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Experimental Investigation of a Method for Selective and Precise Laser De-Coating

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Abstract
Coatings are used in many industrial applications as a protective barrier, improving component properties such as friction, wear resistance, and thermal resistivity. When components become worn, any coatings must be thoroughly removed before performing repairs. Laser stripping is a relatively new technology developed for the entire coating removal. So far, only laser stripping of the entire coatings has been discussed in literature, but its application in selective de-coating layer by layercan extend the usage of this technique. Herein, we describe a new method of selective and precise laser de-coating layer by layer in layer thickness lower than 0,15 µm and demonstrate tise technique on two coatings, namely AlTiN and diamond-like carbon. This method is based on ablation threshold measurement and the application of low laser beam fluences for selective de-coating, layer by layer, in a defined pattern. Then the average minimal removals per layer were estimated for both coatings using first and second harmonic wavelengths. Finally, the usage of this method was proved by chemical analysis of the de-coated areas. The presented method can extend the use of laser coating stripping from actual removal of whole coatings to new areas, for example thickness measurement or inter-layer inspection of coatings.

Keywords Laser · De-coating · Laser stripping · AlTiN · DLC

Introduction

PVD and CVD coatings are widely used in many applications such as cutting tools, molding or forming, as a protective barrier with better properties than the substrate material [1]. In particular, the use of PVD coatings has continued to grow since the 1980s due to their superior properties in comparison with CVD coatings, including high hardness, thermal resistivity and corrosion resistance [2]. However, PVD

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coatings can be limited by their reduced thickness [2]. Therefore, when coatings get damaged during use, the cutting tool [3] or mold [4] need to be repaired and the coating must be completely stripped off. The removal of thin coatings still remains a challenging task, as any damage to the substrate can have critical consequences [1, 5, 6]. Traditional methods of coating removal such as mechanical, chemical [4, 6] or ion beam milling [7] have their own limitations. For example, mechanical stripping isn't suitable for a thin PVD coating layer with high adhesion to a substrate [4]. On the other hand, while chemical stripping is a suitable method for the removal of PVD coatings, the toxic waste caused by the proces is problematic [4]. A promising technology for selective coating removing is focused ion beam milling. This technology allows for the very precise removal of material with no heat affected zone. Ion beam milling is a well used method for coating removal or selective de-coating of multi-layer coatings for residual stress measurement. However, this technology may have limited productivity, as it has a material removal rate which is lower than other competing technologies [7, 8].

Regarding these facts, the laser stripping method seems to be a suitable replacement for conventional methods because it is a comparatively green, very fast process with excellent process control. In addition, laser stripping can be locally focused on functional parts which can further increases the usefulness of this method. For example, a controllable laser ablation and microstructuring of thin TiN films deposited on steel substrates was presented by Kononenko et al. [9]. The main goal of this research was to improve the sliding properties of a TiN coating by using dot pattern structures. For this purpose, a condition for minimal ablation was estimated and presented as an ablation rate (nm/pulse). A study using a TiN/TiAlN coating was performed by B. Gakovic et al. [10]. A femtosecond laser operating at 775 nm was used for ablation threshold measurement followed by dot structuring. The ablation threshold F_{th} for one pulse was 0.66 $J.cm^{-2}$, the incubation coefficient $S = 0.642$, and ablated craters in the coating were presented as a result of this study [11].

