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Analysis of the Modification of Tool Surfaces by Abrasive Blasting and Laser Polishing

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Abstract. The surface treatment of tools plays an important role for the operational behaviour of forming processes. Up to now, industrial standard is the manual finishing of tool surfaces, which can lead to a varying quality of the surface finish and therefore influence the tool service life and the forming results. One method to perform the polishing operation automatically is to remelt the top layer of materials by laser polishing. This is accompanied by a considerable change in the material properties in this zone. Therefore, the effect of laser polishing with respect to the local modification of the tool surface is investigated in this study. The results of the investigations reveal that a precise adjustment of the laser parameters is required in order to reduce the roughness of the surface. The heat input also leads to a significant influence on the microstructure of the material. In this study laser polishing remelts the material up to a depth of approximately 20 µm. Furthermore, it can be observed that the heat input during the process results in a heat affected zone of up to a depth of 30 µm. As a contrast to laser polishing, abrasive blasting is investigated as a roughness increasing surface modification.

Introduction

Since the condition of the tool surfaces significantly influences the process results and the resulting tool loads, they play a predominant role in the field of forming technology. For this reason, polished tools are commonly used in cold forging, with the objective to produce parts with a high surface quality and a long service life of tools [1]. However, the local modification of the tool surfaces, so called tailored surfaces, has the potential to improve forming operations by controlling the material flow even further. This can be seen in the research field of the innovative process class sheet bulk metal forming, whereby the combination of sheet and bulk metal forming leads to a three-dimensional stress- and strain-state, which then results in a complex material flow and reduced workpiece quality [2]. There is the approach to achieve an improvement in the die filling of functional elements and controlling the tool load by locally adapting the tool surfaces. Hereby, the adjustment of the surface roughness plays an important role, as it is directly linked to the resulting friction and the material flow of the process [3]. Through the establishment of a beneficial friction gradient, which means the surface roughening and smoothening in certain tool areas, an improvement of the process result while maintaining acceptable process forces and respectively tool loads can be achieved [4]. To further analyse tailored surfaces, two variants of modifications are investigated within this study. One option for automated tool polishing is laser polishing. Contrary to this, the surface roughening effect of abrasive blasting of tool steel is investigated. For both procedures, the resulting tool topographies are analysed by tactile roughness measurements and microscopic evaluation. In addition to that, the resulting microstructure of the laser polished specimens is evaluated by metallographic methods.

Tool Surfaces and Surface Modification

It is currently the industrial standard to polish tool surfaces for cold forging. This leads to low friction and a reduction of galling [1]. Therefore, it is necessary to obtain an immaculate and reproducible tool surface with clearly defined properties. However, hand polishing of tools is prevalent especially for complex geometries. Thus, the surface quality is dependent on the processor, which results in the potential of fluctuating surface properties [5]. These inherent fluctuations cause a varying service life of the tools, which in turn creates challenges while considering the question of economic aspects of tooling [6]. The automation of the surface finishing of tools therefore offers great potential to improve this situation. This goal can be achieved by laser polishing. The principle of this procedure is based on the local remelting of the tool steel with a laser. During the solidification of the liquid metal, the surface tension of the melt pool leads to a smoothening of the surface. By repeating this process with different parameters, a finely polished tool surface can be achieved [7]. However, laser polishing causes a change in the microstructure in the top layer of the material as a consequence of the heat input. This results in the formation of a remelted and a heat affected zone. The parameters mainly influencing this process are the laser beam diameter, the laser power and the number of repetitions [8]. The second selected surface modification is abrasive blasting. In this process a workpiece, in this case tool steel, is roughened by blasting the surface with an angular blasting medium. This is caused by erosion through microcutting and indentation of the near-surface layer of the material, which leads to a crater-like structure [9].

