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Surface Integrity of Holes Machined by Orbital Drilling of Composites with Single layer Diamond Tools

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Abstract

Orbital drilling of composites was investigated to observe hole surface integrity in terms of surface roughness, delamination, surface burning, and geometric accuracy. Experiments were conducted with a brazed single layer diamond tool of ball-end geometry to drill 220 holes. Cutting forces and temperatures were measured. Micro-observations were made of the hole surface. The results showed that the forces increased sharply during drilling of the first 44 holes followed by a gradual rise. Part temperatures varied between 98-184°C. Surface roughness R_a varied from 13-17 µm. Almost 99% of the holes were drilled without exit delamination; however, 2.3% of the holes showed entrance delamination.

Keywords: Drilling; composites; superabrasive tools

1. Introduction

Orbital drilling (OD) has become a promising alternative to conventional drilling, through which delamination-free holes can be obtained in most cases. Polycrystalline diamond (PCD) and carbide end mills are commonly used in this process. With the former being quite expensive and the latter having a very short life, superabrasive diamond (SAD) tools were investigated in this research, for the high hardness of diamond grains and low tool cost.

This type of tool was previously investigated for this process [1], in which the material strengths were compared for the holes obtained by both conventional drilling using PCD drills and OD using SAD tools. The latter method generated holes which exhibited the highest strengths in static and fatigue compression testing compared to the former one. Surface integrity of the drilled holes was investigated [2] in OD using both SAD tools and carbide end mills, in which thrust force, exit temperature, and R_a values for the SAD tool were found to be higher as compared to those for the end mill. The results were obtained at 5 m/s cutting speed, which might not be suitable for these tools in order to be comparable with the performance of end mills. In another study [3], SAD tools were tested for high speeds, and above 15 m/s it was found that lower forces, temperature, and geometric errors were obtained. No delamination was observed. All these research studies were conducted using flat-end SAD tools and CFRP (carbon fibre reinforced plastic) materials. Core type SAD tools with both flat-end and ball-end geometry were studied in [4]. It was found that the thrust force increased abruptly for the flat-end tool, whereas for the ball-end geometry, the drilling was continued up to 28.5 cm^3 of removed material. Grinding fluid was applied to avoid thermal damage. Also, no fuzzing and exit delamination were observed. A core drill with both roughing and finishing abrasive zones was applied in conventional drilling of CFRP plates [5]. Minor tool wear was observed after an axial drilling length of 21 m. The R_a values and delamination factor were 2~3 µm and ≤ 0.1, respectively. Coolant was applied to keep the part temperature low. The surface integrity, drilling-induced damage with increasing volume of removed material as well as the effect on tool life are yet to be explored in OD. Therefore, an experimental investigation on CFRP materials was carried out, in which cutting force, temperature, geometric accuracies, surface roughness, and defects including delamination, fibre pull-out, thermal damage, and fuzzing were investigated during OD of 220 holes using a ball-end type SAD tool. Optical and Scanning Electron Microscopy (SEM) were used to observe drilling-induced damage and grain wear.

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2. Experimental setup

Orbital drilling was carried out on a 5-axis Makino A88ε machining center using an IBAG high speed spindle attachment with maximum 40,000 rpm spindle speed and 1 kW spindle power. The test materials were 6.35 mm thick carbon/epoxy plates having a $[0/\pm45/90]_{24s}$ stacking sequence. A superabrasive diamond tool with ball-end geometry was used because of its ability to reduce drilling thrust force and tool clogging. The diameters of the tool and hole were 9.525 and 12 mm, respectively. The spindle speed n_s, orbital feed rate v_w, and axial feed rate v_a for pitch p = 0.5 mm were 40,000 rpm, 1500 mm/min, and 97 mm/min, respectively to satisfy the spindle power constraint and to avoid excessive tool clogging due to chip formation. The experimental setup and the tool are shown in Fig. 1. Two composite plates were fastened to two sides of the column, as indicated in the figure. Plate#1 was attached to side 1 of the column, and contained holes which were drilled after every 10 holes. The interim sets of 10 holes were drilled in the plates attached to side 2. Cutting forces and temperature at the hole exits were recorded using a Kistler 9255B dynamometer and a FLIR thermovision A20M infrared camera, respectively. As shown in the inset of Fig. 1, the center point of the tool and 2~3 points on the hole periphery were measured to obtain tool and part temperature. Delamination at the entry and exit sides was analyzed by an Olympus Model GZX12 Optical Microscope. An Olympus G71 inverted microscope was used to observe material clogging on tool surfaces. Diametric deviations, hole circularity, and cylindricity of the drilled holes were measured using a Mitutoyo-Mach 806 coordinate measuring machine. Surface roughness was measured using a Form Talysurf series-2 surface profilometer. The abrasive grains were observed using a JEOL JSM7600F SEM.

