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Effect of cryogenic coolant on turning performance characteristics during machining of 17-4 PH stainless steel: A comparison with MQL, wet, dry machining

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ABSTRACT

Nowadays, metal cutting industries are looking towards new sustainable manufacturing methods to reach the target set by the environmentally conscious regulations in terms of usage and disposal of chemical contaminant conventional coolants without sacrificing the productivity. Machining with cryogenic coolants is an efficient, emerging sustainable manufacturing process. In the current work, a low cost external spray cooling cryogenic machining setup has been developed to spray the cryogenic coolant at the machining zone. In the current work, cryogenic coolant (liquid nitrogen) was used to machine the 17-4 precipitated hardenable stainless steel (PH SS) at varying depth of cut conditions and the results were compared with a minimum quantity lubrication (MQL), wet and dry machining environments. The investigative parameters considered in the present study were cutting temperature, tool wear (flank and rake), surface integrity (surface roughness and surface topography) and chip morphology. Cryogenic machining has given beneficial results compared to other machining environments. Hence, cryogenic machining is the most promising technique for machining of 17-4 PH SS. From the health and environmental point of view, cryogenic machining is a clean manufacturing technique.

Introduction

The demand for high corrosion resistance and high strength materials has been increasing more in many industries. 17-4 PH SS is one of the high corrosion resistance and high strength material due to the major presence of 17% chromium and 4% nickel in its chemical constituents. Because of these favorable properties, this material is having many applications in aerospace, nuclear, chemical and marine fields [1]. Machining of this kind of material under the dry environments leads to poor surface quality and more machining cost. It requires cutting coolants to overcome aforementioned problems but many environmentally conscious regulations encourage the limited usage of conventional coolants due to the chemical contaminants [2]. Hence, the metal cutting industries are looking for environmentally conscious manufacturing techniques.

From the literature, it has been found that cryogenic machining is an environmental friendly manufacturing process. Many researchers have worked with various kinds of difficult to cut materials under the cryogenic environment. Chetan et al. [3] have evaluated the surface roughness, tool wear and chip morphology attributes under the dry, MQL and cryogenic environments during turning of Nimonic 90 alloy. They found beneficial results in cryogenic machining due to the lower cutting temperatures. Bordin et al. [4] have conducted feasibility studies on additive manufactured Ti–6Al–4V under the dry and cryogenic turning processes. They observed fewer surface defects and low tool wear in cryogenic machining over the dry machining due to the low cutting temperatures provided by the liquid nitrogen (LN_2) causes control of both adhesion wear and plastic deformation of the machined surface. Kaynak et al. [5] carried out an experimental study on NiTi shape memory alloy and compared the subsurface characteristics under the cryogenic and dry machining. They observed superior product performance in cryogenic machining due to the significant reductions of cutting zone temperature. Pusavec et al. [6] have conducted experiments on turning of Inconel 718 under the dry, MQL and cryogenic environments. They claimed that cryogenic machining significantly altered the surface and subsurface characteristics due to the low cutting temperatures and improve the product performance greatly. Dhananchezian

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et al. [7] have found advantageous results in terms of cutting temperature, tool wear, surface finish and cutting force due to the reduction of friction between the contact asperities while turning of AISI 304 stainless steel. Krishnamurthy et al. [8] studied the effect of two coolants namely liquid nitrogen and ethanol blended (10%) metal removal fluid on turning performance characteristics during machining of titanium alloy and results were compared with the dry machining environment respectively. It was concluded that ethanol blended metal removal fluid significantly improved the turning performance over the cryogenic and dry machining environments. Also, it was observed that the cryogenic machining improved the turning performance when compared to dry machining environment. Shokrani et al. [9] found a significant reduction in the tool wear as well as surface roughness under cryogenic cooling environment while milling of cobalt chromium alloy over MQL and flood cooling techniques. Sun et al. [10] carried out the turning experiments on Ti-5553 alloy under cryogenic, MQL and flood cooling techniques and investigate the cutting forces, surface roughness and tool flank wear respectively. They found better results in cryogenic cooling conditions due to the effective cooling of machining zone. Jawahir et al. [11] found improved functional performance in cryogenic machining for biomedical components. Also, few modeling studies were done for Ti–6Al–4V alloy under cryogenic and dry machining environments using 3D finite element analysis. They observed that the predicted results were agreed with the experimental results [12,13].

