SURVEY OF DAMAGE MECHANISMS ON PVD COATED HSS HOBS USED IN SWEDISH GEAR MANUFACTURING INDUSTRY

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ABSTRACT

Gear hobbing is widely used for production of cylindrical gears in the Swedish transmission industry. The hob, usually consisting of a homogenous HSS (High Speed Steel) body coated with a ceramic PVD (Physical Vapour Deposition) coating, is designed for regrinding and recoating several times without affecting its cutting geometries. Efficient usage of the tool, considering production costs and gear quality, requires reconditioning before wear starts to affect the gear quality negatively and certainly before tool wear renders reconditioning impossible. Hobs of today generally lack in reliability, making it difficult to judge when they have to be taken out for reconditioning.

This work presents a survey of wear as observed on today's state of the art hobs used by Swedish gear manufactures. It aims to identify damage mechanisms and the common problems in order to enable future production of more reliable hobs. The tools were temporarily borrowed from the production and the analyses were made non-destructively using optical microscopes. This was complemented by destructive cross-sectional analysis on two of the hobs.

Wear was most commonly located on the rake faces and the cutting edges of the cutting teeth. It mainly propagates by discrete fractures which appear to originate at local defects in the coating or at the interface. High intrinsic stress in the coating likely promotes coating spallation and accelerates the wear of the cutting edge.

Keywords: gear hobbing, hob, wear, HSS, cutting tool, PVD

INTRODUCTION

Gear hobbing is a quick and economical method to generate cylindrical gears. Hobbing is a milling process in which a specific milling tool, hob, generates gear teeth in the work piece as the two rotates against each other [1-3]. The hob consists of a large number of cutting teeth arranged to generate specific gear teeth. Each hob tooth is designed in such a way that it can be reconditioned several times without loosing its original cutting geometry. The desired wear scenario is a controlled wear which makes a continuous tool reconditioning scheme possible. This scheme can then simply be designed so that the tool is used in the most economical way. The problem is that hobs, in general, do not show continuous wear behaviour but lack in reliability. This makes it difficult to predict how many gears a hob should produce with sustained gear quality before it is reconditioned to avoid breakdown.

The most common type of hob consists of a homogenous HSS (High Speed Steel) body coated with a wear resistant ceramic PVD (Physical Vapour Deposition) coating, see Fig. 1. It can be considered to be a ceramic composite with its strength limited by the largest defect. It is, thus, important to have good control of the largest defects in both the coating and the steel to reach high reliability. Moreover, in the development towards more reliable hobs, it is important to establish what kind of damages hobs in industrial gear production show. By identifying and understanding the underlying tribological wear mechanisms it is possible to design tribologically improved cutting edges.

Metallurgical cross-sectional analysis and surface studies in SEM (Scanning Electron Microscopy) are valuable methods in wear studies. Both, however, require destructive sample preparations. Optical microscopy allows examination without ruining the tool but the analysis is then often restricted to damage mechanisms rather than wear mechanisms.

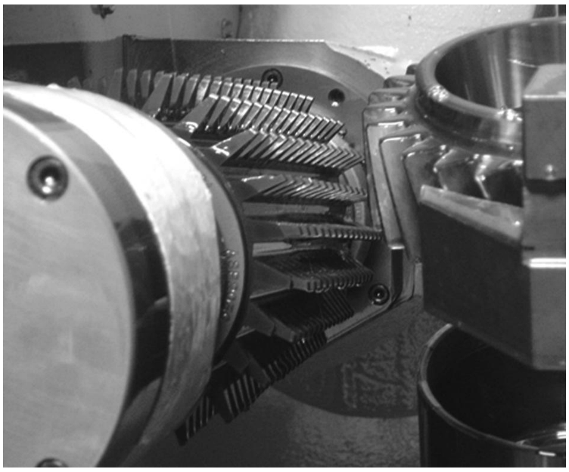

Figure 1. A gear hobbing set-up where the hob, made of a homogenous HSS body coated with a PVD coating, is mounted to the left in the picture. To the right the almost finished work piece is mounted.

This paper is a compilation of wear as observed on eight different hobs from seven different gear manufacturers. The main analysis is non-destructive and made with optical microscopy. As a complement, destructive cross-sectional analyses were made on two of the hobs. All tools are borrowed from normal production to show what type of wear is representative for each manufacturer's production. It aims to provide a knowledge base and to identify common problems to focus on in future studies and developments of gear hobbing tools. It also aims to investigate to what extent the critical wear necessitating reconditioning differs among the different manufactures.

THEORY

Damaging stresses

The intermittent cutting procedure that distinguishes the milling process from other cutting operations like e.g. turning and drilling, always involves a more or less strong shock as the cutting tooth engages the work material, followed by a varying force as the chip thickness changes. The cutting tooth is relatively cool when it enters the work piece, then heated as the chip is formed and yet again cooled down while waiting for the next engagement. This means that the cutting cycle involves both mechanical and thermal shocks [4]. The latter is more pronounced if cutting fluids are used as these decreases temperature more than air does.

In Fig. 2 the characteristic temperature profile for a chip formation process is shown for a general cutting process. The profile is the result of plastic shear of the work material and the sliding of work material against the tool flank and rake faces. The principal heat sources are located at the primary shear zone in the forming chip and in the secondary shear zone which is the frictional contact between the tool and the work material. The highest temperature is reached at the rake face some distance from the cutting edge [2, 5].

