EVALUATING THE PERFORMANCE OF TiN COATING ON PM MILLING CUTTERS USED IN THE MANUFACTURING OF BANDSAWS

Mohammed Sarwar[a,]*, Julfikar Haider[a], Martin Persson[b], Håkan Hellbergh[b]

*, [a] Mohammed Sarwar, School of CEIS, Northumbria University, Ellison Building, Newcastle Upon Tyne, NE1 8ST, UK; Tel.: 0044(0)1912273663; Fax: 0044(0)1912273854; e-mail: mohammed.sarwar@northumbria.ac.uk

[a] Julfikar Haider, School of CEIS, Northumbria University, Ellison Building, Newcastle Upon Tyne, NE1 8ST, UK; Tel.: 0044(0)1709731683; Fax: 0044(0)1709731700; e-mail: julfikar.haider@ northumbria.ac.uk

[b] Martin Persson, SNA Europe, Fiskargatan 1, 53118 Lidköping, Sweden; e-mail: martin.persson@snaeurope.com

[b] Håkan Hellbergh, SNA Europe, Fiskargatan 1, 53118 Lidköping, Sweden; e-mail: hakan.hellbergh@snaeurope.com

ABSTRACT

It has been well established that advanced surface coatings on cutting tools improve wear resistance by modifying the contact conditions between the chip and tool interface. As a result of the recent developments in cutting tool industry, coated tools have made a significant contribution to the metal cutting operations in terms of tool life, cutting time and machining quality. Inspired by the success of advanced coatings on cutting tools, a programme of applying advanced coating on milling cutters to manufacture bimetal (M42 High Speed Steel and D6A Steel) bandsaws has been initiated to improve the productivity or to extend the tool life. TiN coating was deposited on the PM (Powder Metallurgy) HSS milling cutters using Arc evaporation technique after carefully finishing the cutting edges. Previously no scientific investigation was carried out to compare the performance of a coated cutter and an uncoated cutter. A machining test with a milling cutter coated only half of its length was carried out in the production line to evaluate the performance of TiN coating on milling cutters used for producing bandsaws. The coating morphology and thickness uniformity at the cutting edges were investigated in Scanning Electron Microscope (SEM). Flank wear and notch wear were identified as the dominant modes of wear in both uncoated and coated cutters through the study of worn cutting edges. TiN coating reduced the flank wear and notch wear at the crossover point on the flank face of the milling cutter when compared to the uncoated cutter. Significant improvement in quality bandsaw product manufactured with coated teeth of the cutter was also realised.

Keywords: *TiN Coating, Milling cutter, Bandsaw, Wear*

1. INTRODUCTION

The cutting tool industries are constantly facing the very common industrial challenge of reducing cost of machined parts and at the same time improving the quality of the machined surface. These issues are generally addressed by improving cutting tool materials, applying advanced coating, improving the geometry and surface characteristics of the cutting tools, optimising machining parameters etc.. Advanced surface coatings such as TiN on different cutting tools have made significant contributions over the last decades on reducing cost per machined parts through increasing productivity and extending tool life [1-5]. The benefits of advanced coatings come from higher hardness, low friction at the chip tool contact, higher wear resistance, high hot hardness and high thermal and chemical stability. The machined surface quality with the coated cutter can also be improved by avoiding any built-up edge due to the reduced friction between the tool and workpiece.

Production output of bandsaw blades by milling depends largely on the ability of the milling cutters to maintain its cutting edge. The milling cutters used today at Bahco are made from PM HSS material that possess properties that have a reputation for improved wear resistant that can lead to longer production runs with less downtime. However, the PM HSS milling cutters used have struggled to achieve this on production. The milling process at present requires the milling cutters to be sharpened twice, once at the beginning and again midway through the milling process. This procedure leads to machine down time that slows production down by approx. 30 min to 1 hour. While benefits of using PM HSS material in milling cutters have not been satisfactorily obtained at Bahco, the continuing growth in demand for milled bandsaw blades has put pressure on production. Production needs are difficult to meet as this is hampered by machine downtime caused by milling cutters having relatively short production runs. Discussions with milling cutter manufacturers have identified a possible link between the face grinding process and the performance of the milling cutters

Bimetal bandsaws are produced using milling and grinding techniques. Though milling is the cheaper option, the quality of the cutting edges of the bandsaw produced in milling is not of that high standard as in grinding. Generating bandsaw teeth by a multi-point milling cutter is a complex manufacturing process as shown in Fig. 1. The cutting edges of a milling cutter used for producing bimetal bandsaws deteriorate after few hundred milling passes due to the progressive wear. Consequently, the quality of the cutting edges of the bandsaw teeth produced by the worn milling cutter is also affected. Two distinct kinds of burr in the bandsaw are generally observed, namely, side burr and tooth tip burr with a worn milling cutter. In a production environment, the worn milling cutters are reground to remove the wear and to bring the sharp cutting edges back in the cutter. In general, the regrinding process of a milling cutter could take 2-4 hours depending on the amount of wear, tooth form and number of flutes in the cutter. The number of regrinding operations to complete a milling batch (~ 600-1000 passes) could vary from 1-3 times depending on the root to tip height (gullet depth) and pitch of bandsaw, band pack width, machining parameters etc.. Hence, the machine idle time in a batch due to cutter grinding could vary from 4-12 hours, which significantly affects the productivity. The challenge for producing bandsaw by milling is to improve the productivity and maintain a competitive quality of the cutting edges in the bandsaw. One simple solution of this problem would be the improvement of the performance of the cutter, which will maintain a quality cutting edge for a longer period of time and consequently reduce or even eliminate the number of regrinding operations in a batch.

