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Experimental investigations on cryogenic cooling by liquid nitrogen in the end milling of hardened steel

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ABSTRACT

Milling of hardened steel generates excessive heat during the chip formation process, which increases the temperature of cutting tool and accelerates tool wear. Application of conventional cutting fluid in milling process may not effectively control the heat generation also it has inherent health and environmental problems. To minimize health hazard and environmental problems caused by using conventional cutting fluid, a cryogenic cooling set up is developed to cool tool–chip interface using liquid nitrogen (LN_2). This paper presents results on the effect of LN_2 as a coolant on machinability of hardened AISI H13 tool steel for varying cutting speed in the range of 75–125 m/min during end milling with PVD TiAlN coated carbide inserts at a constant feed rate. The results show that machining with LN_2 lowers cutting temperature, tool flank wear, surface roughness and cutting forces as compared with dry and wet machining. With LN_2 cooling, it has been found that the cutting temperature was reduced by 57–60% and 37–42%; the tool flank wear was reduced by 29–34% and 10–12%; the surface roughness was decreased by 33–40% and 25–29% compared to dry and wet machining. The cutting forces also decreased moderately compared to dry and wet machining. This can be attributed to the fact that LN_2 machining provides better cooling and lubrication through substantial reduction in the cutting zone temperature.

1. Introduction

Difficult-to-machine materials, such as AISI H13 hardened steels, are widely used in extrusion dies, die casting dies, hot forging dies and plastic mould dies due to their higher resistance to thermal shock and thermal fatigue, high temperature strength, good toughness, ductility, and dimensional stability during hardening. While machining hardened steel, the contact friction between the tool–workpiece and tool–chip interfaces generates high temperatures on the cutting tool. This generated heat increases workpiece surface roughness, and decreases the tool life and the dimensional accuracy of the work material. The cutting fluid is invariably used as a coolant to reduce the heat generated and friction between the tool–workpiece and the tool–chip interfaces, and also wash away the chips from the tool. Problems with the use of conventional coolants are the potential health hazards to the operating personnel which on contact or inhalation of mist or fumes, and improper disposal of cutting fluids that cause serious environmental problems, such as water and soil pollution [3,30]. The application of a minimum quantity of lubrication consists of a mixture of compressed air and oil droplets to the chip–tool interface, called mist coolant [16,21,18,14,25]. However, applying a mist coolant also poses serious health hazards including eye irritation; Breathing of the mist may also cause serious respiratory problems and air pollution [31].

Researchers have investigated the use of cutting fluid with the high pressure coolant to reduce the cutting temperature and improve machining performance [10,17]. However, the cooling effect of a high pressure coolant does not meet industry standards. When the coolant pressure was increased from 15 to 20.3 MPa, the tool life decreased rapidly due to excessive notch wear reported by Ezugwu et al. [7]. With the applications of chilled air cooling during machining, the tool life and surface finish are improved. Rahman et al. [19] studied the performance of chilled air cooling in end milling on ASSAB 718 mould steel and found improved tool life and surface finish, and reduced cutting forces as compared with dry and conventional coolant cutting. Su et al. [23] studied the effect of dry, flood coolant, nitrogen oil mist, compressed cold nitrogen gas (0 °C and −10 °C), and compressed cold nitrogen gas and oil mist cutting conditions on tool life during high speed end milling of Ti–6Al–4V. It was found that the tool life under compressed cold nitrogen gas and oil mist cooling conditions have increased 2.69 times compared to dry cutting and 1.93 times over nitrogen oil mist. It was also reported that the tool life was less when using a flood coolant because of the effect of mechanical and thermal

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impact, which causes thermal cracks on the cutting edge. Su et al. [24] conducted an experimental investigation on tool wear, surface finish, and chip shape for high speed milling of AISI D2 cold work tool steel under dry cutting, minimal quantity lubrication, air cooling, and air cooling with minimal quantity lubrication conditions. It was observed that the application of air cooling with minimal quantity lubrication techniques resulted longer tool life compared to dry and minimum quantity lubrication.

Yalcin et al. [29] performed end milling on AISI 1050 steel under dry, fluid and air cooling cutting conditions. The experimental results showed that the surface roughness values for air cooling are lower than that of dry milling, and higher compared to those under fluid cooling. It was also reported that the flank wear in air cooling was closer to that in fluid cooling, and higher in dry milling compared to the fluid and cool air cooling systems. Cardoso et al. [15] carried out end milling of AISI H13 and AISI D2 steels with TiAlN coated and PCBN tools, under dry, compressed, and cold air cooling systems. The results indicated that the cold air cooling systems provided better results compared with dry and compressed air cooling conditions. It was noted that the cutting temperature was higher in the machining of AISI D2 steel compared to AISI H13 steel. Ghani et al. [8] studied the performance of P10 TiN coated carbide tools for end milling of AISI H13 steel at a higher cutting speed and found that the feed rate and depth of cut had the most significant effect on tool life. Elbestawi et al. [6] investigated the cutting tool performance and surface finish of AISI H13 tool steel for different process parameters. The experimental results indicated that the average cutting force for a 55 HRC tool was smaller than that for a 45 HRC tool. It was also observed that, the main mode of tool failure for the CBN tool was flank wear.

