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Complementary Machining: Effect of tool types on tool wear and surface integrity of AISI 4140

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Abstract

Complementary Machining is a process strategy for the time-efficient mechanical surface treatment of metallic workpieces. The characteristic of Complementary Machining is that after machining, a mechanical surface treatment is carried out using the cutting tool. The cutting tool moves over the workpiece surface in opposite direction to the machining process and induces an elastic-plastic deformation in the surface layer. Previous investigations have shown the possibility to achieve life-enhancing surface layer states in turning of AISI 4140 with Complementary Machining and to achieve fatigue strengths comparable to those after shot peening.

In this paper, the influence of the tool types and process parameters, such as the feed rate, on the resulting topography and the tool wear, represented by changes of cutting edge microgeometry, during Complementary Machining of AISI 4140 are investigated based on the previous investigations. In addition to different substrates of the cutting insert, the focus of the investigations is also on the influence of tool coating. Both the tool wear and the resulting topography were analyzed tactilely and correlated with the process parameters. The results show a clear influence of the used substrate of the cutting insert and coating on the tool wear and the resulting topography.

Keywords: machining; tool wear; Complementary Machining

Nomenclature

v_c	cutting velocity
v_{st}	surface treatment velocity
f_c	cutting feed rate
f_{st}	surface treatment feed rate
$a_{p,c}$	cutting depth
$a_{p,st}$	surface treatment penetration depth
l_{st}	tool path surface treatment
d_t	distance along cutting edge
K	Form-factor
ΔK	change of Form-factor
$\bar{S}$	average cutting edge rounding
$\Delta\bar{S}$	change of average cutting edge rounding

1. Introduction

In industrial machining applications the efficient production of high-strength metallic components is of major relevance. In addition to cost-effective production, achieving the required surface layer states is one of the most important objectives. This results in optimisation for machining processes, for example with regard to process strategy, like the use of cooling lubricants, or tool selection, like the use of coated tools and the selection of suitable tool substrates [1]. Thus, an influence analysis regarding the cooling lubricant strategies during the machining of AISI 4140 show that the machinability with cooling lubricants increases compared to dry machining [2]. The use of cooling lubricants can change the wear mechanisms. While in dry machining abrasion is one of the dominant wear mechanism in the machining of AISI 4140, in wet machining a

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thermal wear mechanism can be expected [3]. Furthermore, the simulation-based investigations of machining of AISI 4140 show that a tool coating has a direct influence on the thermo-mechanical load [4]. As a result, tool wear can be positively influenced by a suitable tool coating. The beginning of tool wear can not only require an early tool change, it can also have a negative effect on chip formation and the resulting component quality, as [5,6] was able to show when machining AISI 4140 and SS304.

In addition to the optimization of machining processes, additional process steps such as mechanical surface treatment are relevant for the production of high-performance components. Conventional processes such as deep rolling or shot peening represent an additional process step. For this reason, hybrid processes have been developed which integrate a mechanical surface treatment into the preceding machining step. Examples for these hybrid processes are the turn-rolling [7] or the orthogonal turn-rubbing [8], whereby both roughness and a hardening [9] or a change of the residual stresses can be induced [10].

The process strategy Complementary Machining combines machining with a mechanical surface treatment process step using the cutting tool (see Fig. 1). Regarding the orthogonal cutting process, previous fundamental investigations using uncoated tools show the sensitivity of process parameters like penetration depth a_p and surface treatment velocity v_{st} on the process forces and plastic deformation of the surface layer during the process step mechanical surface treatment [11]. This plastic deformation results in fatigue strength-enhancing surface layer states like reduced roughness values and compressive residual stresses. The first transfer of Complementary Machining in the industrially relevant turning process show a significant increase of the fatigue strength up to 63% for 5% probability of fracture compared to fatigue strength after machining for AISI 4140 [12]. Thus, fatigue strength after Complementary Machining is comparable to that which can be achieved by the well-established mechanical surface treatment process shot peening.

