HIGH SPEED GEAR HOBBING WITH CEMENTED CARBIDE HOBS

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As dominating manufacturing process to create external gears, hobbing is of major industrial importance. Hence, a continuous process optimisation to satisfy the demand of the market is necessary. Changing the substrate material is a basic approach in optimization of operation times. Due to acquisition costs and lacking knowledge most companies hesitate to use cemented carbide hobs which endure higher cutting speeds compared to HSS/PM-HSS. Offering experience based knowledge which can be used to revise the cemented carbide application in industry, cutting parameters were varied investigating their influence on the wear behaviour. The impact of high performance cutting parameters within a fly cutting analogy test was examined using different measurement techniques and simulation results.

KEYWORDS
gear hobbing, cemented carbide, wear behavior, fly cutting

1. INTRODUCTION

The competition between companies in industrial countries and between companies of industrial and emerging countries is advancing with further globalization.

Regarding the demand for gears in the past years a continuous increase of about 5.4 % each year can be observed. Taking 134 BN. $ in 2008 as a known fact the forecast for 2018 is about 217 BN $ [Mc Guinn 2013]. The majority of these gears are manufactured for the automobile industry. After OICA, the international federation of automobile manufacturers, the global car production of 2013 counts 58 MM. new cars [N.N. 2014b]. These cars contain a large amount of gears supporting the rise in the demand. Furthermore the current automobile transmission market demands an increasing number of automatic transmissions. These contain gears of smaller module but more gears in total compared to manual transmissions. Therefore high productive and taylored manufacturing processes are needed today and in the future. Concerning the process chain for gears many options to improve the manufacturing processes do exist.

As the dominating manufacturing process for external spur and helical gears hobbing is of major importance for gear production. Within the hobbing both the machine and the tool can be optimised. These components are developed continuously. To increase the productivity in an industrial environment a basic approach is to fully exploit the potential of existing tools and their substrate material. The latest research work for hobs made of powder metallurgical high speed steel (PM-HSS) showed that this substrate is highly efficient up to 250 m/min [Hipke 2011]. A major advance in productivity can be achieved by switching from HSS based substrates to cemented carbide hobs. It is well known that higher cutting speeds can be realised with hobs made of cemented carbide. With about 20%, only the minority of all hobbing tools are fully made of cemented carbide. The majority (60%) of all hobs used in industry are made of HSS and PM-HSS. Also Hobs with cemented carbide inserts do exist (20%) [Falk 2013].

Due to reasons like high investment costs, the lack of knowledge and old machine tools that are not able to realise high cutting speeds the gearing industry is hesitating to use hobs made of cemented carbide.

Cemented carbide as cutting material is already used in hobbing processes for large gears such as gears in wind turbines. In that case inserts made of this durable cutting material are used to increase the performance. [Wennmo 2014, N.N. 2014a].Unfortunately, this tool concept is restricted to small modulus.

The latest research work for cemented carbide hobs is about 10 to 15 years old [Winkel 2004], [Kleinjans 2003], [Kobialka 2001], [Knöppel 1996]. This past research demonstrated that cemented carbide hobs can machine with higher cutting parameters. Furthermore influences on the tool life, wear behaviour and process limits were investigated. Ten years later this knowledge is still important but the frame conditions like substrate and coating properties have changed enormously. Therefore it is necessary to define the limits and economic optima again.

The aim of current research is to identify economic cutting parameters for different gears. Additionally the wear behavior and wear mechanisms are investigated under the conditions of high cutting speeds. Providing experimental knowledge for the industry is one of the major goals of this research work.

Within this paper the first results of a manual transmission gear are presented.

2. PRE-INVESTIGATION

Within the research project three different gears are investigated, including a planetary gear (m_n = 1.23 mm), a typical automotive manual transmission gear (m_n = 2.7 mm) and a gear from a commercial vehicle transmission gear (m_n = 3.45 mm). Until now, results exist for the module 2.7 mm gear setup which are presented in this paper. The material 20MnCr5 (AISI 5115) is a typical gear material and is therefore used for the research. The cemented carbide teeth consisting of K30 carbide are coated with an (Al,Cr)N-based coating. This coating is widely used in modern gearing industry. These and more important characteristics of the gear system are summarized in Fig. 1.