Inspired by the success of advanced hard coatings on cutting tools, a programme has been initiated to use TiN PVD coatings on milling cutters used for producing bimetal bandsaws.

Previously no scientific study has been carried out to evaluate the performance of coated milling cutter against the uncoated one. Milling cutter performance was assesses in terms of flank wear measurement in the cutter teeth and the surface finish of the bandsaw teeth manufactured by coated and uncoated teeth. In this study, a systems approach has been taken into consideration to diagnose what improvements can be achieved with TiN coated milling cutters.

1. The milling cutter material and the TiN coating on the cutter have been investigated to evaluate the coating and substrate characteristics.
2. The cutting edges of the uncoated and TiN coated milling cutters have been studied at the new condition.
3. A machining test with a milling cutter coated only half of its length has been carried out in a full production environment in order to directly compare the performance of TiN coated and uncoated teeth in the cutter.
4. Worn cutting edges of the cutter have been studied to understand the wear modes and mechanisms and to measure the flank wear in the coated and uncoated teeth of the cutter.
5. Bandsaw cutting edges produced by coated and uncoated teeth of the cutter have been studied under microscope and surface roughness of rake and flank faces of bandsaw teeth have been measured.

2. EXPERIMENTAL PROCEDURE

2.1. Workpiece and milling cutter materials

The workpiece material used for manufacturing bandsaws was bimetal steel (M42 High Speed Steel edge wire; 250-330 HV_1 and D6A steel backing material; 180-260 HV_1). The milling cutter substrate material was Powder Metallurgy (PM) Rex 54 HSS, which was hardened and tempered at different stages of manufacturing of the cutter. A typical elemental composition of the cutter substrate material is shown in Table 1.

2.2. Characterisation of cutter substrate material, TiN coating and cutter wear

Uncoated milling cutter teeth removed from a scrap milling cutter were ground and polished. The hardness of the PM HSS was measured by a micohardness tester (CLARK Instrument INC. MHT 1) with a load of 1000 gm. The surface morphology and grain structures of the milling cutter material were investigated under light optical microscope (OLYMPUS BX60M and Colour video camera JVC TK-C1381) before and after etching with Nital solution (10% HNO_3 in Methanol).

Uncoated finished cutters are mechanically deburred and liquid honed prior to final cleaning in Balzers USI multi-stage clean system. Cutting edges are inspected 100% under magnification. The uncoated cutter was preheated to reach a uniform temperature prior to coating deposition. TiN coating was deposited on the milling cutters by Arc evaporation technique (Balzers BAI-1200 or Hauzer HTC-1000) with a deposition temperature of approximately 450^{o}C after carefully finishing the cutting edges. TiN coated teeth from a scrap milling cutter were removed and the fractured microstructure of the coating was investigated in a Scanning Electron Microscope (SEM). SEM was also used to measure coating thickness and uniformity around cutting edges.

The cutting edge conditions of the milling cutters at the new, worn and reground states were investigated using a light optical microscope (MEIJI EMZ-TR) and a high magnification camera (OPTEM International Macro video zoom lens). Worn teeth removed from a scrap coated cutter were also investigated in the SEM. Edge radii of both coated and uncoated cutters at the new condition were measured by a Contracer Profilometer ((Mitutoyo; CBH-400) with the help of FORMPACK profile measurement software.

2.3. Machining test with a half-length coated milling cutter

A new milling cutter was coated by TiN only half of its length and the other half was left uncoated. The information about the half-length coated milling cutter is given in Table 2. The performance of the TiN coating was evaluated by machining bimetal steel with the half-length coated cutter in a bandsaw production line (Fig. 2). The operational details of the milling test are shown in Table 3. The milling cutter machined 600 milling passes without any regrinding at the end of the test. Coated and uncoated teeth of the half-length coated milling cutter at the new and worn conditions were examined under the light optical microscope. The bandsaw tooth quality (Burr, gullet shape, back to tip height etc) was investigated in a Shadowgraph (BATY International Ltd. P14 XLQC) having a magnification of 25×. Flank wear in the coated and uncoated teeth of the cutter were measured by an Image analysis software (Motic Image plus 2.0) after taking the picture of the worn teeth by a Compact Video Microscope (Allen CVM) at a magnification of 50×. Flank wear measurement was also verified by measuring the worn tooth profile in the Contracer profilometer. Back to tip height of the bandsaws manufactured by the half-length coated cutter was measured with a digital (Sylvac) dial gauge having a resolution of 0.001 mm. Surface roughness of the bandsaw teeth manufactured by the coated and uncoated teeth of the cutter by a Contracer (Mitutoyo) surface roughness tester. The bandsaw teeth were also investigated under SEM.

3. RESULTS AND DISCUSSIONS

3.1. Characteristics of PM REX54 HSS cutter material

The hardness of cutter substrate (PM REX 54 HSS) varied from 840-860 $HV_{1.0}$ (equivalent to 65.5 - 66 Rc), which was in the given specification. The surface morphology before etching under the light optical microscope showed non-metallic inclusions dispersed in the material (Fig. 3a). These inclusions were believed to be small sulphide particles, which could result in machinability and grindability benefits with no adverse effect on toughness. In the etched sample, optical microscope revealed smaller grains (25 grains across 0.127 mm diameter circle) with uniformly distributed round carbide particles (Fig. 3b), which will provide required strength at the cutting edges of the cutter.