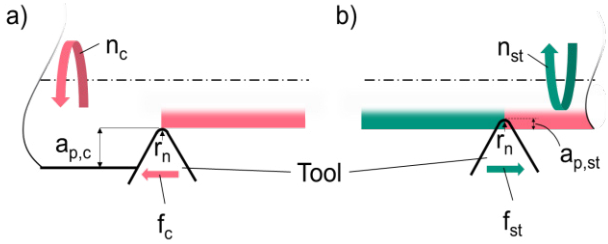

Figure 1. Schematic overview of Complementary Machining during turning [12]

This paper expands the existing knowledge of the process strategy Complementary Machining. The previously published results regarding the surface layer conditions shall be extended by a consideration of the tools. So far this novel process strategy has only been investigated with uncoated tools. However, to make this process relevant for industrial applications, the use of coated tools is essential, as they represent the standard. For a holistic view, different cooling lubrication methods and their influence on tool wear must also be considered. The presented results show the analysis of the influence of different tool coatings and tool substrates on the resulting roughness. Furthermore, the process parameter surface treatment velocity is varied and dry and wet cooling lubricant conditions are investigated. This results in a further understanding of the process strategy Complementary Machining.

2. Experimental setup

The experiments of Complementary Machining during turning of AISI 4140 q&t were carried out on a Weiler Condor turning machine with a cooling lubricant system. The high performance cooling lubricant HPC VEG of Jokisch was used for the lubrication. The diameter of the samples was d = 19.5 mm, on which a tool path for surface treatment of l_{st} = 20 m was machined. Two different tool types were used. On the one hand, uncoated and PVD coated rhombic tools with a wedge angle of 90° and a nose radius of r_n = 0.8 mm were used (Type I). The initial average cutting edge rounding of the uncoated tool was $\bar{S} = 6.13 \pm 3.21$ µm and a form-factor $K = 0.96 \pm 0.31$. For the coated tool of this type the initial average cutting edge rounding was $\bar{S} = 25.14 \pm 6.46$ µm and a form-factor $K = 1.14 \pm 0.25$. These tools had a coating layer of TiAlN + TiN. The tools were fixed in a tool holder with a rake angle γ = -6°. On the other hand, PVD-coated cutting tools with a nose angle of 55° and a nose radius of r_n = 0.4 mm were used (Type II). These tools were equipped with a chip former on the rake face. The cutting edges had an initial cutting edge rounding of $\bar{S} = 38.65 \pm 6.78$ µm and a form-factor $K = 1.29 \pm 0.19$. The tools had a rake angle of γ = -7°. For characterisation of the cutting edge microgeometry the form-factor method by [13] was applied. The cutting edge microgeometry was measured with the Mahr perthometer MarSurf XCR20 and the feed unit PCV 200 in a tactile manner. Each experiment with the different surface treatment parameters was performed with unharmed tools to ensure comparability of the results. Since the experiments are preliminary tests, they were carried out once and should reflect the qualitative progression of the results.

Furthermore, in industrial applications relevant roughness values Ra, Rz and Rt of all specimens were examined tactilely in axial direction according to DIN EN ISO 4287 with a Gauss filter (ISO 16610-21). For this purpose, the GD 25 feed unit for measuring roughness of the perthometer was used. After Complementary Machining, the changes of the cutting edge microgeometry were analyzed and plotted as a function of the distance along the cutting edge d_t as schematically introduced in Fig. 2.

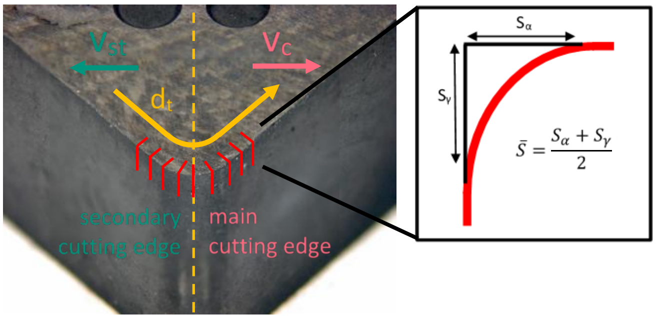

Figure 2. Schematic depiction for analyzing the cutting edge

For a further tool characterization, a metallographic analysis was carried out. The microstructure of the two tool types after preparation is shown in Fig. 3. Etching was performed by Murakami method with a solution of potassium hydroxide and potassium ferricyanide. The images were taken with a reflected light microscope. For analysing the micro hardness HV a Qness micro hardness tester type Q10A with 10x and 40x lens was used. For tool type I the micro hardness of the tool substrate was measured with 1593 ±33.5 HV1. The micro hardness of the tool substrate of tool type II is 1552 ±11.3 HV1.