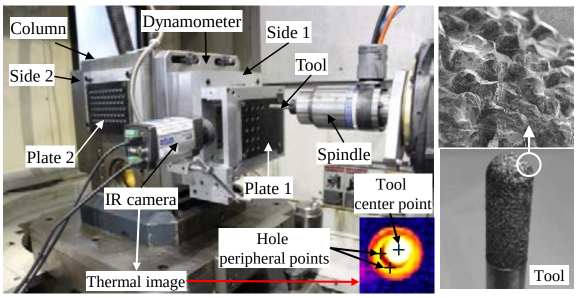

Fig. 1. Experimental setup and cutting tool

3. Experimental results

3.1. Cutting forces and temperature

Figure 2 shows how both forces and temperature varied with increasing number of holes. The forces obtained during the first hole are the basic forces required to drill a hole at this test condition using a fresh cutting tool. As drilling continued both peripheral and thrust forces increased by approximately 90% and 93%, respectively from the 1st to the 220th hole. The forces increased sharply up to the 44th hole followed by a reduction in the rate of force increase. Peripheral force increased by 1% per hole up to 44 holes, which reduced to a 0.175% increment per hole thereafter. Similarly, the thrust force increased by 1% and 0.18% per hole from hole 1 to hole 44 and hole 45 to hole 220, respectively. This observation can be explained by two facts. One is the clogging tendency of superabrasive tools, in which crushed polymers and fractured fibres occupy inter-grain pockets. Therefore, with the continuation of hole drilling, contact pressure increases at the tool-workpiece interface as the fresh chips generated during drilling try to flow through these pockets; thus, squeezing the clogged debris. Another reason can be the wearing out of the tool. The fresh cutting edges of the grains are usually sharp, which rapidly become blunt during machining within a short period of time. Beyond this stage, grain wear is slower. Hence, a typical wear versus time relationship closely resembles the trends of the time variation of force. Similar reasons can explain the increasing trend of cutting temperatures at the exit side of the first 84 holes. The part temperature increased from 98 to 184°C; then, it dropped to 143°C during drilling hole 92 and maintained a steady state with a slight inclination of 12°C. The part temperatures were derived from the recorded infrared images with an emissivity of 0.82 [6]. To investigate whether thermal burn occurred at these temperature levels, the drilled hole surfaces were observed under an optical microscope, which confirmed that there were no burn marks on the surfaces. This is also expected because the glass transition temperature for the used resin (toughened epoxy) is approximately 200°C [7]. Besides, in orbital drilling, the cutting tool constantly rotates along its orbital path; therefore, the point of heat generation at the tool-workpiece interface continuously moves. This prevents the accumulation of heat in a single location on the workpiece surface and eventual thermal damage. High speed drilling also facilitated heat convection.

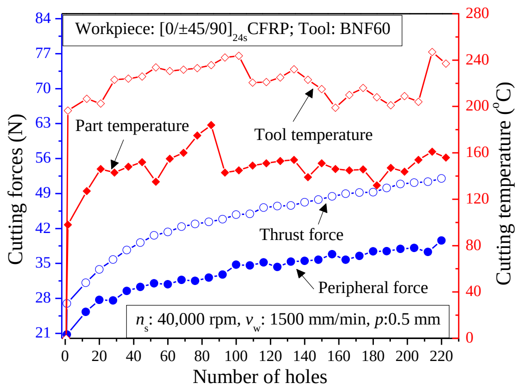

Fig. 2. Variation of forces and temperature with increasing number of holes

3.2. Tool clogging and wear

In order to support the aforementioned explanations for the increasing trends of the cutting forces, the tool surface was observed under both optical and scanning electron microscopes to detect tool clogging and wear, respectively. Figure 3 shows the front face of a clogged tool.