Paper Number (If Known): 810

Title of Paper: Investigating the Performance of TiN and TiAlN Coatings on Milling Cutter Used for Machining Bimetal Steel Strip

Corresponding Author: Julfikar Haider

Full Mailing Address: School of CEIS, Northumbria University, Ellison Building, Newcastle Upon Tyne, NE1 8ST, UK

Telephone: 0044(0)7950622696

Fax: 0044(0)1912273854

E-mail: julfikar.haider@northumbria.ac.uk

Keywords: Milling, Coating, TiN, TiAlN, Wear

Estimation of the length of the manuscript

			Number of words
	Please fill out		*Please fill out*
Number of Pages	9	9 × 250	2250
Number of Tables	2	2 × 150	300
Number of Figures	9	9 × 150	1350
TOTAL NUMBER OF WORDS = 3900			

Investigating the Performance of TiN and TiAlN Coatings on Milling Cutter Used for Machining Bimetal Steel Strip

Mohammed Sarwar and Julfikar Haider*

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

* Julfikar Haider, School of CEIS, Northumbria University, Ellison Building, Newcastle Upon Tyne, NE1 8ST, UK; Tel.: 0044(0)7950622696; Fax: 0044(0)1912273854; e-mail: julfikar.haider@northumbria.ac.uk

Abstract

Surface engineering of cutting tools (single point or multipoint) through advanced coatings (e.g., TiN) has contributed towards considerable improvement of tool life, productivity and machining quality [1] by modifying the tool substrate. New coating species (e.g., TiAlN) are also being developed to further improve the performance of cutting tools. In this study, milling tests were carried out with a TiN and TiAlN coated milling cutter to compare their performance. Physical Vapour Deposition (PVD) technique was used to deposit the coatings after carefully preparing the cutting edges. Flank wear measurement in the milling cutter teeth was used as the criterion for assessing performance of the coatings. It has been found that TiAlN coating has significantly reduced the flank wear in the milling cutter teeth compared to TiN coating both at new and reground conditions of the cutter. Abrasive and adhesive wear were identified as the main mechanisms of the flank wear in both TiAlN and TiN coated teeth. The information should be useful for tool designers, coating suppliers and manufacturing engineers.

1. Introduction

Bimetal band strips are machined using a unique milling operation, which enables economic production of good quality saw teeth. Specially designed solid multipoint cutters are employed in the milling operation where complex cutting action by the teeth in successive flutes forms the sharp saw teeth (Figure 1). Owing to the interrupted nature of the milling operation, the cutter is continuously subjected to cyclic variation of stress and temperature during the machining process. As the workpiece material is not a solid block, rather a stack of many thin strips, the interrupted cutting characteristics are even more pronounced in the milling process. The milling of bimetal strips further complicates the machining process as the milling cutter encounters different materials (M42 HSS, weld and D6A steel) along the depth of cut. Therefore, cutting edges of the milling cutter must withstand this harsh environment to achieve longer production runs with less downtime and without affecting the product quality. PM HSS (Powder Metallurgy High Speed Steel) milling cutters have struggled to achieve this on production owing to the deterioration of the cutting edges after short production runs. This leads to higher machine downtime due to cutter resharpening. A promising solution of this problem would be the improvement of the performance of the cutter by advanced coatings, which will maintain a quality cutting edge for a longer period of time and hence, a reduction of machine downtime.

Advanced coatings produced by Physical Vapour deposition (PVD) process have resulted in an increase in tool life, machining performance and product quality in machining applications. It has been established [1-3] that both single and multipoint cutting tools made from High Speed Steel (HSS) have benefited from PVD TiN coating due to its high hardness, low coefficient of friction, good adhesion etc.. Inspired by the success of advanced hard coatings on cutting tools, a programme of study has been initiated to use PVD TiN coatings on milling cutters used to mill bimetal steel strip. In this study, a new approach has been employed in a machining test with only half the length of the milling cutter is TiN coated. The results showed that TiN coating extended the life of the milling cutter by approximately 35% [4]. It has been demonstrated in the literature that coatings developed by the addition of Al in TiN coating (e.g., TiAlN or AlTiN) can enhance the performance of cutting tools in different machining applications [2, 5, 6]. However, to the author's best knowledge, no scientific reports have been published on the performance of coated milling cutters for machining bimetal HSS strip. The closest operation that can be found in the literature is gear hobbing, where successes have been reported with TiAlN coating over TiN [7-10]. The overall aim of this work is to contribute towards a further understanding of the effects of TiAlN coating compared to TiN coating applied to the milling cutters used for machining bimetal HSS strip.

2. Experimental Methodology

In bimetal steel strip, M42 HSS edge wire (250-330 $HV_{1.0}$) was welded to D6A backing material (180-260 $HV_{1.0}$) as shown in Figure 1. Powder Metallurgy High Speed Steel (PM HSS; 900 HV) was used for the solid milling cutter. A typical elemental composition (wt%) of the PM HSS milling cutter was as follows: 1.30% C, 0.30% Mn, 0.50% Si, 4.05% Cr, 3.05% V, 6.25% W, 5.00% Mo, 8.00% Co, 0.03% S.