module	m_n	**2.7 mm**
pressure angle	α	22.5 °
tool diameter	d_{a0}	**100 mm**
number of starts	z_0	2
number of gashes	i	22
substrate		**cemented carbide (K30)**
coating		**(Al, Cr) N**
helix angle	β	24.5 °
number of teeth	z_2	41
face width	b	29 mm
gear material		**20 MnCr 5**
tensile strength	R_m	590 N/mm²
cutting depth	T	7.7 mm
lubrication		**none**
chip thickness	h_{cu}	varying
cutting speed	v_c	varying

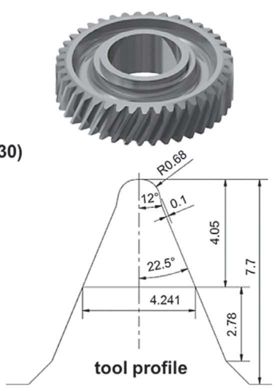

Figure 1. Gear Parameters.

To ensure reliable research results pre-investigations of the initial tools (fly teeth) for example regarding different geometrical properties are necessary.

2.1 CUTTING EDGE RADIUS AND ROUGHNESS

Capturing the state of the fly teeth before machining the roughness of the cutting and flank face and the quality of the cutting edge were examined. It is a fact that changes in the initial conditions of the tool considerably influence the tool life. To assess the cutting edge radius an optical inspection based on fringe projection is used. Both on the leading ("LF") and the trailing ("TF") flank of three randomly chosen teeth 100 light cuts (distributed over 2 mm) were measured. The results of this inspection are presented in Fig. 2. Initial measurement of tool. 2. Also the range of the values is illustrated.

Cutting edge radii between 12 µm and 15 µm were measured on the flanks. Furthermore results of the roughness measurement are illustrated. These were measured at the cutting and flank face of three teeth with a tactile surface profiler.

The edge radii as well as the surface roughness match the industrial standard.

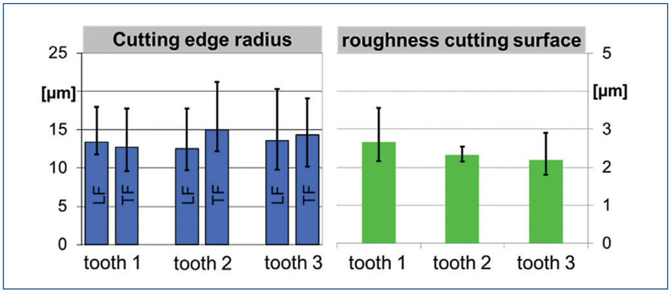

Figure 2. Initial measurement of tool.

2.2 COATING THICKNESS

The fly cutting teeth were PVD-coated utilizing a custom made holder device. This way the shadowing effect of a real hob (Fig. 3) is achieved.

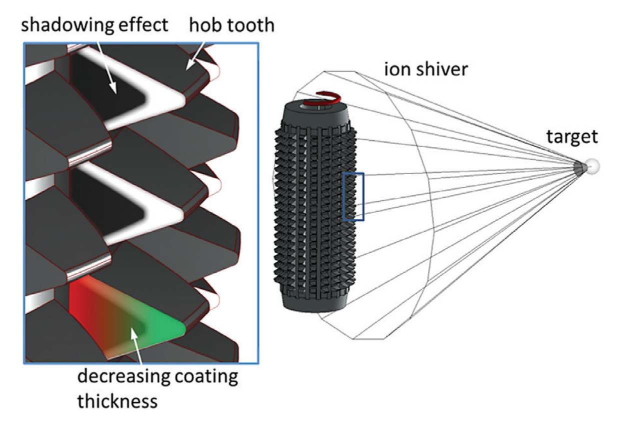

Figure 3. Shadowing effect in coating.

These shadowing effects impel the coating thickness to vary on the cutting face. The tool life is greatly depending on the coating thickness. Therefore it is mandatory to know the thickness distribution on the cutting and flank face to examine wear mechanisms.

