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Tool wear and surface integrity of inconel 718 in dry and cryogenic coolant at high cutting speed

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ABSTRACT

The high speed machining of Inconel 718 represents a significant challenge. This is attributed to the excessive heat generated during the chip formation process, which elevates the cutting tool temperature and accelerates tool wear. The heat generated can shorten the tool life and lead to dimensional inaccuracies. In severe cases, this circumstance can result in product damage. During the milling process, the use of conventional cutting fluids to control heat generation may not be sufficiently effective. This is due to the inability of these fluids to fully penetrate the cutting zone. Such a situation can lead to the development of health and environmental problems. To overcome this dilemma, a cryogenic cooling unit using liquid nitrogen (LN_2) was developed to cool the tool–chip interface. This cooling technique is not only more efficient, but also environmental friendly. This paper presents the experimental investigations conducted to assess the effectiveness of cryogenic cooling for the milling of Inconel 718 in comparison to the dry cutting process. This comparison embraced tool wear rate, mechanism wear, cutting force, surface roughness and microstructure changes. The experiments involved the use of PVD coated with TiAlN/AlCrN ball nose tungsten carbide for varying cutting speeds ranging between 140–160 m/min, a feed rate of 0.15–0.20 mm/tooth, and a radial depth of cut of 0.2–0.4 mm. The axial depth of cut was kept constant at 0.3 mm. The results revealed that the cryogenic cooling process is more effective than dry cutting for reducing tool wear, lowering the required cutting force, improving surface roughness, lessening deformation of microstructure changes at the sub-surface level, and eliminating contamination of the machined part. Notch wear and flaking near the depth of the cut zone are the predominant types of tool failure during the machining of this kind of material. In comparison to dry machining, the utilization of the cryogenic technique reduces the cutting force to 23%, and improves the surface roughness to a maximum of 88%. This can be attributed to the capacity of LN_2 machining to provide better cooling and lubrication through the reduction of heat generation at the cutting zone. The machined surface roughness obtained of less than 0.2 μm could fulfill the demands of the aerospace industry for the finishing of precision components.

1. Introduction

Due to its high-temperature strength, superior creep and elevated corrosion resistance, Inconel 718 is widely employed in the aerospace industry [1]. The race towards the development of an efficient process for the machining of hard materials is becoming more and more competitive. This is due to the need for a process that can successfully meet the demands related to production cost, productivity, and most importantly, product quality. At conventional cutting speeds ranging from 10 to 50 m/min, the use of cemented tungsten carbide tools for the machining of Inconel alloys resulted in low productivity levels [2,3]. High speed machining technology offers many advantages over conventional machining. These advantages include a higher material removal rate, an enhanced machining accuracy, and a better surface finish [4]. However, the high speed machining of Inconel alloys is considerably more challenging as they are classified as difficult-to-cut materials. This is due to (a) their high shear strength, (b) their work-hardening tendency, (c) the presence of highly abrasive carbide particles in their microstructure, (d) their strong tendency to weld and form a built-up edge and (d) their low thermal conductivity [5,6].

The implementation of high speed machining for Inconel alloys calls for more in-depth industrial and academic investigations. The main issue hampering the execution of this process is generated heat that remains in the cutting zone during machining. The build-

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Nomenclature

ae	Radial depth of cut
ap	Axial depth of cut
BUE	Build up edge
DOC	Depth of cut
fz	Feed rate
F_r	Resultant force
F_x	Tangential/ cutting force
F_y	Radial force
F_z	Axial force
Vc	Cutting speed
θ_{opt}	Optimal cutting temperature
Ø	Insert diameter

up of this heat to extreme levels softens the cutting tool material and accelerates the rate of its wear. Other than a negative impact on the surface integrity of the machined parts, this situation can also result in several undesirable microstructural changes known as white layers [7,8]. Theoretically, the surface integrity of the machined parts can be improved by decreasing the cutting temperature. Optimal cutting conditions during the machining process can be realized through the application of a coolant and an appropriate choice of the tool's geometry and cutting parameters. In a previous study, Kitagawa et al. [9] used two types of ceramic single point tools (Si_3N_4 and $A1_2O_3+TiC$) to investigate the effect of various cutting speeds and cutting temperatures on tool wear during the turning process of Inconel 718. The results from this investigation, which involved a cutting speed of up to 500 m/min, indicated that tool wear was mainly due to an abrasive process rather than a thermally activated mechanism. Based on the first law of metal cutting proposed by Makarow, Astakhov [10] reported that ultimate machinability can be achieved at a particular cutting temperature. Known as the optimal cutting temperature (θ_{opt}), it is determined by the material properties of the tool and workpiece material rather than the cutting parameters. The hardness of Inconel 718 is increased with an elevation in temperature of up to 600 °C. Thus, increasing the cutting temperature during the machining of Inconel 718 is deemed non-beneficial [11]. Taking these facts into consideration, researchers have applied a variety of techniques in the industrial domain to increase the productivity of machining. These included the use of cutting fluids as coolants to maintain the cutting temperature below or close to θ_{opt}, as well as procedures that call for an increase in the machining cutting speed.