The milling cutter was coated by TiN half of its length and the other half was coated with TiAlN. Prior to coating, the milling cutters were mechanically deburred and liquid honed. TiN and TiAlN coatings were deposited on the milling cutter by Arc evaporation technique with a deposition temperature of approximately 450 ^{o}C. The coating thickness varied from 3-5 μm. The hardness of TiN and TiAlN coatings was 2300 HV and 3300 HV respectively. The information about the TiN and TiAlN coated milling cutter is given in Table 1. The performance of the TiN and TiAlN coatings were analysed by machining bimetal steel with the coated milling cutter in a CNC milling machine (Figure 2). The operational details of the milling test are presented in Table 2. The machining test was conducted by milling 600 passes without any regrinding of the cutter and another 300 passes after the regrinding of the cutter. TiN and TiAlN coated teeth of the milling cutter at the new, worn (after 20, 300 and 600 milling passes) and reground (after 300 passes) conditions were examined in a Compact Video Microscope (Allen CVM; magnification 50×). Flank wear in the coated teeth of the milling cutter were measured by an Image analysis software (Motic Image plus 2.0) after taking the picture of the cutter teeth by the Compact Video Microscope.

3. Results and Discussions

3.1. Cutting edges of the milling cutter

At the new condition, TiN and TiAlN coated cutting edges of the milling cutter were sharp (edge radius: 9-10 µm) with no burrs. The cutting edges, rake and clearance faces were fully covered with coatings having no sign of substrate exposure owing to flaking of the coating (Figure 3). After regrinding strong burrs were left on the cutting edges due to the lateral flow of material from the grinding action, whereas the rake face was smooth with no burrs left on it.

3.2. Flank wear measurement

Flank wear of a selected coated tooth (5^{th} tooth from each end of the cutter) from all 16 flutes were measured on three different positions of the flank face. The average flank wear of TiN and TiAlN coated teeth from all the flutes after 300 milling passes from the new condition of the cutter are shown in Figure 4. It is apparent from the figure that TiAlN coating has performed better than TiN coating. The average flank wear in TiN coated teeth ranges from 0.101 mm to 0.171 mm whereas, in TiAlN coated teeth the flank wear ranges from 0.052 mm to 0.089 mm. On average 47% less flank wear was observed in TiAlN coated teeth compared to the TiN coated teeth. The higher hardness, toughness and wear resistance of the TiAlN coating compared to TiN coating could be the reason for lower flank wear in TiAlN coated teeth [7].

After 600 milling passes from the new condition of the cutter, the flank wear increased in both TiN and TiAlN coated teeth (Figure 5). In contrast, on average 28% less flank wear was observed in TiAlN coated teeth compared to the TiN coated teeth. This can be reasoned that owing to the higher hardness, TiAlN coating could maintain a smaller flank wear up to a certain number of milling passes (300 passes) and once substantial flank wear is developed in the TiAlN coated teeth, the wear progresses at a slightly higher rate than that wear in TiN coated teeth. After 300 milling passes from the reground condition of the cutter, TiAlN coated teeth showed 24% less wear compared to the TiN coated teeth (Figure 6). Therefore, it is clear that the performance of TiAlN coating decreased compared to TiN coating at the reground condition of the cutter.

Figure 7 summarises the comparative performance of TiN and TiAlN coatings at different stages of the milling test. Both at new and reground conditions of the cutter, TiAlN coated teeth showed smaller flank wear compared to TiN coated teeth. However, the TiAlN coated teeth performed best at the new condition of the cutter where the coating was on both rake face and clearance face. It should be noted that for the same number of milling passes (300 passes) the reground cutting edges exhibited higher flank wear than the new cutting edges. This is because of the absence of coating on the rake face and lack of cutting edge sharpness at the reground condition compared to the new condition (Figure 3).

Again, the flank wear in all the coated teeth was not always consistent having very little difference between the flank wear of TiN and TiAlN coated teeth in some cases. 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 [3, 10]. A total systems approach combining tool materials, tool design, manufacturing quality, surface preparation and appropriate coating characteristics is necessary to achieve consistent beneficial performance from the coated multipoint cutting tools.

3.3. Wear modes and mechanisms

Flank wear has been identified as the principal mode of failure in both TiN and TiAlN coated teeth, Figure 8. Other researchers [11] have also concluded that flank wear is the principal failure mode in a HSS milling cutter while machining annealed steel. The flank wear in both TiN and TiAlN coated teeth of the milling cutter was characterised by non-uniform width and the width of the flank wear in TiAlN coated teeth was maximum at the wedge area and gradually decreasing along the cutting edges. However, the width of flank wear in TiN coated teeth was more uniform along the cutting edges. Another distinguishing feature in TiN coated teeth was the formation of crater on the exposed flank face.

Notch wear usually develops at the crossover point on the flank face, where the saw tooth tip forms (Figure 1). In the earlier investigation, significant reduction of notch wear was noticed in TiN coated teeth compared to uncoated teeth [4]. Generally, no considerable notch wear on the flank face was observed in TiN and TiAlN coated teeth. No significant wear on the rake face (crater wear) was found. No thermal cracks or plastic deformation was also observed in the coated teeth of the milling cutter even having the cyclic variation of stress and temperature in the coated teeth due to the intermittent cutting action. This could be due to relatively lower feeds and speeds used during the milling operation.