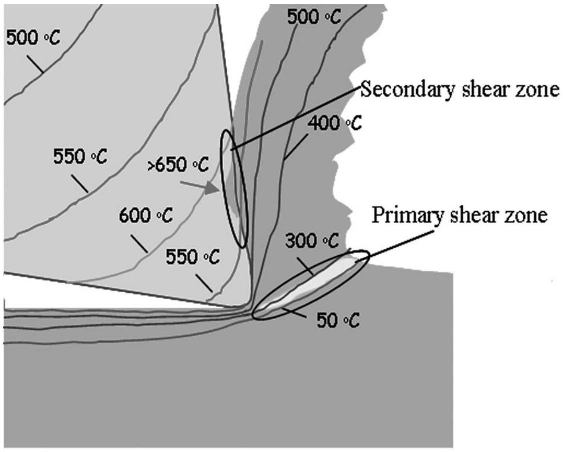

Figure 2. General temperature distribution of a HSS metal cutting edge during the chip formation process [5].

Conceivable damage mechanisms of coated HSS cutting tools

General wear, frequently encountered on HSS cutting tools translated specifically to a hob tooth, is presented in Fig. 3 [5, 6]. The performance of the tool is limited by crater wear, flank wear, edge chipping or combinations of these. The dominating wear depends on cutting process, cutting parameters, work material and tool material. Depending on the same parameters the wear evolves gradually by abrasive or adhesive wear, through plastic deformation, by loss of material through discrete fractures, or by combinations of these. Underlying reasons for discrete fractures might be local mechanical load concentrations and/or fatigue.

In order to protect HSS-tools against wear, coatings produced by PVD have become standard. The superior hardness of the coating protects the tool from abrasive wear. The coating is also chosen to have relatively low affinity to the elements in the work material which counteracts the welding mechanism that is a prerequisite for adhesive wear. Furthermore, by applying a coating, the tool temperature can be reduced due to improved contact conditions [5, 7]. On a coated tool wear can either propagate by abrasive and mild adhesive wear leading to a slow and gradual removal of the coating, which is the desired mode of wear, or by fatigue and discrete detachment of the coating [8]. The two latter phenomena leaves the substrate exposed prematurely which leads to an accelerated wear situation.

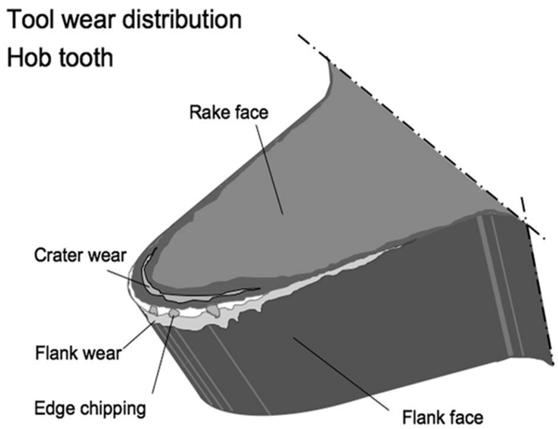

Figure 3. Characteristic wear for HSS cutting tools translated on to a hob tooth.

Discrete coating detachment can have a number of causes. The preparation of the tool surface is one critical stage when trying to avoid this. Industrial grinding processes more or less always result in burrs at the edges and, on a smaller scale, along the ridges on the ground surface as exemplified in Fig. 4. The burrs can be described as thin flakes of severely deformed material. When such burrs are present under a hard, brittle coating they will function as initiation points for cracking and are sure to be broken off almost immediately when the tool is exposed to external stress, leaving areas of unprotected substrate. It is therefore important to remove these burrs from the substrate surface before the coating is deposited.

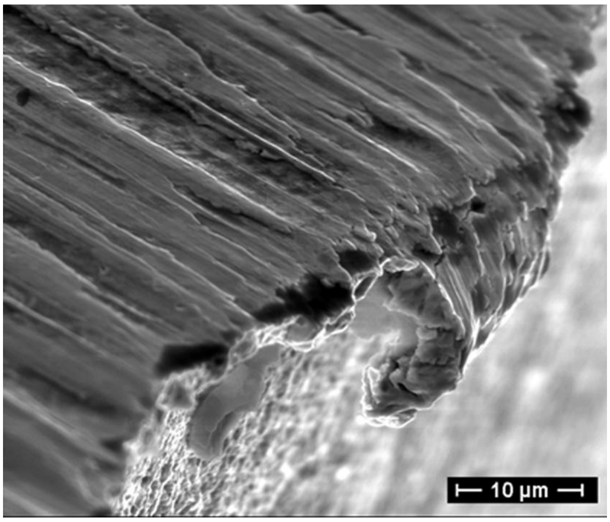

Figure 4. Scanning electron microscope image showing an example of a large burr hanging by over the edge of the ground surface. Burrs are also seen on ridges on top of the ground surface.

Thermally induced phase transformations in the HSS substrate can also reduce the adhesion of the coating [5]. Grinding of the HSS surface prior to coating often involves high temperatures. If the temperature locally exceeded the austenitising temperature, the HSS material matrix in the surface will transform to hard and brittle untempered martensite on top of a layer of softened tempered steel [9, 10]. When coated, this altered material will constitute a weakened layer between the coating and “healthy” HSS and will act destructively on the apparent adhesion of the coating. Of course, excessive temperatures in the cutting process can also lead to discrete coating delamination. HSS starts to show significant thermal softening for temperatures above 500 °C [9]. When the substrate temperature exceeds this temperature, the substrate more easily yields under the contact pressure, which results in brittle coating fracture and a rapid wear of the exposed, softened HSS.

