Wear Characteristics of Ultra-Hard Cutting Tools when Machining Austempered Ductile Iron

Ashwin Polishetty, Dr. Moshe Goldberg and Dr. Guy Littlefair

Abstract— Nodularised Ductile Cast Iron, when subjected to heat treatment processes – austenitising and austempering produces Austempered Ductile Iron (ADI). The microstructure of ADI also known as “ausferrite” consists of ferrite, austenite and graphite nodules. Machining ADI using conventional techniques is often a problematic issue due to the microstructural phase transformation from austenite to martensite during machining. This paper evaluates the wear characteristics of ultra hard cutting tools when machining ADI and its effect on machinability. Machining trials consist of turning ADI (ASTM Grade 3) using two sets of PCBN tools with 90% and 50% CBN content and two sets of ceramics tools; Aluminium Oxide Titanium Carbide and Silicon Carbide – whisker reinforced Ceramic. The cutting parameters chosen are categorized as roughing and finishing conditions; the roughing condition comprises of constant cutting speed (425 m/min) and depth of cut (2mm) combined with variable feed rates of 0.1, 0.2, 0.3 and 0.4mm/rev. The finishing condition comprises of constant cutting speed (700 m/min) and depth of cut (0.5mm) combined with variable feed rates of 0.1, 0.2, 0.3 and 0.4mm/rev. The benchmark condition to evaluate the performance of the cutting tools was tool wear evaluation, surface texture analysis and cutting force analysis. The paper analyses thermal softening of the workpiece by the tool and its effect on the shearing mechanism under rough and finish machining conditions in term of lower cutting forces and enhanced surface texture of the machined part.

Index Term— ADI, Cutting force analysis, Surface texture analysis, Tool wear analysis

I. INTRODUCTION

In recent times, Austempered Ductile Iron (ADI) has been in increasing demand due to its wide range of balanced and advantageous material properties, which include high strength-weight ratio, excellent wear resistance and high yield strength. Rising demand for materials with high strength-weight ratio makes ADI (Austempered Ductile Iron) an attractive alternative for materials in different sectors of engineering as it provides reduced material usage. The automotive industries use ADI to reduce the weight of automotive engines and other ancillaries in order to meet the latest environmental regulations on climate change and emissions [1]. ADI outperforms steel (forged and cast), and aluminium, in terms of cost per unit yield strength.

As a result, cost reductions can be achieved in high strength applications. The typical use of ADI in automotive industries includes components such as crankshafts, connecting rods, CV joints, tow hooks and differential spiders [1]. ADI is ideal for use in high wear applications such as excavator teeth, mining wear plates and agricultural ground engagement components due to its high strength and work hardening capability [2].

A. Background of the material-ADI

The typical microstructure of ADI (ASTM Grade 3) is shown in Fig.1, where three distinct fractions can be seen namely: - austenite (white background), ferrite (needle like structure) and graphite (spheroidal nodules). Table I contains the chemical composition of the ADI (ASTM Grade 3). Table II states the material properties of ADI (ASTM Grade 3).

![Fig. 1. Typical microstructure of ADI (ASTM Grade 3)](image)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cu</th>
<th>Ni</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.65</td>
<td>2.8</td>
<td>0.1</td>
<td>0.00</td>
<td>0.02</td>
<td>0.9</td>
<td>0.0</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Table I

<table>
<thead>
<tr>
<th>Hardness</th>
<th>388 BHN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>1221 N/mm²</td>
</tr>
<tr>
<td>Elongation</td>
<td>7.2%</td>
</tr>
</tbody>
</table>

Table II

Fig.2 shows the production of ADI [3]. The two-stage heat treatment process involves decomposition of austenite to ferrite and enriched austenite at the first stage. In the second stage, austempering is conducted in a controlled manner in order to avoid the decomposition of enriched austenite to ferrite and carbide. To ensure the ideal combination of...
mechanical properties, the heat treatment parameters should be optimised after the completion of the first reaction (AB) known as austenitisation at temperatures of 840°C - 950°C (1550°F – 1750°F) and at the onset of the second reaction (DE) known as austempering at temperatures of 230°C – 400°C (450°F – 750°F) [4].