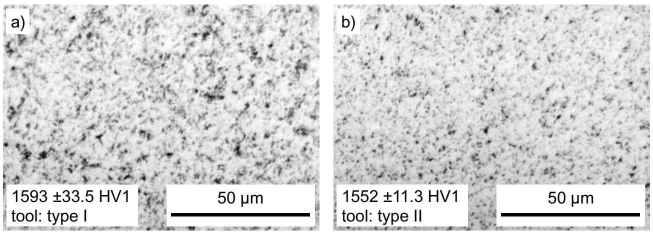

Figure 3. Analysis of microstructure and micro hardness of tool type I (a) and tool type II (b)

Tab. 1 shows the used process parameters cutting velocity v_c and surface modification velocity v_{st}, cutting depth $a_{p,c}$ and penetration depth $a_{p,st}$ as well as feed rates f_c and f_{st} for machining and mechanical surface treatment. In the experiments, machining was always carried out without lubrication and the subsequent mechanical surface treatment was carried out with and without lubrication.

Table 1. Process parameters for machining and mechanical surface treatment during turning.

		machining	mechanical surface treatment
v_c; v_{st}	[m/min]	100	10; 50; 100
f_c; f_{st}	[mm/rev]	0.16	0.045
$a_{p,c}$; $a_{p,st}$	[µm]	100	10

3. Results and discussion

3.1. Roughness

In Fig. 4 the measured roughness Ra, Rz and Rt after machining is shown. This roughness is the initial condition which is to be reduced by the following mechanical surface treatment. A lower roughness was measured after machining with the coated tools than for the uncoated ones. Machining with tool type I achieved a Ra value over 40% lower for the coated tool than for the uncoated tool, for Rz the value is 30% lower. Similarly large values are achieved after machining with the tool type II. Hence the macrogeometry has a slight influence on the topography during machining. The condition of the tool surface and the microgeometry of the cutting edge seem to have a significant influence. On the one hand, the coating of the rake face can reduce friction between the chip and the tool and thus reduce chip compression and cutting forces. This simplifies chip formation and allows a more uniform chip flow, resulting in a more homogeneous surface. This can be seen in the reduced standard deviation of the Rz and Rt values in comparison with the uncoated tool type I. Most significant is the low standard deviation for tool type II, which has a chip former on the rake face that further simplifies chip flow. On the other hand, the coated tools have a significantly larger initial average cutting edge rounding. For tool type I, the measured average cutting edge rounding for the coated tool is three times larger than for the uncoated tool. In the case of the coated tool type II, the average cutting edge rounding is even more than five times larger than the one of the uncoated tool. The rounding of the cutting edge also has an influence on the resulting topography after machining. It has already been shown in other investigations [14] that tools with larger edge rounding can achieve better topography.

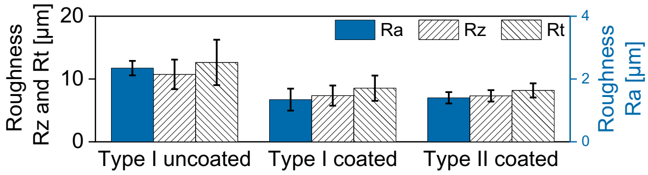

Figure 4. Resulting roughness after machining of AISI 4140 with coated and uncoated tools; v_c = 100 m/min, f_c = 0.045 mm/rev, $a_{p,c}$ = 100 µm, dry machining

After Complementary Machining, the resulting roughness values without lubrication are shown in Fig. 5a. The percentages represent the decrease of the roughness due to the mechanical surface treatment value after machining. The process step mechanical surface treatment within the process strategy Complementary Machining using the uncoated tool type I was not possible, rapid wear was observed and the tool