Experimental Procedure

In order to investigate the effects of surface modifications on the high-speed powder metallurgical steel S390 microclean, a plate with the dimension of 100 x 60 x 11 mm³ and the hardness 63 HRC is manufactured. The choice of material was based on the fact that previous studies [10] frequently focused on hot working tool steels, aluminium and titanium alloys. As a standard processing route in tool manufacturing, Milling – Hardening – HSC Milling – Grinding is chosen for this study. On this plate, the surface is locally modified in facets of the size 15 x 15 mm² by abrasive blasting and laser polishing according to Fig. 1. The distance between the facets is approximately 3.75 mm. The analysis of the obtained surfaces takes place in two steps. First, the topography and the surfaces roughness are measured with the confocal laser scanning microscope Keyence VK-X200 and the perthometer Mahr MarSurf GD120. The tactile surface measurements are carried out according to DIN EN ISO 4287 and the direction of the measurement tracks is perpendicular to the initial grinding marks. The laser polished samples are subsequently examined in further detail using metallographic analysis methods in order to determine the material changes due to the remelting process. Therefore, the light microscope Olympus BH2-UMA and the scanning electron microscope (SEM) Carl Zeiss Merlin Gemini 2 are used.

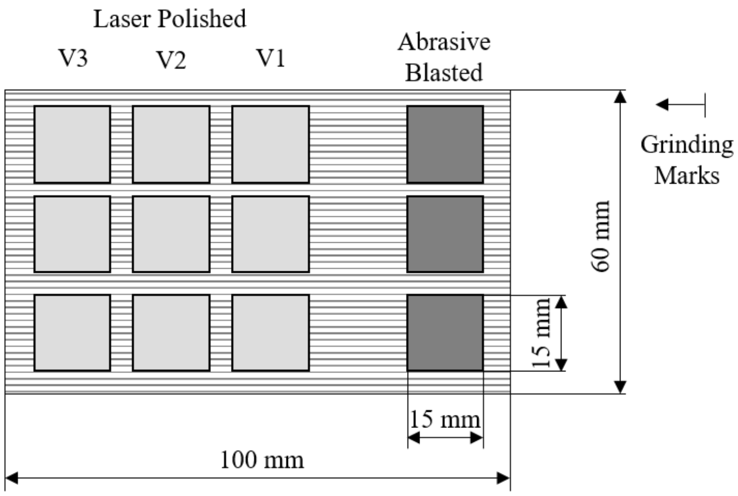

Fig. 1: Layout of the examined plate made of tool steel S390 microclean 63+2 HRC with surface

The reference surface of the tool steel for investigations is finely ground to Rz = 0.86 µm. Based on this, the specimen is modified by abrasive blasting with a blasting medium consisting of angular Al_2O_3 particles in the size range of d = 100 – 400 µm and a hardness of 1800 HV. The blasting of the surface is realised with a distance of h = 40 mm from the nozzle to the workpiece at an angle of α = 90° and a pressure of p = 3 bar. Studies in [11] have shown that the surface roughness reaches a saturation after a certain amount of blasting time. Therefore, the process is continued until an even surface result of the specimen is achieved. The abrasive medium and the process parameters were selected in order to achieve a highly roughened surface in accordance to the results of a previous study [12], in which the process results of abrasive blasting were investigated. In order to polish the tool steel by locally remelting the material, a continuous wave laser source is chosen. To prevent oxidation of the metal, inert gas is used during laser polishing. The different process parameter variants are given in **Table 1** and the process is conducted by the company *Bestenlehrer*. In order to achieve an even surface finish, the polishing process is carried out in several laser passes. Thereby, a distinction is made between macro and micro polishing [7]. The parameters in this study are selected so that the macro polishing is performed during the first laser pass. The lower scanning velocity results in a deeper heat input [13], in order to homogenise the initial surface and surface near microstructure. The following laser passes are carried out with increased scanning velocity to further reduce the surface roughness. The first exposure starts at an angle of 90° to the grinding marks. Subsequently, the following repetitions are performed perpendicularly to the previous exposures. The aim of choosing these parameters is to increase the intensity and the duration of the heat input into the material from V1 up to V3 to further analyse the material changes and the resulting surface roughness as a consequence of the remelting process.