Visual and microscopic examinations after a few milling passes revealed that both TiAlN and TiN coatings were removed first from the wedge area of the cutter teeth in an irregular manner exposing the substrate (Figure 9) [10]. TiN coating was also removed from the main cutting edges; however, there was very little evidence of removal of TiAlN coating from the main cutting edge at that stage. The wedge area, the initial contact point with the workpiece, is generally prone to high stress concentration and a relatively lower coating thickness is expected at the sharp cutting edge. This led to the early removal of the coatings as observed by other researchers [12]. No macro flaking or premature delamination (indication of poor adhesion) of the coatings from the flank face was observed. Therefore, a combination of microchipping and gradual removal of the coatings after few milling passes starting from the wedge area of both TiN and TiAlN coated teeth was found to be the initial wear mechanism.

Built-up edge (BUE) [13] is formed by the strong adherence or welding of the workpiece material to the cutting edges. When BUEs reaches a critical point, they are broken intermittently with the fragments of cutter material coming away with the chip [12]. As the workpiece material was relatively soft and sticky in nature, built-up edge formation was quite commonly seen at the exposed cutting edges of the cutter teeth. Strong evidences of BUEs formation were found in both TiN and TiAlN coated teeth after 600 passes from new condition and 300 passes from the reground condition of the cutter, but the BUEs were less prominent after 300 passes from the new condition of the cutter (Figure 8). After 600 passes the substantial wear completely exposed the cutting edge, flank face and a small area of rake face near the cutting edge and this condition could favour the formation of BUEs. Again, after regrinding there was no coating at all on the rake face and the small burr left on the flank face might act as an initiation point of the adhesive wear.

The flank wear was developed due to the gradual removal of coatings by the abrasive action between the tool material and machined workpiece material. Once the coating was removed from the flank, the tribological contact took place between the exposed tool substrate and workpiece material causing even more abrasive wear. The flank wear then propagated by the removal of coating fragments of almost full coating thickness from the free edge of the coatings [10]. The hard particles from the workpiece or coating fragments play a major role in the progression of flank wear [7].

4. Conclusions and Future Work

The cutting edge of both TiN and TiAlN coated teeth of the milling cutter at new condition appeared sharp with no burr or coating flaking. TiAlN coating exhibited higher wear resistance than TiN coating both at the new and reground conditions of the cutter due to its higher hardness, toughness and wear resistance when machining bimetal steel with PM HSS milling cutter. However, TiAlN coating showed the best performance at the new condition of the cutter owing to the presence of coating in both the rake and clearance faces. Irregular flank wear was found to be the dominant mode of wear in both TiN and TiAlN coated teeth. The coating removal process started at the tip of cutter tooth (wedge area) and then started to progress along the length of the cutting edges. The investigation identified that abrasive wear and adhesive wear with built-up edge formation were the governing mechanisms of flank wear in both TiN and TiAlN coated teeth. The machining test with a half-length coated milling cutter appeared to be an effected method for evaluating the performance of different coatings in a complex production line.

In future, experiments will be performed by applying the similar approach used in this paper to evaluate the performance of other newly developed coatings such as AlCrN and nanocomposite coatings (e.g., AlTiSiN) for the milling of bimetal HSS steel strip [2].

Acknowledgement

The authors gratefully acknowledge the support from the tool manufacturing company and the School of CEIS, Northumbria University, UK to carry out this research work.

References

1. M. Sarwar, Surf. Coat. Technol., 108-109 (1998) 612.

2. W. Kalss, A. Reiter, V. Derflinger, C. Gey and J.L. Endrino, Int. J. Refract. Met. Hard Mater., 24 (2006) 399.

3. M. Sarwar, D. Gillibrand and S.R. Bradbury, Surf. Coat. Technol., 41 (1991) 443.

4. M. Sarwar, J. Haider, M. Persson and H. Hellbergh, 3rd International Conference on Surfaces Coatings and Nanostructured Materials, Barcelona, Spain, (2008) p.70.

5. M. Arndt and T. Kacsich, Surf. Coat. Technol., 163–164 (2003) 674.

6. S. PalDey, S.C. Deevi, Mater. Sci. Eng., A342 (2003) 58.

7. J. A. B. O. dos Santos, W. F. Sales, S. C. Santos, A. R. Machado, M. B. da Silva, J. Bonney and E. O. Ezugwu, Int. J. Adv. Manuf. Technol., 31 (2007) 629.