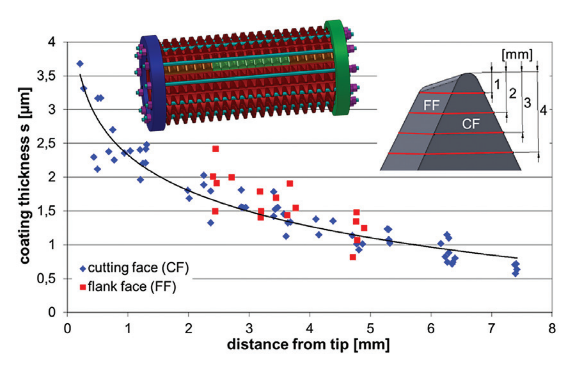

Figure 4. Coating thickness distribution.

The results shown in Fig. 4 clarify that the coating thickness is continuously decreasing from tip to the root. At the tip the thickness counts about 3.5 µm due to the advantageous coating process. Also this value matches the industrial standard. At the root only 0.75 µm coating thickness was measured. At this spot the cutting process load is very small, thus the reduced coating thickness is not critical.

The thickness did not differ between cutting face and flank face.

3. WEAR INVESTIGATION

The wear investigation was performed by using a well-established analogy test [Joppa 1977]. Fig. 5 is comparing the tool concepts of real hobbing and the analogy test.

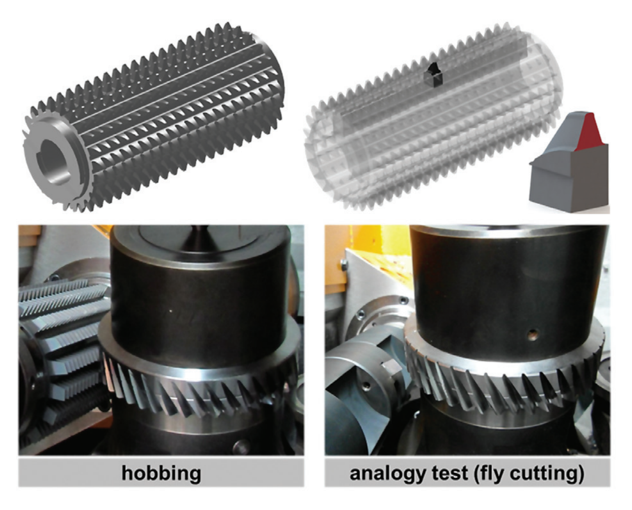

Figure 5. Fly cutting as analogy test for hobbing.

Within that test a single fly cutting tooth or multiple (corresponding to the number of starts) fly cutting teeth are being shifted tangentially alongside the work piece successively representing all the generating positions of a real hob. The revolutions of the tool and the workpiece are coupled. The cutting speed and the axial feed (according to different chip thicknesses after Hoffmeister [Hoffmeister 1970]) were varied to examine their influence on the tool life and the wear mechanism.

In the following discussion about the wear, the tool life of a real hob ("L") and the tool life of a fly cutter in the analogy test ("L_{FC}") will be distinguished. Generally the tool life of a fly cutter is increased compared to a real hob because there are less or no chip jams. A ratio L/L_{FC} of about 1/3 can be assumed [Klocke 2009, Winkel 2004].

Reaching the wear criterions a tool life matrix depending on cutting speed and chip thickness (axial feed) can be created. The diagram in Fig. 6 corresponds to the experimental design in which the cutting speed v_c was varied between 400 m/min and 1200 m/min. Furthermore the Hoffmeister chip thickness $h_{cu,max}$ was successively increased from 0.1 mm (f_a = 1.2 mm/rev) up to 0.28 mm (f_a = 8.7 mm/rev).

Comparing both the cutting speed and the chip thickness test series differences do arise regarding the wear development. Remaining a constant chip thickness of 0.16 mm and increasing the cutting speed will force the tool life to constantly decrease. Even at a cutting speed of 1200 m/min the substrate material is still able to bear the load. It is not collapsing even though the wear criteria are quickly reached. At a small cutting speed of 400 m/min the tool life gains its maximum. Below that cutting speed no tests were performed because this is already the industrial state of the art and the aim of the research project is to look ahead towards higher cutting speeds.

In contrast to this continuous behaviour the tool life is not showing clear dependencies when the chip thickness is varied at a constant cutting speed of 500 m/min. At small feeds the tool life is considerably decreased. This is caused by the increased absolute number of tooth contacts. Having a maximum at a chip thickness of 0.18 mm the tool life is settling at a constant low level if the chip thickness is further increased. Again it appeared that the substrate material is able to endure high chip thicknesses up to 0.28 mm. Compared to an immense cutting speed increase the loss in tool life is even smaller when the chip thickness is extremely high.

