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Procedia CIRP 69 (2018) 882 – 887

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Resource Efficient Regrinding of Cemented Carbide Milling Tools

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Abstract

Cemented carbide tools are often used for milling operations that cause high thermal and mechanical process loads, e.g. machining processes for titanium alloys. However, the disposal of those tools after one life cycle would significantly reduce their resource efficiency. Therefore, regrinding operations are crucial in order to recycle worn tools and ensure an economical as well as resource efficient manufacturing process. The main challenges during regrinding are the precise quantification of present defects and the subsequent determination of the grinding allowance. As it is, a worker performs both tasks using his individual estimations. Consequently, the estimated grinding allowance is often too low or too high. This either decreases the lifetime of the reground tools due to remaining defects or reduces the resource efficiency since more material than necessary is removed. This paper investigates the determination of the grinding allowance and the environmental impact of regrinding operations on the life cycle of the investigated tools. It is shown that about 12.5% percent of the worn tools are being unnecessarily disposed of. Furthermore, the resource efficiency of tools with small breakouts might be increased by 20% if the recommended allowance strategy is utilized. The tool wear of the grinding tools is also taken into consideration in order to further increase the resource efficiency of the whole life cycle, including milling tool and grinding wheel. The results show that small grain sizes and low grain concentrations are not suitable for efficient regrinding processes since higher wear and consequently higher geometrical inaccuracies of the reground tools occur.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference

Keywords: Resource Efficiency; Regrinding; Cemented Carbides; Milling Tools

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1. Introduction

The international trade and exchange of cutting tools makes up a yearly market volume of up to 13 billion € [1]. About half of those tools consist of cemented carbides [2] that are used in a wide field of different machining applications, e.g. in the aerospace and automotive industry. The positive tool properties like corrosion resistance, high hardness and toughness allow the milling of hard to machine materials like titanium alloys [3]. The lifetime of those tools ends after up to 60 minutes due to defects of the cutting edge. However, the majority of the tool including its core and shank remains without damages and therefore might be recycled. Regrinding operations may remove the damaged parts of the tool and therefore are eligible to significantly extend the life cycle by resharpening the worn tools. This allows a multiple tool utilization before removing the cemented carbide tools from the manufacturing cycle. Consequently, the same number of cemented carbide tools may be used for much longer machining times and the resource usage per tool lifetime may be decreased significantly by regrinding. This is of particular importance since the production of cemented carbides comes along with significant health risks for the production workers and is harmful to the environment [4]. The growing number of regrinding operations of many companies due to their increasing focus on sustainability leads to an increasing market share of milling tools without coating. The absence of coatings makes the often uneconomic removal of the coating before regrinding needless and problems during the recoating process of the tools are avoided. Consequently, the regrinding operation itself becomes more important regarding the whole life cycle of a cemented carbide milling tool.

Peer-review under responsibility of the scientific committee of the 25th CIRP Life Cycle Engineering (LCE) Conference
doi:10.1016/j.procir.2017.11.028

Currently, industrial regrinding operations rely on the knowledge and experience of workers that are responsible for the regrinding operation. The worker estimates defect size and grinding allowance for the regrinding operation of every single worn tool only based on his experience and without any help of technical measurement equipment besides magnifying glasses. The unavoidable errors in this estimation lead to additional resource losses of cemented carbides due to too large estimated allowances or to subsequent regrinding operations since defects remain at the cutting edge. Those additional regrinding processes require further energy, lead to additional grinding wheel wear and may decrease the amount of possible regrinding operations per tool.

Another important aspect in the life cycle of milling tools is their quality and thus lifetime. A higher tool quality represented by higher residual compressive stresses and minimized cutting edge chipping as well as surface quality of rake and clearance face can directly influence the resulting tool load during a milling process as well as the durability of subsequent coatings [5]. The grinding wheel specifications may have a significant influence on those core values since the final grinding operation has a major influence on the residual stresses and surface roughness values [6]. However, the size of the grains as well as the grain concentration also influence the wear of the grinding tool and thus have an impact on the resource efficiency of the regrinding operation.

Therefore, the present paper investigates the potential of precise defect size measurements. Furthermore, it points out possible resource savings compared to an industrial regrinding operation and investigates the influence of different grinding wheel specifications on the grinding tool wear and the ground milling tools.

