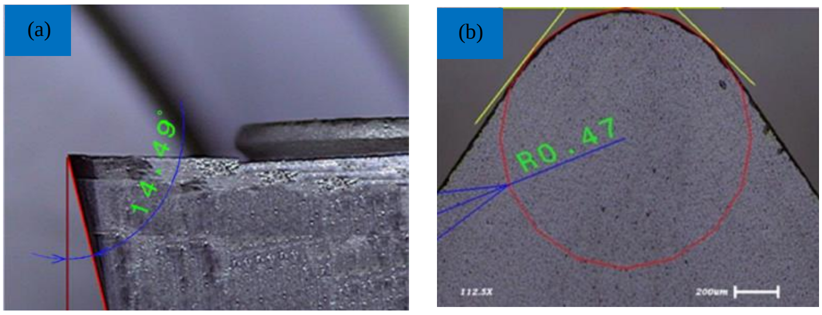

Figure 2. Image of the tool used in the experimental experiment by the VMS machine. a) Clearance angle of the tool, b) Tool nose radius

To measure the radius of the tool nose, its image was obtained by the optical microscope through Video Measurement System imported in Catia software and three lines drew tangent to the edges of the tool as shown in Figure 2b; A tangential circle drew on these lines using the Tri tangent circle command. The actual radius of the tool was measured precisely from the surface at a magnification of 112.5X.

Setup of experimental experiments

Turning of germanium part on NC lathe model TN50D and tool holder made according to Figure 3 in 9 tests to measure the adequate spindle speeds, and also the effect of different feed rates on the surface roughness and texture was performed. Cutting this optical piece in the dry machining facilitates the collection of the obtained chips and their recycling.

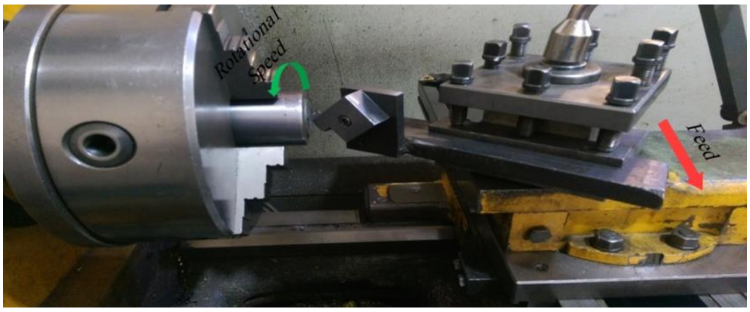

Figure 3. NC lathe and tool holder used in the experimental test

2.2 Experimental test planning

The tests performed in this experimental study have fixed and variable parameters, which fixed parameters, are shown in Table 1. The experiment was performed in Taguchi form based on tables No.2 and No.3 in 9 rows of tests.

Table 1. Specifications of fixed parameters in machining tests

Characteristics	Chosen
Cutting depth (µm)	50
Nose radius (µm)	470
Rake angle (degree)	45
Clearance angle (degree)	14.5
Kapa angle (degree)	~16
Workpiece material	Ge

Table 2. Parameters and test levels in the planned design

Factors	First level	Second level	Third level
Spindle speeds(RPM)	500	750	1000
Feed rates(µm/rev)	50	80	110

Table3: Planned design using Taguchi test

Run	SS(RPM)	Feed rate (µm/rev)
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

3. Results and Discussion

3.1 Surface texture

Machined surfaces according to Tables 2 and 3 in 9 test rows investigated to evaluate the spindle speed and proper feed rate at which the machined surfaces have a healthier surface texture in terms of microcracks, bumps, micro craters, and surface pits; the images of each machining level presented in Figure 4.