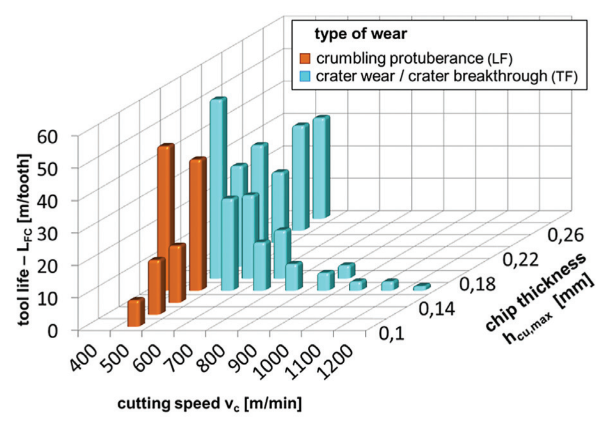

Figure 6. Tool life and wear phenomena.

Within the experiments two different wear patterns did occur. The change of critical wear from flank wear to crater wear is exemplified by the different colours in the diagram. At low cutting speeds and low chip thicknesses the less critical wear pattern "crumbling substrate removal" does occur at the start of the protuberance (see Fig. 7). This geometrical element and especially the spot where the protuberance flank meets the original tooth flank are known to be wear critical. The occurring wear itself is less critical because it evolves continuously and can be well anticipated. With the used gearing and process parameters this wear emerges on the leading flank. According to gear manufacturing industry a maximum flank wear of 120 µm is acceptable in this case of application.

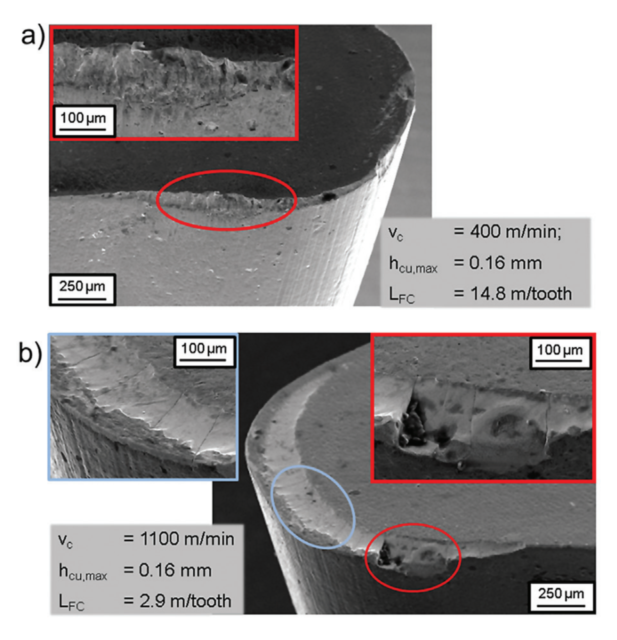

Figure 7. Wear phenomena a) crumbling protuberance (LF), b) crater wear and crater breakthrough (TF).

Increasing the load on the tooth by raising the cutting speed and/or the chip thickness the critical wear phenomenon changes. This more critical wear phenomenon is situated on the cutting face. Due to material flow crater wear is emerging on it. Decreasing tool lives with higher cutting speeds might correspond with an increase in process temperature. The substrate material gets softer and tougher and is therefore less durable against abrasive impact. Though, crumbling effects become less important whereas the support strength of the substrate material decreases with the temperature which supports breaking of the coating. In the latter case the substrate is no longer protected and is directly exposed to the chip.

On the other hand low tool life follows very small chip thicknesses. This might be induced by the corresponding massive increase in number of cuts and tooth flank contacts which is equal to more wear inducing hits on the brittle tool.

The crater wear is not typical in hobbing with cemented carbide. In the past years hobbing machines got improved and offer machining with high cutting speeds today. Due to considerably increased cutting speed the load on substrate and coating did increase as well. After some point thermal cracks are induced following increased process temperatures and temperature gradients. Crack formation and crater erosion do also evolve relatively steadily. In the case of application a maximum crater depth of 60 µm is allowed. The crack weakened edge reacts sensitive. A collapse of the cutting edge in terms of crater breakthrough can occur abruptly. In the researched case the edge collapse occurred on the trailing flank.