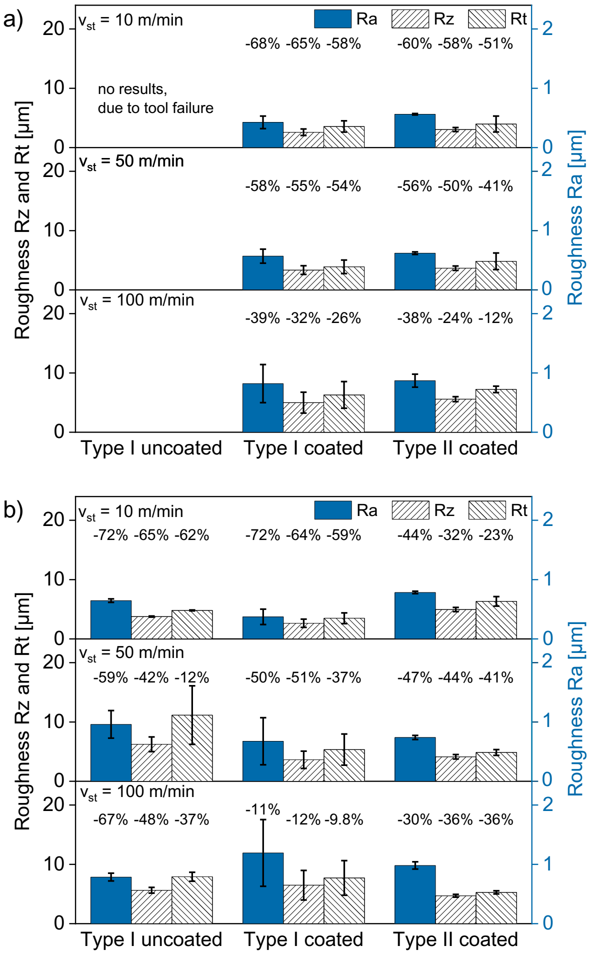

Figure 5. Resulting roughness after Complementary Machining of AISI 4140 without lubrication (a) and with lubrication (b); f_{st} = 0.045 mm/rev, $a_{p,st}$ = 10 µm, l_{st} = 20 m

failed (see chapter *3.2 Tool wear*). In this way it was not possible to process the specimens and there are no measured values available for this specific case. Regardless of the process parameters and tools used, the process strategy can reduce the roughness compared to the machined surface. An increase of the measured roughness values can be seen for the coated tools of type I and II with increasing surface treatment velocity. For tool type I this behavior is more pronounced, here the values of Ra and Rz almost double with an increase of v_{st} from 10 m/min to 100 m/min. The standard deviations increase with the surface treatment velocity as well. It can also be seen, that slightly lower roughness values are achieved with tool type I than with type II, but the larger standard deviations are also present here.

The resulting roughness when using lubricants during mechanical surface treatment is shown in Fig. 5b. Here, the surface could be treated with the uncoated tool type I. For the use of lubricants, a non-uniform behaviour is shown for the tools. While the roughness values and standard deviations for tool type I increase with increasing surface treatment velocity, those for tool type II remain unchanged or show a minimum at v_{st} = 50 m/min. In contrast, uncoated tool type I has the highest roughness values and standard deviations at this velocity. It is shown that for the coated tools the use of lubrication does not necessarily lead to an improvement of the resulting topography. For the coated tool type I, even higher standard deviations occur with increasing surface treatment velocity compared to machining without lubricant. With tool type II, there is nearly no difference, although the standard deviation is slightly smaller when lubricant is used.

In mechanical surface treatment with type II tool, the process is less sensitive to surface treatment velocity and lubrication. One reason for this is the macrogeometry of the cutting edge. Since the tool type II has a smaller nose radius, a larger deformation gradient in the feed direction is obtained than with tool type I. With tool type I, more tool revolutions are needed to cause the same surface deformation. On the other hand the deformation gradient in machining direction depends on the surface treatment velocity. Due to the macrogeometry, tool type II achieves a high deformation gradient and the surface treatment velocity of the surface treatment has a subordinate influence on the mechanical surface treatment.