2. Analysis of different allowance determination strategies

The precise and quick determination of different sizes of cutting edge defects in a timely manner is hard to achieve due to difficult measurement conditions. Tactile measurement devices rely on the precise positioning of the probe and have to follow the geometry of the cutting edge, which changes with each milling tool specification and tool diameter. Consequently, tactile measurements are elaborate and too time-consuming for industrial regrinding operations since many tools have to be evaluated. Contrary, optical measuring instruments may measure the tool wear mostly independent of the cutting tool geometry in a timely manner. However, the related software is often not developed for the purpose of evaluating cutting tools. Consequently, precise measurement devices are not common in industrial regrinding operations. Most companies still rely on manual defect size estimations of their workers. According to the workers experience, for tools without visible defects an allowance of 100 µm is chosen on rake and flank face and the tool is reground. If visible damages are detected, the milling tool is reground only at the rake face using an allowance of 500 µm. The flank face is not reground yet in order to keep the diameter loss as low as possible. This process is repeated until no visible damage is left. Finally, another 100 µm allowance is reground from rake and flank face in order to remove non visible defects like micro cracks and to create a sharp cutting edge.

This approach, however, has multiple weaknesses regarding the life cycle of the milling tools. The relatively low allowance on the flank face may not be sufficient in order to remove all present damages. The two characteristic defects of the investigated cemented carbide milling tools with a diameter of 25 mm and 4 teeth are big spallings and micro cracks, which cannot be detected with non-destructive measurement methods [7]. Both kinds of damages may reduce the lifetime of the reground tools significantly if they are not properly removed. The investigation of the cross sections of 35 worn milling tools using a Topcon SM 510 W scanning electron microscope (SEM) has shown multiple cracks with a diameter of below 0.5 µm and a length of up to 450 µm. Those cracks occur at both faces and therefore might not be removed with flank face allowances of 100 µm as they are currently used in the industrial application.

Furthermore, the spalling geometry on both faces often has a low depth but a high length. This leads to high grinding allowances if only the rake face is reground in order to remove the spalling on both of the faces as it is done in the industrial process. Fig. 1 shows the defect size at the cutting edge of different milling tools with the corresponding allowances that are required for the removal of all defects on the rake and the flank face. It clearly indicates that the total grinding allowance for removing the defects by grinding both faces is significantly lower than the required allowance for only grinding the rake face due to the geometrical shape of the spalling.

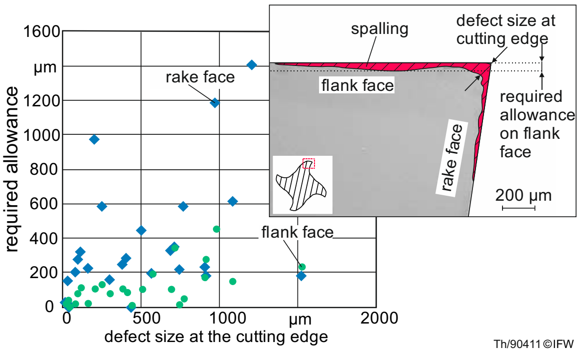


Fig. 1. Required allowance at the rake or flank face that is necessary in order to remove all spallings and other defects on the flank face

This leads to the conclusion that the total amount of removed material may be reduced by regrinding both faces without prioritizing the rake face. Fig. 2 shows the required allowances orthogonal to the rake and flank face as well as the corresponding defect size of the investigated tools. It indicates that an allowance of 150 µm on both flanks is sufficient for the removal of measured defects with a size of up to 300 µm. For defect depths bigger than 300 µm the allowance should amount to 50% of the measured value on each flank.

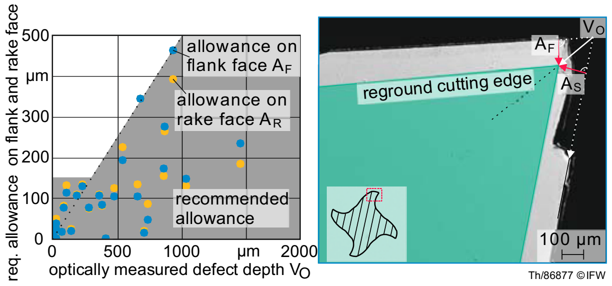


Fig. 2: Recommended allowance for the removal of breakouts and spallings

Equally regrinding both faces allows to extend the life cycle of milling tools with extraordinary big spallings. In some cases, the industrial grinding strategy requires rake flank allowances of up to 1500 µm for the removal of a single large breakout on the flank face. This leads to a reduction of the stability of the cutting edge, making the tool inapplicable for milling operations. Therefore, according to the industrial regrinding strategy, the worn tool is getting disposed even though small allowances on the flank face would have removed the present defect due to its low depth.