Fig. 2. A typical austempering cycle

This heat treatment produces a unique microstructure within the material. The ferrite and carbon stabilized austenite combine and form alternating layers with a distinctly needle like appearance known as acicular ausferrite and it is where ADI obtains its high strength and hardness. Spherical graphite nodules are found within this matrix of ausferrite and these promote the good fatigue characteristics. [5].

Research efforts have provided machinists with innovative techniques to machine less machinable materials. Previous experimental results and research data on machining studies of ADI leave numerous gaps regarding the nature of the cutting mechanism. However, Chang et al, have reported on research work associated with ADI crankshaft development for Chrysler automobiles [6]. Pashby and Wallbank, reported a reduction in tool life when machining ADI at elevated cutting speed for a range of cutting tool materials [7].

Seah and Sharma, evaluate the machinability of ADI by integrating an index value as a part of the machinability assessment [8]. The amounts of unreacted residual austenite present in the microstructure play an important role in the machinability of ADI. On machining ADI with high Unreacted Residual Austenite (URA) content, URA changes to martensite due to the high residual stress and heat involved. The surface is work hardened and resists further machining, eventually leading to tool failure [9]. Yamamoto et al. also report that strain induced phase transformation leads to poor machinability of ADI [10]. Another detrimental aspect is that carbides formed along cell boundaries due to poor casting quality which are hard and brittle phases have a negative influence on the machinability of ADI [11]. Katuku et al. reported wear, cutting force and chip characteristics when dry turning ADI with PCBN tools under finishing conditions; depth of cut 0.2mm, feed rate 0.05mm/rev and cutting speeds ranging from 50 to 800 m/min [12].

II. EXPERIMENTAL PROCEDURE

The aim of the experimental investigation was to establish the machinability characteristics of ADI using both PCBN and ceramic cutting tools when machining ADI and also to evaluate the machining characteristics of ADI (ASTM Grade 3) by analysing tool wear, cutting force and surface texture of the machined part, as shown in Fig.3.

Experimental design consisted, turning circular ADI components under extreme and moderate conditions, referred to henceforth as roughing and finishing conditions. The roughing conditions comprise of constant cutting speed (425 m/min) and depth of cut (2mm) combined with discrete feed rates of 0.1, 0.2, 0.3 and 0.4mm/rev. The finishing conditions comprise of constant cutting speed (700 m/min) and depth of cut (0.5mm) combined with discrete feed rates of 0.1, 0.2, 0.3 and 0.4mm/rev. Table 3 tabulates the eight permutations for the experimental design under roughing and finishing conditions. The cutting tools in consideration are two sets of PCBN tools with 90% and 50% Cubic Boron Nitride (CBN) content and two sets of ceramics tools; Aluminium Oxide Titanium Carbide and Silicon Carbide – whisker reinforced Ceramic. Table 4 illustrates the tool characteristics of PCBN and Ceramic cutting tools. The cutting tools had their cutting edges rounded and the effect of the rounded cutting edge geometry on tool wear, surface texture and cutting force is discussed in the results. Dry conditions or no coolant was used for the machining trials. The machine used for the purpose was a Cincinnati Milacron 200/15 turning centre.
equipped with Kistler platform cutting force dynamometer (9257B) to measure the three orthogonal cutting forces.

