Cryogenics 59 (2014) 76–83

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

# Influence of cryogenic cooling on surface grinding of stainless steel 316

G. Manimaran [a,*], M. Pradeep kumar [b], R. Venkatasamy [a]

[a] Department of Mechanical Engineering, Saveetha Engineering College, Chennai 602105, India
[b] Department of Mechanical Engineering, CEG Anna University, Chennai 600025, India

ARTICLE INFO

Article history:
Received 9 February 2013
Received in revised form 18 November 2013
Accepted 22 November 2013
Available online 1 December 2013

Keywords:
Cryogenic cooling
Environment
Machining
Stainless steel
Grinding

ABSTRACT

The objective of the present investigation is to evaluate the improvements in the grinding force and surface roughness by the application of $LN_2$ (liquid nitrogen) as a coolant in the cryogenic grinding process. Cryogenic machining is an environment concerned green manufacturing process. The grinding experiments were conducted on stainless steel 316 in three environments, namely, dry, wet and cryogenic cooling. The experimental results show that a reduction in the grinding zone temperature leads to excellent benefits in the machining performance. The cryogenic coolant offers 37% and 13% reduction in the grinding forces compared to dry and wet cooling. The surface roughness under cryogenic cooling is found to produce 59% and 32% lesser values and fewer defects, compared to surfaces ground with dry and wet cooling. The enhancements realized by the delivery pressure of the cryogen, with respect to the grinding forces, and surface roughness were also studied.



## 1. Introduction

Mechanical energy is produced by the grinding process during relative movement between the grinding wheel and the work material. This energy is mainly converted into heat during material removal process, leading to a temperature increase in the grinding zone. Friction and plastic deformation process responsible for transformation of frictional energy into thermal energy. External friction between the abrasive grain and work surface, as well as between the chip and abrasive grain are partly responsible for the heat generation during grinding. However, heat also develops as a result of internal friction through displacement processes and plastic deformations [1]. The excessive heat affects the mechanical properties of the work material and grinding wheel, and reduces the machining performance. The coolants applied to the machining zone absorb the maximum heat, and transfer the remaining heat to the work material and tool. The coolant supply is also difficult in grinding process, due to the large contact area between the grinding wheel and work material, resulting thermal damages to surface of the work material. Therefore, the use of a cutting fluid during the grinding operation is very essential. The coolant types, method of supply, and delivery pressure are critical for heat dissipation [2]. The major problems with the oil based conventional wet coolants are, environmental pollution due to the boiling of the cutting fluid, smoke, health of the operators and difficulties in storage and maintenance [3]. The current industrial production uses about a few hundred million gallons of harmful polluting cutting fluids. The cryogenic coolant, if substituted as a cutting fluid, can avoid environmental problems associated with cleaning and disposal [16].

In dry grinding, plastic deformation and high temperature can influence the formation of a thin layer of hard and brittle surface called white layer. The layer appears white under an optical microscope whose properties are different from bulk material, so it is detrimental to fatigue life and surface integrity [4]. Grinding in dry conditions generates the cutting marks, micro-grooves, oxidation and subsurface damages [5]. There is a need for developing a new technology to avoid or minimize the use of cutting fluids. One alternative is the MQL (minimal quantity lubrication) technique, in which a small quantity of oil is applied, with high pressure air as the carrier. In the MQL technique, a large volume of oil mist is discharged into the environment. Hence, MQL technique is also not safe with reference to operator's health and environmental pollution. The alternative method which has attracted attention is cryogenic machining using liquid nitrogen ($LN_2$) as a coolant [18]. The application of $LN_2$ as coolant in different machining processes like turning [6,7], and milling [8] produced improvements in generation of defect free surfaces, lower grinding forces and higher material removal rates (MRR) due to the effective control of grinding zone temperature.

Ben Fredj and Sidhom [9] found that surfaces ground with cryogenic cooling produced fewer surface defects, and reduced

* Corresponding author. Tel.: +91 44 26811499; fax: +91 44 26811009.
E-mail addresses: manimaran_me@hotmail.com, manimaran_me@yahoo.co.in (G. Manimaran), pradeep@annauniv.edu (M. Pradeep kumar), principal@saveetha.ac.in (R. Venkatasamy).

0011-2275/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cryogenics.2013.11.005

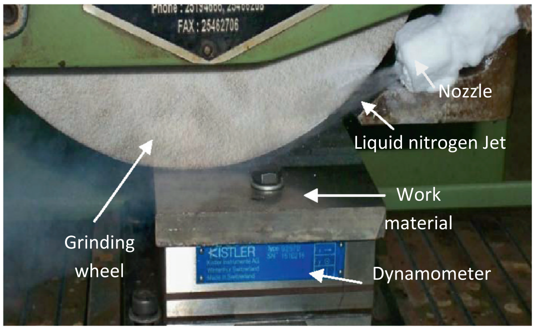


**Fig. 1.** The experimental setup with $LN_2$ delivery.

**Table 1**
Grinding conditions.

| | |
|---|---|
| Machine | 2.25 KW Hydraulic surface grinder |
| Grinding wheel | Aluminum oxide ($Al_2O_3$) A60K5V |
| Diameter of wheel | 250 mm |
| Width of wheel | 25 mm |
| Work piece | Stainless steel 316 |
| Wheel speed ($V_S$) | 31.4 m/s |
| Depth of cut (DOC) | 10–40 µm in steps of 10 |
| Table speed ($V_w$) | 0.1, 0.125 and 0.15 m/s |
| Feed | 10 µm |
| Environments | • Dry.<br>• Soluble oil.<br>• Liquid nitrogen. |
| Dressing | Single point diamond dresser |
| Dressing depth | 10 µm |