The equal distribution of the grinding allowance on the rake and flank face considers the tradeoff between the diameter loss of the workpiece due to regrinding of the flank face and the loss of stability of the cutting edge due to material removal at the rake face. Additionally, the removal of micro cracks is ensured since the minimum allowances for the crack removal according to Denkena et al. have been utilized [7]. Therefore, constant tool lifetimes of the reground tools are to be expected.

The possible environmental and economical savings due to the new strategy are still not clear. Therefore, worn milling tools with the same specifications have been evaluated in regards of the defect size in two ways. Firstly, an experienced industry worker has estimated the defects. Secondly, the tools have been precisely measured using a Keyence VR 3000 stripe light projection microscope.

Fig. 3 shows the resulting allowances for both grinding strategies. The industrial strategy requires an up to 10 times higher allowance on the rake face while only slightly lower flank face allowances for small defects are reached (see milling tool 1 to 11). The increase of the allowances for larger defects (tools 12 to 16) in the proposed strategy, however, is necessary in order to compensate the increasing length and depth of micro cracks at heavily damaged tools. This compensation is not considered in the industrial regrinding strategy and therefore a risk of remaining micro cracks is present according to Denkena et al. [7]. The worst possible case, as seen in milling tool number 9 and 13, is that tools are unnecessarily getting disposed due to large defects on the flank face. However, this may be avoided by equally regrinding rake and flank face as suggested in the new strategy.

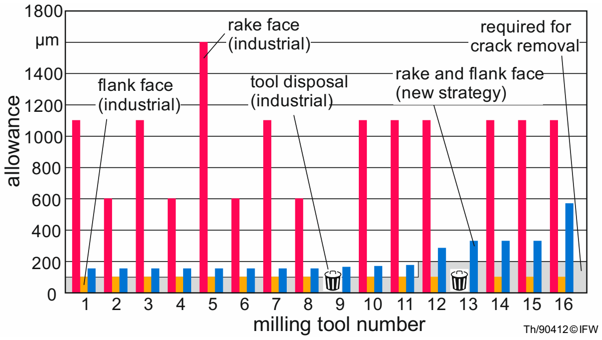


Fig. 3: Allowance on each flank according to the common industrial and the newly developed strategy

3. Resource losses and environmental impacts

The disadvantages of the industrial grinding strategy compared to the new strategy are summarized in Fig. 4. The unnecessary disposal of 12.5% of the investigated tools has a major influence on the resource efficiency of the milling tools since subsequent regrinding operations may not be performed. This can reduce the tools life cycle by up to 80% since a single tool otherwise is reground at least four times. Furthermore, the remaining 87.5% of the tools may show a reduced lifetime during subsequent milling operations. This effect occurs either due to remaining micro cracks, detected for 25 % of the tools, or due to a weakening of the structural stability of the cutting edge caused by high rake face allowances. Those high allowances on the rake face lead to more material removal than necessary and therefore significantly decrease the amount of supporting material at the back of the cutting edge (see Fig. 4b). Therefore, the tooth strength decreases and faster tool wear as well as tool failure may occur.

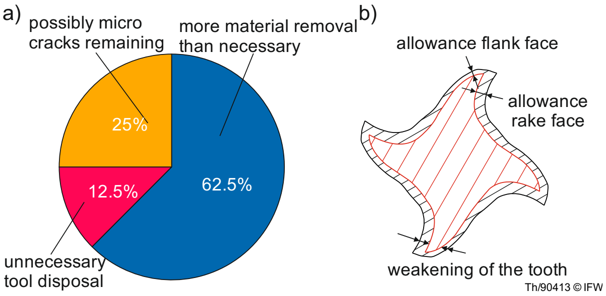


Fig. 4: a) Errors during industrial regrinding operations and b) weakening of the tooth due to excessive regrinding