Extensive research in the theme of laser stripping of coatings was done by S. Marimuthu et al. [1], in the wider context of reusing cutting tools. In one of their works, the ablation rate (μm/pulse) was used to explain the observed ablation depth. Additional prameters, namely laser fluence and number of pulses, were estimated for a stationary de-coating process. An appropriate laser beam overlap was computed for larger area de-coating with respect to the number of pulses need for coating removal in one place. As a result of this study, an ablation threshold for a 2 μm thick CrTiAlN coating was estimated, together with successful coating removal from a steel substrate using a fluence of 2 J/cm^2, a laser beam overlap of 90%, a scanning speed of 4.2 mm/s and a frequency of 100 Hz. Succesful removal of the coating was estimated based on the comparison between the depth profile measurement and the coating thickness together with an optical control. A different approach (in terms of productivity) was chosen by our research group in the study "Investigation of Multiparameter Laser Stripping of AlTiN and DLC C Coatings" [5]. In this paper a nanosecond laser was used for productive laser stripping of TiAlN and DLC coatings. Succesful DLC coating removal was also presented by Assruin et al. [3] using a KrF excimer laser operating with a frequency of 25 Hz. In this study an ablation depth (μm) was presented for different laser fluences and number of pulses used. The main focus of their study was the complete removal of the coating, but without emphasising accenting the lowest removal rates. Coating removal was futher analysed by elemental energy dispersive spectroscopy (EDX). Research focused on the laser de-coating of a DLC/CrC interface coating was presented by Zivelonghi et al. [12]. In their paper, a parameter called the 'average etching rate' (with a value of 1.1 µm/loop) was presented, which represents the average removal thickness for one pass of the laser beam.

While the research of laser stripping has developed over the last two decades, a precise laser de-coating process is not a well described area of a research. However, this knowledge is crucial for two advanced laser applications: first, the laser structuring of coatings, and second, precise laser de-coating for complete coating stripping - without affecting the substrate material or for the selective de-coating of multi-layer coatings.

In this paper a method for the selective laser de-coating process layer by layer is presented and demonstrated for two conventional coatings: AlTiN and DLC W. Both coatings are used for cutting tools or molds because of their unique properties, while both of them are absolutely different and difficult to stripped by conventional methods. Based on the found papers in literature, our study expands the knowledges about ablation behaviour of AlTiN and DLC coatings under common femtosecond laser operating in near-IR spectrum. The main motivation of this paper is to find an approach for obtaining the minimal average removal thickness per single layer, and demonstrate the posssibilites of the selective de-coating method layer by layer for multi-layer coatings. The second goal of this study is to establish certain parameters, namely laser fluence and the number of repetitons required for succesful coating removal with minimal substrate damage. Both goals are assessed by an optical and EDS chemical analysis.

Materials and Methods

For the experiments, two different types of coating were used, namely AlTiN and DLC W. Both coatings had different compositon, properties and layer thickness, as shown in Table 1. The coatings were deposited on a flat face of a round sample (i.e., the substrates) with a diameter of 20 mm and a height of 5 mm. Sintered carbide was chosen as the substrate material, with a composition of 90% WC and 10% Co. Coating thickness was measured using a Calo tester equipped with a rotating ball. The composition of the coatings was provided by the supplier (Slechta a.s, Czech Republic).

For the experiments, a femtosecond laser source (CARBIDE- 40 W, LightConversion) with maximal output average power of 40 W was used. The laser source was installed into a micromachining station Master 1 (ELAS Ltd.) with 5 mechanical and 2 optical axes. Such a laser system enables the generation of two harmonic wavelengths: 1030 nm and 515 nm. The laser beam is delivered from the source by optical path, equipped with attenuators, polarization changers, power meters etc. to the galvo - scanner (InteliScan14, Scanlab) and focused by a F-theta lens (160 mm) to the focal plane. The beam diameter in the focal plane was 30 µm for both harmonic wavelengths.

Table 1 Properties of coatings used for the experiments

Coating	AlTiN	DLC W
Underlayer composition and thickness [μm]	none	CrN, 1.4
Substrate	Sintered carbide WC-Co10	
Total thickness range [μm]	3.8 to 4.1	2.1 to 2.4
Hardness [HV]	3300 ± 300	1600 + 150
Composition [Wt%]	Ti = 42,3 Al = 29 N = 25.6 Others = 3.1	W = 58.3 Cr = 38.7 O = 1.9 Others = 1.1
Special properties/usage	High toughness, high thermal stability—operational temperature max. 900 °C; abrasion protection for cutting tools [2, 13]	Friction coefficient agaist steel 0.06; for molds and forming tools [14]

A confocal microscope, (VK-X 1000, Keyence) was employed for optical analysis of the de-coated areas. This device enables depth measurements in the nanometer range, with a horizontal resolution of 50 nm. Multifile Analyzer software (Keyence, Japan) was used for analysis of the stripped area depth.

