Available online at www.sciencedirect.com

SCIENCE DIRECT®

Surface & Coatings Technology 200 (2006) 2970 – 2977

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

A comparison of five categories of carbon-based tool coatings for dry drilling of aluminum

Jean M. Dasch[a,*], Carolina C. Ang[a], Curtis A. Wong[a], Yang T. Cheng[a], Anita M. Weiner[a], Leo C. Lev[a], Erkan Konca[b]

[a]GM Research and Development Center, 30500 Mound Road, Warren, MI 48090, United States
[b]University of Windsor, Canada

Received 22 July 2004; accepted in revised form 10 April 2005
Available online 24 August 2005

Abstract

Due to high costs, infrastructure demands, and environmental concerns, there is motivation to move toward dry machining, i.e., machining without the use of metal removal fluids (MRFs). Aluminum, as used in light-duty engines and transmissions, is particularly difficult to machine dry because of its tendency to adhere to the tool as temperatures rise. Machining performance suffers when machining is done without MRFs. For example, tool life during drilling is reduced from >10,000 holes/drill with MRF to about 40 holes/drill without MRF (dry). The challenge, then, is to reduce the heat build-up through improved tribological surfaces on the tool. In this study a variety of carbon-based coatings on drills were tested to determine their performance in both bench and machining tests. Coatings included metal-containing carbon, graphitic, hydrogenated and hydrogen-free diamond-like carbon, and diamond. The best coatings gave a >100-fold improvement in performance compared to an uncoated drill.

Keywords: Dry machining; Tool coatings; DLC; Diamond; Aluminum alloy; Pin-on-disc

1. Introduction

Increasingly, machining operations are being performed dry to avoid the airborne mist and disposal issues associated with metal removal fluids (MRFs), as well as the high costs of MRFs estimated to be 16% of the cost of machining [1–3]. Vehicular powertrains, which were commonly made of cast iron, could often be machined dry due to the graphite contained in cast iron. However, powertrains are moving toward lighter materials, notably cast aluminum, to improve fuel economy. Although aluminum is a relatively soft material that can be easily machined using MRFs, temperatures rise under dry conditions and the aluminum adheres to tool surfaces. An emerging issue, then, is the development of materials or processes to enable dry machining of aluminum. This is not a simple task in that over 10,000 holes can be drilled with a single drill using MRFs. Using the same conditions, but without MRFs, only about 40 holes can be drilled before tool failure.

Variables that affect dry drilling of aluminum were investigated through a National Center for Manufacturing Sciences (NCMS) study and tool coatings were shown to be one of the important variables that could improve performance [4]. Studies have shown that carbon-based coatings, such as diamond or diamond-like carbon (DLC) are promising as tool coatings when machining aluminum [5,6]. Chemical vapor-deposited (CVD) diamond coatings show great promise for machining non-ferrous materials [7], but deficiencies remain in adhesion of the coating to carbide tools [8], tool weakening during pretreatment [9] and inconsistent quality [10]. In addition to diamond coatings, other carbon-based coatings have shown success for aluminum machining [11–13].

* Corresponding author. Tel.: +1 586 986 1597; fax: +1 586 986 1910.
E-mail address: jean.m.dasch@gm.com (J.M. Dasch).

0257-8972/$ - see front matter
doi:10.1016/j.surfcoat.2005.04.025

Table 1
Categories of carbon-based coatings tested in study [14]

Coating category	Hardness (GPa)
Me-a-C:H	10–20
a-C	10–40
a-C:H	20–40
ta-C	60–80
CVD diamond, t-C	>80

The purpose of this study was to test a range of carbon-based tool coatings using laboratory friction tests as well as actual drilling tests. Five categories of coatings were tested, using the grouping designation of Franz and Quinto [14], including metal-containing carbon (Me-a-C:H), graphitic (a-C), hydrogenated DLC (a-C:H), hydrogen-free DLC (ta-C) and diamond (t-C), as shown in Table 1. The coatings tested differed in production method, thickness, hardness, metal and hydrogen content, bonding, and coefficient of friction. Coatings from each group were studied as candidates to enable dry drilling of aluminum.