Table 1: Process parameters for the laser polishing of the tool steel S390 microclean

	V1			V2		V3		
Laser Passes	1st	2nd	3rd	1st	2nd	1st	2nd	3rd
Laser Power [%]	70	40	40	70	70	70	90	90
Scanning Velocity [mm/s]	340	1,000	1,000	340	1,000	340	1,000	1,000
Track Offset [µm]	40	5	5	40	5	40	5	5

Experimental Results and Discussion

In the following chapter, the resulting roughness and topography of the surface modified tool steel S390 microclean are discussed. Furthermore, the impact of laser polishing on the material is presented by metallographic analysis.

Topographies of the modified Tool Surfaces. To give an overview of the surfaces in this study, Fig. 2 displays laser scanning microscope images of the resulting topographies. The ground reference surface (Fig. 2 a) is characterized by directional marks, which is a result of the abrasive grinding medium [14]. In this case, this procedure generates a fine surface finish with a low profile depth. As an example of the laser polished surface, the topography of the variant V2 is shown in Fig. 2 b. The linear remelting of the top layer of the material leads to a wave-like surface structure, which is oriented in scanning direction. The erosion processes during abrasive blasting (Fig. 2c) form a crater-like texture resulting in a high roughness.

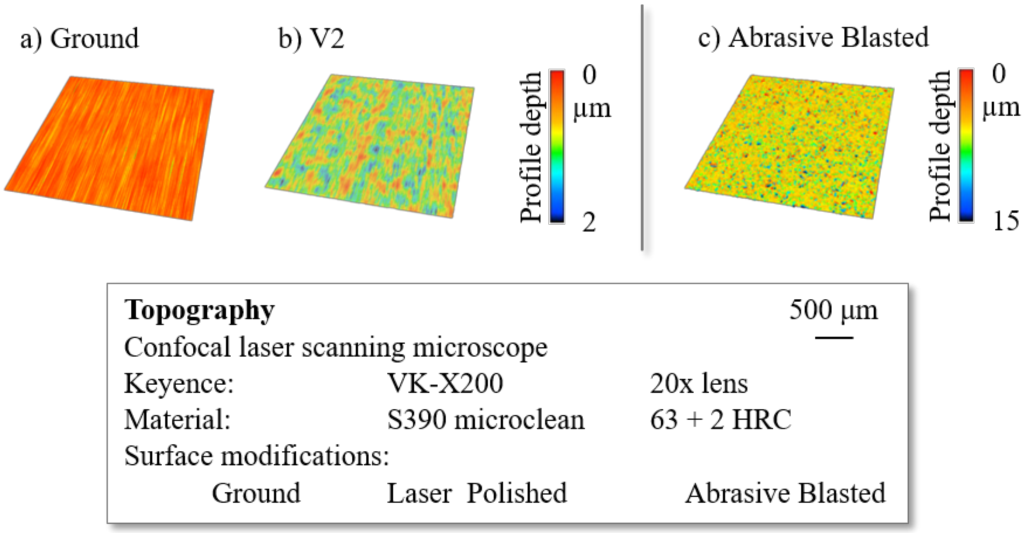

Fig. 2: Surface topographies of a) ground, b) laser polished and c) abrasive blasted surfaces

In Fig. 3 SEM images of cross-sections of the tool steel S390 microclean are shown. The even distribution of carbide and a low proportion of pores in the powder metallurgic produced high-speed steel are visible. Regarding the displayed surfaces, grinding (Fig. 3 b) leads to a smooth surface finish, whereas abrasive blasting results in a rough topography. The impact of the angular blasting medium causes the formation of sharp craters by indentation and erosion. In addition to this, further surface damage in the form of microcracks occurs. This can cause a limitation of the tool service life, as this damage can lead to crack growth and ultimately tool failure at a very early stage [15].

