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Cutter path orientations when high-speed finish milling inclined hardened steel

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Abstract The use of high-speed milling (HSM) for the production of moulds and dies is becoming more widespread. Critical aspects of the technology include cutting tools, machinability data, cutter path generation and technology. Much published information exists on cutting tools and related data (cutting speeds, feed rates, depths of cut, etc.). However, relatively little information has been published on the evaluation of cutter paths for this application. Most of the research focuses on cutter path generation with the main aim on reducing production time. Work concerning cutter path evaluation and optimisation on tool wear, tool life and relevant workpiece machinability characteristics are scant. This paper investigates and evaluates the different cutter path orientations when high-speed finish milling inclined hardened steel, at a workpiece inclination angle of 75°. The results demonstrate that employing a vertical downward orientation achieved the longest life. However, in terms of workpiece surface roughness, vertical upward orientation is generally preferred.

Keywords Cutter path orientations · Hardened steel · High-speed milling

1 Introduction

Trends to make use of HSM as a viable technology has led to advancements in diverse areas on tool materials, machine tool design, computer-aided design/computer-aided manufacturing (CAD/CAM), tool materials, etc. The use of HSM for the production of moulds and dies is becoming more widespread. Critical aspects of the technology include cutting tools, machinability data, cutter path generation and technology. Much published information exists on cutting tools and related data (cutting speeds, feed rates, depths of cut, etc.), however, relatively little information has been published on the evaluation of cutter paths for this application.

Most of the research focuses on cutter path generation techniques. Studies with regard to cutter path evaluation on tool wear and tool life, surface integrity and relevant workpiece machinability characteristics are scant. Therefore, a detailed knowledge on the evaluation of cutter path strategies and orientations when high-speed rough and finish milling is essential in order to improve productivity and surface quality, respectively. The present work deals with some aspects related to the evaluation on the machinability of hardened AISI H13 hot work tool steel of 52
Rockwell Hardness C scale when high-speed finish milling using designated cutter path orientations.

Proper selection of the cutter path strategy is crucial in achieving desired machined surfaces. Without considering the impact of cutter path selection with adequate consideration of the machining parameters such as cutting forces, vibration analysis, tool life, cutting temperature and workpiece surface integrity, the result can lead to catastrophic cutter failure and therefore lead to unnecessary waste of time, cost and poor surface quality.

Wang et al. [1], Prabhu et al. [2], Lakkaraju and Raman [3] and Jamil [4] conducted analytical studies to identify the best cutter path strategies and the optimum angle orientation of a cutter path with respect to a plane workpiece. The studies were carried out on plane surfaces without internal islands of material. The analytical models developed by the researchers mentioned above do not take into account the state of tool wear on a cutter that is influencing the length cut. The ignorance of considering tool wear can result in poor tool life and workpiece surface quality.

For finish milling free form moulds and dies, the cutter path varies along the surface curvature. When finish milling using a 3-axis or 5-axis NC machine, the tool axis with respect to the workpiece surface is crucial in achieving optimum surface quality and accuracy [5]. A minimum tool or workpiece inclination angle, known as Sturz method or inclined method [6], is defined such that the cutter axis or workpiece material is tilted at a constant angle with respect to a surface normal. Ball nose cutters are generally used for finish milling because the cutter readily adapts to machining free form surfaces. However, finish milling on a plane surface generally results in poor tool life since the effective cutting speed at its tip is zero and the effective chip space is very small [7]. A minimum cutter or workpiece inclination angle is therefore needed to avoid cutting at the tip of the cutter.

Several researchers have addressed cutter path orientations on inclined workpiece surfaces over the past fifteen years. Elbestawi et al. [8] investigated high-speed finish milling of AISI H13 hot work tool steel, and concluded that a significant increase in tool life was observed when upward milling at an inclination angle of 10°. Tonshoff and Camacho [9] deduced that in general, maximum flank wear decreased with increase in cutter inclination. Schulz and Hock [7] concluded that a vertical upward orientation at an inclination angle of 15° was found to be the best for maximum tool life because the cutting forces on the cutting edges and the cutter vibration were minimum. Chu et al. [10] revealed that vertical upward orientation at low inclination angles at better stability than vertical downward orientation as faster cutting speeds with the former resulted in lower cutting forces. However, as the inclination angle increased, vertical downward orientation became more favourable because the angle between the tool axis and resultant cutting force was much smaller than with vertical upward orientation. Ng et al. [11] carried our experiments based solely on 45° workpiece inclination angle on ball nose end milling Inconel 718 nickel based super alloys. Their results showed that milling in a horizontal downward orientation gave the lowest tool wear and longest length cut regardless of tool coatings used. Gaida et al. [12] deduced that tool life was lower for 60° inclination angle compared to 15° inclination angle. They deduced that this could be due to the difference in cutting speed distribution along the contact zone and the chip formation process at different inclination angles.

None of the aforementioned studies have dealt specifically with high speed finish milling inclined hardened steel at an inclination angle of 75°. Nevertheless, studies on cutter path strategies when rough milling hardened steel have been carried out and reported [13–17]. The aim of the present study is to investigate high-speed finish milling an inclined workpiece surface with a view of using an extreme cutting angle inclination to simulate the effect of different cutter path orientations when finish milling hardened moulds and dies, through its machineability assessments, in order to identify the best cutter path orientation.

2 Experimental procedure

2.1 Workpiece material and tooling

Hardened AISI H13 hot work tool steel with a nominal composition of 0.38% C, 1.00% Si, 0.35% Mn, 5.00% Cr, 1.30% Mo, 1.00% V and Fe balance was used throughout the experimental work. Its hardness was measured with an instrumental portable hardness tester to ensure that a nominal bulk hardness of 52 HRC was achieved. The workpiece material was wire electrical discharge machined into blocks with dimensions of 120 mm × 120 mm × 30 mm. The surface of each block was ground to ensure flatness.

In this experiment, 6-flute ultra-fine grain VC-6MDB ball nose end mills were used. The cutters were coated with a monolayer (Al,Ti)N film with a thickness of about 2.5 μm. The cutter has a diameter of 10 mm, helix angle of 45° and a radial rake angle of −14°.

2.2 Experimental equipment and setup

All cutting tests were performed on a vertical prismatic high-speed machining centre. This has a continuously variable speed of 200–20000 rpm with a maximum spindle power of 15 kW and variable feed rates up to 15 m/min. All machining tests were conducted dry. In addition, high-pressure air blast delivered through a nozzle was directed at the cutting zone for all machining tests conducted. A tool overhang of 60 mm was employed throughout the tests to avoid tool holder collision with the workpiece fixture setup. A dial indicator was used to ensure that an accurate workpiece inclination angle of 75° was achieved. All cutters were checked prior to machining to ensure a tool runout of less than 10 μm. These were assessed using a dial indicator with a resolution of 0.001 mm.

Tool wear was measured using a toolmaker’s microscope with a magnification of 30X equipped with digital micrometer heads with a 0.001 mm resolution.