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The Performance of PVD Coated Grade in Milling of ADI 800

M. Ibrahim Sadik, and Toril Myrtveit

***Abstract*—**The aim of this investigation is to study the performance of the new generation of the PVD coated grade and to map the influence of cutting conditions on the tool life in milling of ADI (Austempered Ductile Iron). The results show that chipping is the main wear mechanism which determines the tool life in dry condition and notch wear in wet condition for this application. This due to the different stress mechanisms and preexisting cracks in the coating. The wear development shows clearly that the new PVD coating (C20) has the best ability to delay the chipping growth. It was also found that a high content of Al in the new coating (C20) was especially favorable compared to a TiAlN multilayer with lower Al content (C30) or CVD coating. This is due to fine grains and low compressive stress level in the coating which increase the coating ability to withstand the mechanical and thermal impact. It was also found that the use of coolant decreases the tool life with 70-80% compare to dry milling.

***Keywords*—**Austempered Ductile Iron (ADI), coating, chipping, milling, tool performance.

I. Introduction

ADI (Austempered Ductile Iron) it is a type of cast iron which has great potential to improve the design of the components of nodular cast iron and substitute steel parts. This is due to the excellent mechanical properties of ADI. The industrial introduction of ADI as a material for design and construction of the components with specific fatigue strength has been increased in recent years. To achieve the right optimum of weight, strength and cost different demands on different processes (design, casting, heat treatment and machining) had been imposed. A good machinability index after heat treatment is one of the most important factors for this industrial introduction of ADI. The ADI had been introduced in different industries for design of suspension part, transmission components, engine components which are exposed to high levels of load and rolling stock manufacturing industry [1]–[3]. However the machinability of some higher grades (ADI900, ADI1000 and ADI1200) is the main obstacle for implementation of ADI in wider application.

M. Ibrahim Sadik is with Sandvik Tooling, R&D Materials and Processes - TRT, Stockholm, Sweden (+ 46 8 726 64 98; fax: + 46 8 18 67 05; e-mail: Ibrahim.sadik@ sandvik.com).

Toril Myrtveit is with Sandvik Tooling, R&D Materials and Processes - TRC, Stockholm, Sweden (e-mail: toril.myrtveit@ sandvik.com).

II. Work Piece Material and Experimental Set-Up

The work piece material consists of square bars with dimension of 90 x 60 mm and 500 mm length for laboratory testing. Table I and Fig. 1 below describes the chemical composition respective microstructure of the work piece material (ADI800). The analysis of the microstructure for all samples shows that the material consists of austenite and bainitic ferrite where the graphite nodules are uniformly distributed. The microstructure seems to be austenitised at 950 C^0 and austempered at 400 C^0 which gives a hardness of 260 – 300HB and tensile strength of 800 – 850 Nmm2.

TABLE I
The Microstructure of AD800 Used in This Investigation

Symbol	Quantity
C	3.51
Si	2.46
Mn	0.17
P	0.015
S	0.008
CU	0.18
Cr	0.02
Ni	1.56
MO	0.12
Ti	0.007

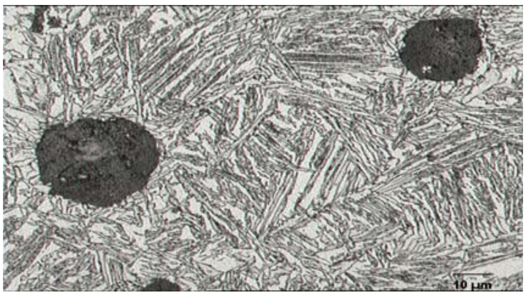


Fig. 1 The microstructure of AD800 used in this investigation

Fig. 2 below depicts the set-up for both wet and dry milling in this investigation, where a 90 degrees cutter (R390 - 080Q27-17L) was used for dry and wet face milling.

Fig. 2 The set-up for dry and wet milling testes

Table II describes the cutting data used in this investigation while Table III shows the coatings and insert geometry used.

