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New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V

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ABSTRACT

The use of cryogenic coolant in metal cutting has received renewed recent attention because liquid nitrogen is a safe, clean, non-toxic coolant that requires no expensive disposal and can substantially improve tool life. This work investigates the effectiveness of cryogenic coolant during turning of Ti-6Al-4V at a constant speed and material removal rate (125 m/min, 48.5 cm^3/min) with different combinations of feed rate and depth of cut. It is found that the greatest improvement in tool life using cryogenic coolant occurs for conditions of high feed rate and low depth of cut combinations. However, this combination of machining parameters produces much shorter tool life compared to low feed rate and high depth of cut combinations. It is found that preventing heat generation during cutting is far more advantageous towards extending tool life rather than attempting to remove the heat with cryogenic coolant. Although cryogenic coolant is effective in extracting heat from the cutting zone, it is proposed that cryogenic coolant may limit the frictional heat generated during cutting and limit heat transfer to the tool by reducing the tool–chip contact length. The effect of cryogenic coolant on cutting forces and chip morphology is also examined.

1. Introduction

The high chemical reactivity, low thermal conductivity and relatively high hardness and strength of titanium alloys make machining difficult at high speeds. Consequently, machining speeds of titanium are an order of magnitude slower than that of aluminium. This exacerbates the cost, especially for many aerospace components where it is a common practise to remove over 90% of the material in order to fabricate a single component. Needless to say, the cost of machined titanium components could be substantially reduced by improving material removal rates and productivity without incurring addition disadvantages or costs (i.e. quality, tooling costs, etc.). This is the goal of the machining industry.

There are numerous pathways to achieve this goal. Examples include process optimisation by improving the efficiency of the machining process through correct tool selection and efficient programming to minimise the non-cutting time (in CNC milling). Other key pathways are to improve the tool life via tool design (better materials, coatings, etc.), improved tool cooling strategies, reducing the cutting forces through lubrication or thermal softening of the workpiece [1–3].

In addition to abrasive wear, it is understood that tool failure occurs by adhesion–dissolution–diffusion [4], a mechanism exacerbated by high cutting temperatures. Therefore, increasing the material removal rate without deteriorating tool life will not be possible without addressing the heat generated at the cutting zone. Some recent advances in this area have been through the use of high pressure air, liquid coolants [5–7] or though the application of cryogenic coolants [4,8,9]. Using liquid nitrogen (LN) as a coolant is becoming particularly attractive because it is a clean, inexpensive, non-toxic fluid that has no environmental contamination issues.

A number of studies have investigated the use of liquid nitrogen as a coolant for titanium turning operations and all report improvements in the tool life compared to dry cutting [4–7]. The most common variable studied is the effect of cutting speed on tool life with and without cryogenic coolant. Although the cutting speed has a substantial effect on the material removal rate, it is not the only factor, and the other two cutting parameters are often overlooked (feed rate and depth of cut).

Table 1 shows the cutting parameters used in a number of studies associated with turning of Ti-6Al-4V. While the cutting

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Table 1
Cutting parameters from literature for turning Ti-6Al-4V.

	Reference	Cutting speed, V_c (m/min)	Feed rate, f (mm/rev)	Depth of cut, a_p (mm)	M.R.R (cm^3/min)
Cryogenic	Hong et al. [6,7]	60–150	0.254	1.27	19–48
	Wang and Rajurkar [8]	132	0.20	1.0	26
	Venugopal et al. [4,9]	70, 85, 100, 117	0.20	2.0	27–46
Cryogenic air	Sun et al. [10]	7–280	0.19, 0.28	1.0	1.3–59
High pressure coolant	Palanisamy et al. [11]	75	0.25	2.0	37
	Nandy and Paul [12]	85	0.20	2.0	33
	Ezugwu et al. [13]	175–250	0.15	0.5	13–18.6
Laser assisted machining	Dandekar et al. [14]	107, 150, 200	0.075	0.76	6–11.3
	Sun et al. [15]	20–230	0.214	1.0	4.2–49
Other	Hughes et al. [16]	50, 80, 120	0.15, 0.25	0.25	1.86–7.5
	Che-Haron and Jawaid [17]	45–100	0.25, 0.35	2.0	22–68.5

speeds often overlap, there can be significant variations in the depth of cut and feed rates used. The reasons for selecting the feed rate and depth of cut are not usually reported, and therefore, it is unclear whether the parameters used are the optimum cutting parameters for extending tool life. It is easy to understand that the material removal rate can be kept constant by increasing the depth of cut and decreasing the feed rate or vice versa at a constant cutting speed. However, it is still unknown which combination of these conditions provides the maximum benefit to tool life during machining titanium alloys with cryogenic coolants. In machining SUS 304 stainless steel, Khan and Ahmed [5] reported that the greatest improvement in tool life when machining with cryogenic coolant occurred at higher feed rates rather than higher depths of cut.