8. J. Vetter, Surf. Coat. Technol., 76-77 (1995) 719.

9. M. Zlatanović and P. Stošić, Vacuum, 39 (1989) 557.

10. J. Gerth, M. Larsson, U.Wiklund, F. Riddar, S. Hogmark, Wear, 266 (2009) 444.

11. K.L. Rutherford, S.J. Bull, E.D. Doyle and I.M. Hutchings, Surf. Coat. Technol., 80 (1996) 176.

12. C.Y.H. Lim, S. C. Lim and K. S. Lee, Surf. Eng., 16 (2000) 253.

13. W. König, R. Fritsch and D. Kammermeier, Surf. Coat. Technol., 49 (1991) 316.

List of Tables

Table 1. Details of TiN and TiAlN coated milling cutter

Cutter Type	Cylindrical
Cutter tooth pitch	6/10 TPI
Cutter material	PM REX 54 HSS
Surface treatment	TiN and TiAlN (coated half length)
Rake angle	0^o
Chip breaker in teeth	None
Helix angle	10^o Right hand helix
Lead length	2851.05 mm
Diameter	160.78 mm
Length	159 mm
Number of flutes	16
Number of teeth in a flute	22/23

Table 2. Operational details of the milling test with TiN and TiAlN coated milling cutter

Product description	Bimetal HSS Strip (Strip width: 20 mm; Strip thickness: 0.9 mm; Tooth form: 6/10 TPI)
Milling machine	Kesel L79-S2-NC
Number of bands in the pack	26
Band pack width	23.4 mm
Feed rate	63.5 mm/min
Spindle speed	65 rpm
Surface speed	32.85 m/min
Maximum depth of cut	2.11 mm
Feed per tooth	0.122 mm
Coolant	Flood cooling with water soluble fluid