Another important factor for the resource efficiency of the regrinding process is the diameter reduction of the reground tools. The regrinding of rake and flank face both reduces the diameter of a tool in different scale, depending on the tool orthogonal clearance α_f and the rake angle α_r. Both angles are defined as 8° for the present case. The reduction of the diameter d_{red} by regrinding is then approximated using the allowance on the rake face $a_{e,r}$ and flank face $a_{e,f}$ as follows:

$$d_{red,r} \approx 2 * \sin \alpha_r * a_{e,r} \quad (1)$$

$$d_{red,f} \approx 2 * \cos \alpha_f * a_{e,f} \quad (2)$$

The possible savings in regards of diameter loss are presented in Fig. 5. It shows that savings of up to 300 µm per regrinding operation are possible for breakouts of up to 400 µm size when using the newly developed allowance strategy. Consequently, the average diameter loss of the tools 1 to 12 is reduced by 102 µm. This means for the application case of milling tools with a diameter of 25 mm, which are reground until a diameter of 23 mm is reached, that the average amount of regrinding operations may be increased from 4 to 5 cycles. Thus, for the investigated tools with an application time of 30 minutes the total lifetime is extended from 150 minutes to 180 minutes. This increases the economical and environmental efficiency of the investigated cemented carbide tools by 20%. Consequently, 20% less resources are required for the same milling time and less Cobalt has to be processed, leading to less health risks for the production workers of the cemented carbides. However, the positive effects of a reduced Cobalt production, e.g. the health risks, the reduced energy demand due to less sintering operations and the CO_2-savings due to less transportation of resources can hardly be estimated since they vary strongly depending on the used transportation and production methods.

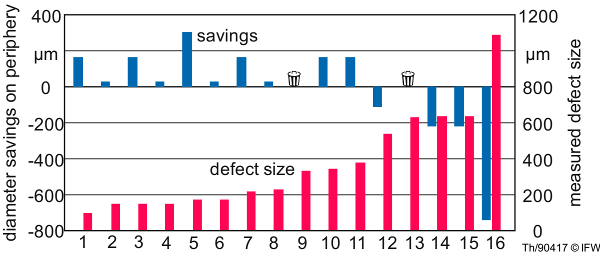


Fig. 5: Possible savings when using the developed regrinding strategy

However, the figure also shows negative values representing more diameter loss compared to the industrial strategy for tools with defects bigger than 400 µm. The significantly increasing flank face allowances for bigger defects lead to strongly decreasing diameters of the reground tools. This ecological disadvantage may be solved by adapting the developed strategy for larger defects. However, when doing so, the lifetime of the reground tools in dependency of the strength of the cutting part should be considered. Even though equally sized allowances on flank and rake face, as suggested by the new strategy, seem to have a negative effect on the environmental efficiency, they might be more efficient if the average tool lifetime is increased and the amount of tool failures is decreased due to higher structural strength of the cutting part.

Besides the material savings of the milling tools, the usage of energy should be considered during regrinding. The industrial regrinding strategy requires up to 3 grinding processes for large cutting edge damages. In contrast, the proposed allowance strategy always removes the required amount of material in one step. This saves up to 65% of the machining time with its corresponding energy demand. Therefore, all savings affect the energy and material aspects of the milling tool life cycle.

4. Regrinding of worn milling tools

The second important step after the determination of the optimal allowance is the regrinding process itself, which generates the final surface of the milling tool and therefore influences the tools lifetime and thus life cycle. The energy demand of this process can be strongly influenced by the feed rate since it determines the duration of the grinding process. However, the highest possible feed rate with satisfactory workpiece quality also depends on the grinding wheel specification. Furthermore, feed rate and wheel specification influence the grinding wheel wear and consequently have an environmental impact on the life cycle. Therefore, this paper investigates the grinding wheel wear for different feed rates.

4.1. Experimental setup

A Walter Helitronic Vision 400L grinding machine has been used for all grinding experiments. The machined milling tools are made out of Extramet EMT 210 cemented carbide, have a diameter of 22 mm before grinding and four cutting edges with variable pitch. Both, the periphery and the face of the tools are machined using 1V1 hybrid bonded grinding wheels for the flutes, 11V9 hybrid bonded wheels for the flank faces and 12V9 resin bonded grinding wheels for the milling tool's orthogonal rake angle at the face of the tool. The different utilized toolsets are presented in Table 1. Furthermore, the feed rate is varied in three steps (50; 90 and 130 mm/min) and each experiment is repeated two times. The cutting speed is kept constant at 20 m/s and the grinding tools are sharpened but not profiled after each experiment.