In addition to these substrate related causes it has been shown that residual stresses in the coating itself may promote fracture and delamination [10]. Hard PVD coatings on HSS typically possess compressive stresses in the order of 1-5 GPa. On a perfectly flat and smooth substrate of infinite extent, these stresses would not generate any normal or shear stresses at the interface, see Fig. 5a. They would only act positively on the coatings cohesion. However, tool surfaces deviate quite a lot from this ideal case as it has a certain surface roughness and has a limited geometrical extent. The tool surface is composed by grooves, ridges and edges, all interacting with the compressive stresses to generate stresses across the interface (Fig. 5b and c). The ratio between the substrate radius and coating thickness is of great importance for the magnitude of such induced interfacial stress. An increased ratio helps to reduce the maximum interfacial stress. When the system is subsequently put to service and external stress is superimposed, coating detachment readily occurs in regions where the interface is already experiencing high tensile normal stress, i.e. along the coarse ridges and along the cutting edge of the tool. The surface topography and the edge radius are thereby two important factors to control in order to avoid premature failure due to discrete coating detachment. In fact, also other types of irregularities such as pores (Fig. 5d) impurities, carbides, topographic variations etc. in the interface will induce local stress fields and may have negative effects on the coating adhesion.

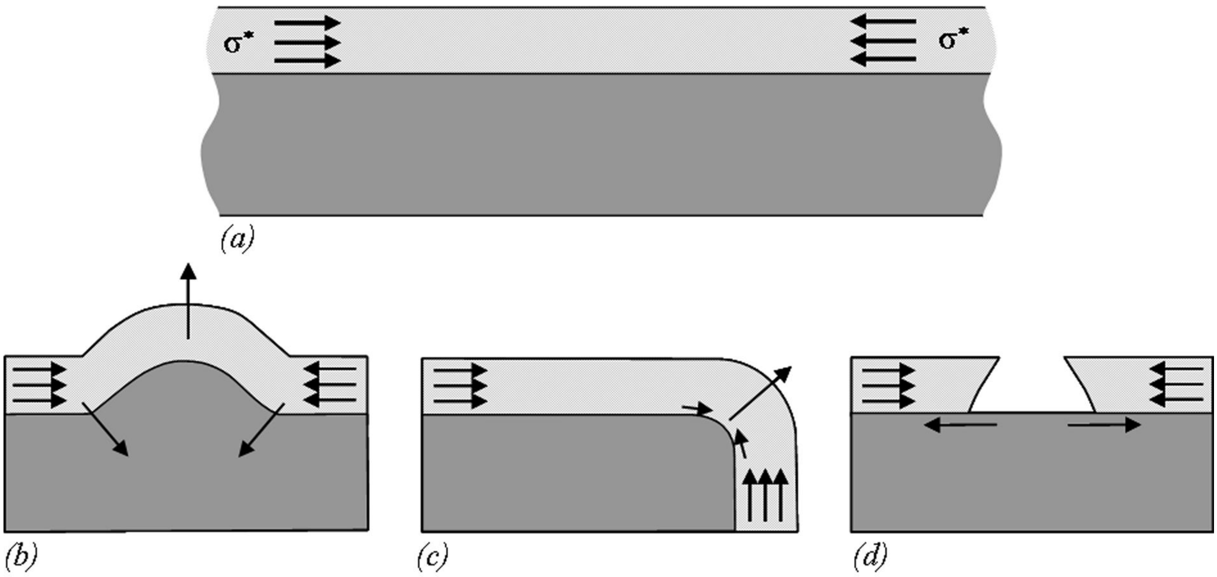

Figure 5. Illustrations of an "infinite" coating on a perfectly flat and smooth substrate having a compressive residual stress σ^* (a) which generates a tensile "lift-off" stress at a ridge (b) and an edge (c) plus shear stresses at the edges of a pore (d).

STUDIES OF WEAR IN INDUSTRIAL HOBBING

Tools and cutting conditions

Hobs were selected, and borrowed from the production line, from seven different Swedish gear manufactures. The hobs were taken out of production when the gear manufacturers considered it to be time to recondition them. The selection was done regardless to type of operation i.e. coarse cutting, fine cutting etc. Each hob was chosen to show characteristic wear representative for the specific production line by the manufactures themselves.

The eight hobs that have been analysed are presented in Table 1. Seven of these have been cutting by climb hobbing and one by conventional hobbing. Two of them have been cutting without any cutting fluid while the other six have been cutting with different oils as cutting fluids. Of course, the selection also comprises different combinations of coating, tool material and work material as shown in Table 1 and 2.

Dominating damage mechanisms

A non destructive analysis using optical microscopy was done on the eight hobs. One representative cutting tooth is selected from each hob for illustrating the characteristic wear. The dominating damage mechanisms on the different hobs boils down to flank wear, edge chipping and crater wear. Even though the hobs are divided according to dominating damage mechanisms below there was nearly always a mix of the mechanisms that have been active.

Flank wear

Wear dominated by flank wear was only observed on hob A. The wear on this hob is rather extensive and it is located at the cutting edge, see Fig. 6. The coating surrounding the worn area on the tooth flank, see Fig. 6b, appears to have a more or less full coating thickness without any discoloration. This indicates that the flank wear has not been propagating by gradual removal of superficial material but rather by discrete failures. Another fact, supporting this, is that the cutting edge is not worn uniformly but instead it is full of notches. Furthermore, the rake face appears to consist of rather large ridges and grooves and the notches in the cutting appear to be associated to these, which are indicated by arrows in fig 6a

The hob has, contrary to the others, been cutting by conventional hobbing that involves high mechanical loads on the cutting edge and sliding of the tooth flank against the work piece under high pressure.

Table 1. Tool material, coating material and cutting parameters for the eight studied hobs labelled A through H.

Tool label	A	B	C	D	E	F	G	H
Tool material	ASP2030	ASP2030	S390	ASP2052	ASP2030	ASP2030	ASP2052	S390
Coating material	AlCrN	AlCrN	AlCrN	AlCrN	TiAlN	TiCN	AlCrN	TiAlN
Module	1	1.74	3.25	6.95	4	4.87	3.75	2.45
Cutting mode	Conven-tional hobbing	Climb hobbing	Climb hobbing	Climb hobbing	Climb hobbing	Climb hobbing	Climb hobbing	Climb hobbing
Speed [m/min]	110	120	75	70	80	124	170	180
Feed [mm/rev]	0.31	4	4	3	3.5	5	3	3
Coolant	Oil	Oil	Oil	Oil	Oil	Oil	Air	Air

Table 2. Type, hardness and chemical composition of work material in which the hobs have been milling.