List of Figure Captions

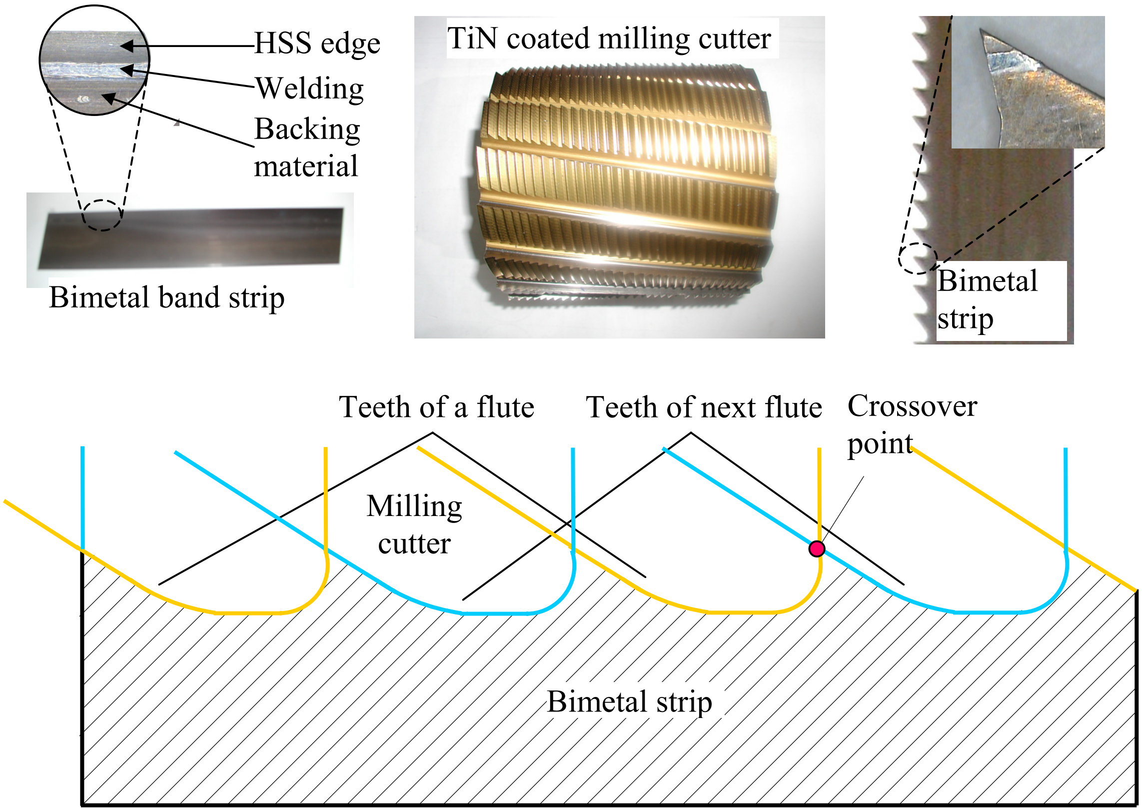

Figure Number: 1

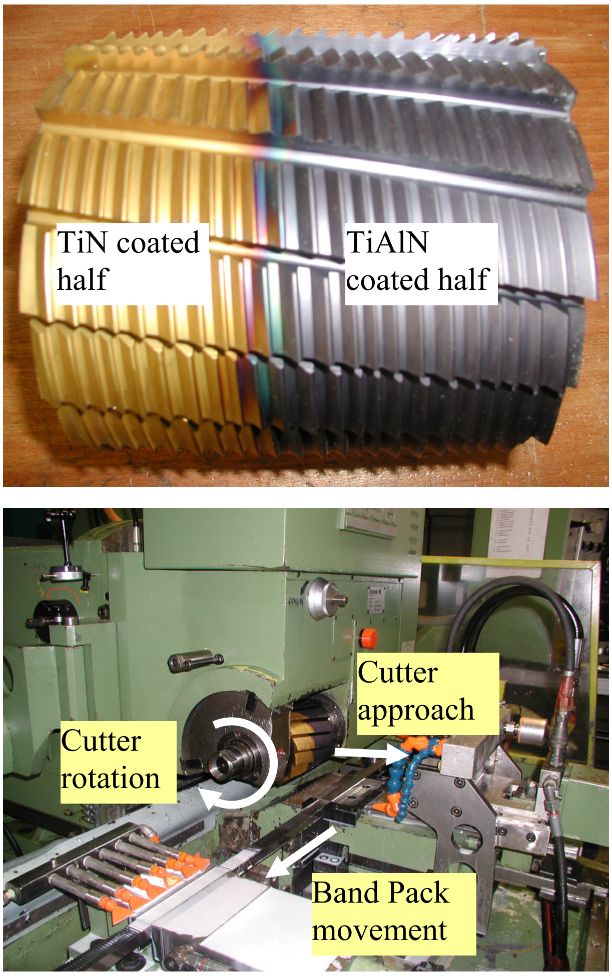

Figure Number: 2