Table 1: Grinding wheel specifications used for the investigations

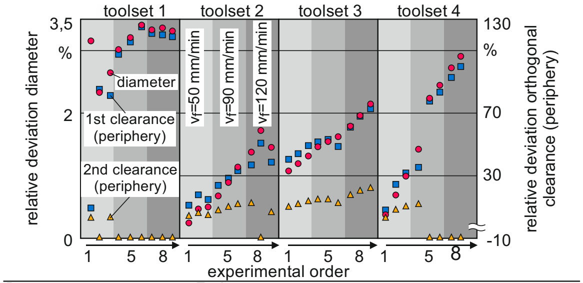
Toolset	1V1	11V9	12V9
TS 1	D35 C100	D46 C100	D46 C100
TS 2	D54 C100	D54 C100	D54 C100
TS 3	D76 C100	D64 C100	D64 C100
TS 4	D54 C100	D54 C50	D54 C50

A Walter Helicheck optical measuring machine is used for the geometrical evaluation of the ground tools and imprints of the grinding wheels are taken after each experiment. Those imprints are measured by a Mahr LD 130 contour measuring machine in order to estimate the grinding wheel wear at the edges.

4.2. Influence of grinding wheel specification and feed rate on the milling tool and grinding wheel wear

The influence of the feed rate and grinding wheel specification on the relative deviation of the diameter, pitch and the clearance angles on periphery and face of the milling tool are presented in Fig. 6 and Fig. 7. It is shown that the grinding wheel specification has a major impact on the geometry of the reground milling tools and wheel wear, which is furthermore influenced by the feed rate. All tool sets show an increasing deviation of the clearance angles on the periphery for increasing experimental number. However, the inclination angle of the deviation varies per toolset as well as feed rate and therefore indicates the different wear behavior of the wheels.

The first toolset with the lowest grain size shows the fastest tool wear due to lower grain protrusion. The friction between bonding and the cemented carbide milling tool lead to an overload of the wheel, which consequently experiences extensive tool wear at the grinding point. This leads to rapidly increasing deviations of the clearance angles on the periphery of the milling tools. Eventually, after grinding three milling tools with a feed rate of 50 mm/min the wheel wear has progressed so far that the 2nd clearance is not ground anymore since the grinding point of the grinding wheel is not engaging the milling tool. The same effect is visible for the third toolset. However, the bigger grain size with a lower concentration delays the loss of engagement during the manufacturing of the 2nd clearance until a feed rate of 90 mm/min is used. The higher wear resistance of grinding toolset four can also be observed if the 1st clearance and the diameter of the milling tool is taken into consideration. The slower but constant increase of the deviation indicates a continuous wear for toolset four, while the first toolset shows rapid tool wear until 3.5% deviation regarding the milling tools diameter is reached. At this point, the milling tools diameter is equal to the diameter before regrinding, meaning that the 11V9 grinding wheel does not engage the milling tool and material removal does not occur on the flank face. This can also be seen in the strongly scattering pitch values (see Fig. 7) of toolset one.



Process parameters:
v_c = 20 m/s
v_f = var.
$a_{e,periphery}$ = 300 μm

Tool parameters:
grain type = diamond
grain conc. = var.
grain size = var.
bond = hybride/resin
wheel shapes = 11V9/12V9/1V1

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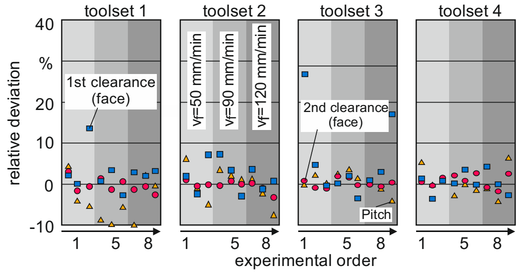
Fig. 6: Deviation of the periphery geometry of reground tools depending on toolset and feed rate