TABLE II
CUTTING DATA USED IN THIS INVESTIGATION

Vc m/min	fz mm/tooth	ap (mm)	ae (mm)	Z
130	0.18	7.5	50	4

TABLE III
THE INSERTS USED IN THIS INVESTIGATION

Variant	Coating	Thickness (µm)	Geometry	Insert
C20	PVD	4	R390-170408M-KM	
C30	PVD	4	R390-170408M-KM	
C40	CVD	9	R390-170408M-KM	

The PVD variants (C20 and C30) are coated with different Al:Ti ratio where C20 has a relatively high Al-content and C30 has a lower Al-content. This is reflected in Fig. 2 where it is observed that the C20 has a glassy appearance typical of the very fine grained structure of high-Al AlTiN PVD-coatings. Typically, higher Al-content is associated with better flank wear resistance.

C30, on the other hand shows a more columnar structure reflecting the larger grains associated with a lower Al-content. The C30 coating is a multilayer structure, as is seen on Fig. 3, where thin lamellas of TiAlN-layers with different Al-content are stacked. Multilayer structures are usually showing enhanced toughness and thus enhanced ability of withstand both thermal and mechanical load cycling. Multilayers are also generally believed to delay crack propagation.

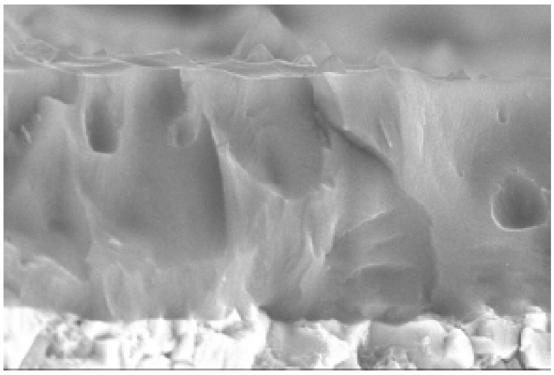


Fig. 3-a PVD coating C20

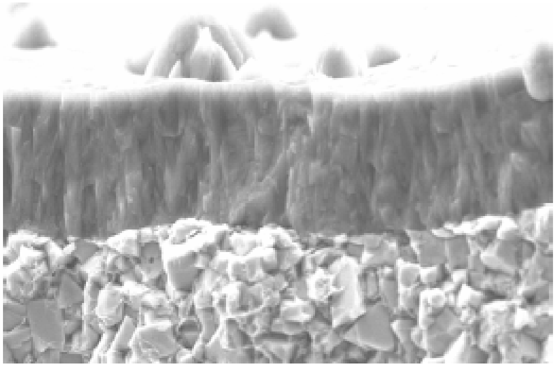


Fig. 3-b PVD coating C30

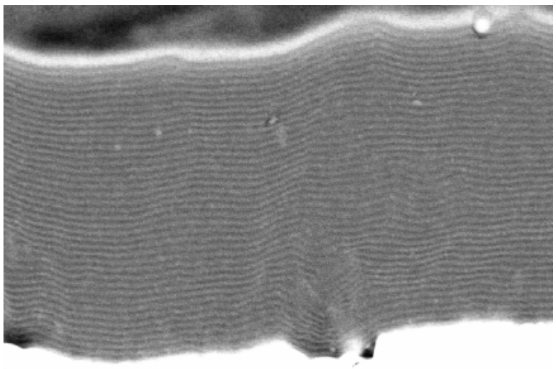


Fig. 3-c Multilayer structure of coating C30 showing the stacking of TiAlN-layers

The C40 coating was deposited using Chemical Vapor Deposition (CVD). The C40 coating consists of an inner TiCN-layer and an outer Al2O3-layer (se Fig. 4). CVD coatings are characterized by low tensile stresses while PVD coatings have high compressive stresses. Further, CVD-coatings often exhibit so called cooling cracks and together with the tensile stresses this will make CVD-coated cutting edges more brittle than PVD-coated ones.