Hob:	A	B	C	D	E	F	G	H
Type of work material:	Case hardening steel	Case hardening steel	Precipita-tion hardening steel	High grade alloy steel	Case hardening steel	Case hardening steel	Case hardening steel	Case hardening steel
Reference steel:	17NiCr MoS6	16MnCr S5	*	21NiCrM o5H	20MnCr S5	20NiCr MoS2-2	20MnCr S5	SS 142172
Hardness: (HB)	150-190	160-200	222-266	260	150-190	150-180	150-190	200

*Chemical composition (%)

Fe	C	Si	Mn	P	S	Al	N	V
97,701-98,611	0,42-0,46	0,42-0,46	0,70-1,00	<0,035	0,04-0,06	<0,03	0,009-0,014	0,07-0,1

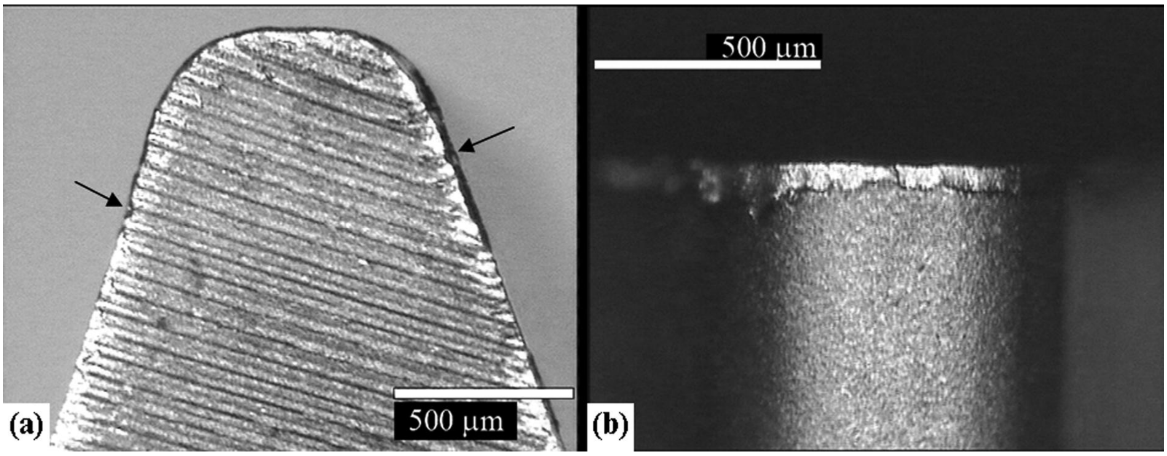

Figure 6. Pictures of a worn tooth representative for hob A: Bright areas of exposed HSS are seen close to the cutting edge on the tooth rake face (a). Extensive wear of the coating as well as the HSS at the cutting edge seen from the tooth flank face (b).

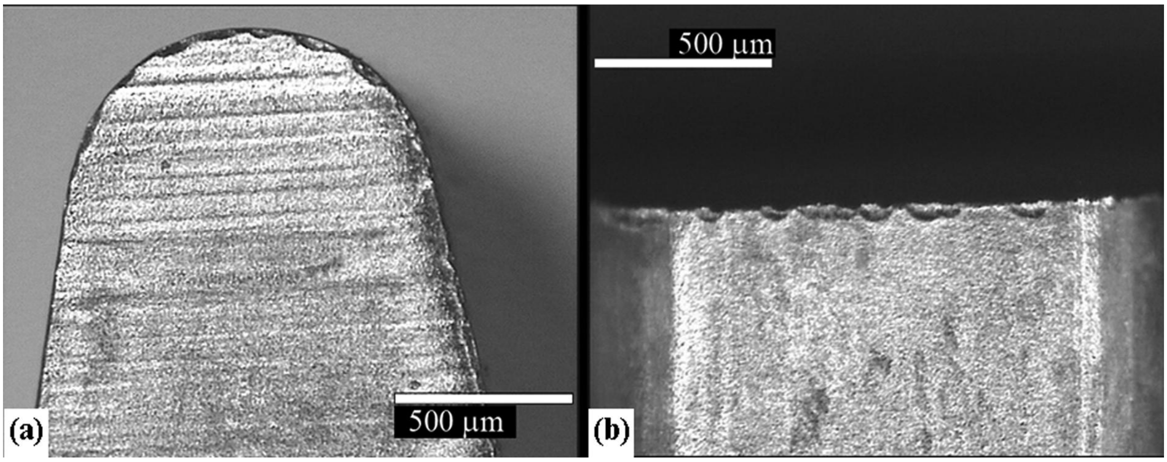

Figure 7. Pictures of a worn tooth representative for hob B: Secondary to edge chipping the coating is exposed to mild wear which appears as dark areas on the rake face (a). The jagged cutting edge is seen from the tooth flank face in (b).