Summarizing the two occurring wear phenomena Fig. 7 is exemplarily illustrating SEM-pictures of a tooth flank and cutting face. The teeth did machine in climb hobbing strategy.

4. SPECIAL TESTS

4.1 INCREASING THE NUMBER OF STARTS

The investigations mentioned in chapter 3 showed that cemented carbide hobs can bear increased chip thicknesses (see Fig. 6). One way to achieve these is an increase in axial feed f_a. Unfortunately this goes along with an increase in the depth of the feed marking (δ_x) which is technologically disadvantageous for later machining processes in the manufacturing chain.

Another way to advance the productivity through high chip thicknesses at constant cutting speeds is to increase the number of starts of a hob.

Hobbing with an increased number of starts is characterized by a decrease in generating positions. To realize a matching fly cutting process for research purpose without redesigning a new tool the number of gashes can be easily decreased to gain equivalent chip thicknesses.

The resulting tool lives after simulating less generating positions are compared in Fig. 8.

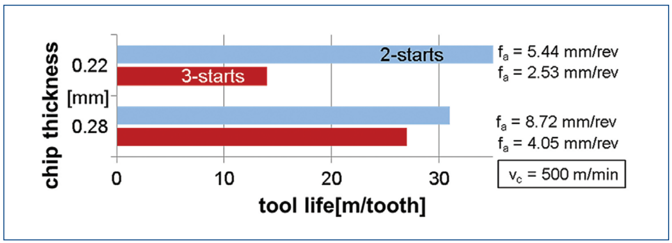

Figure 8. Effect of increased number of starts.

The diagram compares the tool lives at 2 different chip thicknesses for two and three number of starts. In both cases the tool life is smaller when hobbing with 3 starts. Explaining why the tool life in cutting with 3 starts increases from 0.22 mm to 0.28 mm chip thickness it has to be considered that the absolute axial feed is less than hobbing with 2 starts at the equal chip thicknesses. At these smaller feeds the total amount of chips and chip removals is increased, which seems critical for cemented carbide tools. With an increase in feed the ratio of number of impacts and applied load is more advantageous.

Changing the chip thickness from 0.22 mm to 0.28 mm while increasing the number of starts from 2 to 3 the productivity can be raised by about 10%. The depth of feed marks decreases from 35 µm to 25 µm in that case.

The tool lives at 0.28 mm chip thickness are at one level. Therefore the studies showed that increasing the number of starts is one way to optimize the hobbing process. The maximum axial feed (depth of feed marking) are not exceeded and an inconvenient chip size is generated.

4.2 UP-CUT HOBBING

Generally, climb hobbing is used in the gearing industry. To perform an overall research for the cemented carbide substrate, also the tool performance in up-cut hobbing is of interest. In the gearing industry up-cut hobbing is used to eliminate flank surface defects occuring in climb hobbing [Stuckenberg 2011].

Fig. 9 is illustrating the yielding tool lives of this additional research.

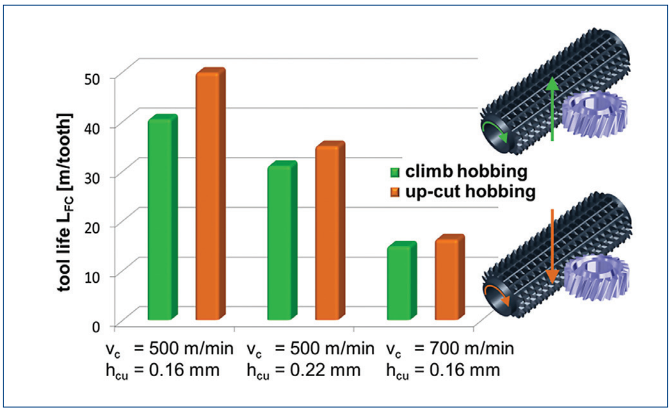

Figure 9. Tool life depending on hobbing direction.