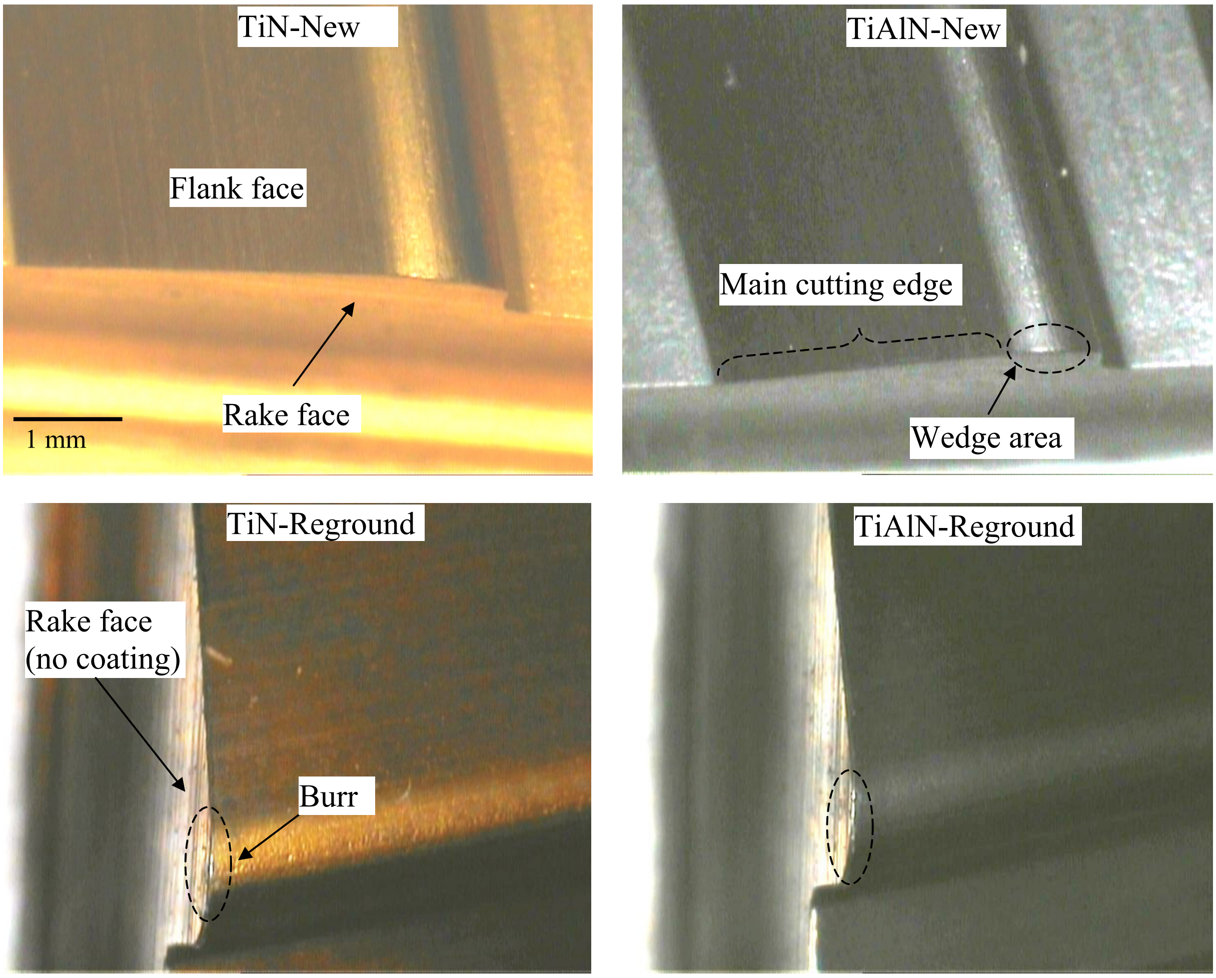

Figure Number: 3

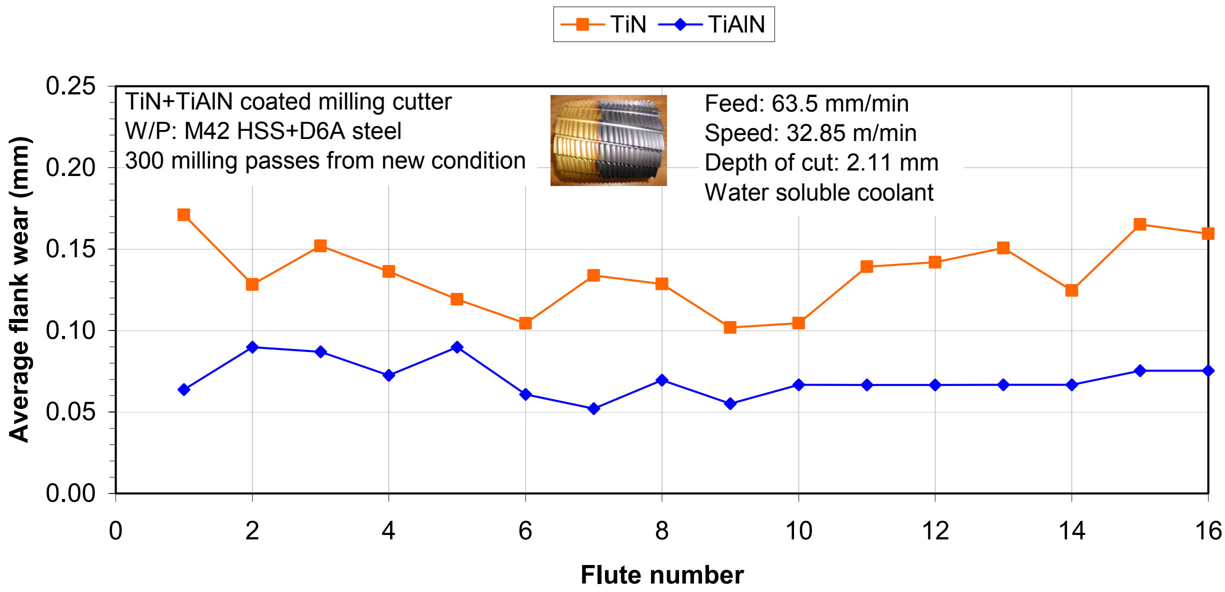

Figure Number: 4