### TABLE III
**MACHINING PARAMETERS FOR ROUGHING AND FINISHING CONDITIONS**

<table>
<thead>
<tr>
<th>Tool Name</th>
<th>Specification Type</th>
<th>Tool Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool A - 90% CBN + 10% Ceramic binder (Amborite)</td>
<td>RNMN 120300T, 6° negative rake angle</td>
<td>Solid polycrystalline crystal with high Cubic Boron Nitride (CBN) content and relatively coarse grains.</td>
</tr>
<tr>
<td>Tool B - 50% CBN + 50% Ceramic binder (DBC50)</td>
<td>RNMN 120300S0220F, 6° negative rake angle</td>
<td>Carbide backed polycrystalline with reduce CBN content and fine grain structure.</td>
</tr>
<tr>
<td>Tool C - Aluminium oxide (Al₂O₃) + Titanium carbide (TiC)</td>
<td>RCGN – 4V T2A</td>
<td>Used for machining of cast iron and steels which exceeding 32 Rockwell (Rc), at high-elevated temperature.</td>
</tr>
<tr>
<td>Tool D - Silicon carbide single crystals (Whisker reinforced ceramic)</td>
<td>RCGN – 4V T1</td>
<td>Exhibits a unique material that holds advantageous properties such as high hardness, high thermal shock resistance and high melting point.</td>
</tr>
</tbody>
</table>

### TABLE IV
**CUTTING TOOLS IN THE EXPERIMENTAL WORK**

<table>
<thead>
<tr>
<th>Roughing conditions</th>
<th>Finishing conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting Speed (m/min)</td>
<td>Depth of Cut (mm)</td>
</tr>
<tr>
<td>1 425</td>
<td>2</td>
</tr>
<tr>
<td>2 425</td>
<td>2</td>
</tr>
<tr>
<td>3 425</td>
<td>2</td>
</tr>
<tr>
<td>4 425</td>
<td>2</td>
</tr>
</tbody>
</table>

For the ease and better understanding of the results, the main task was divided into sub tasks; evaluating the machining process using the tool wear and cutting force analysis; and machined component using the surface texture analysis. Comparison between the results obtained for Tool A, Tool B, Tool C and Tool D justifies the performance characteristics of each cutting tool. The machining trials were performed on a CNC machine programmed with finishing and roughing operations that compromised one continuous pass of “metal removal”. One pass of metal removal incorporated removing material from an ADI casting of 250mm diameter with a 40mm material thickness dimension, as displayed in Fig.4. The metal removal process was repeated four times with various feed rates for either roughing or finishing machining conditions. This array of machining conditions was then applied four times, each time using a different cutting tool, producing in total eight discrete trials for each cutting tool. After each trial, the cutting inserts were examined under an optical microscope, in order to evaluate and record the tool flank wear (Vbmax). The cutting tool inserts were replaced each time in order to provide a fresh cut edge. The surface texture measurements (Ra) were automatically measured using a well calibrated electronic instrument (Talysurf VI) in order to ensure traceability, repeatability and confidence in the results.

**Fig. 4. ADI specimen before machining**

### III. RESULTS AND DISCUSSION

The obtained results are illustrated graphically and the results are interpreted according to the pre-defined machinability assessment criteria. The results from the tool wear analysis, surface texture analysis and cutting force analysis on ADI (ASTM Grade 3) subjected to turning operation using Tool A, Tool B, Tool C and Tool D are all independently reported.

**A. Tool wear analysis**

Klocke et al. reported extreme crater wear located very close to the cutting edge is a characteristics tool wear phenomenon of ADI [13]. Due to the round nature of the cutting edges, there was no crater and notch wear but flank wear was present in differing levels of significance.

Flank wear (Vbmax) for the Tool A, Tool B, Tool C and Tool D are reported in the form of graphs in Fig.5 and Fig. 6.

**Fig. 5. Tool wear analysis for roughing operation**
The analysis indicates the tool wear developed on the flank plane of the cutting tool during roughing machining can be classified as natural low wear. Both Tool D and Tool A exhibited resilience during the roughing operation. The analysis of the tool wear developed for finishing machining condition indicates that Tool D (SiC) and Tool B (50% CBN content) were most durable when compared to their counterparts enduring least damage. In general, the tool wear appears mostly the consequence of the adhesive/abrasive wear mechanisms because of the mechanical removal of the surface layers at low cutting speeds and at high cutting speeds resulted in diffusion type of wear associated with Fick’s law which considers issues related to heat transfer and thermo-softening as time based diffusion factors [14]. The graphs indicate that the tool wear increases as the feed rate increases. Overall, the amount of tool wear for the roughing operation was higher when compared to the finishing operation. Comparing the roughing and finishing cutting conditions, Tool D proved to be a versatile tool producing good results.