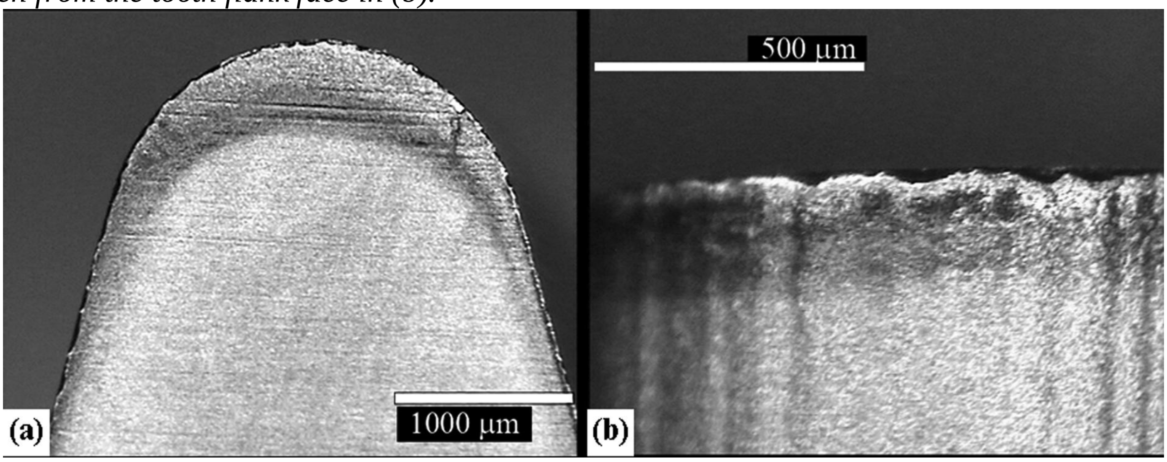

Figure 8. Pictures of a worn tooth representative for hob C. The edge is worn by discrete failures (edge chipping) while the coating on the rake face is exposed to mild wear, seen as dark areas (a). The jagged cutting edge is seen from the flank face in (b). Note how the edge chippings seem to correlate with the coarse ridges on the flank face.

Edge chipping

The dominating wear of hob B and of hob C is edge chipping, see Fig. 7 and 8. Secondary to the edge chipping, a mild wear of the coating can be seen as a dark area on the tooth rake face. The edge chippings are most probably consequences of point defects in the cutting edge. The coating is removed by discrete failures exposing small areas of HSS that has a significantly lower wear resistance than the coating, resulting in a hollowed cutting edge. If the failures are initiated in the coating, the interface coating/HSS or in the HSS bulk is not possible to determine from this superficial analysis. On hob C however, the notches in the cutting edge seem to be connected to the ridges on the tooth flank face, se Fig. 8b.

Crater wear

The remaining hobs all have crater wear as the dominating wear type although the appearance and location of the formed craters vary between the hobs.

On hob D the wear is characterised by a crater that is formed on the rake face in close connection to the cutting edge, see Fig. 9a. Nearby, a large chip has been removed from the cutting edge. Chipping also occurs on other parts of the cutting edge, which is seen in Fig. 9b.

Hob E, shown in Fig. 10, has a crater that is formed in the same area of the rake face as the crater on hob D. Contrary to hob D, no significant edge chipping is seen on hob E, see Fig. 10b. Due to the fact that the edge of the crater is uneven it has likely been growing by discrete coating failures rather than a mild, continuous wear.

Hob F suffers from both severe edge chipping and crater wear as shown in fig 11. Discrete areas of exposed HSS result in grooves on the tooth rake face that accrete to a larger crater close to the cutting edge. The edge chipping is extensive and the cutting edge appears to be completely devoid of coating material, see Fig. 11b. A certain amount of flank wear, mainly located at the ridges present on the flank face, can also be seen.

Hobs G and H have both been operating without presence of cutting fluid. For hob G, the crater is located close to, and extends along, the cutting edge as shown in Fig. 12a. Small edge chippings are seen in the edge. Furthermore, work material is welded onto the rake face giving its central part a rough appearance. The fact that work material is attached to the tool indicates adhesion and high friction between the tool rake face and the formed chip. On hob H, cracks and dimples are seen in the coating on the rake face close to the cutting edge, see Fig. 13. In connection to these cracks a crater is formed. This type of appearance indicates thermal softening of the HSS. As the HSS softens, the coating looses its support and collapses by brittle cracking when external load is peaking.

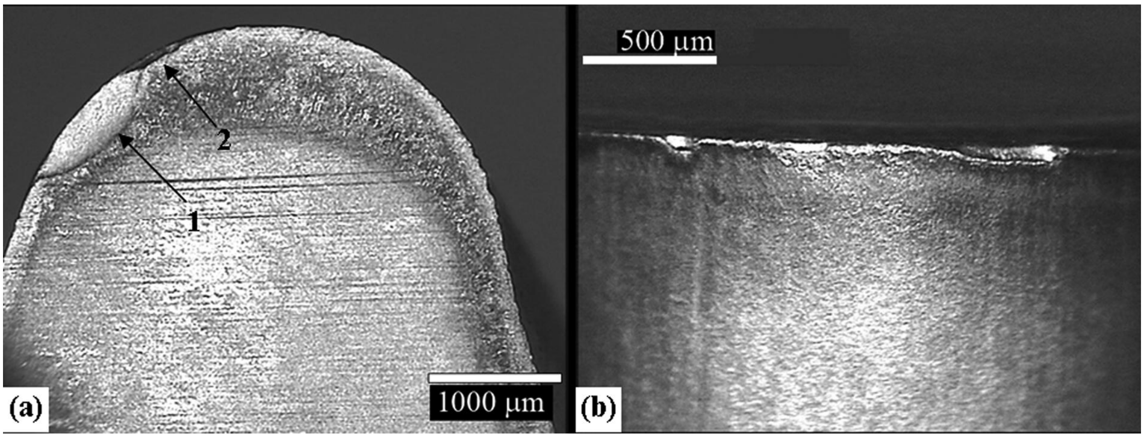

Figure 9. A worn tooth representative for hob D: A crater is formed in connection to the cutting edge on the rake face (a) indicated by arrow 1. Above the crater, a large chip has been removed from the cutting edge, indicated by arrow 2. The cutting edge seen from the tooth flank face reveals the presence of several discrete failures in the cutting edge (b).