The emerging tool lives of up-cut hobbing always surpass these of climb hobbing. In climb hobbing the maximum wear behaviour is continuous and that is where the disadvantage of up-cut hobbingis stated. The wear is barely noticeable in up-cut hobbing until the tool immediately collapses from one workpiece to another. The tooth gets fully destroyed and a common rework cannot be performed. Fig. 10 is showing pictures of two consecutive teeth. The damage can easily be seen.

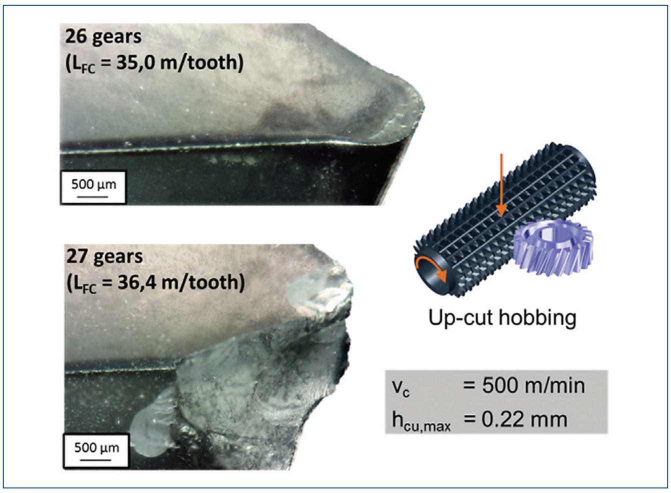

Figure 10. Tool failure in up-cut hobbing.

To perform up-cut hobbing with cemented carbide in spite of that a safety factor is necessary. Unfortunately the gain in tool life cannot outmatch this safety related decrease in tool usage.

4.3 CUTTING WITH LUBRICATION

Especially in small and medium sized companies wet machining and the use of lubrication is widely established. At the same time the perfect lubricant and corresponding optimized cutting parameters are uncharted.

To examine how lubrication affects the tool life in hobbing with cemented carbide tests were performed with a solid jet cooling (flow rate: 50 l/min). Fig. 11 is presenting the results of this study.

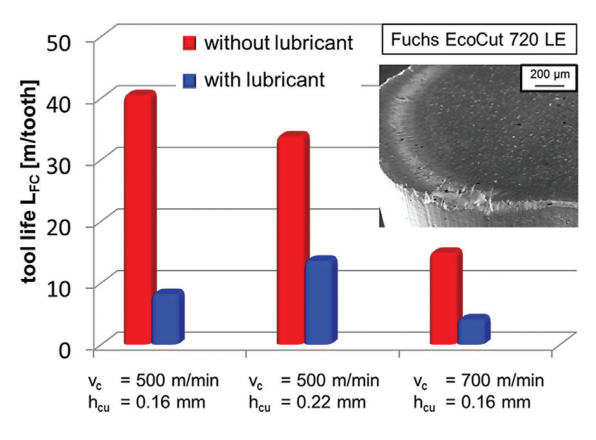

Figure 11. Hobbing with and without lubricant.

In all the three experiments the tool life did decrease essentially. The reasons for this behaviour are probably thermal shocks inflicted on the tool. Lubricants extract more heat from the tool than air does. That way the fly cutter gets heated up and cooled down with a high frequency, which induces residual stress. The stress deteriorates the tools crack resistance and leads to earlier crack formation. Directly comparing chip thicknesses of 0.16 mm and 0.22 mm the tool life increases with rising thickness. This can be explained with the total amount of impacts during the process (thermal cycle) which is higher at 0.16 mm.

The wear phenomena in wet machining are likely to those in dry machining. However, cracks and wear appear earlier.

5. SIMULATION

To detect the causes of wear it is rewarding to simulate the hobbing process. Available software which is able to geometrically reconstruct the process utilizing interpenetration calculation is SPARTA pro [Klocke 2000]. The resulting load parameters were analysed with a self-developed software.

Matching the load distribution with measured wear patterns from the real test it is possible to examine causes of wear and understand the wear behaviour.

One possible illustration of this wear-to-simulation-comparison is illustrated in Fig. 12.

In the center of the upper and lower part of the figure the pseudo color image resulting from a tactile surface measurement is illustrated. The crater wear can easily be quantified. Both the surrounding lines express the distribution (of maximum values of all generating positions) of the typical load parameters chip thickness $h_{cu,max}$ (blue line) and the cutting lengthl_{max} (red line). The thin outer line which is equidistant from the tooth profile equals the 100%-border. At this extend the load parameters reach their maximum. The corresponding absolute values are mentioned in the center of the particular images. The load distribution is scaled to this border.