3.2. Characteristics of TiN coating on milling cutter

Under SEM, the coating fracture morphology appeared very densely packed with no distinguishable feature, which indicated good quality of coating (Fig. 4). After examining the interface between the coating and the substrate, it appeared that the coating was also well adhered. However, the thickness of the coating varied between 2 μm - 4 μm around cutting edges of milling cutter.

3.3. Uncoated and coated cutters at new and worn conditions

Edge radius of an uncoated cutter at new condition was very small (~ 7 μm -9 μm), which was typical of grinding process. On the other hand, edge radius of a coated cutter at new condition was slightly higher (9 μm - 12 μm) than that of uncoated cutter due to the coating on the cutting edges. At new condition both the coated and uncoated edges were sharp with no burr. After examining many cutters, flank wear and notch wear were identified as the principal mode of wear in both coated and uncoated cutters. The abrasive wear and adhesive wear with the detachment of built-up edges were the governing mechanisms of the flank wear as shown in Fig. 5. No macro flaking of the TiN coating from the flank face was observed. The built-up edge and abrasive wear were more clearly revealed under SEM (Fig. 6). Similar abrasive and adhesive wear were also observed in the uncoated cutters. Notch wear at the crossover point on the flank face was quite common in small tooth form cutters. Notch wear was not observed in big tooth form cutters and full form cutters (roughing flute followed by finishing flute). In many coated cutters notch wear was significantly lower. It was established that notch wear at the crossover point on the flank face was related to the tooth tip burr in the bandsaw. In the uncoated and small tooth form cutters, strong burrs are left in the flank face after regrinding due to material flow from the grinding action. In the coated and big tooth form cutters, cutting edges are sharp with no burrs left in the flank face after regrinding. The coating could provide hard surface to prevent any material flow as burr after regrinding. Furthermore, TiN coating on milling cutter also offered more confidence in operating at higher feeds and speeds. The premature failure of the cutter generally occurred due to the rubbing with the band, hard join-up welding in the band or thinner flute width at the end of the cutter life.

3.4. Machining test results with the half-coated cutter

Ideally the coated cutter should machine more number of bandsaw passes before regrinding compared to the uncoated cutter. However, no dramatic difference between the coated and uncoated cutter was observed in the production line. No scientific studies have been carried out until now to directly compare the performance of coated and uncoated cutters. In a production line it is difficult to compare the performance of an uncoated and a coated cutter in two separate batches even with the cutters of same tooth form. There are number of factors that could affect the performance of the cutters such as set-up of band pack, number of bands in the pack, manufacturing precision of the cutter, machine condition etc. The machining test with the half-length coated cutter would eliminate any variable from the machine, cutter and set-up point of view to compare the performance of a coated cutter and an uncoated cutter.

The main criteria used for evaluating the performance of TiN coating was based on the abrasive flank wear measurement.

Cutting edges of the new coated and uncoated teeth of the half-length coated cutter were sharp with no burr. After 300 milling passes coating started to break off from the flank face and adhesive wear with built-up edge developed in both coated and uncoated teeth. Flank wear and adhesive wear with the built-up edge also increased after 600 passes. In some flutes the built-up edges broke off along with the cutter material both in coated and uncoated teeth. Notch wear at the crossover point on the flank face of the cutter were also visible in both coated and uncoated teeth. Fig. 7 shows the coated and uncoated teeth at new condition, after 300 milling passes and after 600 milling passes. Flank wear in the coated teeth after 600 passes was in the range of 0.10 mm to 0.22 mm whereas, the flank wear in the uncoated teeth was in the range of 0.13 mm to 0.35 mm when measured using image analysis software. The measurement was also verified in few selected teeth by profiling them across the flank face. Flank wear in the coated and uncoated teeth of the half-length coated cutter was in the range of 0.17 mm to 0.20 mm and 0.25 mm to 0.34 mm respectively when measured by the Contacer profilometer.

Flank wear in a selected coated tooth and uncoated tooth of all 16 gashes were measured on three different positions on the flank face. Fig. 8 shows the amount of flank wear at one position near the crossover point and the percentage of reduction of flank wear by TiN coating. The coating reduced the flank wear up to 40% compared to the uncoated teeth. However, the flank wear in the coated teeth was not always consistent. In some flutes flank wear in the coated teeth were equal to the wear in the uncoated teeth. Complex cutting action by the multipoint milling cutters compared to single point cutting tools, lack of manufacturing accuracy of the cutter teeth and variation in the quality of the coating on complex geometry of every tooth could be responsible for this kind of variation. It should be noted for multi-point tools, such as milling cutters, the overall performance is determined by the combination of cutting edge, rake face and gullet characteristics. Furthermore, it is important that all teeth are manufactured to the same specification in order to maximise the tool performance and life, as a multi-point tool is only as good as its weakest tooth [5]. A total systems approach combining tool materials, tool design, manufacturing quality, surface preparation and appropriate coating characteristics is necessary to achieve beneficial performance from the coated multipoint cutting tools.

3.5. Bandsaw produced by half-length coated cutter

No significant difference in terms bandsaw cutting edge quality (tooth tip burr, edge sharpness etc.) was found between the bandsaw teeth formed by the coated and uncoated teeth of the cutter. The bandsaw teeth produced at the beginning of the milling and after 300 passes were sharp with no tip burr. However, after 600 passes, the cutting edge quality of the bandsaw teeth slightly deteriorated due to the wear in the milling cutter. At the beginning of the milling, the gullets of the bandsaw teeth formed by the coated part of the cutter appeared shinier than the teeth formed by uncoated part of the cutter.