3.2. Tool wear

The failure of the uncoated tool type I in mechanical surface treatment without lubrication can be attributed to the microgeometry. Since the uncoated tool type I has a small initial rounding of the edge, this can be very sensitive to tensile stress. Due to the friction during the mechanical surface treatment, such tensile forces are exerted on the cutting edge. Lubrication can reduce the friction between the tool and the workpiece and thus also the forces on the cutting edge. The use of lubrication can prevent the cutting edge from breaking. Fig. 6 shows the cutting edge after Complementary Machining of AISI 4140 of uncoated and coated tools. In this case, the mechanical surface treatment was executed without lubrication. On the rake face of the uncoated type I tool, a large breakout is visible starting from the cutting edge. Comparing to the two coated tools, there are no visible chipping marks on the cutting edge, only a slight adhesion of the material to the surface. The shell-shaped breakout on the rake face indicates a brittle behaviour of the tool. This could be caused by the edge microgeometry and the microstructure of the tool substrate. As shown in Fig. 3, the type I tool has a greater hardness than the type II tool. A direct comparison of the microstructures also shows a coarser grain structure for the type I tool. On the flank face, which is in contact with the workpiece during mechanical surface treatment, no breakouts were observed. In this area, the tool is mainly subjected to compressive stress, which does not cause breakouts in the brittle cutting material. The process causes tensile stresses at the cutting edge, which lead to breakouts along the rake face.

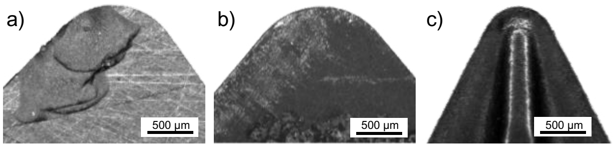

Figure 6. Tool wear after Complementary Machining of AISI 4140 with uncoated (a) and coated tools type I (b) and type II (c) without lubrication

Fig. 7 shows the changes of the cutting edge microgeometry characterised by the change of form-factor K and the change of average cutting edge rounding after Complementary Machining with uncoated tools and with lubrication. For the high surface treatment velocity of 100 m/min no significant changes in average cutting edge rounding could be observed. In the area of the cutting edge d_t = -100 µm to 0 µm the mechanical surface treatment was carried out, in the area d_t = 0 µm to 400 µm the machining was carried out. However, in the transition zone between the areas active in machining and mechanical surface treatment changes of the form-factor occur. On the one hand with decreasing surface treatment velocities increasing changes of average cutting edge rounding could be observed. This can be explained by the increased adhesion tendency as a result of the uncoated tool and the accompanying friction coefficient. On the other hand unsteady progressions of the changes of the cutting edge microgeometry could be observed. It can be assumed that increased adhesion tendencies can lead to stick-slip-like effects and therefore to increased tool wear in some areas of the cutting edge.

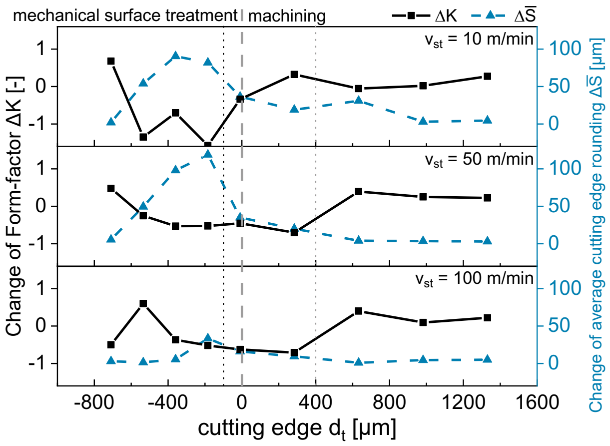

Figure 7. Cutting edge microgeometry after Complementary Machining using uncoated tool type I with lubrication; f_{st} = 0.045 mm/rev, a_{st} = 10 µm

The changes of the cutting edge microgeometry in sectors where no interaction between tool and specimen should have taken place should be noted. This is particularly the case for the process step mechanical surface treatment. The reasons have not yet been fully clarified. However, it is assumed that process instabilities as well as inaccuracies with regard to the penetration depth of only 10 µm have led to sections of the cutting edge being in contact that theoretically should have no contact with the specimen.