Recently, experiments have been conducted to study the effect of LN_2 cooling on tool wear, surface roughness and dimensional consistency in the turning operation [28,20,4,27]. It was found that cryogenic cooling by LN_2 jets provided reduced tool wear, better surface roughness and higher dimensional accuracy as compared to dry and wet machining, due to the substantial reduction in the cutting temperature, which enables maintenance of the sharpness of the cutting edge.

In machining, the application of LN_2 into the tool–chip interfaces should provide effective cooling and lubrication without polluting the environment. However, more work is required to explore the potential of using LN_2 cooling in the machining of hardened steels. Therefore, a new LN_2 cooling system was developed for reducing the cutting zone temperature. In this system, the LN_2 is applied to cool the cutting zone, particularly tool–chip interface by using nozzle. LN_2 can easily penetrate into the tool–chip interface to reduce the cutting temperature. The objective of this research is, to experimentally investigate the influence of three machining conditions such as dry, wet and LN_2 cooling on the cutting temperature, tool wear, surface roughness, and cutting force, for end milling of hardened AISI H13 tool steel under different cutting speeds and feeds.

Table 1
Experimental parameters.

Constant conditions:
Type of operation: Slot milling
Workpiece material: Hardened AISI H13 tool steel
Tool holder diameter: 16 mm
Length of cut: 150 mm
Axial depth of cut, a_a : 0.5 mm
Number of inserts: 2
Helix angle: 30°
Type of inserts: XDHT 090308 – HX (P20)
Tool holder: WIDIA M680 – 90° shoulder mill
Experimental variables:
Cutting speed, v: 75,100,125 m/min
Feed rate, F_z : 0.02 mm/tooth
Cooling method: Dry, wet and cryogenic cooling (LN_2)

2. Experimental setup and procedure

The experiments were conducted on a CNC vertical machining centre (ARIX VMC 100). The workpiece material for investigation was AISI H13 hardened tool steel of hardness 52 HRC; It had material dimensions: 150 × 100 × 50 mm. Flat bottom end mill P20 TiAlN PVD coated carbide inserts were used in this study. The cutting parameters used in this experiment are listed in Table 1. Dry machining was performed without using any coolant. The problem with dry machining is less cooling ability of air, making it ineffective for the removal of heat during machining. In general, the rate of heat removal depends on the convection heat transfer coefficient and temperature of the cutting fluid. An increase in the convection heat transfer coefficient with high pressure air (≈2000 W/m^2 K at pressure of 4–7 bar) compared to dry machining (≈20 W/m^2 K) [2,11]. In wet machining, commercial grade soluble oil was used with a volumetric oil water ratio of 1:20. Large quantities of coolant are used at low pressure to remove the heat generated from the cutting zone. However, the reduction of the cutting temperature in the cutting zone is only to a certain extent. At higher cutting temperature, the conventional coolant effect is reduced because the heat transfer coefficient is decreased as a result of boiling of the coolant. In order to reduce the cutting temperature and improve the machining performance, the recent method of a cryogenic coolant system was designed to inject liquefied nitrogen

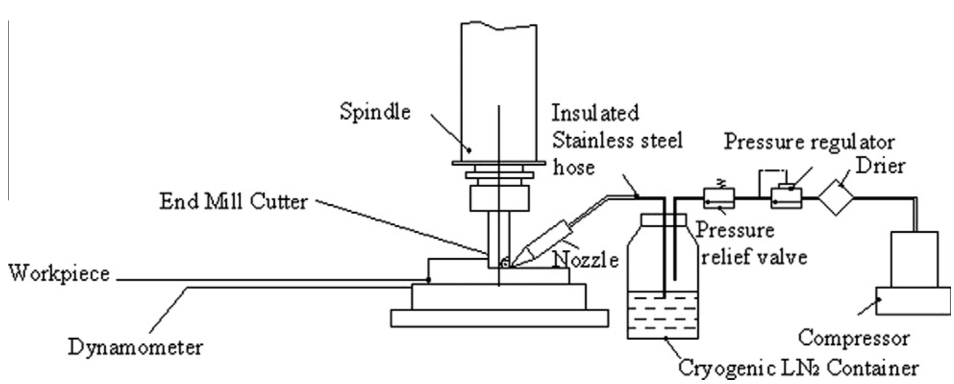

Fig. 1. Illustration of cryogenic cooling setup.