Fig. 9 shows that under SEM a better surface characteristics can be observed in the bandsaw teeth manufactured by coated teeth of the milling cutter. This fact was further evidenced by the surface roughness of the bandsaw teeth manufactured by the coated and uncoated teeth of the milling cutter (Fig. 10). The surface roughness of both the rake and clearances faces was reduced. Less friction between the cutter teeth and workpiece can be attributed for the better surface finish in the bandsaw teeth manufactured by the coated teeth of the milling cutter.

No noticeable difference was found in the tooth tips of the bandsaws milled at the beginning and after 300 passes but the bandsaw tooth quality started to deteriorate after 600 passes. In all three individual sample bandsaws (Front, middle and back of the pack) prepared after 300 passes, the back to tip heights were within the specification (± 0.05 mm) and very uniform across the length of the pass. At the end of the milling batch (after 600 passes) the back to tip heights in three actual bandsaws were also individually within the specification, although there was a slight tendency of tapering. While the bandsaw tooth quality slightly deteriorated after 600 passes due to wear in the cutter, still the back to tip height were fairly uniform and within the specification. This also suggested that even with the cutter having flank wear of approximately ~0.30 mm inch was capable of producing fair quality of bandsaws.

4. CONCLUSION

On the basis of the test carried out, the following conclusions can be drawn:

1. The cutting edge of both TiN coated and uncoated teeth at new condition looked sharp with no burr or coating flaking.
2. The physical and structural properties of PM HSS cutter material were within the given specification. TiN coating was densely packed and well adhered on PM HSS cutter with a thickness varying from 2 µm - 4 µm.
3. Flank wear and notch wear at the crossover point were found to be the principal modes of wear in both coated and uncoated milling cutters. The investigation identified that abrasive wear and adhesive wear with built-up edge formation were the common mechanism of flank wear in both coated and uncoated cutters.
4. TiN coating at the new condition of the cutter reduced the flank wear by 10-40% compared to the uncoated cutter in many flutes but in some flutes little or no improvement was found.

5. No fundamental difference in edge quality bandsaw teeth formed by coated and uncoated teeth was found. However, TiN coating significantly reduced the surface roughness in the bandsaw teeth.
6. A total systems approach combined with materials, design and manufacturing process is required to exploit the beneficial effect of hard coatings on multipoint cutting tools.

A similar approach has also planed to undertake in order to evaluate the performance of other coatings such as AlTiN.

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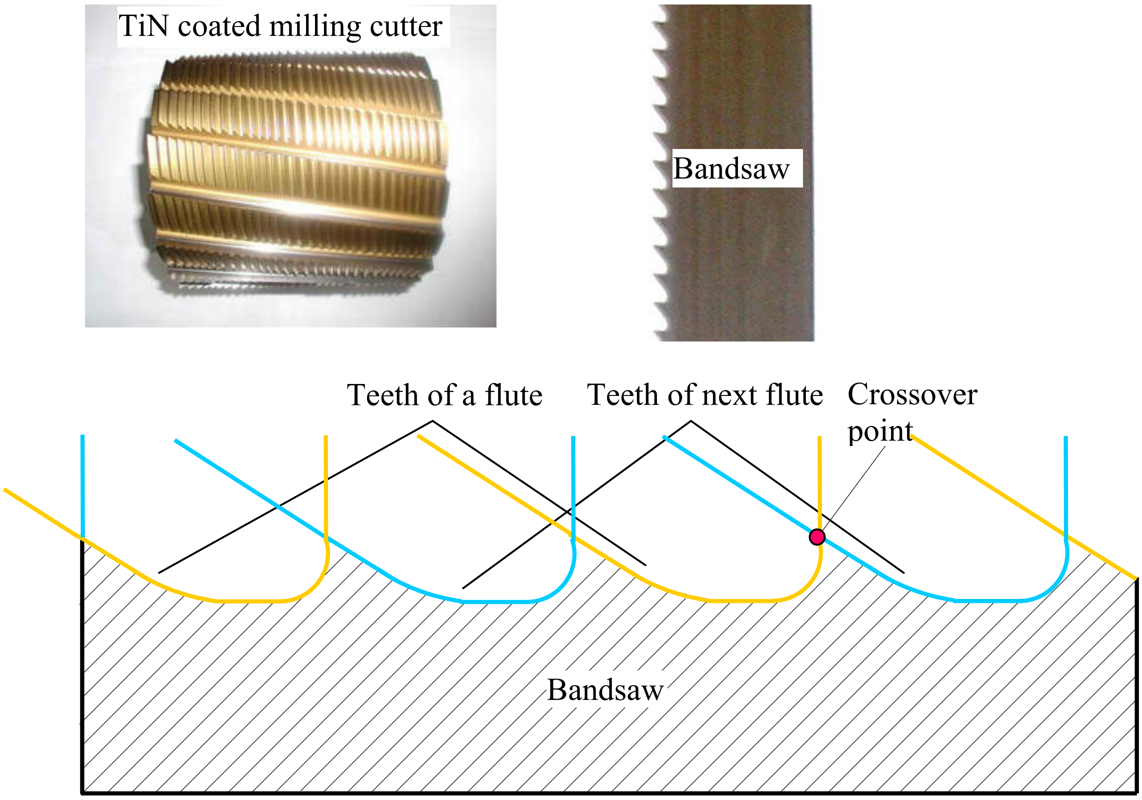
LIST OF FIGURES