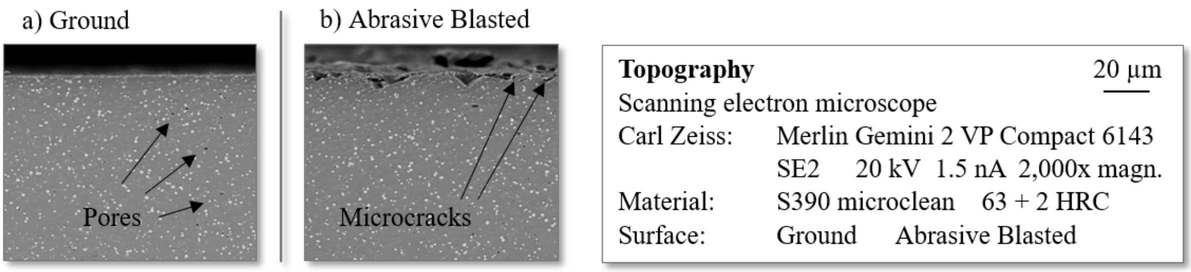

Fig. 3: SEM images of the cross-sections of a) ground and b) abrasive blasted surfaces

In the following section, the roughness values of the investigated surfaces are discussed. A summary of the values for the maximum height of the profile Rz and reduced peak height Rpk is given in Fig. 4. The Rpk values indicate to which degree the roughness peaks exceed the core roughness [16] and therefore have a significant impact on the formation of the tribological system. The finely ground reference surface is characterized by Rz = 0.86 µm and Rpk = 0.07 µm. Based on this, laser polishing with the parameter variants V1-V3 and abrasive blasting is conducted. Variant V1 results in a higher roughness Rz = 1.11 µm in comparison to the initial surface. By the adaption of the laser parameters in variants V2 and V3, the roughness level is reduced to Rz = 0.81 µm respectively Rz = 0.82 µm. In comparison to the ground surface, the laser polishing creates a wave-like surface structure (see Fig. 2). Therefore, a significant increase of the Rpk values is measured. Variant V2 has the lowest value of the laser polished surfaces with Rpk = 0.15 µm. Overall, when discussing both roughness parameters, it should be noted that both V1 and V3 are affected by surface oxidation. This may be a consequence of the additional remelting step in comparison to variant V2 (see Table 1) because studies [17] have shown that oxidation of laser processed materials is significantly influenced by the accumulation of heat. Therefore, the longer duration of the heat input of process variants V1 and V3 might lead to the formation of an oxide layer and thus to an influence on the measured surface structure. This is also indicated by an increased oxygen content in EDX measurements. Since this process is not equally pronounced in all facets of the variants V1 and V3, an increase in standard deviations can be observed. Abrasive blasting of the surfaces causes a strong increase of the roughness as already shown in the topography images (see Fig. 2 c). This results in Rz = 12.35 µm and Rpk = 2.42 µm.

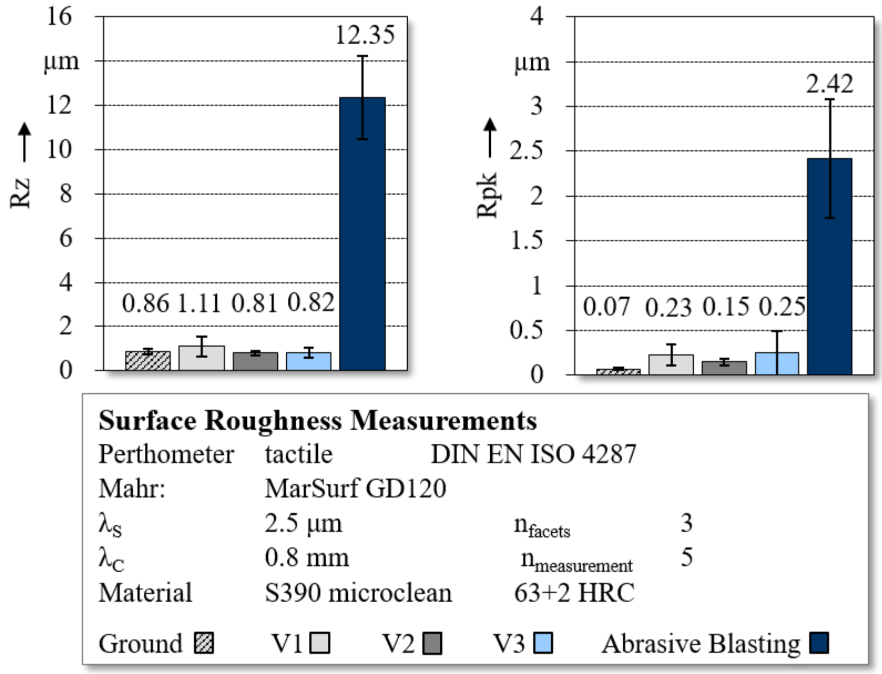

Fig. 4: Influence of the surface modifications on the roughness of the tool steel S390 microclean