A. Surface texture analysis

The surface texture assessment was conducted using a Taylor Hobson, Talysurf VI, surface roughness instrument at a cut off length of 0.8mm and 90° to the lay. The sampling length (Meter Cut Off) is sufficiently long to include a reliable amount of roughness data and yet short enough to exclude waviness from the measurement. The specimen was mounted in a flat V-shaped fixture on a granite surface. The arithmetic roughness parameter (Ra) refers to a numerical value for the surface. The graphical illustration of the surface texture values for both roughing and finishing operation is shown in Fig.7 and Fig. 8 respectively.

B. Cutting force analysis

The talysurf instrument automatically measured the Ra values in this work. The finite radius at the stylus tip fails to produce a true trace of the surface texture as it physically unable to penetrate the deepest valleys of the profile resulting in truncation of the narrow deep valleys. The surface texture obtained for tool A (90% CBN) was maximum for all machining conditions. The cutting speed determines the surface texture condition due to its influence on the temperature of the tool/workpiece interface. Overall, the surface texture deteriorated as the feed rate increase – as would have been expected.

The most optimised surface finish was obtained by employing cutting speed (700m/min) coupled with feed rate (0.1mm/rev) and depth of cut (0.5mm).
Due to the round cutting edges and the direction of tool motion, the cutting force measured indicates that the radial force was a dominant force. During machining, the tangential force was insignificant and played a marginal role and axial force was less dominant as expected for a turning operation. Hence, the cutting force analysis to machine ADI using the Tool A, Tool B, Tool C and Tool D was done with respect to the radial force. Fig. 10 and Fig. 11 shows the graphical illustrations of the variation in cutting force for roughing and finishing operation respectively for the Tool A, Tool B, Tool C and Tool D. As seen in the graphs, under roughing conditions, Tool D and Tool A gave the best performance and under finishing Tool B and Tool D gave the best performance producing lower cutting forces. The relationship between the cutting force and the thermo-softening effect of the workpiece can be seen in the graphs in terms of lower cutting force for high cutting speeds.

IV. CONCLUSION

The comparative study on wear characteristics of ultra-hard cutting tools when machining ADI has resulted in the following inferences.

1) Machining ADI requires cutting tool inserts having high toughness and efficient thermal conductivity. For rough machining operations, inserts having high CBN content are required in order to provide fast dissipation of heat. For finish machining, a relatively low thermal conductivity insert is required in order to concentrate the heat in the shear zone leading to softening of the work piece and reduction of insert wear on the cutting edge.

2) The amount of tool wear generated for the roughing operation was greater than the finishing operation. The tool wear graphs indicate that the effect of increase in tool wear as feed rate increase, which is predominant on PCBN tools and less effective on ceramic tools. Attrition wear was dominant at low cutting speeds and diffusion wear at high cutting speeds.

3) Cutting speed plays an important role in determining the surface texture by controlling the temperature of the tool/work piece interface. Feed rate demonstrated a dominant factor on the machined surface texture. The surface roughness values (Ra) increased at high feed rates generating greater cusp heights in the profile and vice-versa.

4) The benchmark analysis between PCBN and ceramic tooling indicated that Tool D (SiC) and Tool B (50% CBN content) are suitable for light cuts, high-speed machining operations or finishing, whilst Tool D (SiC) and Tool A (90% CBN content) are suitable for heavy cuts or rough machining. The cutting tool D (SiC) offers versatile solution and is suitable for both rough and finish machining. Machining ADI using Tool C (TiC) has not produced any advantageous machining results.

5) The cutting speed demonstrated a strong correlation with the cutting forces. The cutting force was low at high cutting speeds due to thermo-softening in the shearing zone. The thermo-softening effect due to the heat generated around the cutting zone had an impact on finish machining as low cutting forces were recorded.

6) Overall, ADI is a rapidly emerging material with useful mechanical properties. The purpose of using ADI in various design criteria will rely on the research outputs related to machining the material with ease and efficiency.
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REFERENCES