Process parameters:
v_c = 20 m/s
v_f = var.
$a_{e,periphery}$ = 300 μm

Tool parameters:
grain type = diamond
grain conc. = var.
grain size = var.
bond =hybride/resin
wheel shapes =11V9/12V9/1V1

Th/90414 © IFW

Fig. 7: Deviation of the face geometry and pitch depending on toolset and feed rate

The toolsets two and three show a constant wear behavior for the three investigated feed rates (see Fig. 6). This indicates that the grinding wheels may withstand a higher process load and that the investigated cutting speed to feed rate ratios of 8000 to approximately 13000 do not represent the grinding wheels limits. However, the cutting edge quality should be taken into consideration when further increasing the feed rate. The differences in the wear behavior of both mentioned 11V9 grinding wheels differs in the gradient of wear and the starting point. The lower gradient of the third toolset results of the increased grain size since larger grains withstand larger loads before breaking out. The higher deviation of the third toolset after its first experiment is caused by geometrical inaccuracies of the grinding wheel that already existed before the regrinding operation. This can also be seen in the constant tool radius of the 11V9 wheel of toolset 3 (see Fig. 8).

However, the deviation at the face of the milling tool does not vary besides the expected scattering of the measured values (see Fig. 7). The already determined tool wear does not have a significant influence on the manufacturing process of the face geometry even though the same 11V9 grinding wheels are utilized. As presented in Fig. 8, different parts of the grinding wheel engage with the milling tool during different grinding operations. There is a contact point between grinding wheel and milling tool when grinding the periphery. It is located on the edge of the grinding tool and therefore a high load is applied to its radius. The subsequent wear of the structural less stable tool radius leads to increasingly worse accuracies during the machining of the periphery. Consequently, the highest increase considering the edge radius is found for toolset one, which has been identified as the least wear resistant tool concept.

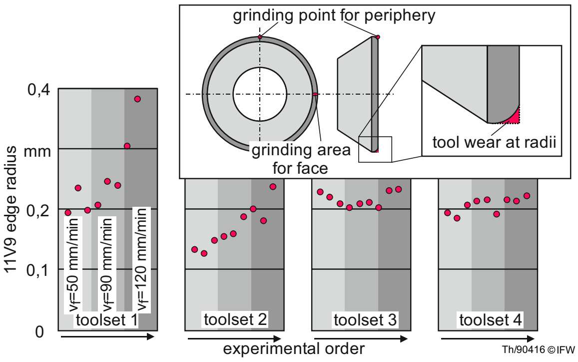


Fig. 8: Wear of the 11V9 edge radii and grinding points for different operations during regrinding

Contrary to the periphery, the face machining does not suffer accuracy losses since the whole width of the grinding tool engages the workpiece (see Fig. 8) with a feed in the radial direction. Therefore, even grinding tools with worn edge radii may still be able to machine precise face geometries.

Summarizing, toolsets two and three with the highest grain concentration and size are the best options regarding the tool wear during regrinding of cemented carbide tools. They show a constant wear rate independent of the feed rate and therefore are well suited for productive regrinding operations.

5. Summary and outlook

This paper investigated different aspects of the life cycle of worn cemented carbide milling tools. First, two strategies for the determination of the grinding allowance during regrinding were compared. The developed strategy allows up to 20% more regrinding cycles if breakouts of up to 400 µm size are considered. Furthermore, the amount of required regrinding operations for the removal of cutting edge defects was reduced by up to 65%. This allows significant energy savings since the processing time on the grinding machine was significantly lowered.

Secondly, investigations regarding the grinding wheel wear have been carried out. The results show that the wheel wear at the radii has a major influence on the geometrical accuracy of the milling tools peripheral geometry. The resource efficiency regarding the grinding tools may be increased by using grains with a size of 54 µm to 76 µm and a concentration of C100. Therefore, the increased tool lifetime optimizes the resource usage considering grinding wheels.

Future investigations will consider the influence of the different grain sizes and concentrations on the cutting edge quality and surface roughness. Furthermore, the lifetime of the reground milling tools will be investigated depending on the strategy and parameters utilized during the grinding process.

Acknowledgements

The authors would like to thank the Federal Ministry for Economic Affairs and Energy (BMWi) Germany for their organizational and financial support within the project “Autoregrind” (IGF No. 19121 N).

Supported by:
Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

Industrielle
Gemeinschaftsforschung
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