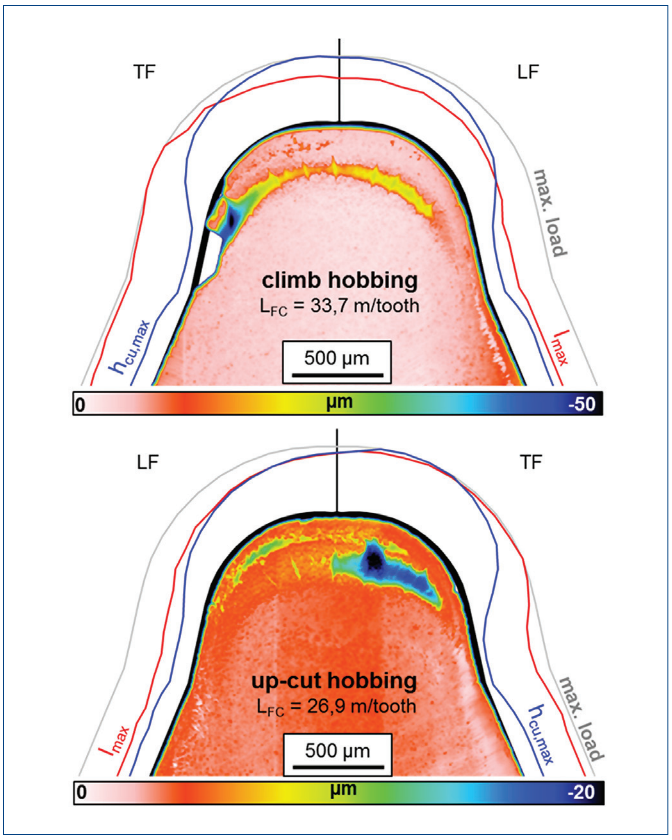

Figure 12. Comparison of crater wear and simulated load parameters (vc = 500 m/min; hcu,max = 0.16 mm).

In climb hobbing the maximum crater depth occurs above the start of the protuberance on the trailing flank. At this point the cutting length reaches a maximum and the chip thickness shows a minimum. Therefore, it can be assumed, that the depth of the crater is mostly determined by the cutting length. The crater breakthrough is exactly at the spot with the minimum chip thickness. Hence the answer might be that the distance from cutting edge to crater centre is depending on the chip thickness. At very small chip thicknesses the crater is moving close to the cutting edge. If this scenario occurs together with a high crater depth (cutting length) a weak point develops at the edge that can lead to the collapse. The area in the pseudo colour picture where the colour is missing equals the spot on the cutting surface that is missing due to the collapse and cannot be measured anymore. A likely picture of the real wear can be seen in Fig. 7.

In up-cut hobbing the maximum values for both kinds of loads are reached at about the centre of the tip radius on the leading flank. At the same spot the maximum of the crater wear did emerge. According to the statements in the previous paragraph the large chip thickness at the maximum spot is responsible for the crater being far off the cutting edge. Therefore there is no crater breakthrough.

For both the maxima ($h_{cu,max}$ and l_{max}) are at the same location at the profile it is hard to say which kind of the load is essentially responsible for the wear in up-cut hobbing.

6. COST CALCULATION

To transport the result of the research into the industry it is important to assess them economically. Assuming the values in Table 1, tool costs, machine costs and total costs can be calculated for different cutting parameters.

Due to the continuous change of tool life depending on the cutting speed a cost optimum can be calculated (Fig. 13).

machine-hour rate	80 €/h	number of reworks	12
tool price	5500 €	rework costs	315 €
correction factor (real tool)	0.35	chip-to-chip time	5 s
industrial cutting speed	350 m/min	industrial axial feed	0.14 mm/rev

Table 1. Economical frame.

In the examined case the optimum cutting speed at a chip thickness of 0.16 mm is 520 m/min. The spot is marked in the diagram. In the industrial environment such a gear is usually cut with 350 m/min, which is below the optimum, reaching tool lives L of about 10 m/tooth.