Figure Number: 1



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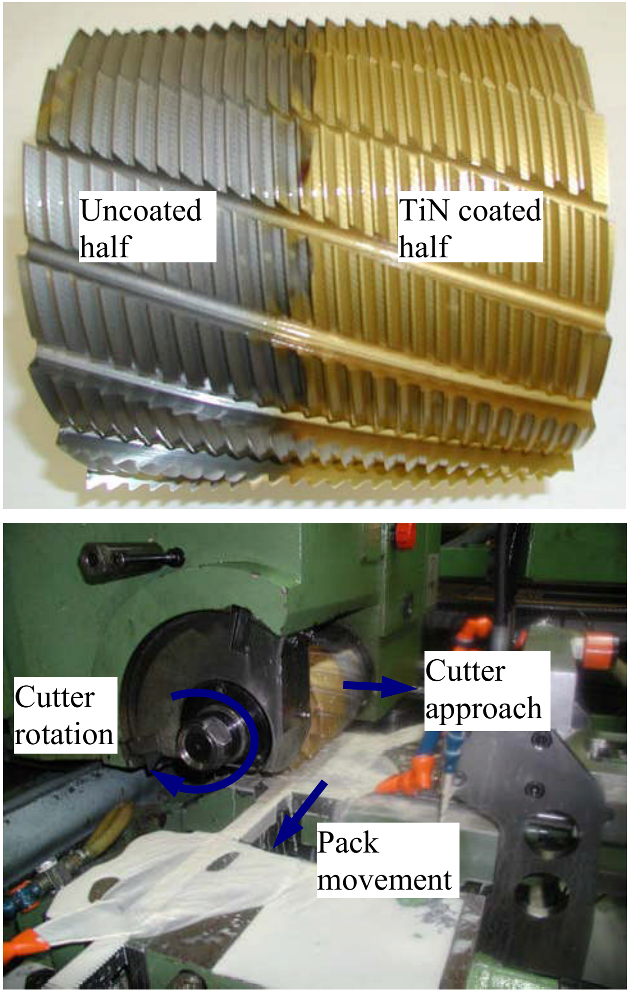

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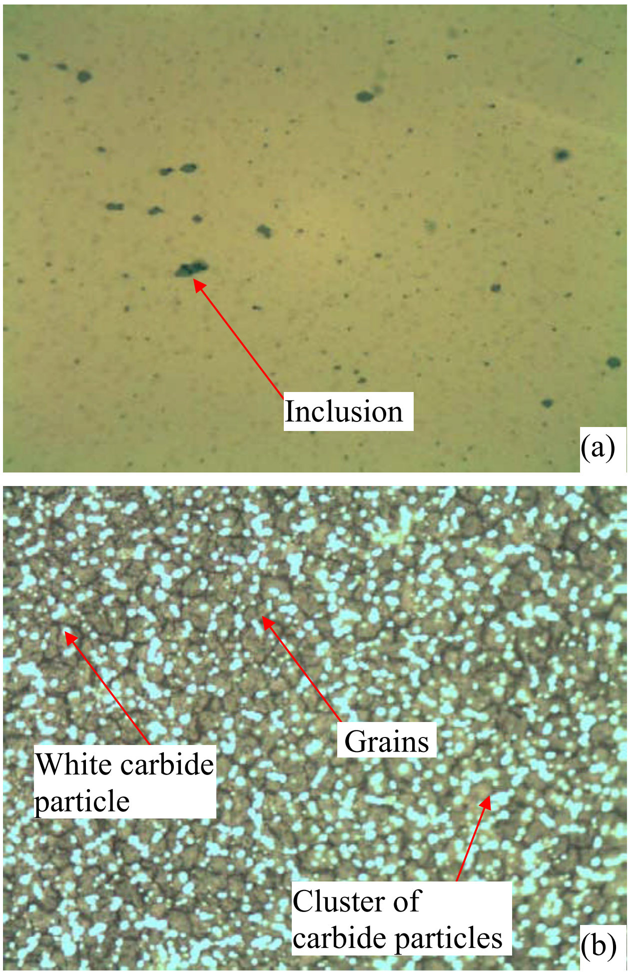

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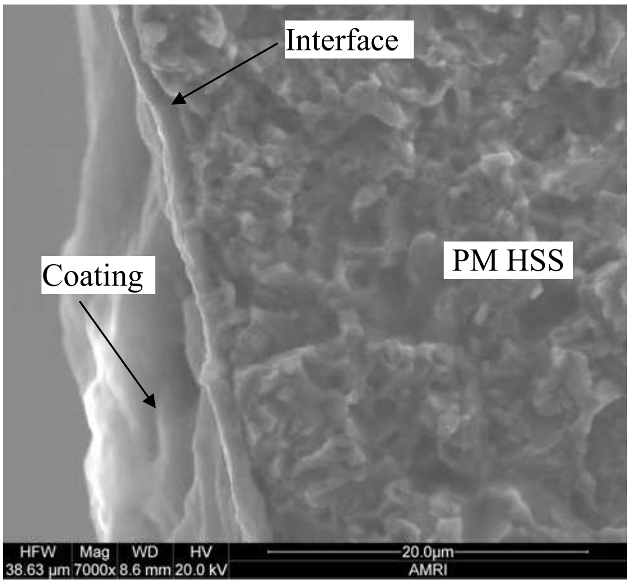

