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Tapping of Al–Si alloys with diamond-like carbon coated tools and minimum quantity lubrication

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ABSTRACT

The deep hole drilling and tapping of automotive powertrain components made of hypoeutectic Al–Si alloys are of considerable importance. This work investigates the dry and minimum quantity lubricated (MQL) tapping of Al–6.5%Si (319 Al) alloys as alternatives to conventional flooded tapping. Two types of tests were done in comparison with flooded tapping. In the first set dry tapping experiments were performed using diamond-like carbon (DLC) coated and uncoated HSS taps. HSS-dry tapping caused immediate tool failure within less than 20 holes due to aluminum adhesion, resulting in high forward and backward torques. DLC-dry tapping improved tool life considerably and exhibited small torques. The second set of tapping experiments used MQL and only uncoated HSS taps. The use of MQL at the rate of 80 ml/h produced similar average torques to flooded tapping, and a high thread quality was observed. DLC coatings' low COFs against 319 Al limited the temperature increase during DLC-dry tapping to 75 °C. The low COF of DLC against aluminum was responsible for preventing built-up edge (BUE) formation and thus, instrumental in improving thread quality. The use of MQL reduced the tapping temperature to 55 °C. The mechanical properties of the material adjacent to tapped holes, evaluated using hardness measurements, revealed a notable softening in the case of HSS-dry tapping, but not for MQL tapping. The presence of sulphur and phosphorus-based additives in MQL fluids proved beneficial in preventing aluminum adhesion.

1. Introduction

Tapping is one of the most intensively utilized machining operations for obtaining internal threads in Al–Si castings. Tapping is also typically one of the final machining operations to be performed. As such if a tapping tool fails, the workpiece has already accrued significant added value and, in most cases, the costs of scrapping or re-working it are very high. The breakage of a thread-cutting tool significantly impacts the productivity of the process. In the case of Al–Si castings – an important class of lightweight materials – a leading cause of tool breakage is the transfer of aluminum onto the tool surface. Warrington et al. (2005) reported that during dry tapping, the aluminum chips formed have a tendency to adhere to the thread surfaces, causing them to clog in a very short period of time. This adhesive interaction affects the tool surface, making it difficult for the chips to be cleared from the cutting zone. Consequently, chips fill the pitches of the tap, causing the torque to increase and with it, the probability of tool breakage increases substantially.

Dasch et al. (2006) reported the benefits of using carbon-based tool coatings, specifically diamond-like carbon (DLC) coatings to reduce the intensity of the tool/workpiece adhesive interaction during the dry drilling of Al–Si alloys. This report is in agreement with the tribological tests, which have clearly demonstrated the aluminum adhesion mitigating properties and low friction characteristics of DLC coatings as noted by Konca et al. (2006). Bhowmick and Alpas (2008a) observed that in addition to prolonged tool life, lower torques and thrust forces were also maintained—particularly when 40 at.% hydrogen-containing DLC coatings on high speed steel, HSS, drills were used during dry drilling. Another strategy for reducing adhesion between the workpiece and the tool is to use a minimum quantity of lubrication (MQL)—fed to the machining point in fine droplets at the rate of 10–100 ml/h (Boothroyd and Knight, 2006). The MQL agent is generally mineral oil, but some applications have also utilized an emulsion or water (Bhowmick et al., 2010). Previous studies on ferrous alloys investigated the tapping operation with taps that had a variety of different cutting edge geometries or in conjunction with a suitable coating. A survey of the existing literature on tapping research as it relates to ferrous and nonferrous alloys, principally aluminum alloys, is given in the following paragraphs.

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Chen et al. (2007) studied the role that cutting edge geometry played in the tapping of austenitic stainless steel by comparing the performances of straight fluted taps with a helix angle of 0° and spiral pointed taps with a helix angle of 34°—both in conventional flooded (oil–water emulsion) conditions at a speed of ~60 rpm and a feed rate of 1.00 mm/rev. A slight decrease in average torque to 4.5 N m was observed during tapping with the spiral flute compared to the conventional straight flute taps (5.0 N m). Veldhuis et al. (2007) studied the influence that the presence of a perfluorpolyether (PFPE) film on HSS steel tools had on torque responses during the tapping of mild steel in flooded (oil–water emulsion) tapping conditions at a speed of 260 rpm and a feed rate of 1.58 mm/rev. PFPE was deposited by dipping the tool into the solution, which provided an even coating to the rough tool surface. The presence of PFPE on the HSS tool surface reduced the torque slightly to ~21 N m, compared to ~25 N m when an uncoated tap was used. Reiter et al. (2006) evaluated the dry tapping performance of austenitic stainless steel using conventional hard metallurgical coatings, including CrN, CrC, TiCN and TiAlN—comparing them to the new, DLC coatings that incorporate WC. DLC coatings displayed the lowest average torque (5.25 N m) followed by TiAlN (7.43 N m), CrN (7.19 N m), TiCN (6.85 N m) and CrC (6.55 N m)-coated HSS tools. Flank built-up edges (BUEs) were observed during the tapping with DLC-coated tools, while no significant BUE occurred with conventional TiCN or TiAlN coatings.