The chip thickness was then varied at the optimum point of the cutting speed to gain an optimum in that dimension too. As shown in Fig. 14, the total costs decrease altering the chip thickness from 0.1 mm up to 0.28 mm.

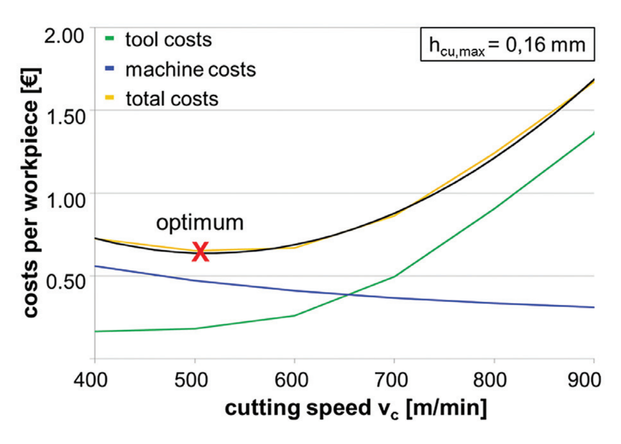

Figure 13. Manufacturing costs depending on cutting speed.

A global minimum is set at a chip thickness 0.28 mm. For hobbing is generally coupled with later hard machining procedures in the process chain, further restrictions apply. The maximum depth of feed marks considering gear grinding is about δ_x = 25 µm. At the optimum chip thickness of 0.28 mm the depth of feed marks counts about 70 µm which is impractical for the typical process chain. All the chip thicknesses between 0.22 and 0.28 mm generate depths of feed marks above 25 µm and are therefore of no use for the cost optimum (gray background in the diagram). In the valid area a local cost optimum emerges for a chip thickness of 0.18 mm.

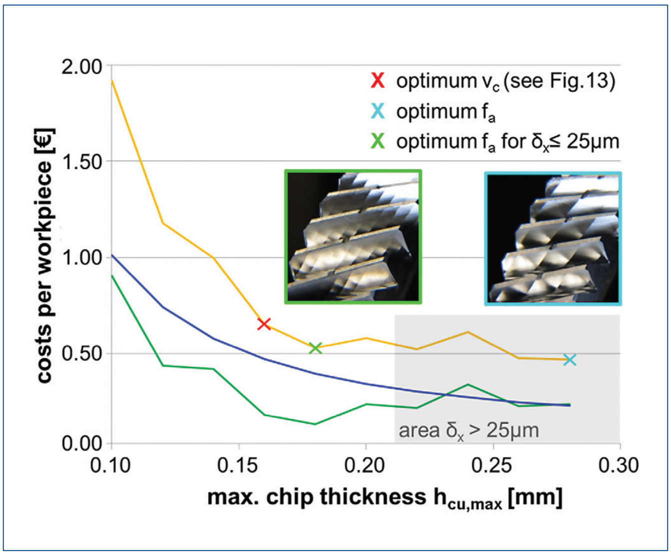

Figure 14. Manufacturing costs depending on chip thickness.

Adjusting the cutting parameters for the examined case of application the total costs can be reduced by 35%.

7. CONCLUSION

Cemented carbide as substrate material proved itself capable in hobbing with high cutting speeds and chip thicknesses. Even at maximum loads corresponding with decreased tool lives the process is more efficient than current industry standards.

Optimizing the cutting parameters for a special case of application costs for hobbing with cemented carbide hobs can be reduced by more than 30% compared to standard industrial parameters.

The possibility to efficiently realise hobbing processes with maximum chip thicknesses of 0.28 mm requires the set-up of a second hobbing procedure (second cut) to ensure depths of feed marks below 25 µm for later machining operations such as gear grinding.

By means of process simulation causes for different wear phenomena were found. Nevertheless, a forecast of the wear behaviour without any experimental tests is still not possible.

Furthermore the increase in number of starts was presented as a way to exploit the further potential of substrate material. Also up-cut hobbing is a potential solution to fix individually occuring problems such as flank surface defects.

In further tests the results of the research for gears with modulus 2.7 mm which are presented in this paper will be compared to larger (m_n = 3.45 mm) and smaller (m_n = 1.23mm) gears. Until then it is not clear if the results are gear specific or generally valid.

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