The measurements of the changes of the cutting edge microgeometry after Complementary Machining presented in Fig. 8 proves the observations in Fig. 6. Due to the coatings no significant tool wear occurred both for the mechanical surface treatment without and with lubrication. In Fig. 8a the changes of form-factor K and average cutting edge rounding are shown. In particular for a low surface treatment velocity of 10 m/min no relevant changes of the cutting edge microgeometry occur. Only at higher surface treatment velocities a slight increase of the cutting edge microgeometries can be detected. As already seen in the investigations using the uncoated tool, the changes of the cutting edge microgeometry occur in the area which is in contact during the mechanical surface treatment. With increasing surface treatment velocities the resulting temperature increases. On the one hand, this thermal load on the cutting edge can lead to premature tool wear. On the other hand, increasing temperatures in the contact area result in increasing adhesion tendencies and thus in increasing roughness values, as seen in Fig. 5a.

Fig. 8b confirms this trend. At a low surface treatment velocity of 10 m/min, there is also no significant change in the form-factor K and the average edge rounding. When increasing the velocity to 100 m/min, a change in the cutting edge geometry can be observed. The average rounding of the cutting edges increases both in the areas affected by the mechanical surface treatment and the machining. In the same dimension the form-factor K decreases in both areas. Since there is a decrease here and thus the form factor K decreases, this indicates wear on the flank face. It can be seen that lubrication has a minor influence on wear and its location. Due to the high circumferential speed, it is possible that no lubricant will get into the contact zone between tool and workpiece. It is rather in the area of machining that a slightly increased wear can be seen in comparison to surface treatment without lubrication. Here the cooling effect of the lubrication can have an influence. On the one hand, thermal softening is reduced and process forces increase. On the other hand, a larger temperature gradient occurs at the cutting edge due to cooling, which stresses the substrate. This effect is not only evident in tool wear, but also in the slightly increased roughness and standard deviation with lubricated surface treatment in Fig. 5b. For Complementary machining using tools with a form-factor of K = 1 and 2, FE simulations in previous publications have shown that the average cutting edge rounding increases after machining and the form-factor K decreases [15].

The effect of Complementary Machining with and without lubrication on the changes of the cutting edge geometry for the

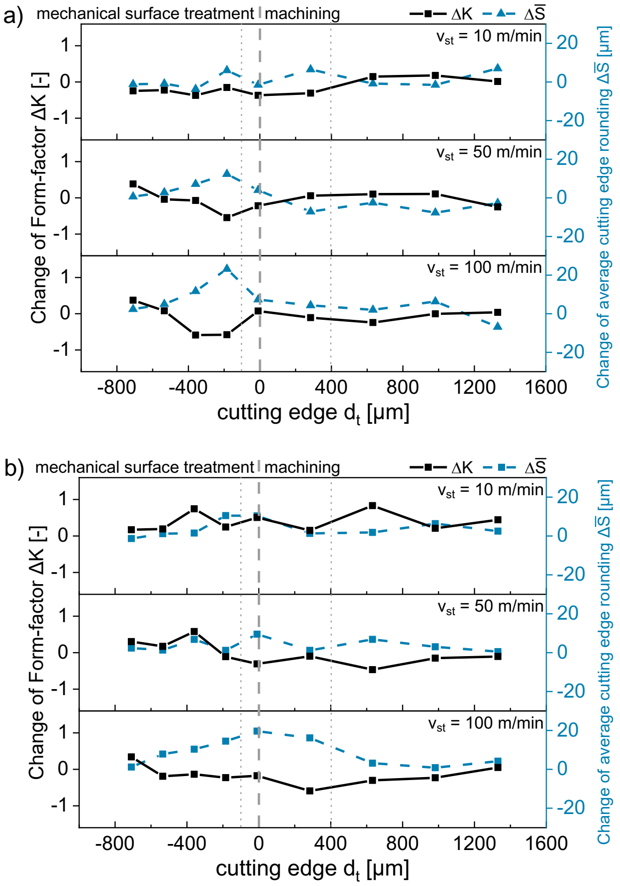

Figure 8. Cutting edge microgeometry after Complementary Machining using coated tool type I without lubrication (a) and with lubrication (b); f_{st} = 0.045 mm/rev, a_{st} = 10 µm