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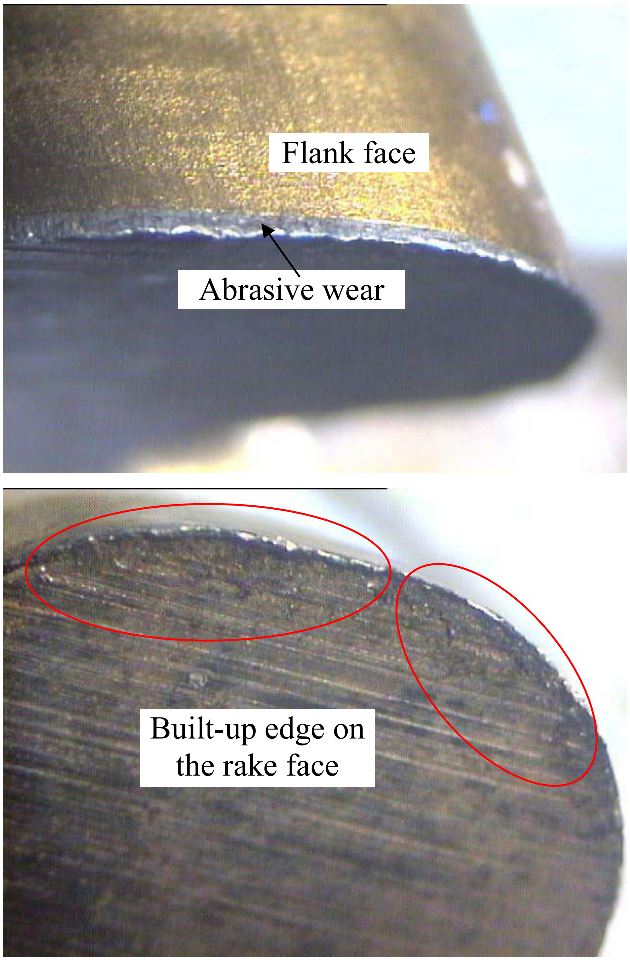

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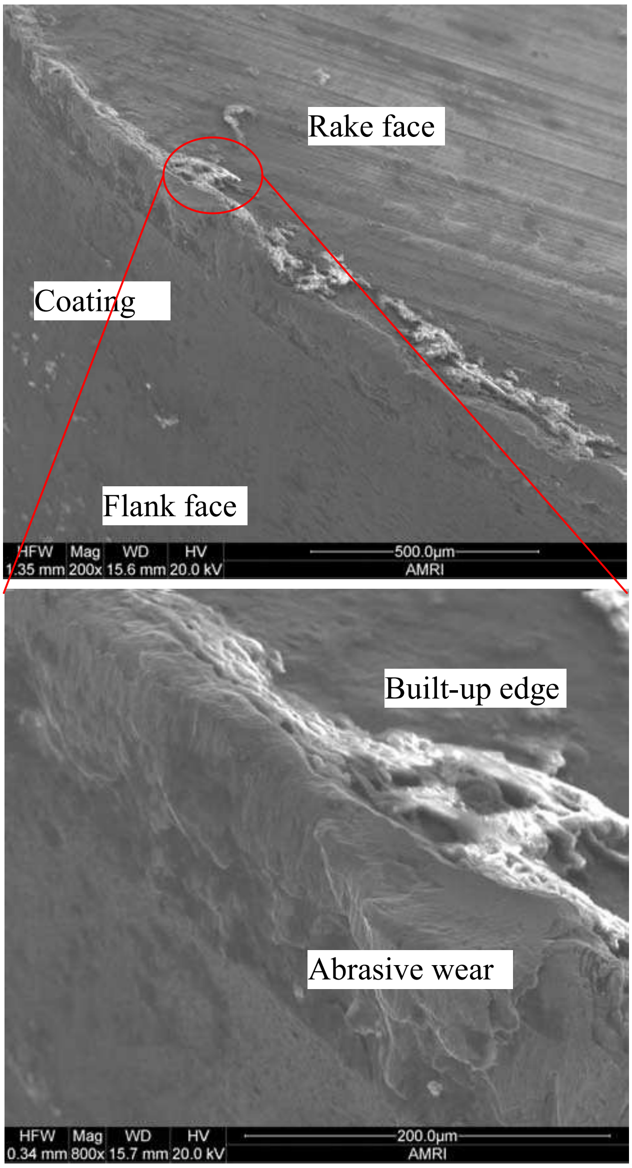