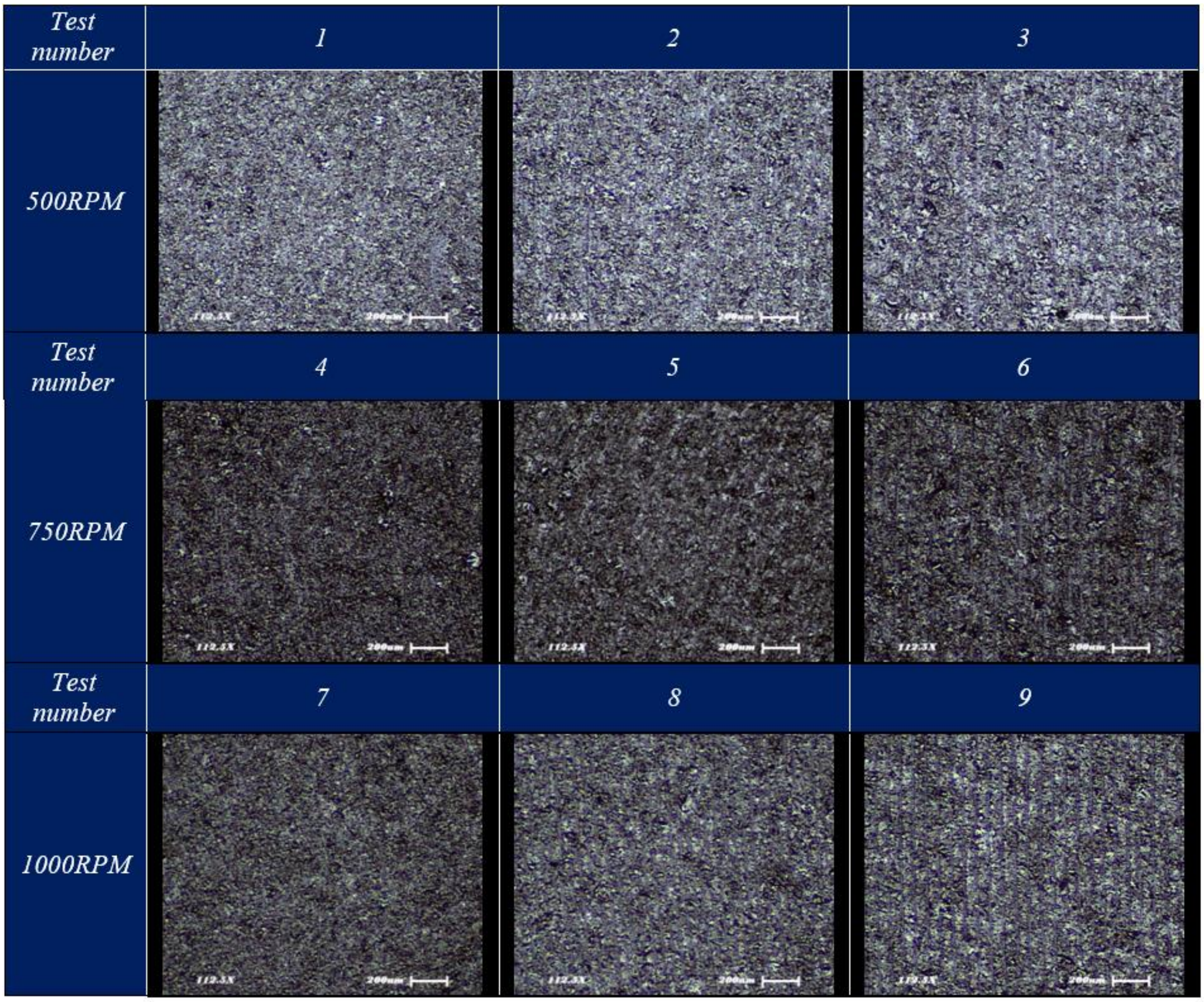

Figure 4. Surface texture images of machined samples with different spindle speeds and different feed rates from the NC lathe

According to the images in Figure 4, the surface damage has decreased by 22% in test number 4 compared to test number one. The process of reducing the changes in surface damage between test 7 compared to test 4 decreased by almost 9.5%.

The produced surface in test number 5 compared to test number 2 in terms of surface damages is reduced by approx.13%, and the process of reducing changes in surface damage between the two tests numbers 8 and 5 is equal to approximately 15%. Between tests 6 and 3, surface damages such as microcracks, micro craters, and Surface pits decrease about 19% for test6, which is a downward trend of surface damage between tests 6 and 7 with an approximately 23% reduction for test 7.

Produced surface in the two tests No.6 compared to the test No.9 in the cutting depth of 50 μm and the feed rate of 110 μm/rev of the relevant test had an increase of approximately 5% in surface damage.

Due to the surface damage and porosity that occurred for the machined surfaces in Tests 1 to 9, and the results of the experiments in the previous paper [22], it is not recommended to use tools with a tip radius below 0.8 mm at a depth of 50 microns or more. The selected spindle speed for cutting of Ge material on the NC lathe is 1000RPM for decreasing the surface damage in the above tests.