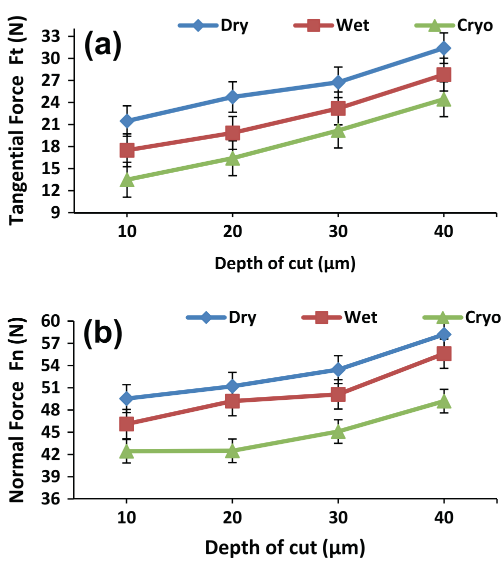


**Fig. 2.** The variations in the (a) Tangential force (b) normal force with depth of cut (work speed = 0.125 m/s, pressure = 3 bar).

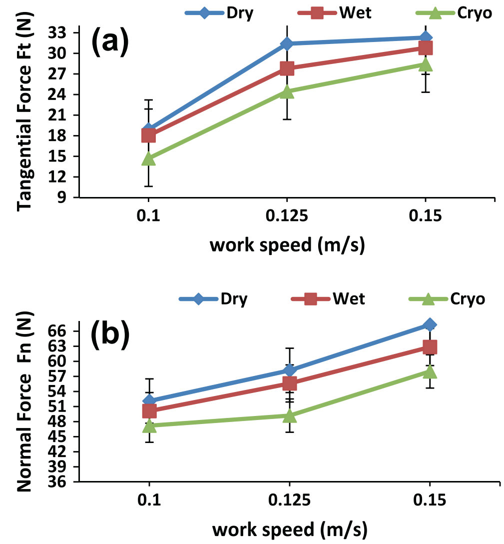


**Fig. 3.** The variations in the (a) Tangential force and (b) normal force with work speed (depth of cut = 40 µm, pressure = 3 bar).

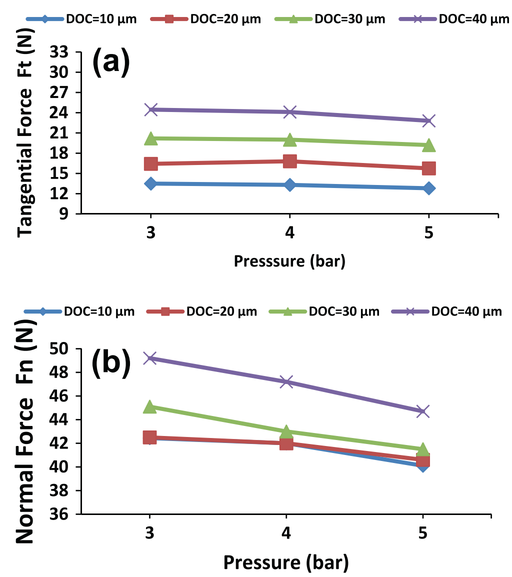


**Fig. 4.** The variations in the (a) Tangential force (b) normal force with delivery pressure at various depth of cut (work speed = 0.125 m/s).

grinding forces. Fathallah et al. [10] conducted experiments under cryogenic cooling and conventional cooling, with the objective of finding the effects of the cooling mode on the ground surface integrity of hardened AISI D2 steel. It was found that the material removal rates could be increased several times without affecting the surface residual stresses under cryogenic cooling. The surface roughness, residual stress and sub-surface damages are reduced to a great extent with the application of cryogenic cooling.

Venkatrao [11] summarizes that cryogenic machining with liquid nitrogen is safe and environment friendly. Nitrogen is a non-hazardous gas, that constitutes about 79% of the atmospheric air. Cryogenic gases have a wide variety of applications in industries such as health, electronics, manufacturing, automotive and aerospace industries, particularly for cooling purposes. Liquid nitrogen is the most commonly used element in cryogenics. It is produced industrially by the fractional distillation of liquid air. Nitrogen melts at −210 °C and boils at −198 °C. It is the most abundant gas, colorless, odorless, tasteless and non-toxic. Hence the nitrogen discharged into the atmosphere in cryogenic process was safe with regard to the operator's health, and had an insignificant impact on the environment.

Bhaduri et al. [12] conducted experiments with white, grey alumina and cBN (cubic boron nitride) grinding wheels, with neat oil and cryogenic cooling. They found that neat cooling oil is more suitable for grinding low carbon steel compared to cryogenic cooling. The main reason is the large scale adhesion and breakage of grits. Cryogenic cooling is also not effective when grinding Ti–6Al–4 V titanium material with the monolayered brazed type cBN grinding wheel. The chemical interaction between the work