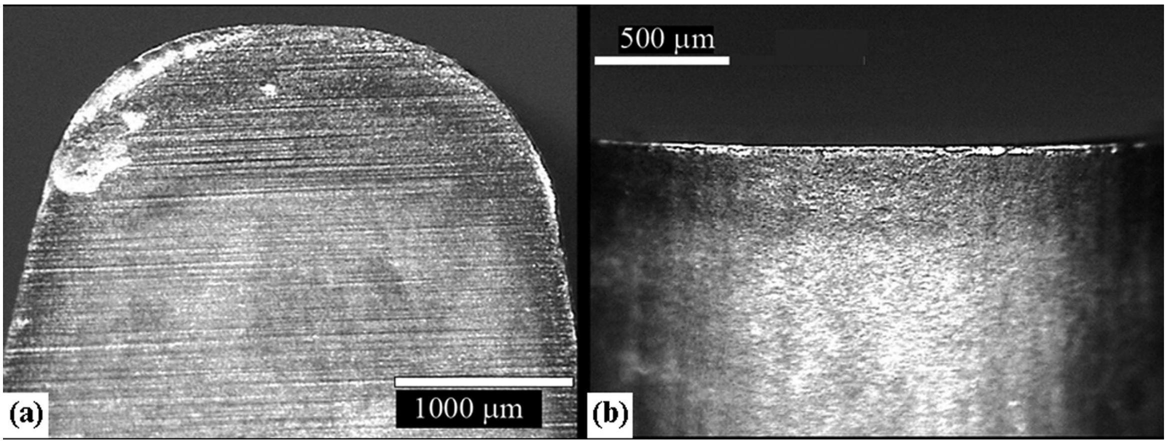

Figure 10. A worn tooth representative for hob E: An irregularly shaped crater is formed close to the cutting edge on the tooth rake face (a). No significant edge chipping can be seen at the cutting edge (b).

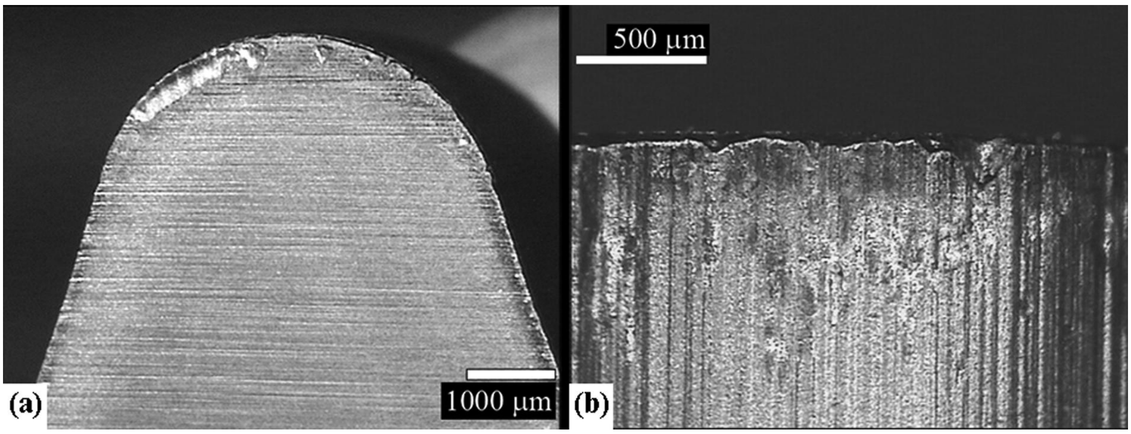

Figure 11. A worn tooth representative for hob F: A large crater is seen close to the cutting edge along with smaller isolated craters on the rake face (a). The coating on the cutting edge is completely removed and extensive edge chipping is seen (b). A mild flank wear located primarily on the ridges of the flank face can also be seen.

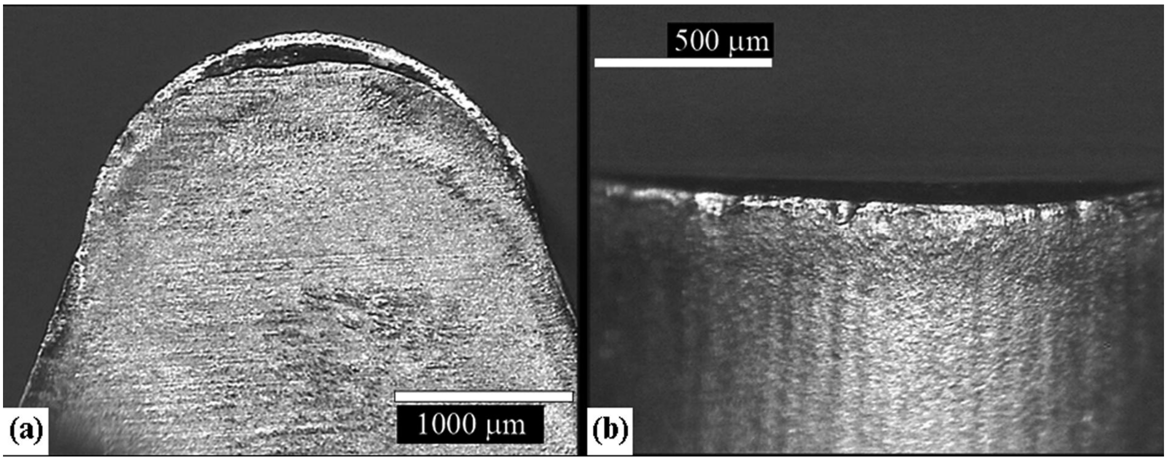

Figure 12. A worn tooth representative for hob G: A crater is located on the rake face in close connection to the cutting edge and follows the line of the edge (a). The area just beneath the crater appears to be polished which is seen as a smooth, dark area. The rough appearance of the surface further down on the rake face is due to work material welded on to the surface. The cutting edge, seen from the flank face, reveals small edge chippings in the edge (b).

