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Wear, cutting forces and chip characteristics when dry turning ASTM Grade 2 austempered ductile iron with PcBN cutting tools under finishing conditions

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ABSTRACT

Experimental studies of wear, cutting forces and chip characteristics when dry turning ASTM Grade 2 austempered ductile iron (ADI) with polycrystalline cubic boron nitride (PcBN) cutting tools under finishing conditions were carried out. A depth of cut of 0.2 mm, a feed of 0.05 mm/rev and cutting speeds ranging from 50 to 800 m/min were used. Flank wear and crater wear were the main wear modes within this range of cutting speeds. Abrasion wear and thermally activated wear were the main wear mechanisms. At cutting speeds greater than 150 m/min, shear localization within the primary and secondary shear zones of chips appeared to be the key-phenomenon that controlled the wear rate, the static cutting forces as well as the dynamic cutting forces. Cutting speeds between 150 and 500 m/min were found to be optimum for the production of workpieces with acceptable cutting tool life, flank wear rate and lower dynamic cutting forces.

1. Introduction

The automotive industry, which is extremely competitive, is interested in austempered ductile iron (ADI) because it offers properties similar to those of heat-treated alloy steels. These include high strength, high hardness, excellent toughness, high ductility, good fatigue properties and useful wear characteristics at lower cost and reduced weight.

Because of these properties, ADI is difficult to machine in the austempered condition. With regards to other engineering ductile cast irons, the relatively high strength and hardness of ADI as well as the inclination of its retained austenite to strain hardening lead to short contact length and higher mechanical loads on the cutting tool's edge (Yamamoto et al., 1995). The relatively high ductility of ADI favours its adhesion on the cutting tool and brings also about higher temperature on the cutting tool's edge (Klocke and Klöpper, 2002). Because of higher specific loads and higher temperatures that develop on the cutting tool's edge when machining ADI in its austempered condition, cutting tools often suffer relatively high flank and crater wears compared to hardened steels and other engineering grey cast irons. The severe crater scar that develops very close to the cutting tool's edge exposes the latter to fracture damage (Pashby et al., 1993). Of course, the higher cutting temperatures as well as the relatively low thermal diffusivity and short contact length of ADI could also expose the cutting tools' edge to thermal softening (Gekonde and Subramanian, 1995).

In these conditions, cutting tools for machining ADI should fundamentally yield at the same time: high hot hardness and strength, excellent hot chemical inertia as well as high toughness. Such cutting tools are ideal and do not rigorously

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speaking exist in the present cutting technology. However, they are the purpose of the continuous research undertaken in the field. Coating technology appears to be an alternative. Nowadays, coatings on cutting tools are being used to improve the tribological properties of cutting tools in this ideal way (Knotek et al., 2001). Results show significant improvements in some cases, especially at relatively low cutting speeds. However, the issue of the mechanical stability (flaking) of these coatings sometimes reduces the expectations. Thus, it is a matter of finding a compromise cutting tool material and or coating as well as optimum machining parameters.

Machining of ADI in its austempered condition is highly desirable because it can yield the tight tolerances and surface finishes generally required (Klocke et al., 2007), save machining time and thus reduce costs (Klocke and Klöpper, 2002). In depth fundamental understanding of interactions involved in this particular machining of ADI in its austempered condition should show the way to the optimum cutting tool material and or coating as well as optimum machining parameters (productive cutting speeds and feed rates, etc.). These outcomes would be among the last obstacles to be overcome before intensifying the use of this material in the automotive industry.

This very complex issue attracts great interest from the cutting tool industry since nearly two decades. The comprehensive research conducted hitherto on the machinability of various grades of ADI is almost very little. It has so far addressed few fundamental questions concerning the cutting performance and wear mechanisms of various types of cutting tools under various machining parameters and conditions.

Pashby et al. (1993) investigated on the wear of Al_2O_3, Al_2O_3–TiC, Al_2O_3–SiC_w, and Si_3N_4–Al_2O_3 ceramic cutting tools when dry turning ADI close to ASTM Grade 2 under conditions close to light roughing (depth of cut: 2 mm; feed rate: 0.18 mm/rev; cutting speed: 100–450 m/min). They reported that flank wear was the main wear mode although tool fracture occurred at the highest speed. Si_3N_4–Al_2O_3 ceramic cutting tools suffered accelerated wear whereas Al_2O_3–SiC_w ceramic cutting tools significantly underperformed Al_2O_3 and Al_2O_3–TiC ceramic cutting tools under most conditions. Fracture damage on the tools' cutting edge and chemical interaction between tool and workpiece were identified as important wear mechanisms in controlling tool life.