Impact of Laser Polishing on the Tool Steel. Laser polishing is based on remelting the surface-near zone. For this reason, it is necessary to further investigate the material integrity of this area. In Fig. 5 SEM images of the surfaces and cross-sections of the laser polished tool steel S390 microclean are shown. For comparison, Fig 5 d) displays the surface of the ground reference surface. The grinding process leads to the exposure of the evenly distributed carbides in the material.

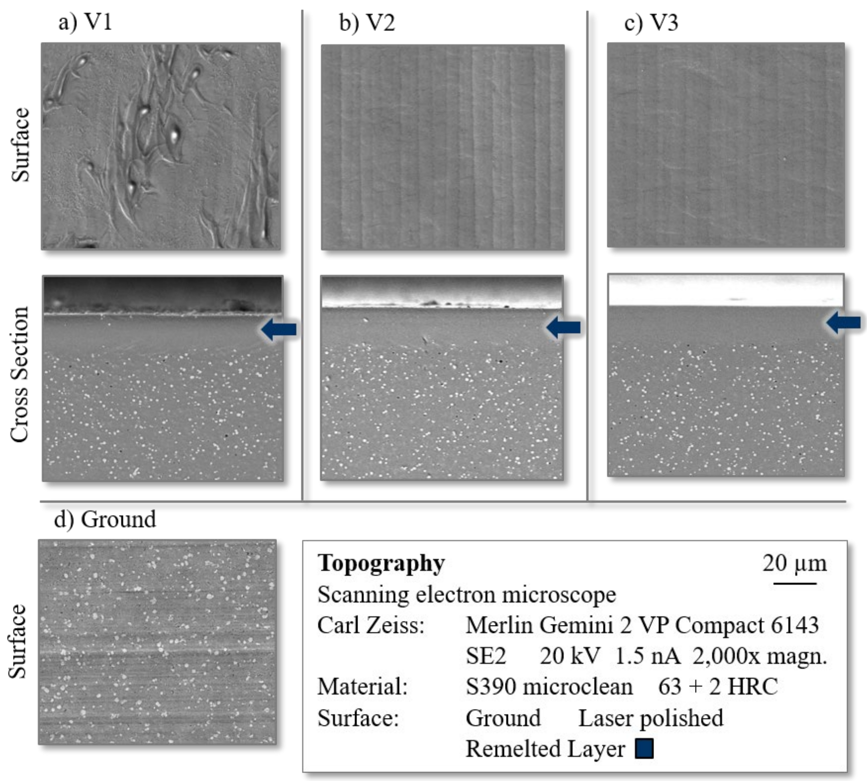

Fig. 5: SEM image of the surface and cross-sections of laser polished surfaces

By melting the material during laser polishing, these carbides are dissolved and the alloying elements are generally homogeneously distributed in the remelted layer, which is approximately 20 µm deep for all process parameters. In addition, pores and defects of the powder metallurgical material are removed. This can be seen in the SEM images of cross-sections in Fig. 5 a-c). A more detailed analysis of the material composition of the specimens can be seen in Fig. 6. The EDX analysis shows the dissolution of the clusters of certain alloying elements in the surface-near zone is visible. This is particularly the case with vanadium, silicon and tungsten. Furthermore, the iron distribution in this zone is more homogeneous than in the base material. This context shows good accordance with the results given in [13]. Looking at the resulting surfaces in Fig. 5 a-c), some conspicuous features are visible. In b) and c), the tracks of the individual laser paths are clearly visible. Due to the fact that the individual grains have different orientations, they react differently to the remelting process. The varying deformation of neighbouring grains forms a step structure [18]. This can be seen in Fig. 5 b) and c). When using laser polishing with variant V1, certain elevations and microstructures occur on the surface of the steel (see Fig. 5 a). In the literature, different explanations for the formation of surface structure can be found. First, melting of the metal can lead to vaporization of the metal due to impurities and the ejection of this gas can build up crater-like structures [19]. Another approach suggests that the laser power is only sufficient to melt the material except the carbides, which have a higher melting temperature. Those remaining solids may form a microstructure on the surface of the remelted material [18]. First EDX measurements of the variant V1 have shown that there is a higher carbon concentration in the surface area as a result of laser polishing. Furthermore, the laser power of the third polishing pass and therefore the heat input is low, which may suggest a persistence of carbides. However, this aspect requires further investigation.