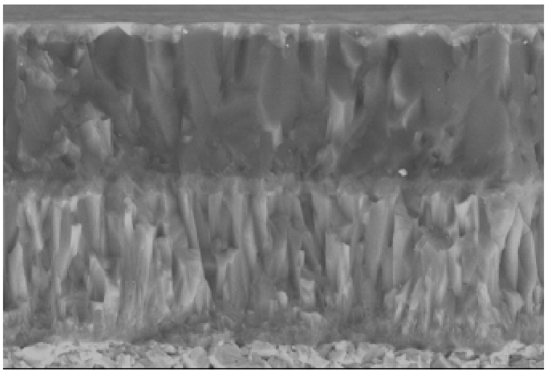


Fig. 4 The C40 coating with an inner layer of TiCN and an outer Al203 layer

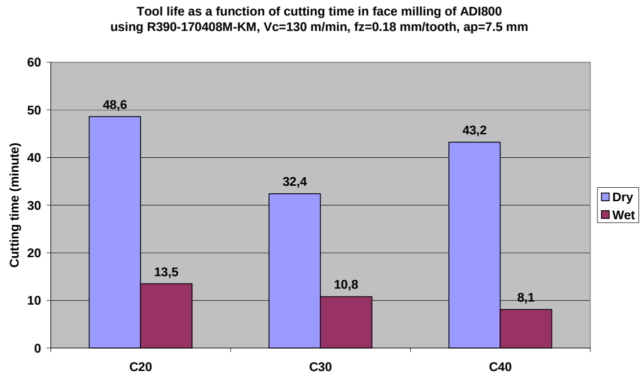


Fig. 5 The tool performance in dry and wet milling of ADI 800

III. Results and Discussion

Figs. 5 and 6 describe the tool performance and wear development in both dry and wet applications. According to Fig. 5 the best tool performance can be achieved by C20 which is PVD coated and optimized for milling of nodular cast iron. This new coating process for grade C20 creates a coating with small grains and low compressive stresses which leads to high abrasive wear resistance. The combination of crack-free coating, compressive stress and high abrasive wear resistance gives superior tool performance. The figure shows that a CVD coated grade (C40) is the second best candidate for dry milling of ADI. This is due to the thicker coating thus giving better wear resistance. On the other hand the CVD coated grade shows poor performance in wet condition. CVD coatings have tensile stresses and generally they have 'cooling cracks'. These pre-existing cracks will constitute a starting point for wider and deeper cracks due to thermal/mechanical intermittent loading. According to above the state of the stress in combination with coating thickness will delay or prohibit the crack propagation which resulted in long tool life. The figure also shows that the milling condition in terms of wet/dry has very large influence on the tool performance. According to the results the tool life can be decreased by 60-80% when the coolant is used.

The performance of coating C30 is interesting. Despite the multilayer structure which is commonly believed to give better toughness and crack inhibition, the coating performs less well than C20 in both dry and wet operation. The results indicate that the wear resistance clearly is more important than toughness in this operation. It is also interesting to note that the difference between dry and wet milling is less for coating C30, reflecting the tougher coating. The CVD-coating C40, which performs reasonably good in dry operation due to the coating thickness, degrades very much in wet operation where the propagation of the pre-existing cracks are rapidly degrading the coating.

Fig. 6 below describes the wear development for the variants in both dry and wet milling. The analysis of the wear shows clearly that the cutting tool exposed for different wear mechanisms depending on the cutting conditions (wet/dry). The figure shows that the tool is exposed to abrasive wear which is mixed of flank wear and small chipping of the cutting edge during the dry milling. In this case the wear development is very slow, especially the flank wear and resulting in long tool life. The chipping size increases by the cutting time faster than the flank wear and limit tool life in terms of unacceptable surface finish and/or high sound.

The figure indicates clearly that the tool is subjected for rapid wear development in wet condition.