2. Procedure

Coating suppliers were selected to provide the coatings shown in Table 1. Each supplier was asked to coat steel coupons for pin-on-disc testing, as well as carbide and high-speed steel (HSS) drills for machining tests. Drill coatings were pre-examined for surface irregularities using optical and scanning electron microscopy. The hydrogen content of the coatings was determined by Elastic Recoil Detection by the University of Western Ontario.

Pin-on-disc testing was performed on the coated steel discs using an ISC 450 Tribometer from Implant Sciences. The pins were made from the same aluminum alloy used for drilling tests and the tip machined with a 2-mm radius. Each test was conducted at three temperatures, 120 °C, 260 °C, and 400 °C, for 1000 revolutions at a speed of 130 rpm and a load of 0.5 kg.

Machine tests consisted of drilling 19-mm deep, blind holes in aluminum plates until drill breakage. Approximately 400 holes were drilled in each 28 × 15 × 2.5-cm sandcast B319 plate with T5 heat treat (BHN500 hardness = 80). B319 is a cast aluminum alloy containing 5.5–6.5% silicon, 3–4% copper and 0.1–0.5% magnesium. Dry drilling was found to be very sensitive to the composition and metallurgy of the aluminum. For consistency, the same lot of B319 aluminum was used for all the tests reported here. To estimate temperatures during drilling, thermographic images were made using an infrared camera of the side of the aluminum plate 2.5 mm from the hole being drilled.

Prior to starting the machining tests, 5 drill geometries and 15 speed-feed combinations were evaluated to choose optimal conditions for these tests. The drills chosen were 6.35-mm (¼″), 2-flute, high-helix, 118° point angle HSS drills (Precision Twist) and 6.35-mm, 3-flute, 30° helix, 130° point angle carbide drills (Kennametal). The HSS drills were tested at 61-m/min speed and 0.13-mm/rev feed. The carbide drills were tested at 213-m/min speed and 0.18 mm/rev feed. Spindle power was monitored during drilling. The drills were tested to failure, typically resulting from fracture of the drill after its flutes became clogged with aluminum. The total number of holes drilled with a single drill were counted as well as the number of holes until the first hole that was not to specifications as determined when a 6.35-mm dowel could not be inserted into the hole.

3. Results

3.1. Coatings

The coatings tested in each group are shown in Table 2, including the coating type, the category, the designation used in the paper, and the hydrogen content. Six of the eight coatings were analyzed for hydrogen content and at least one within each category. A description of each coating follows.

- Me-DLC: The Me-DLC coating had a titanium aluminum nitride interlayer with a tungsten-containing carbon coating on top [15]. It was 3-μm thick, of which 2/3 was TiAlN and 1/3 WC/C. It had a lower sp^3 content than the HDLC coatings. The hydrogen content was low near the surface (0.038 H/C), but increased to 0.14 with depth.
- Graphitic: The graphitic coating was deposited by sputtering from a graphite target and was primarily sp^2 carbon with a low hydrogen content [16]. It had a total thickness of 1.2 μm with a 0.2 μm Cr interlayer and 5% to 8% Cr in the graphitic layer.
- Blend: The Blend coating was treated as a blend of the graphitic and the HDLC. As with the graphitic coating, it was sputtered from a graphite target. However, the hydrogen content of the coating was fairly high suggesting that an organic source was also present in the deposition chamber. It had a thickness of 1.5 μm.
- HDLC: Coatings from two suppliers were tested in the hydrogenated DLC group. The HDLC1 was a 4–5-μm layered coating with the highest H content of the coatings

Table 2
Coatings tested in study

Coating type	Category	Designation	Hydrogen H/C atom ratio
Metal-containing	Me-a-C:H	Me-DLC	0.038 to 0.14
Graphitic	a-C	Graphitic	0.013
Blend	a-C/a-C:H	Blend	0.27
Hydrogenated DLC	a-C:H	HDLC1	0.34
		HDLC2	ND
Nonhydrogenated DLC	ta-C	DLC1	<0.01
		DLC2	ND
CVD Diamond	t-C	Diamond	0.016