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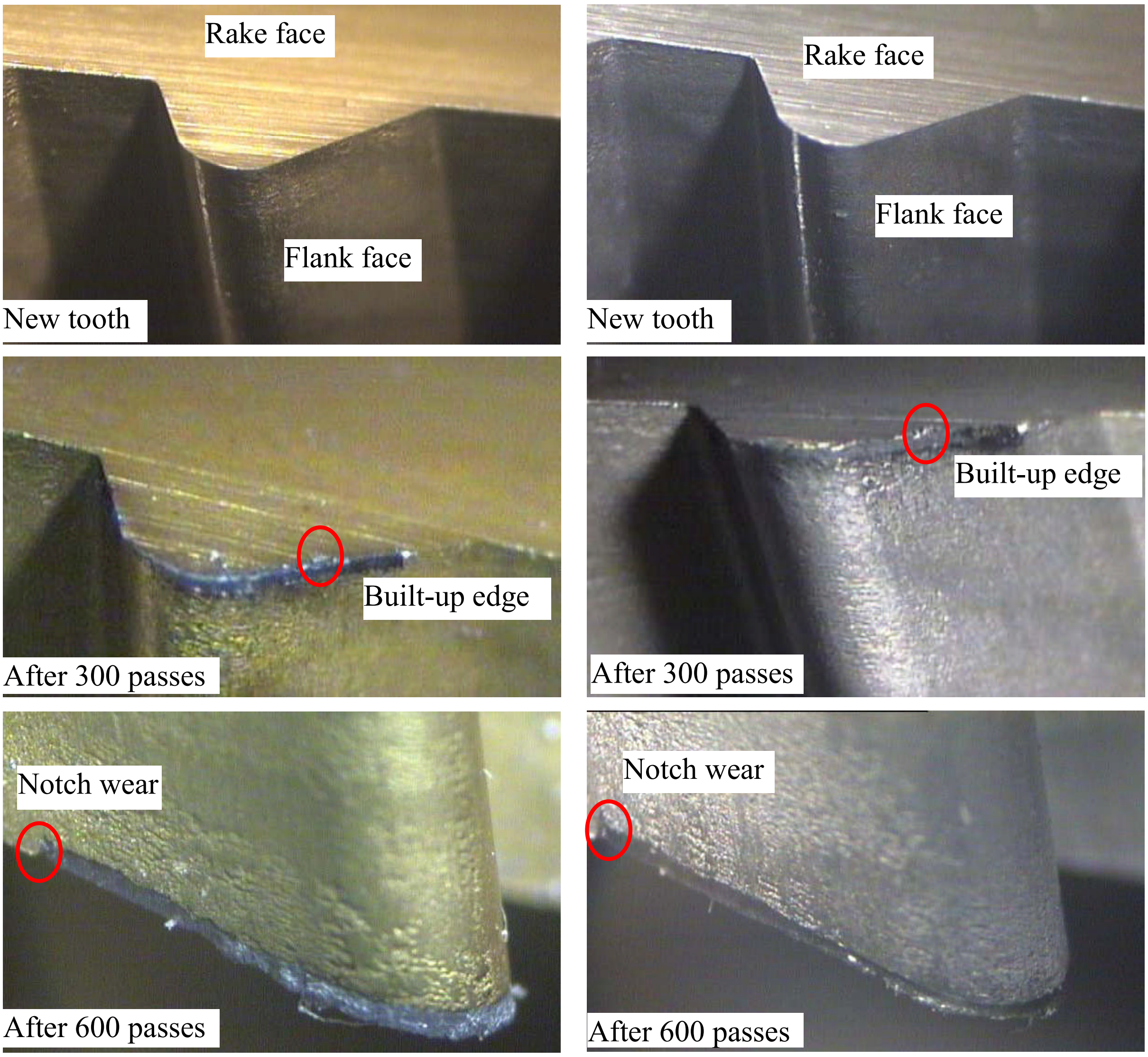

Coated teeth **Uncoated teeth**

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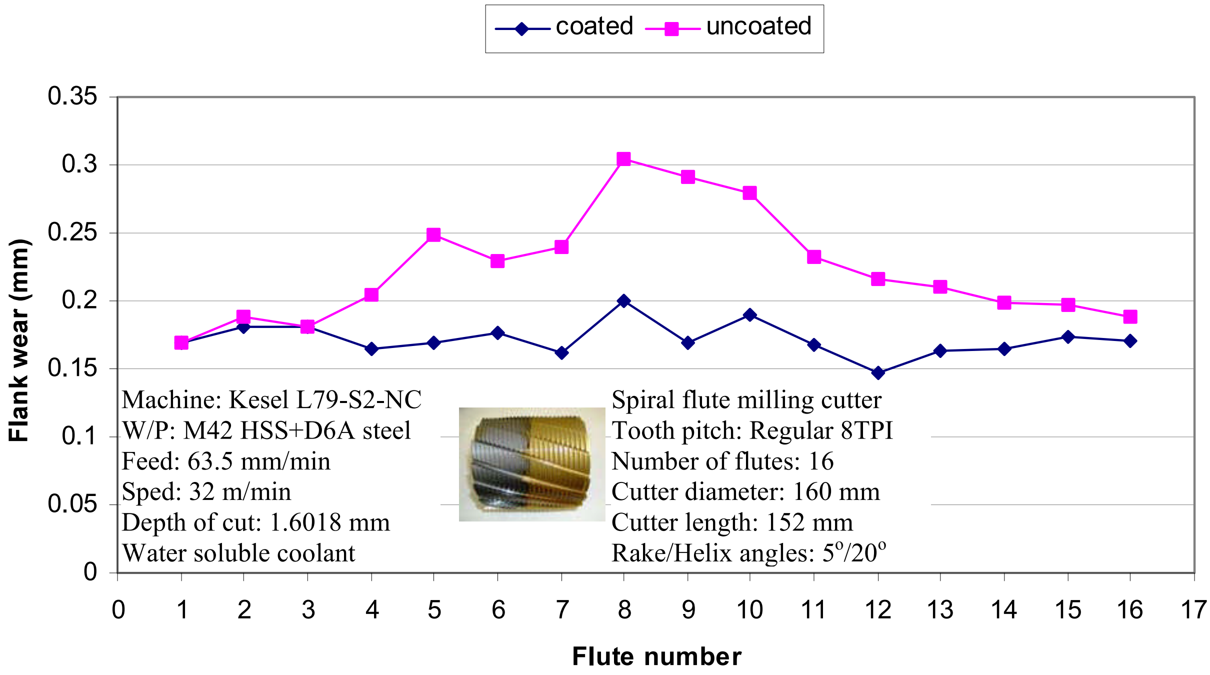