A Zeiss field emission scanning electron microscope (FESEM; ULTRA PLUS) equipped with an energy-dispersive spectrometer from Oxford Instruments (EDS; X-Max 50) was used for the EDS/SEM analysis of the surface. The weight% of each element in the surface layer was obtained from a square area with a side length of 200 μm.

The method presented is based on the ablation threshold measurement followed by a selective de-coating process in a defined pattern, using laser fluences that are multipes of the ablation threshold. As a result, the minimal average removed thickness (ART / μm) per layer is established. According to the work proposed, the experiments were divided into two parts: first, measuring of the ablation threshold while varying the number of pulses, and second, the selective de-coating of two different coatings, with the goal of ablation being obtaining the thinnest as possible layers and estimation of ART for one lasered layer.

The experimental determination of the ablation threshold was performed with regard to several references [15–17]. The ablation threshold, expressed by the threshold fluence (F_{th}), is the minimum energy required to ablate at least one atom from the material [15]. The method of determining the ablation threshold is based on Eq. (1) [17]:

$$D^2 = 2 \cdot w^2 \cdot \ln\left(\frac{F}{F_{th}}\right) \tag{1}$$

where w is the focused beam diameter and F is the applied laser fluence, which corresponds with pulse energy (E_p). In this experiment, a line of spots was ablated, with increasing power from one spot to the next. Each spot was created with the same number of pulses. The diameter of the ablated spots was then measured using a VK-X1000 optical microscope (Keyence). In order to reduce uncertainty, each spot was ablated ten times in a row, therefore the value of the spot diameter for the appropriate fluence was averaged from ten measurements. Then, the squared diameter was plotted (y-axis) against the fluence (x-axis). Linear regression was used to determine the threshold fluence – i.e. the value of fluence where D^2 equals zero.

In this study, the ablation treshold was measured and calculated for five different numbers of pulses (N) in one spot: 1, 10, 50, 100, 1000; this was performed for two different harmonics (IH = 1030 nm, IIH = 515 nm). Using Eq. (2) [15, 16] incubation coefficients (S) were calculated for each number of pulses and then averaged.

$$F_{th}(N) = F_{th}(1) \cdot N^{S-1} \tag{2}$$

The main goal of the selective de-coating experiment was to find the minimal controlled coating removal for one layer, which should be found in the submicrometer range. Driven by this idea, the experimental procedure was designed. Coatings were selectively removed in the shape of a rectangle with a length of 22 mm and a width of 2 mm, by means of a linear hatching strategy with one direction of scanning. Then, another pass with a shorter rectangle (20 mm long, 2 mm wide) was applied over the first one using the same scanning strategy. This process was repeated ten times, as illustrated in Fig. 1. The reason for this experimental strategy was to create a profile with ten steps of depth, which can be easily produced and measured. In total, 10 profiles were prepared for each coating using a different fluence, directed by the fluence threshold and its multiples (from 1x to 10x). For the second iteration of this experiment, a shorter step between multiples of F_{th} was used for better observation of the de-coating limits. A constant overlap of 90% and a constant frequency of 200 kHz was used for coating removal. An overlap of 90% was used for continuity with the ablation threshold, i.e., a 90% overlap corresponds with 10