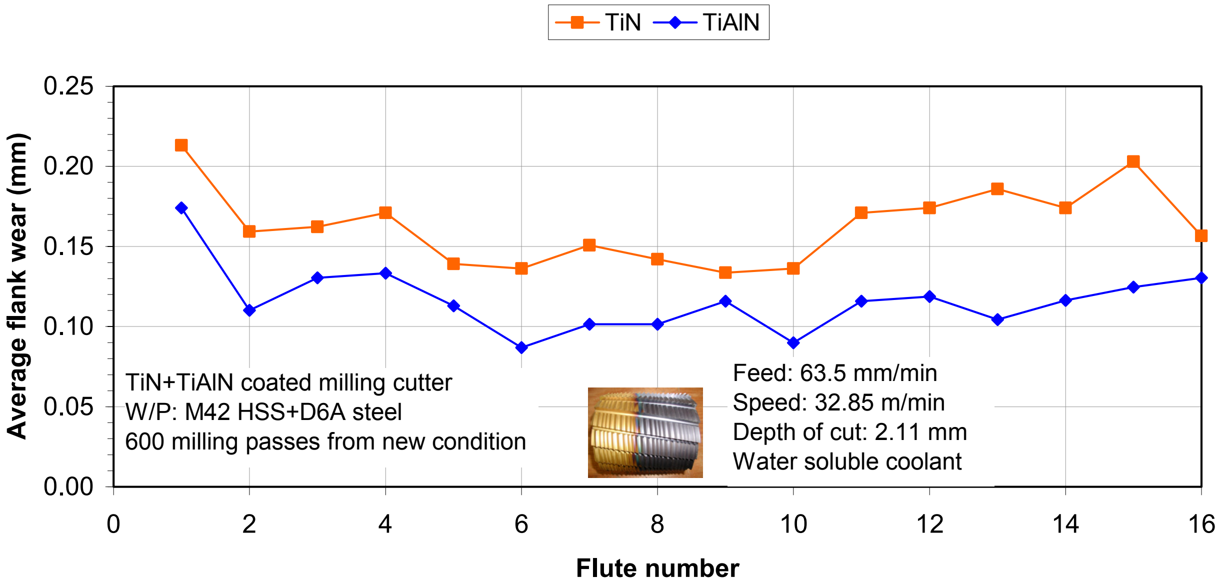

Figure Number: 5

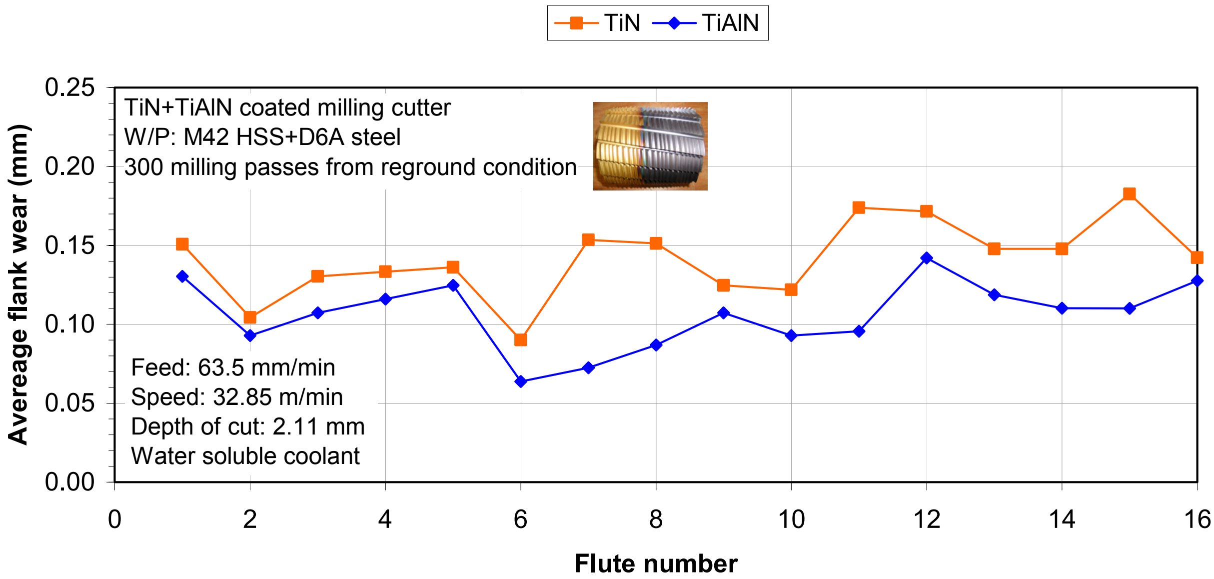

Figure Number: 6

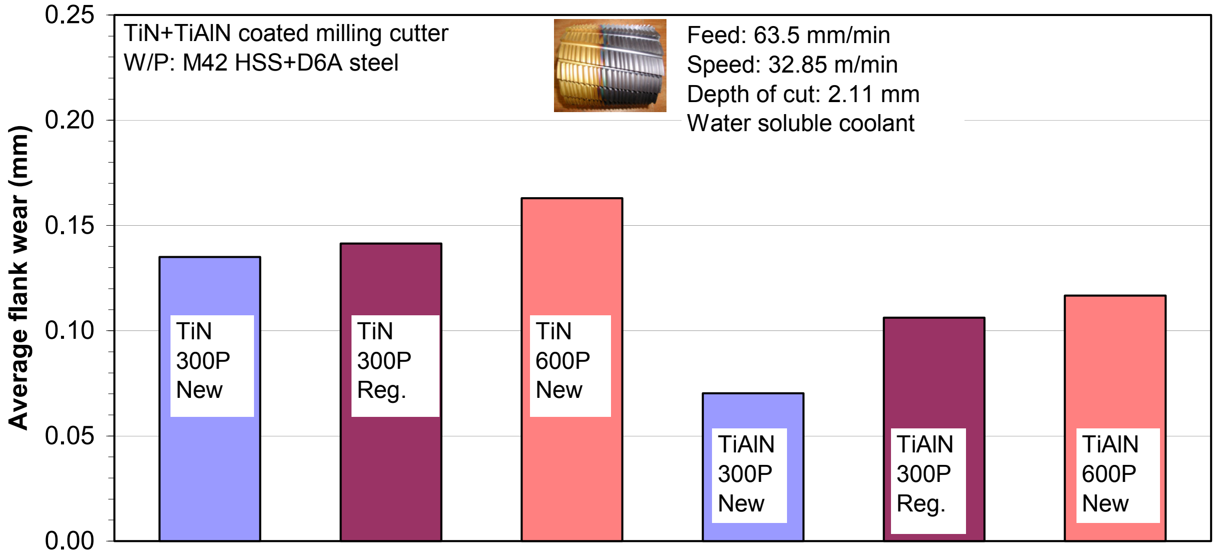