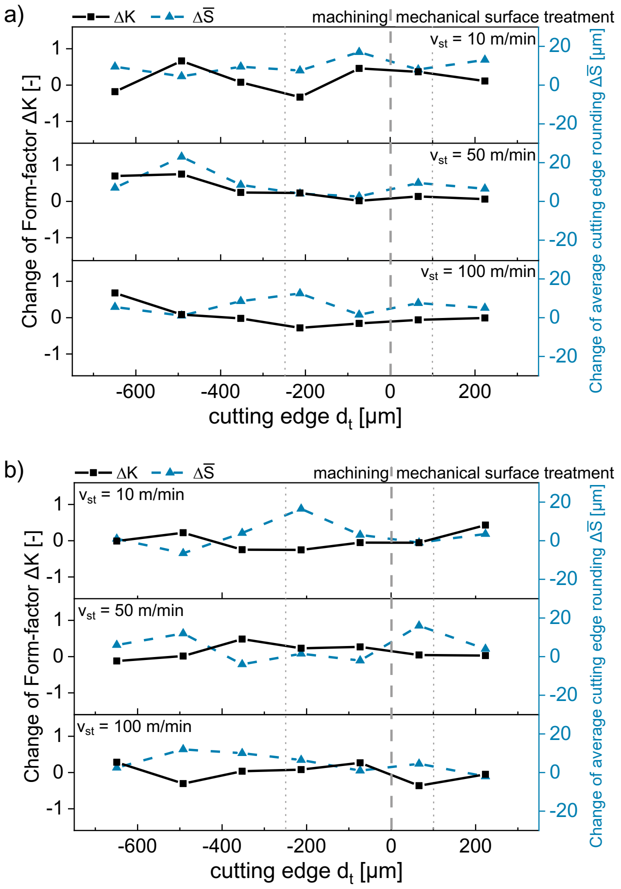

Figure 9. Cutting edge micro geometry after Complementary Machining using coated tool type II without lubrication (a) and with lubrication (b); f_{st} = 0.045 mm/rev, a_{st} = 10 µm

coated tool type II is shown in Fig. 9. In comparison with the coated type I tool, the change of the average edge rounding and form-factor K results in a lower dependence of the surface treatment velocity. The change of the average edge rounding as well as the form-factor K is more homogeneously pronounced over the velocity range. In the area of the cutting edge d_t = -300 µm to 0 µm machining was carried out, in the area d_t = 0 µm to 100 µm the mechanical surface treatment was carried out. In the sectors where there should have been no contact between specimen and tool, changes in the average cutting edge rounding and the form-factor K were measured. This is more pronounced for cutting without lubrication than for cutting with lubrication. It can be assumed that process instabilities and penetration depth inaccuracies are more pronounced here. This leads to contact between tool and sample or chips, where ideally no contact should take place. For surface treatment without lubrication, a slightly higher increase in the average edge rounding can be seen at a velocity of 10 m/min.

For tool type II, the influence of the lubrication and the surface treatment velocity on tool wear is marginal. As already shown in Fig. 5, the influence of these parameters on the roughness is also not very pronounced. The fact that tool types I and II are different substrates, a different tool wear behaviour may be present.

4. Conclusion and outlook

In this paper the influence of different tool types and lubrication strategies on the resulting roughness and tool wear for the process strategy Complementary Machining has been examined. For the investigated uncoated tool it could be shown that the usage of lubrication is indispensable, otherwise a tool failure will result. However, uncoated tools with lubrication also lead to increased tool wear and the accompanying high roughness values.

Both investigated coated tool types have proven to be suitable for the Complementary Machining in respect to the tool wear that occurs. No significant tool wear could be observed for all examined surface treatment velocities. However, the surface treatment velocity has a relevant influence on the resulting roughness for tool type I. With increasing surface treatment velocity, increasing roughness values could be observed. For tool type II no dependency of roughness on the surface treatment velocity and lubrication could be observed. The differences between tool type I and tool type II can be explained with the different nose radius and the accompanying contact conditions between tool and specimen.

In summary, coated tools are principally suitable for the process strategy Complementary Machining of AISI 4140. However, the tool macrogeometry has a significant influence on the process sensitivity and the resulting surface layer states.

In further investigations, the influence of further lubrication strategies like cryogenic cooling on the resulting tool wear as well as the resulting surface layer states after Complementary Machining will be examined.

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