Since the industrial focus is to improve the material removal rate, the aim of this work is to determine the optimal cutting parameters at a high cutting speed and material removal rate for both dry cutting and cutting using cryogenic coolant. Typical conventional cutting speeds for turning titanium depend on the tool and operation but these speeds are of the order 45–90 m/min with feed rate and depth of cut combinations producing material removal rates of the order of 3.5–65 cm^3/min [18]. The work presented here is seeking to determine the best combination of feed rate and depth of cut at a constant speed of 125 m/min and material removal rate of 49 cm^3/min. This speed and material removal rate were selected because it is an industry goal to cut titanium alloys at speeds in excess of 100 m/min and the benefits of cryogenic coolants are reportedly less at high speeds compared to low speeds [4]; therefore, the true benefits of cryogenic coolant can be assessed at industrial cutting targets.

2. Experimental

The workpiece material used in this study was β-annealed Ti-6Al-4V (Fig. 1) with a prior-β grain size of approximately 1 mm, α-lath thickness of 5 μm and a hardness of 323 ± 37 Hv. Turning was performed on a Torrent manual lathe fitted with a Bonfiglioli Vectron Synplus variable speed drive. The variable speed drive was adjusted after each cut to ensure constant speed as the diameter of the workpiece reduced. The starting diameter of the workpiece was 105 mm. Seco WMNG 120408 MF1 WC inserts (rake angle +6, clearance angle 0 and with chip breaker) were used in a Seco JetStream™ tool holder with an entry angle of 95°. A 3-component force sensor (Kistler Model ZZZ9257A) was placed under the tool holder to record the dynamic changes in the cutting forces throughout testing. Lab-View Signal Express® software was used to log the data with a sampling rate of 1 KHz.

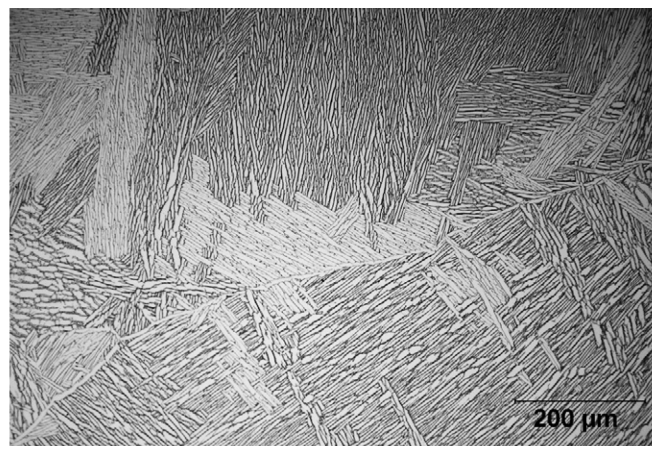

Fig. 1. Microstructure of Ti-6Al-4V workpiece.

Table 2
Cutting parameters investigated.

Cutting speed, V_c (m/min)	Feed rate, f (mm/rev)	Depth of cut, a_p (mm)	M.R.R (cm^3/min)
125	0.36	1.1	48.61
125	0.20	2.0	48.53
125	0.15	2.7	48.69

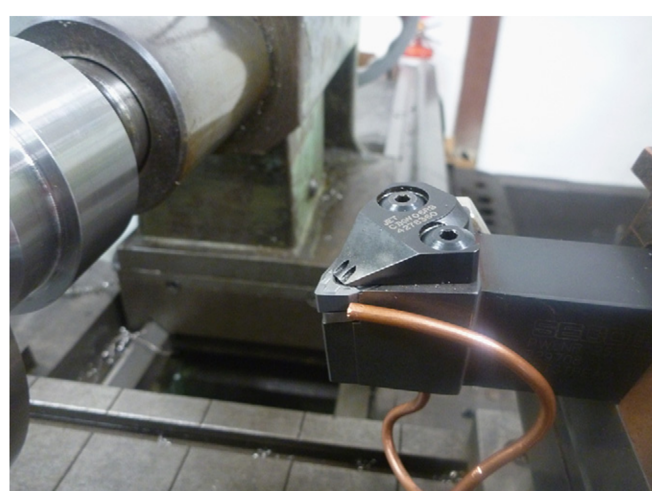

Fig. 2. Photograph of tool holder and coolant delivery nozzles.