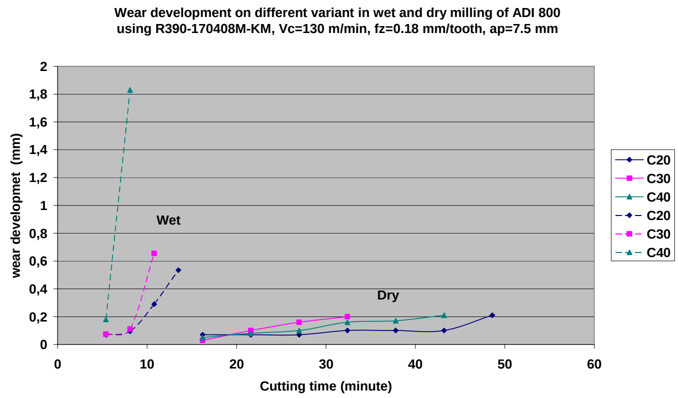


Fig. 6 The wear development on different variants in wet and dry milling of ADI 800

The main wear mechanism in wet condition is notch wear which is a result of intermittent load (thermal/mechanical) in combination with local cracks propagation, that is why the CVD-variant is exposed for faster and larger notch than the PVD – variants (see Figs. 6 and 7).

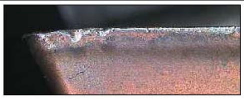
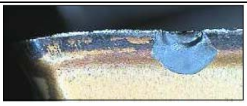
 C20 after 50 minutes dry milling	 C20 after 13.5 minutes wet milling
 C30 after 32.4 minutes dry milling	 C30 after 10.8 minutes wet milling
 C40 after 41 minutes dry milling	 C40 after 8.1 minutes wet milling

Fig. 7 The status of the inserts in the end of the tool life

The difference in performance between the CVD-coated variant (C40) and the PVD coated (C20) could be explained by the study of wear mechanism in different stage of wear development.

Figs. 8 and 9 describe the ability of the coating to withstand the abrasive wear and the crack initiation in the early stage of the cutting process. A comparison between the CVD and PVD status on the same cutting time shows that the CVD-coated expose higher wear rate and thermal cracks compared to the PVD-coated edge. This is due to the fact that the new PVD coating (C20) has a fine grained structure in combination with compressive stresses. The compressive stresses make the cutting edge tougher and it is therefore able to withstand crack propagation. On the other hand the CVD coating (C40) has a coarse grained structure, tensile stress and preexisting cracks which accelerate the crack propagation.

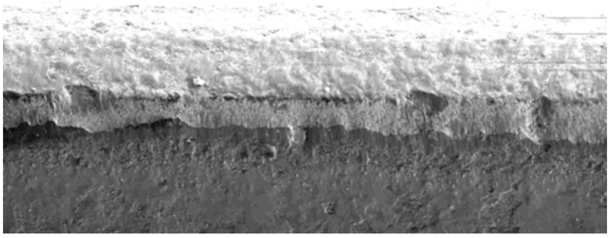


Fig. 8 PVD-coated edge (C20) after 10 minutes dry milling

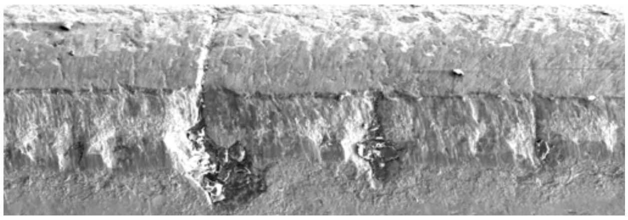


Fig. 9 CVD-coated edge (C40) after 10 minutes dry milling

IV. Conclusion

The chipping mechanism is the main wear mechanism which determines the tool life in dry condition, while notch wear is the determining mechanism in wet milling of ADI.

The wear development shows clearly that the new PVD process on grade (C20) has better ability to withstand the mechanical and thermal impact than C30 and C40 in milling of ADI. This is due to the difference in stress, grain structure, Al content and lack of preexisting cracks in the coating.

The coolant decreases the tool life with 70-80% compared to dry milling for all kind of coating.

In spite of the high toughness of the C30 coating, the C20 coating with high Al content gives better performance than the C30 – multilayer with low Al content in milling of ADI.

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