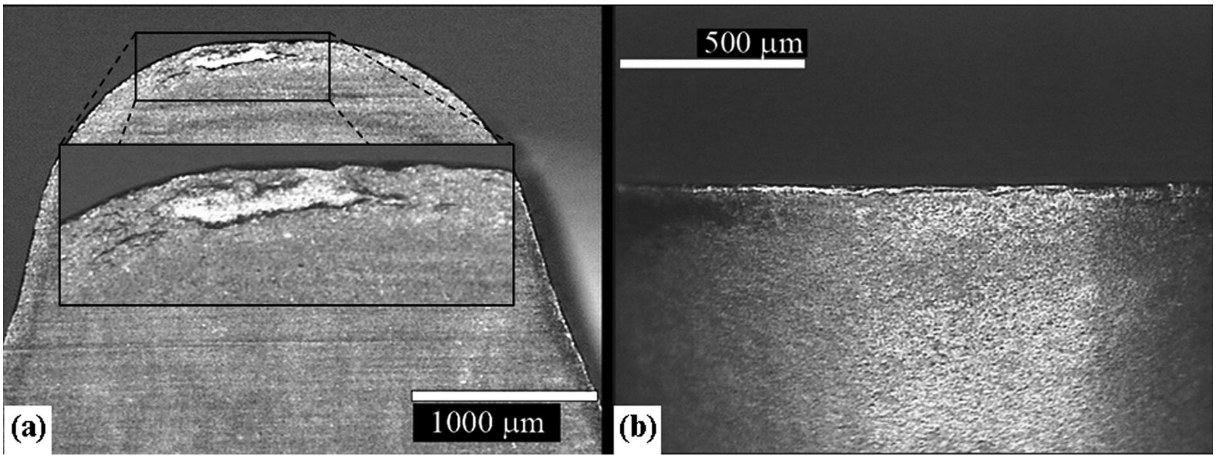

Figure 13. A worn tooth representative for hob H: Cracks parallel to the cutting edge are seen in the coating on the rake face (a). These cracks result in the formation of a crater and eventually the exposure of the HSS. No significant edge chipping can be seen in the cutting edge (b).

<u>Cross-sectional analysis in SEM</u>

Due to its destructive nature Cross-sections were made on hobs B and E only. All other tools were intended to be reconditioned and put back in production after the optical examination was completed.

Cutting teeth that not have been involved in any cutting processes can be found farthest out in the rows of teeth on the hobs. The number of chips produced per tooth often increases towards the centre of the row of teeth due to tool shifting schemes. This makes it possible to survey the propagation of damage mechanisms.

Cross-sections of unused or barely used teeth on both hob B and E show flaws in the coating around the cutting edge. On hob B, Fig 14 a, the coating is non-existing or very thin around the edge while it is rather thick on the rake- and flank face of the tooth. Steps where the coating thickness is reduced rather abruptly can also be seen on both the flank- and the rake face. Similar, on hob E the coating is thinner close to the cutting edge then on the adjacent faces, cf fig 14 b. The interlayer, seen as a thin light band between the coating and the HSS substrate in fig 14 b, is also interrupted and missing on some parts around the edge indicating that the coating has spontaneously chipped during growth in the coating process. The extent of cracks found close to the edge support this observation.

Moreover, cross-sections of worn teeth show that the coating is prone to crack at or adjacent to irregularities in the substrate/coating interface as well as at defects in the coating itself. A cohesive coating failure linked to a substrate surface irregularity on the rake face on a tooth from hob B can be seen in Fig. 15. A cross-section of a worn tooth on hob E reveals that chunks of coating material are removed from the rake face due to cracks initiated at pores in the coating/HSS interface and at coating defects, see Fig. 16.

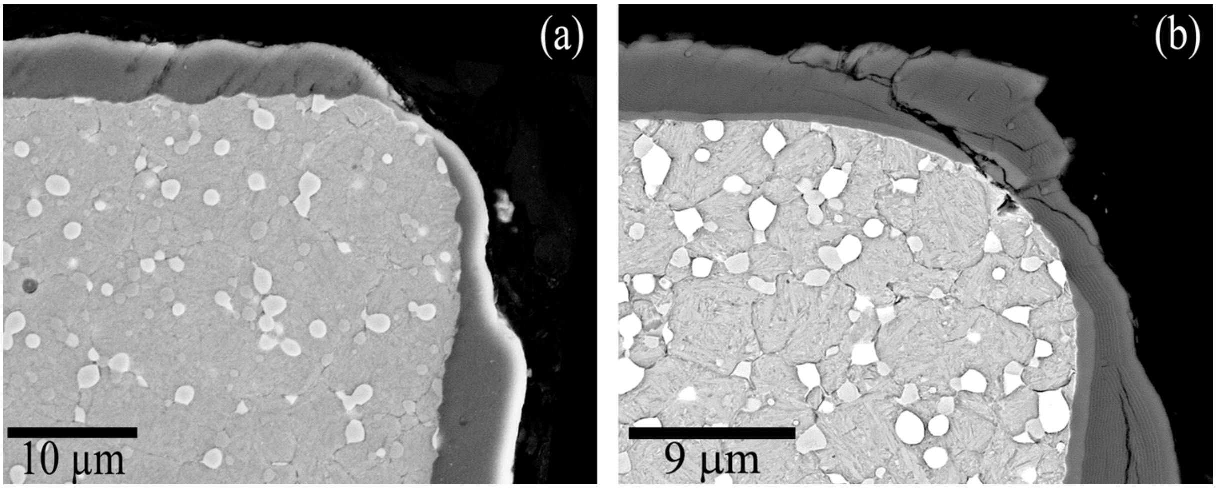

Figure 14. Cross sections of the cutting edge on unused teeth taken from hob B (a) and hob E (b). The upper horizontal side is the rake face. The dark gray layer is the PVD-coating.
the coating/HSS interface and at coating defects, see Fig. 16.