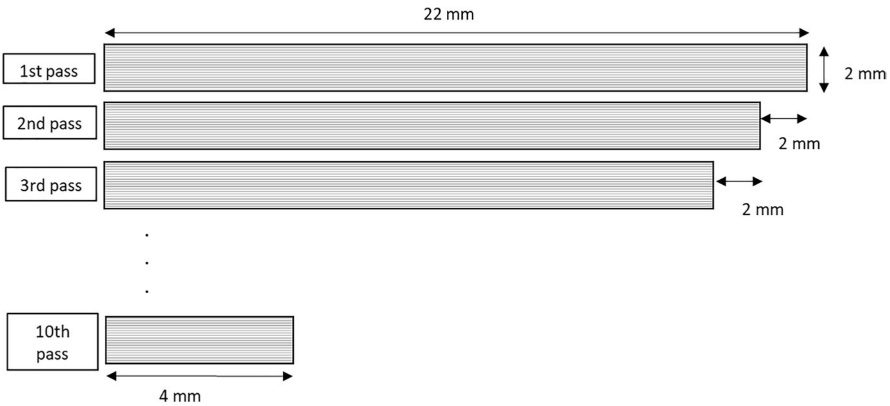


Fig. 1 Ilustration of the laser stripping strategy

pulses in one spot. All important laser and scanning parameters used are displayed in Table 2.

The removal profiles of each coating were scanned and analyzed using a Keyence optical microscope. Firstly, the depth steps of each profiles were measured three times, and can be seen in Table 3 as the removed depth values. Then, the removed depth values were estimated as the difference between actual and previous laser pass. It means, that for the second laser pass the removed thickness was 0.66 µm. Similarly, the other values were computed. Finaly, the ART values were computed from the removed thickness observed in the coating. Also the standard deviation of the ART was estimated as the minimal and maximal removed thickness per one layer (Table 3).

Finally, as an example of the selectively de-coated areas, one sample for each coating and wavelength was further analysed by SEM/EDS. The choice of sample for analysis depends on one main criterium, which was the complete stripping of the coating after 8–10 passes with minimal removals in substrate. Also any significant change in the different layers of multi-layer coatings was of interest. For this samples, the surface roughness expressed by Sa (arithmetical mean high) of each area was evaluated. Parameter Sa is defined in norm ISO 25,178 [13] and can be defined as an extension of well known Ra parameter for areas. In this case, the choosed area for measurement was 1.5 to 1.5 mm and Gaussian filter was used for evaluation of the results.

Results and Discussions

Determination of the Ablation Threshold

Ablation threshold values obtained (threshold fluences - F_{th}) in relation to the number of pulses applied, N (in logarithmic coordinates), are displayed in Fig. 2.

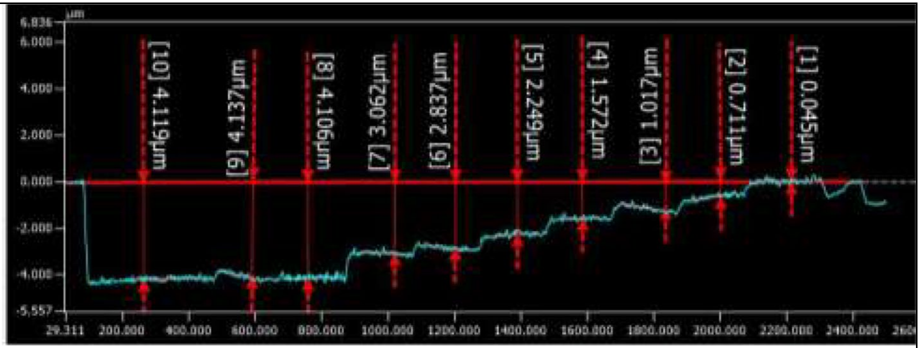
Comparing results for both coatings, a higher ablation threshold was observed for AlTiN at both harmonics used. Moreover, IH led to higher threshold fluences than IIH for both coatings, especially for lower number of pulses.

The obtained threshold fluence for the AlTiN coating was F_{th} = 0.196 J/cm^2 for IH and F_{th} = 0.260 J/cm^2 for IIH respectively. The lowest ablation threshold determinated for the DLC W coating was F_{th} = 0.058 J/cm^2 for IH and F_{th} = 0.094 J/cm^2 for IIH respectively. Obtained values of threshold fluences were found to be in agreement with the threshold values reported in the literature, see Table 4, although different laser devices were used.