Literature shows that different kinds of hard to cut materials were machined by using LN_2 as a coolant. 17-4 PH SS has key applications in aerospace and marine industries. So, selection of suitable machining technique for machining of 17-4 PH SS need to be identified for improving the product performance. To the author's best knowledge, no report was found in the literature on feasibility checking of cryogenic, MQL, wet and dry cooling environments for turning of 17-4 PH SS. In the present work, turning experiments were conducted on 17-4 PH SS and compared the tool wear (flank and rake), chip morphology and surface integrity (surface roughness and surface topography) under the cryogenic, MQL, wet and dry environments at varying depth of cut and constant cutting velocity, feed rate conditions respectively.

Materials and methods

17-4 PH SS workpiece material was machined using 'KIRLOSKAR' lathe machine under the cryogenic, MQL, wet and dry machining environments. The experimental details considered in the present work are depicted in Table 1. In the present study, experiments were carried at a different depth of cut conditions by keeping the cutting velocity and feed rate parameters as constant. Constant parameter levels were determined by conducting optimization studies. According to the pilot experiments, the range of depth of cut was considered. In the present study, based on the tool manufactured recommendations, cutting tool selection was done for machining the 17-4 PH SS. Cryogenic coolant as well as MQL coolant was supplied at the machining zone with the experimental setups developed by the authors [14]. Fig. 1 depicts the machining zone images at different cooling conditions.

'MITUTOYO SJ301' surface tester was used to measure the average surface roughness value (R_a). Actual surface roughness value is taken by measuring the surface roughness value at five different locations on each machined sample and average of five measurements. 'ZEISS' optical microscope has been used to measure the tool wear as well as chip morphology analysis. A fresh cutting edge of cutting insert was selected to conduct each experiment for four minutes. In the present work, tool wear (flank and rake) was observed and measured after the end of the four minutes. Tool wear mechanisms and surface defects on machined samples under all machining environments were carried out using 'JEOL-JSM-638OLA' Scanning electron microscope (SEM). Analysis of surface topography of machined surfaces was carried out by using confocal laser 3D surface tester of model 'LEXT OLS 4100'. A calibrated 'CENTER 350' infrared thermometer has been used to measure the machining zone temperature. While measuring temperature with the infrared thermometer, chip accumulation and coolants abrupt the infrared rays, so, the temperatures that have been measured in the present work may not indicate the actual cutting zone temperatures.

Results and discussion

Effect of depth of cut on cutting temperature under different cutting environments

As the depth of cut increases, cutting temperature increases under all cutting environments as depicted in Fig. 2. This is a result of an increase of friction between the tool and workpiece as a depth of cut increases which causes an increase in cutting temperatures. At a high depth of cut of 1 mm, cryogenic machining produced 44 °C cutting temperature at the machining zone, whereas, MQL, wet and dry machining has developed 79 °C, 88 °C and 151 °C respectively. At this condition, the cutting temperature reductions found in cryogenic machining was 44%, 50% and 71% respectively compared to MQL, wet and dry machining conditions. At the same point, the temperature reduction found in MQL machining was 10% and 48% respectively over the wet and dry machining conditions. This may be due to the better lubrication effect provided by the MQL mist at the machining zone. From Fig. 2, it was perceived that the lower cutting zone temperatures were found in cryogenic machining over other machining environments. This difference in

Table 1
Experimental conditions.

Workpiece material and size	17-4 PH SS round bar and (Ø 50 mm × 300 mm)
Cutting inserts	AlTiN physical vapour deposition (PVD) coated KC5010 tungsten coated carbide inserts (An International standard organization (ISO) designation of SNMG120408 MP), Kennametal made
Tool holder	ISO specification of PSBNR 2020 K12
Working insert tool geometry	Inclination angle: −6°, rake angle: −6°, clearance angle: 6°, major cutting edge angle: 75°, nose radius: 0.8 mm
Turning process parameters	Cutting velocity (v): 78.5 m/min Feed rate (f): 0.143 mm/rev Depth of cut (d): 0.2, 0.4, 0.6, 0.8 and 1 mm
Environments and coolants used	Cryogenic cooling (LN_2); dry (no coolant); MQL and wet (emulsion based flood coolant in 1:20 ratio)
Cutting fluid supply	For cryogenic cooling — compressed air: 4 bar, flow rate:0.45 kg/min; MQL cooling — compressed air: 4 bar, flow rate: 70 ml/h (through external nozzle); wet cooling — flow rate: 6 l/min (through external nozzle)
Nozzle diameters used to spray coolant for different environments	Cryogenics and MQL — Ø 1 mm, wet — Ø 10 mm