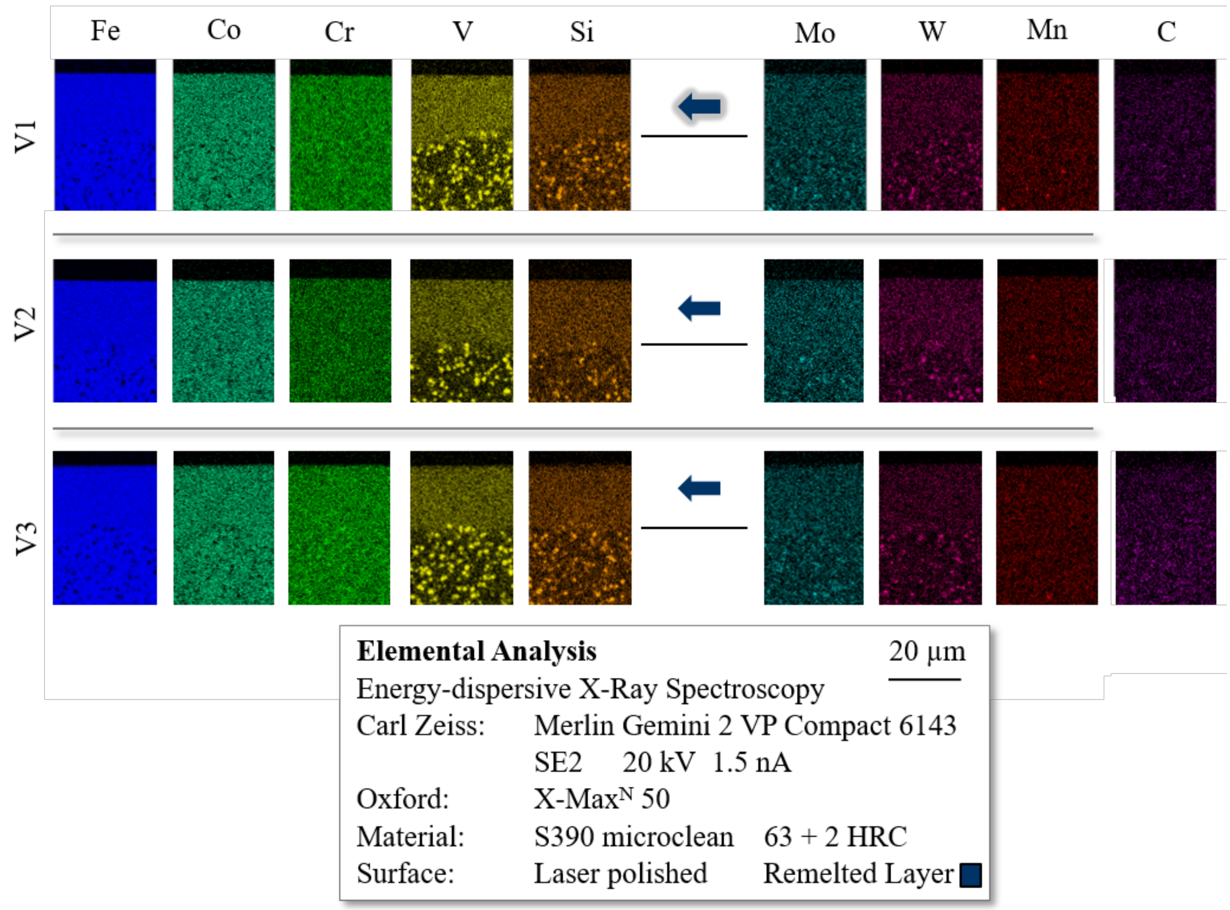

Fig. 6: Elemental analysis of the laser polished specimens by EDX

It should also be noted that the heat input during laser polishing has a significant influence on the surface-near microstructure of the material. Fig. 7 shows a comparison of light microscope images of laser polished specimens, which are etched with cold V2A between 60-90 seconds to evaluate the effects of laser polishing. Heat transfer into the material leads to a remelting of the material up to a depth of approximately 20 µm for all process parameters. Furthermore, a heat affected zone up to a depth of about 30 µm can be identified. In this zone, a change of the microstructure and retained austenite can be identified as a consequence of the heat influence.

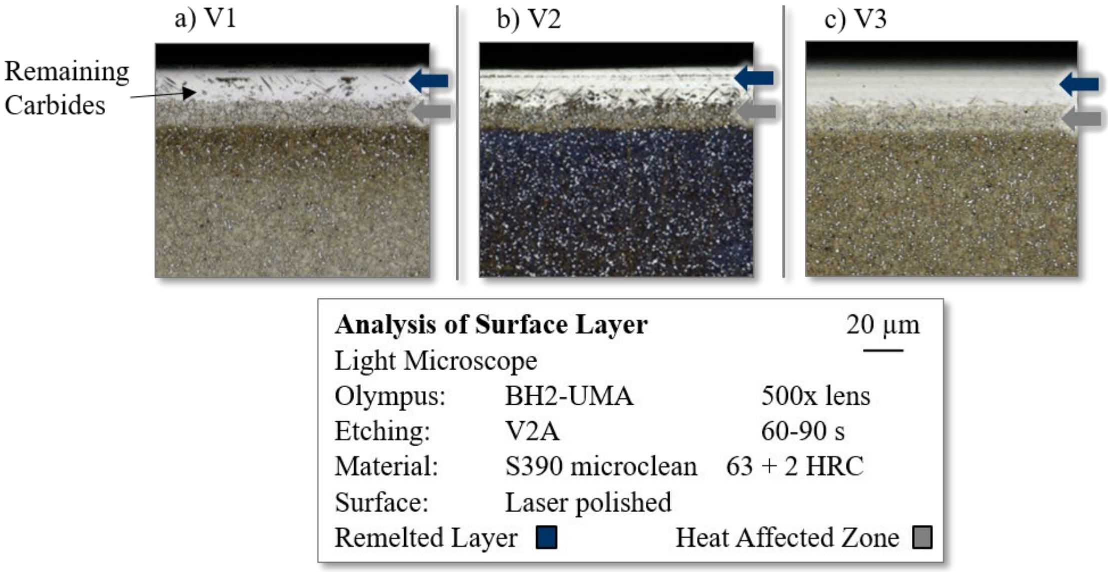

Fig. 7: Analysis of the surface layer of laser polished specimens with parameter variant V2

Summary and Outlook

In this study, the effects of the surface modifications abrasive blasting and laser polishing on the tool steel S390 microclean with an initial ground reference surface were investigated. Main focus was set on the effects of these processes on the resulting surface topography and the surface-near area. By abrasive blasting, the roughness of the material was significantly increased. The surface shows a crater-like structure and microdefects, which has to be taken into consideration for possible use in a tool system. When carrying out laser polishing, the results showed a strong dependency of the selected process parameters. In this study laser polishing consisting two laser passes reduced the surfaces roughness in comparison to the finely ground initial surface. Polishing with three laser passes resulted in the negative effect of surfaces oxidation as a consequence of the heat input. In general, the sequential remelting during laser polishing creates a wave-like surface topography. Furthermore, the remelting and the heat input have extensive effects on the surface-near material. On the one hand, a homogenization of the material is achieved, but on the other hand, the heat input leads to substantial changes in the microstructure of the material. In future studies the impact of these surface modifications on the service life and the operational behaviour of tools will be carried out in order to evaluate the application potential of these modifications as tailored surfaces in forming processes. Thereby the further analysis of the resulting microstructure, residual stresses and microhardness is intended.

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