Table 2 Laser parameters used for the selective de-coating experiment

Wavelength (λ) [nm]	1030, 515
Spot diameter in focus (2ω) [mm]	0.03
Pulse duration (τ) [ns]	261
Repetition rate (f) [kHz]	200
Pulse overlap (S_p) [%]	90
Hatch distance (H_y) [µm]	6.2
Scaninig speed (v_x) [mm/s]	600

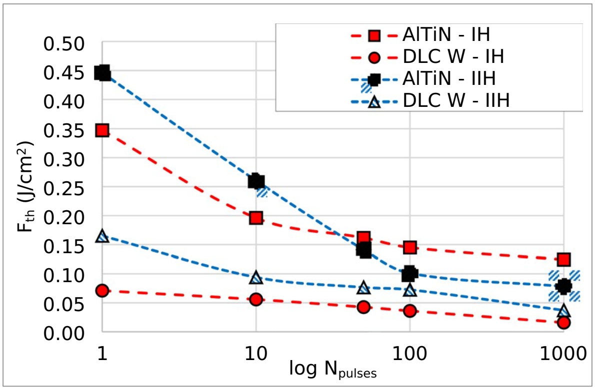
Table 3 Method of de-coated profile evalutation, labelled with the removed depth, removed thickness per one layer and average removed thickness (ART) for AlTiN coating, for IH and $F/F_{th} = 2.3$



Measured depth profile from the optical microscope										
N° of laser passes	10	9	8	7	6	5	4	3	2	1
Removed depth [µm]	4.119	4.137	4.106	**3.062**	**2.837**	**2.249**	**1.572**	**1.017**	**0.711**	0.045
Removed thickness per one layer [µm]	0.018	0.031	1.044	**0.225**	**0.588**	**0.677**	**0.555**	**0.306**	**0.666**	0.045
ART - average removed thickness per one layer with the standard deviation									$0.503^{0.677}_{0.225}$	

Highligted bold values were take in account for ART calculations

Fig. 2 The dependence of F_{th} on the applied number of pulses N for AlTiN and DLC W coatings (IH – 1030 nm, red lines; IIH – 515 nm, blue lines)



From the different number of pulses applied, incubation coefficients were calculated and are shown in Table 5. Incubation factors characterize the response of the material to cumulative ablation; these were calculated according to Eq. (2) and are displayed in Table 5. It was found that the highest S value was obtained for the DLC W coating for IH. Thus, the lowest S value was calculated for AlTiN for IIH. A lower incubation coficient value means a lower ablation threshold for more pulses. Under these conditions, absorption increases, as reported e.g. in [19], and more material can be removed for the same energy applied. The values of the incubation coefficient are dependent on the specific laser-matter interaction. In the references [1, 10, 12] the S values ranges from 0.7 to 0.9 for similar materials.

Experiments on Selective De-Coating

The developed method of selective de-coating calculates the ratio of applied and threshold fluences for 10 pulses, with fluences expressed by the ration (F/F_{th}) ranging from 1 to 10. The threshold fluence for 10 pulses can be transferred to the motion of

Table 4 Reported fluence threshold values in the literature for TiAlN and DLC coatings

Coating	Used laser device, number of pulses (N)	F_{th} (J/cm^2)	Ref.
TiAlN/TiN	$\tau = 200$ fs, $\lambda = 775$ nm, N = 20	0.39	[10]
TiAlN	$\tau = 120$ fs, $\lambda = 800$ nm, N = 1	0.63	[17]
TiAlN	$\tau = 20$ ns, $\lambda = 248$ nm, N = 1	1.85	[17]
DLC + DLC:Cr (6.2 µm)	$\tau = 1$ ps, $\lambda = 532$ nm, N = 1	0.2–0.3	[12]
DLC with different electric field intensity distribution	$\tau = 10$ ns, $\lambda = 1064$ nm, N = 1	0.6, 0.8, 1.2, 1.5	[18]