During the machining process, the utilization of conventional cutting fluids is considered effective for controlling the cutting temperature while enhancing the machinability of certain materials. However, the high cutting temperature generated during the machining of nickel alloys (such as Inconel 718) tends to evaporate the cutting fluid, which proceeds to form a gaseous cushion over the hot surface. In such a situation, the passage for the flow of cutting fluid to the cutting zone will be blocked [2,10,11]. Moreover, as the use of conventional cutting fluids is deemed detrimental to the environment, it is crucial that an effective disposal system for this contaminant is put in place. Put plainly, the use of conventional cutting fluids is not only ineffective, but can also prove to be costly. Furthermore, under certain circumstances, the application of conventional cutting fluids can exacerbate machining conditions as well as threaten the health of workers [12].

Among the alternative methods for enhancing the machining performance during the cutting of hard materials is the cryogenic technique. This technique employs nitrogen gas as a coolant. A significant advantage that comes with the utilization of nitrogen gas is that it is environmentally friendly. As such, it can be released and evaporated back into the atmosphere without any harmful effects [13]. Although the use of cryogenic coolants has been investigated since the 1950s, these investigations have been restricted by the high costs associated with early cryogenic technology. Previous studies on the cryogenic method commended its positive impact on machining performance [14,15]. To date, numerous studies employing a variety of approaches have been conducted on cryogenic machining.

While a major portion of investigations on cryogenic machining focused on the turning operation, the milling operation drew considerably less attention [16]. This circumstance is attributed to the high possibility of thermal crack development on the cutting tool resulting from intermittent cutting operations and other procedural problems. The main objective of this study is to evaluate the effectiveness of cryogenic cooling using liquid nitrogen. This investigation focused on the machinability of Inconel 718 during the ball nose end milling process. A series of machining experiments involving varying cutting parameters (cutting speed, feed rate, axial depth of cut and radial depth of cut) were conducted under cryogenic and dry cutting conditions. Tool wear, wear mechanism, cutting force, and surface integrity were examined to evaluate the effects of the cryogenic cooling process on the machined surface. Comparisons were then made between the cryogenic and dry cutting procedures.

2. Experimental set-up

Cryogenic and dry cutting procedures were conducted with the utilization of a CNC milling machine (DMC 635 V eco by Deckel Maho Seebach GmbH, Germany), which is capable of achieving a maximum speed of 8000 RPM. The liquid nitrogen for cryogenic machining was delivered directly to the cutting zone during the cutting process via a nozzle. This can be observed in Fig. 1. A rectangular block of age-hardened and solution-treated Inconel 718 alloy with a dimension of 150 × 100 × 50 mm was employed as the workpiece material. The hardness of the prepared workpiece was 42 ± 2 HRC. All the surfaces of the workpiece were face milled prior to the experiment. This is to ensure the removal of the original skin layer, which normally contains hard particles such as oxides or carbides. The chemical composition of the workpiece material is displayed in Table 1. A Sumitomo ball nose type milling cutter was used for the machining test. This cutting tool, with anominal diameter of 16 mm, is attached to a BIG Hi-Power

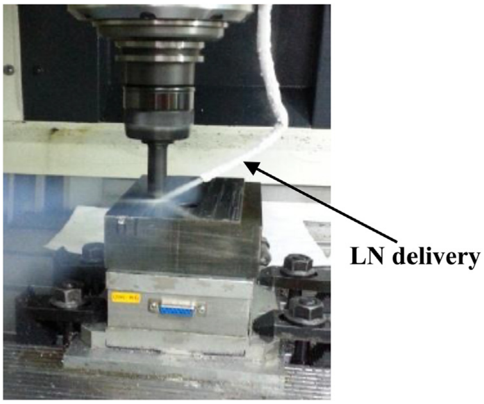

Fig. 1. Liquid nitrogen delivery.