Only a few studies have been conducted on the tapping of aluminum alloys. Srivastava et al. (2004) investigated the form tapping of 319 Al alloys and focussed on the performance of uncoated HSS, uncoated carbide and TiN-coated HSS taps in flooded (semi-synthetic oil) conditions at a speed of 1100 rpm and a feed rate of 1.25 mm/rev. In form tapping, threads are not created by chip removal, but by the plastic deformation and displacement of the material. TiN-coated HSS taps produced lower torque (~0.07 N m) when compared to uncoated HSS (~0.61 N m) and uncoated carbide (~0.14 N m) tools. Zedan et al. (2010) investigated the effects of iron content during the conventional tapping of Al–Si alloys using TiN-coated HSS taps at speed and feed rates of 400 rpm and 1.25 mm/rev, respectively, in flooded tapping conditions (synthetic fluid). An increase in the average tapping force of 470 N was observed for Al–12% Si–0.46% Fe, due to a significant amount of iron-rich intermetallics—compared to Al–7% Si–0.30% Fe (250 N).

Meanwhile, some research has been conducted on the application of MQL to the drilling of aluminum alloys, a machining process akin to tapping, but less complicated. Klocke and Eisenblaetter (1997) investigated the effect that MQL has on the drilling of aluminum–9% silicon alloys using a carbide drill. It was reported that a synthetic ester-based MQL fluid supplied at a rate of 10 ml/h resulted in a decrease in cutting torque to ~3 N m compared to ~10 N m generated during dry drilling. Kelly and Cotterell (2002) conducted a comparative study of the dry, MQL and flooded drilling of a wrought aluminum–4.5% magnesium alloy (5080 Al). The maximum torque generated during MQL drilling using vegetable oil-based MQL supplied at 20 ml/h was 2.2 N m, which compared favourably with dry drilling conditions using a carbide drill, which generated a maximum torque of 3.8 N m. MQL appeared to perform slightly better than flooded drilling with mineral soluble oil, for which the highest torque was 2.4 N m.

Braga et al. (2002) studied the MQL drilling of an aluminum 319 alloy using a carbide drill, and reported that MQL drilling using mineral oil supplied at a rate of 10 ml/h generated a maximum thrust force of 1260 N—comparable to the 1250 N measured during soluble oil flooded drilling. Results revealed that the average torque of 3.71 N m measured for the flooded drilling of aluminum 319 alloy conditions was comparable to that measured for the vegetable oil MQL using DLC-coated HSS drills (Dosbaeva et al., 2008). The cutting performance of DLC-coated HSS drills in a distilled water spray (30 ml/h) used as the MQL agent (H_2O-MQL) was also examined by Bhowmick and Alpas (2008b). The H_2O-MQL cutting of 319 Al using DLC-coated drills reduced the average drilling torque to 1.65 N m, compared to dry drilling (4.11 N m) at a level similar to the performance under the water soluble flooded conditions (1.75 N m).

Despite the research efforts reviewed above, a significant knowledge gap exists regarding the effects that MQL tapping has on tool life, torque requirements and the thread quality of aluminum alloys. The objective of this work is to assess whether the MQL tapping of Al–6.5% Si (319 Al) can demonstrate a comparable performance to conventional flooded tapping. The role of DLC-coated tools in reducing the torque and increasing the tool life during dry tapping of 319Al is also considered. This particular alloy was selected due to the widespread use of 319 Al castings in automotive engine blocks, cylinder heads, crank cases, transmission cases and especially for upper valve components—where deep hole drilling and tapping are the essential machining operations. In the meantime, it should be noted that tapping at high speeds will contribute to the industry's efforts to reduce overall production times. Currently, tapping operations on aluminum are typically performed in medium speed ranges of 400 (10 m/min)–1000 rpm (25 m/min) (Srivastava et al., 2004; Zedan et al., 2010). With this in mind, the tapping experiments in this work were conducted at 2000 rpm (50 m/min). Tapping performance was evaluated through forward and backward torque measurements in the workpiece material. The heat generated during tapping using coated and uncoated tools under various conditions was determined and correlated with the results of tribological tests, which were used to determine coefficients of friction (COFs) between 319 Al and DLC-coated and uncoated HSS steel under dry and lubricated sliding contact. The quantitative metallography of the tool surfaces and a differential scanning calorimetry (DSC) of the MQL fluid were also carried out and used to analyse the factors influencing aluminum adhesion to the tool surface as a way of rationalizing performance measures like tool life and thread quality.

2. Experimental details

2.1. Description of workpiece material and cutting tools for drilling and tapping

The workpiece material tested was a sand-cast hypoeutectic 319-grade aluminum–silicon alloy consisting of (in wt.%) 6.5% Si, 3.5% Cu, 0.1% Mg, 0.5% Mn, 0.35% Ni, 1.0% Zn, 1.0% Fe, 25% Ti and the balance aluminum. The bulk hardness of the 319 Al was 72.40 HR-15T, measured as Rockwell Superficial Hardness using a 1.59-mm diameter ball and a 15 kg load. The workpiece was in the form of rectangular blocks of 30 cm × 15 cm × 2.5 cm and tested in as-cast condition.

The cutting tools used for the tapping were 8.00 ± 0.01-mm diameter HSS spiral taps with the commercial designation of M8 × 1.25 with the following composition (in wt.%): 0.95% C, 6.00% W, 5.00% Mo, 4.20% Cr, 2.00% V, and the balance Fe. A schematic of the spiral taps used is shown in Fig. 1a. The tap consisted of three spiral flutes with 1.25 mm pitch length and 90° flute angle. The angle between pitches was 60°. The diameter of the tap was 8 mm and the overall length is 95 mm. The cutting tools used for the drilling (prior to the tapping experiments) were 6.35 ± 0.01-mm diameter twist drills, also made of the same HSS material as the taps, The average hardness of the HSS material was 64 ± 2.50 HRC.

DLC coatings were deposited on the taps using a plasma-enhanced chemical vapour deposition process (PECVD). The DLC