Figure Number: 7

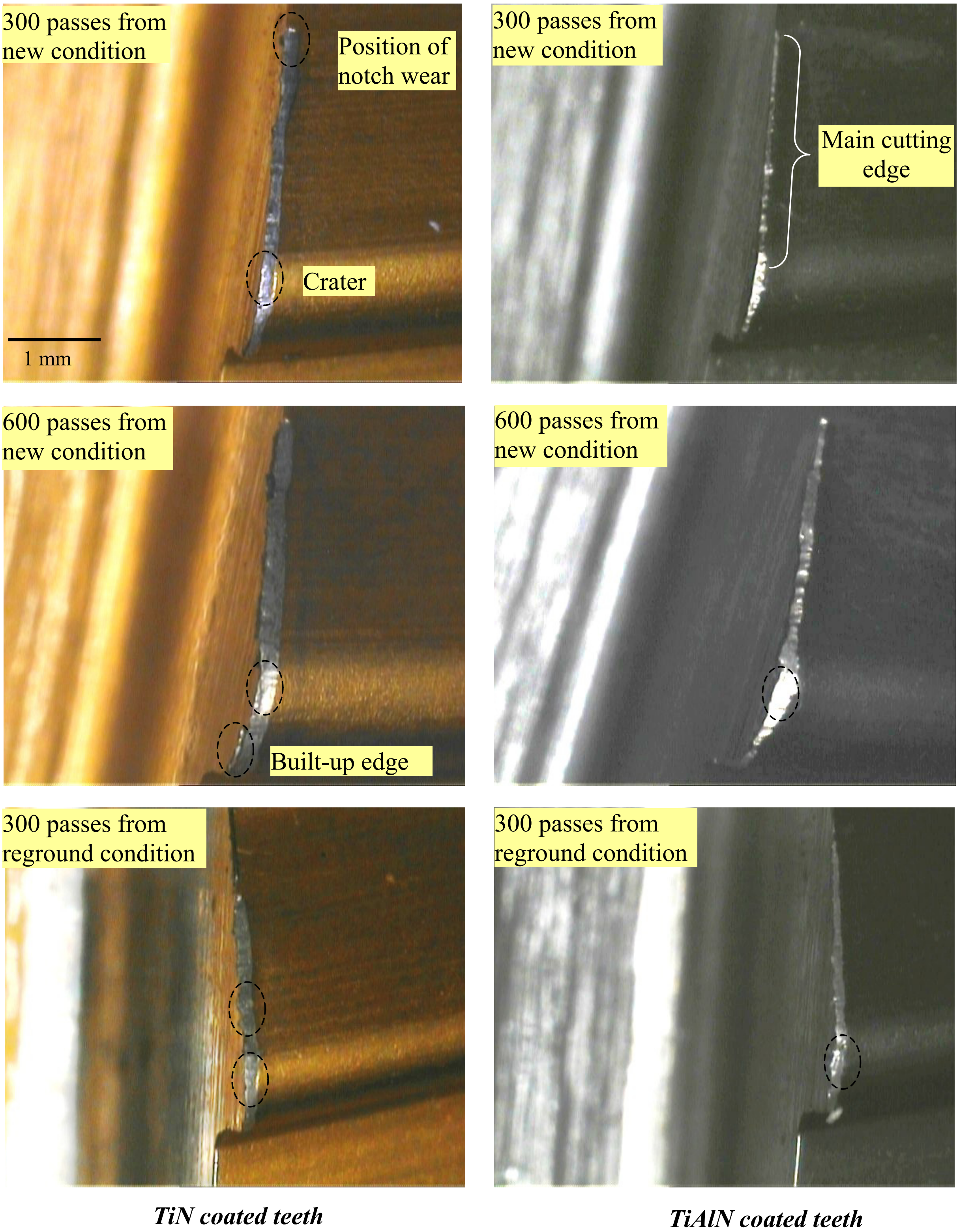

Figure Number: 8

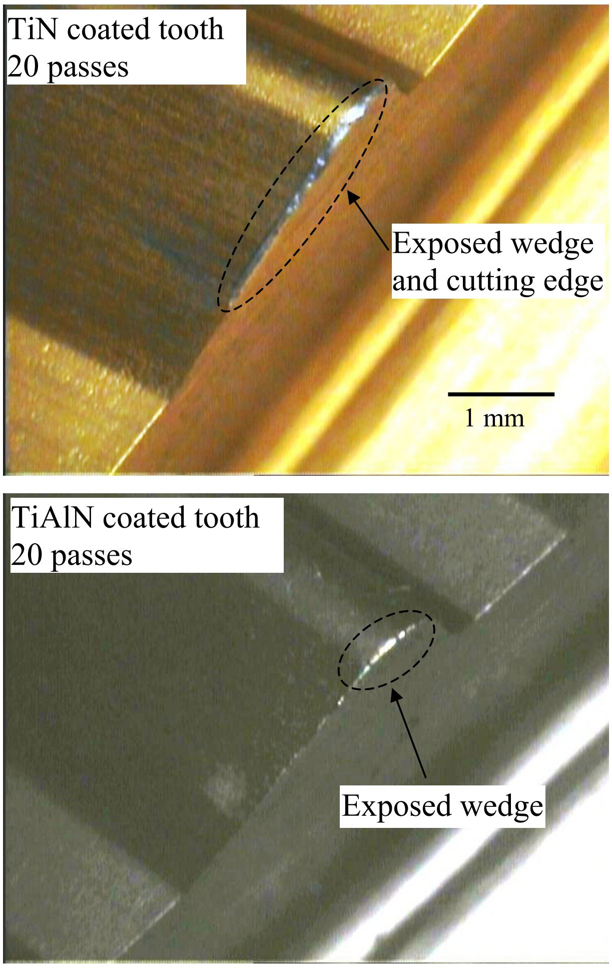

Figure Number: 9