Masuda et al. (1994) investigated on the cutting performance and wear mechanism of P20 cemented carbide cutting tools, Al_2O_3–ZrO_2 (5 wt.%), Al_2O_3–ZrO_2 (20 wt.%), Al_2O_3–TiC (30 wt.%), Al_2O_3–SiC_w–ZrO_2, Al_2O_3–SiC_w–TiC and Si_3N_4 ceramic cutting tools when dry turning ADI close to ASTM Grade 1 under conditions close to light roughing (depth of cut: 1 mm; feed rate: 0.1 mm/rev; cutting speed: 50–400 m/min). They reported that Al_2O_3–TiC (30 wt.%) inserts had the longest life at a low cutting speeds of about 100 m/min and less, and ZrO_2-toughened Al_2O_3 inserts had a longer tool life at cutting speeds of about 250 m/min or more. Al_2O_3–SiC_w–ZrO_2 and Al_2O_3–SiC_w–TiC ceramic cutting tools exhibited flaking fracture at 250 m/min whereas Si_3N_4 ceramic cutting tools had no wear resistance at all. Cemented carbide inserts had longer life at very low cutting speeds. As cutting speed rose, the flank wear rate increased slightly for Al_2O_3–TiC (30 wt%) inserts. In contrast, it decreased for ZrO_2-toughened Al_2O_3 inserts due to the monoclinic-to-tetragonal transformation of ZrO_2 at high cutting temperatures.

In order to elucidate the mechanism of poor machinability of ADI, Yamamoto et al. (1995) investigated on the turning of ADI close to ASTM Grade 1 with Al_2O_3–SiC_w cutting tools under conditions close to light roughing (depth of cut: 1.5 mm; feed rate: 0.2 mm/rev; cutting speed: 6–300 m/min). Their results showed at cutting speed lower than 36 m/min, the strain-induced residual austenite to martensite transformation occurred in the chips as well as the damaged layer of the machined surface. This strain-induced transformation was responsible of the poor machinability of ADI. At higher cutting speeds this strain-induced transformation occurred only in the damaged layer of the machined surface and not in the chips.

Wada et al. (1998) investigated on the wear of coated cemented carbide cutting tools, coated Al_2O_3 ceramic cutting tools and coated Si_3N_4 ceramic cutting tools in dry turning of ADI close to ASTM Grade 2 under conditions close to light roughing (depth of cut: 1 mm; feed rate: 0.2 and 0.4 mm/rev; cutting speed: 30–400 m/min). They found that Ti(C,N)–Al_2O_3–TiN coated P10 carbide inserts had the slowest flank wear progress with regard to TiC–Al_2O_3–TiN coated P20 and TiN coated K10 carbide inserts. TiN coated Al_2O_3 ceramic inserts had tool wear progress similar to Ti(C,N)–Al_2O_3–TiN coated P10 carbide inserts. Abrasive wear was observed on the flank face of TiN coated Al_2O_3 and TiN–Al_2O_3–TiN coated Si_3N_4 ceramic inserts at relatively low cutting speeds. The flank wear of TiN–Al_2O_3–TiN coated Si_3N_4 ceramic inserts increased rather slowly at the high feed rate of 0.4 mm/rev. On the other hand, the TiN coated Al_2O_3 ceramic inserts had a tendency to fracture easily at this high feed rate of 0.4 mm/rev.

Klocke and Klöpper (2002) investigated on the turning of ADI close to ASTM Grade 1 with coated cemented carbide cutting tools (Al_2O_3 coated K10, Ti(C,N) coated K10, TiN–Al_2O_3 coated P15), Al_2O_3 and Si_3N_4 ceramic cutting tools under conditions close to light roughing (depth of cut: 1 mm; feed rate: 0.2 mm/rev; cutting speed: 120–400 m/min) with and without cutting lubricants. They pointed out that coated cemented carbides cutting tools could be successfully used in the range of low cutting speeds. In the range of high cutting speeds, the use of Al_2O_3 ceramic cutting tools was attractive. The performance of Si_3N_4 ceramic cutting tools was very poor. Cutting lubricants were very effective in the reduction of the flank and crater wear scars of cemented carbide tools, particularly at relatively high cutting speeds.

Goldberg et al. (2002) studied the dry interrupted facing of an ASTM Grade 3 ADI with Al_2O_3–TiC and Al_2O_3–SiC_w ceramic cutting tools under conditions close to light roughing (depth of cut: 2 mm; feed rate: 0.1–0.4 mm/rev; cutting speed: 425 m/min) and finishing (depth of cut: 0.5 mm, feed rate: 0.1–0.4 mm/rev; cutting speed: 700 m/min). Their results indicated that Al_2O_3–SiC_w ceramic inserts performed better than Al_2O_3–TiC ceramic inserts both for rough interrupted facing and finish interrupted facing at high cutting speeds. The lack of overwhelming performance for Al_2O_3–TiC ceramic inserts in this very situation would be linked to their poor thermal shock resistance. They reported that the tool wear characteristic was exclusively flank wear which was a direct consequence of adhesive–abrasive wear mechanism.