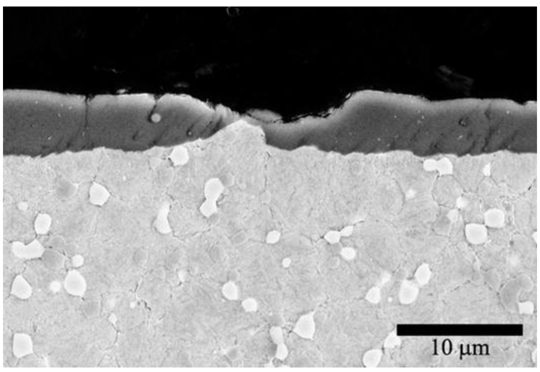

Figure 15. Cross-section of the rake face on a cutting tooth from hob B. The coating (dark gray layer) has chipped close to a ridge in the HSS substrate (light gray) surface.

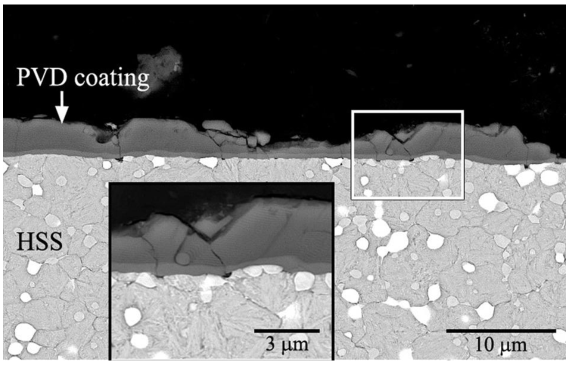

Figure 16. Cross-section of the rake face on a cutting tooth from hob E. The PVD coating is fractured and cracks can be seen originating at irregularities in the interface and in connection to droplets in the coating.

DISCUSSION

The overall impression of the studied hobs is that the wear mainly propagates by discrete failures. This means a non-continuous wear of the PVD-coating resulting in exposed areas of HSS. This leads to undesirable accelerated wear of the tool as the HSS has a much lower wear resistance than the coating.

Discrete failures in the cutting edge resulting in edge chippings are seen on six of the eight hobs. The exact mechanisms and the reasons for the edge chipping can not be conclusively determined from the superficial study made with optical microscopy. However, it is reasonable to believe, supported by the selective cross-sectional analysis, that high residual stresses in the coating, combined with different kinds of defects in the substrate surface and/or coating as well as sharp cutting edges play dominant roles. As described above, high stresses are induced in the substrate-coating interface, especially at substrate edges like the cutting edge. If these local stresses become excessive they will lead to coating detachment as soon as the tool is subject to external stress, or even spontaneously before that, resulting in exposed HSS. The magnitude of the stresses is connected to both the coating thickness and the edge radius which therefore are important factors to consider when attempting controlling the wear.

The dominant damage mechanisms on the hobs, B and E, are characterised as edge chipping and crater wear respectively. The cross-sections, however, reveals that the underlying wear mechanisms are much the same for the two. Nevertheless, the location and extent of the damages differ. On hob B the weakest point, limiting tool life, is the sharp cutting edge in combination with a thick coating. This leads to flaking of the coating around the edge and accelerated wear of the exposed HSS resulting in a jagged cutting edge. On hob E, on the other hand, the weakest points are irregularities in the coating itself and in the interface between coating and substrate. Here, the cohesive coating failures are thus located at the rake face, although close to the cutting edge, resulting in craters where exposed HSS has been worn of.

On hob C the edge chippings seems to be connected to the ridges on the flank face of the tooth (*c.f.* Fig. 8b). These ridges are relatively high and therefore probably carries most of the load which may have resulted in local plastic deformation and chipping. The two hobs that are more or less free from edge chippings, hobs E and H, both have quite smooth flank faces. There is therefore reason to assume that the surface topography on both the rake face and the flank face are important to minimize in order to control this wear behaviour, not only from the adhesion point of view but also to achieve a beneficial load distribution during cutting.

Apart from the edge chippings the wear is mainly located to the rake faces of the hobs. Five of the eight hobs are showing wear resulting in the formation of one or several craters on the rake face. The shape and location of most of these craters give the impression that the wear is dominated by numerous discrete failures rather than by continuous wear. The failures are supposedly connected to “isolated” defects which lower the wear resistance considerably on a local scale. This is supported by the cross-sectional analyses that clearly show cracking and flaking of the coating adjacent to interface irregularities and/or coating defects (droplets) for both hob B and E.

The wear on hob A has been characterised as flank wear which might be a bit misleading. Flank wear is often described as mild abrasive and/or adhesive wear of the flank face when sliding against the surface of the work piece. On hob A, on the other hand, the edge seems to be worn down more drastically and on a larger scale as it has a more jagged appearance. This is supposedly a consequence of a large grinding marks at the cutting edge combined with high external stresses. The wear, however, is propagating on the flank face and thus referred to as flank wear.

CONCLUSIONS

This survey of damage mechanisms on PVD coated HSS hobs used in Swedish gear manufacturing industry shows that edge chippings and formations of craters on the rake face close to the cutting edge are the most frequently encountered. The appearances of the two types of damages imply that they propagate by discrete failures involving cracking and flaking of the coating around the cutting edges, at irregularities in the substrate/coating interface or in the coating itself. Improved substrate surface preparation, improved cutting edge geometry and controlled residual stress levels in the coating are essential issues that have to be addressed in the development towards more reliable hobs.

ACKNOWLEDGMENTS

Financial support from the KUGG project within the VINNOVA MERA program is gratefully acknowledged. The authors would also like to thank all the participants in the KUGG network that have contributed with material to this study.

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