3.2 Surface roughness

The roughness of the machined surfaces with different spindle speeds and different feed rates for the tests measured from Table3 along 5mm and four surface roughness lines. The mean surface roughness results of each test were entered into the software and then compared to the average surface roughness (Ra), the root mean square (Rq), and highest peak roughness up to the valley (Rt) was analyzed and presented according to Figure 5.

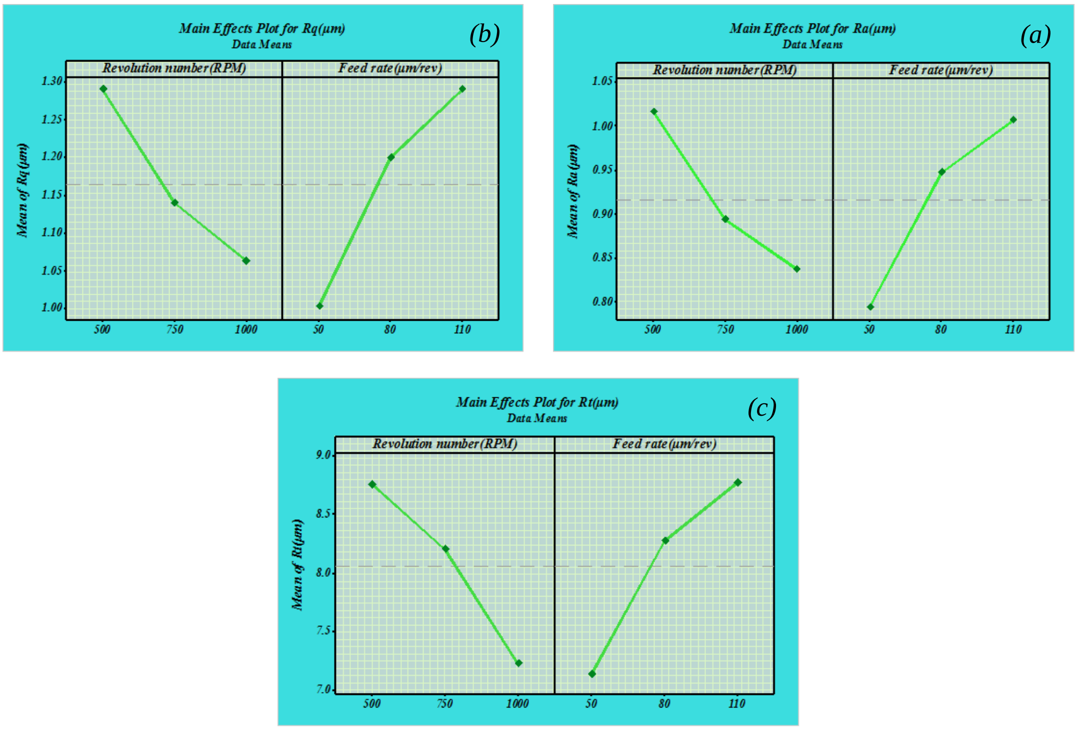

Figure 5. Design analysis of the Taguchi experiment for A) Mean average surface roughness (Ra), b) Mean root mean square (Rq), and c) Mean maximum peak-to-valley height (Rt)

The numerical values of Ra, Rq, and Rt increased from a feed of 50 to 110µm/rev in a cutting depth of 50µm of germanium material by approximately 26, 29, and 23, respectively as shown in Figure4. Rq roughness and Rt roughness for the spindle speed of 1000RPM to 500RPM reduced by approximately 18%.

4. Conclusion

Based on the surface morphology in the tests performed, the surface damage including fractures, microcracks, bumps, and surface pits in the produced surface reduced by increasing the spindle speed and decreasing the feed rate.

Produced surface morphology in the two tests No.6 compared to the test No.9 in the cutting depth of 50µm and the feed rate of 110µm/rev of the relevant test had an increase of approx.5% in surface damage. Also, surface damage between test number7 compared to test number4 decreased by almost 9.5%, which indicates the increased spindle speed with decreased feed rate improves surface damage. According to the analysis of the surface roughness results, the surface roughness increases with increasing feed rate and decreasing spindle speed in this tested range. Surface roughness Rq and Rt for the spindle speed of 1000 to 500 RPM reduced by approximately 18%.

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