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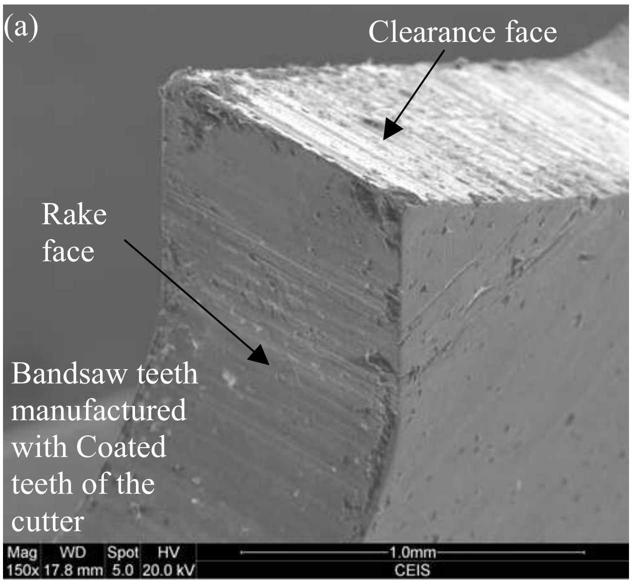

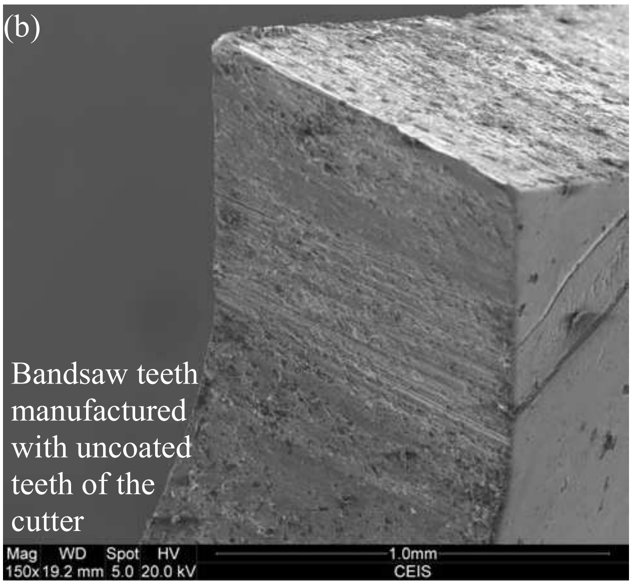

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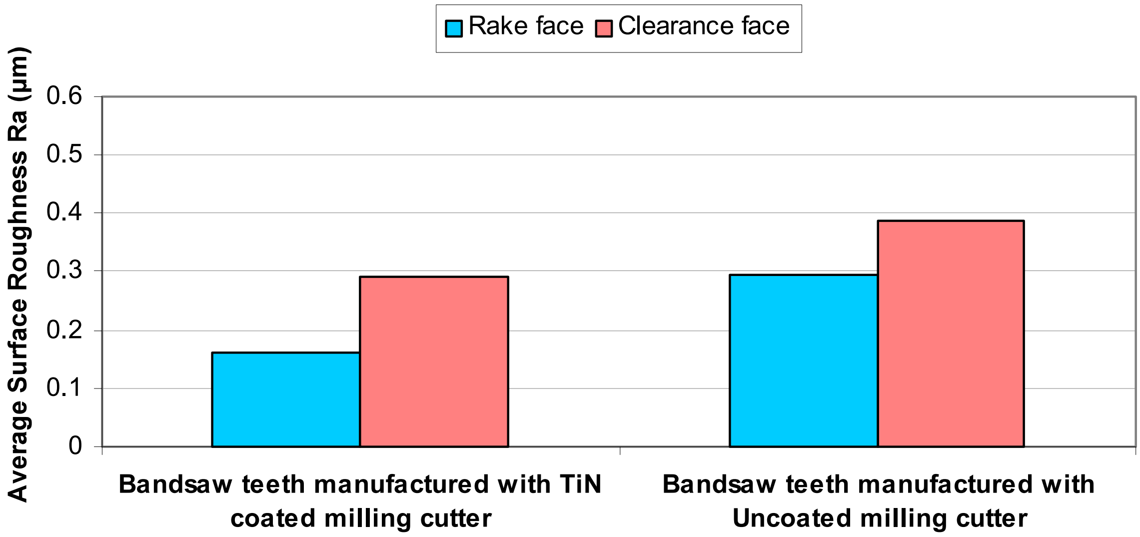


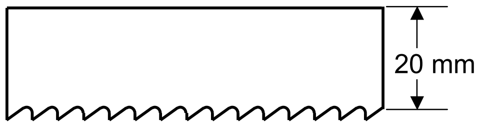
Table 1: Typical elements in PM Rex 54 HSS cutter substrate material

Element	C	Mn	Si	Cr	V	W	Mo	Co	S
Weight percentage (%)	1.30	0.30	0.50	4.05	3.05	6.25	5.00	8.00	0.03 max

Table 2. Details of half-length TiN coated milling cutter

Cutter Type	Parallel
Cutter manufacturer	Gleason
Cutter tooth pitch	Regular 8 TPI
Cutter material	PM REX 54
Surface treatment	TiN (coated half length)
Rake angle	5^{o}
Helix angle	20^{o}
Lead length	1380 mm
Diameter / Length	160 mm/152 mm
Number of flutes	16
Number of teeth in a flute	23

Table 3. Operational details of the milling test with half-length TiN coated milling cutter

Bandsaw product description  	Band width: 20 mm Band thickness: 0.9 mm Tooth form: Regular 8 TPI
Milling machine	Kesel L79-S2-NC
Feeds	63.5 mm/min
Spindle speed	65 rpm
Surface speed	32 m/min
Maximum depth of cut	1.6018 mm
Feed per tooth	0.122 mm
Number of bands in the pack	26
Coolant	Flood cooling with water soluble fluids