Table 5 Incubation factor calculated by Eq. (2) for various coatings and radiation wavelengths

Incubation factor S (-)	IH	IIH
AlTiN	0.80 ± 0.04	0.72 ± 0.03
DLC W	0.85 ± 0.04	0.79 ± 0.02

the laser beam with 90% overlap. For better resolution, only parameters resulting in lower average removed thickness (ART*)* per single layer for both analysed coatings are displayed in the graphs in Fig. 3. For each value, the minimal and maximal values of ART per pass are shown as the error bars. In addition, the diagrams of coating thickness and composition are shown to provide a better explanation of the average removal layer thickness in relation to the total thickness of the coating. In Fig. 3-b) a detailed view of the beginning of the graph is displayed. Additionally, third degree polynomial trendlines are shown.

Also, theoretical zero values of ART for F/F_{th} =1 were added to the results in Fig. 4. The theory states that for this threshold fluence, only one atomic layer measuring one tenth of nm, is ablated [20]. In real applications, the thickness of the material removed is measurable by optical or confocal microscope and can be observed with higher multiples of F_{th}, which can be seen in results shown. In the graphs, error bars represents the minimal and maximal removed thickness per one layer as desribed in "Materials and Methods" section. The lowest measurable values

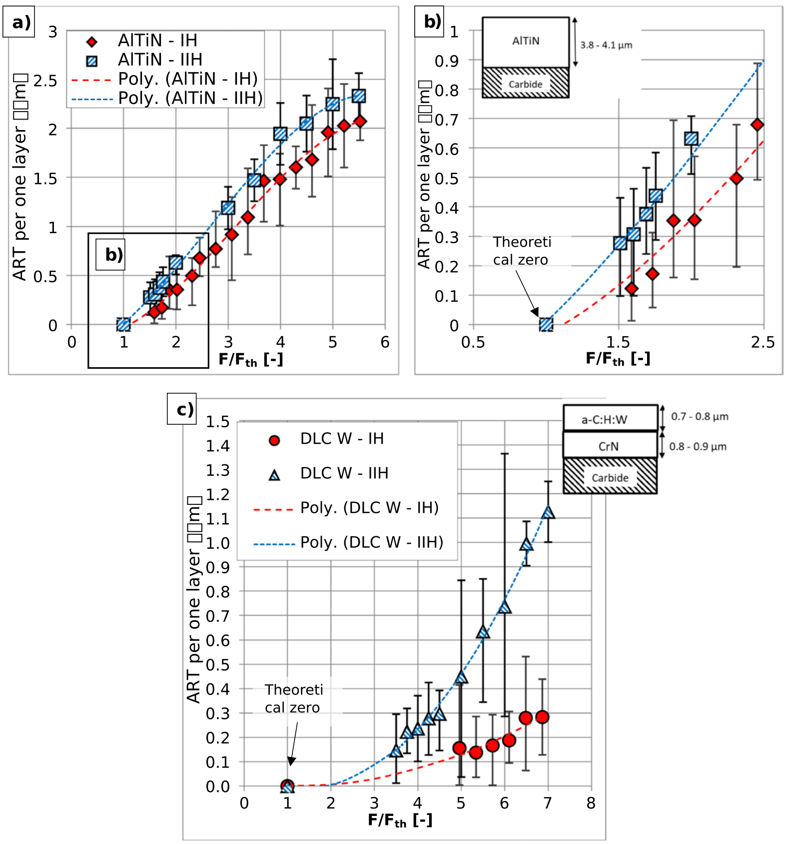


Fig. 3 ART in one layer for different F/F_{th} ration for both tested coatings and harmonic wavelengths (IH – 1030 nm, red line; IIH – 515 nm, blue line)

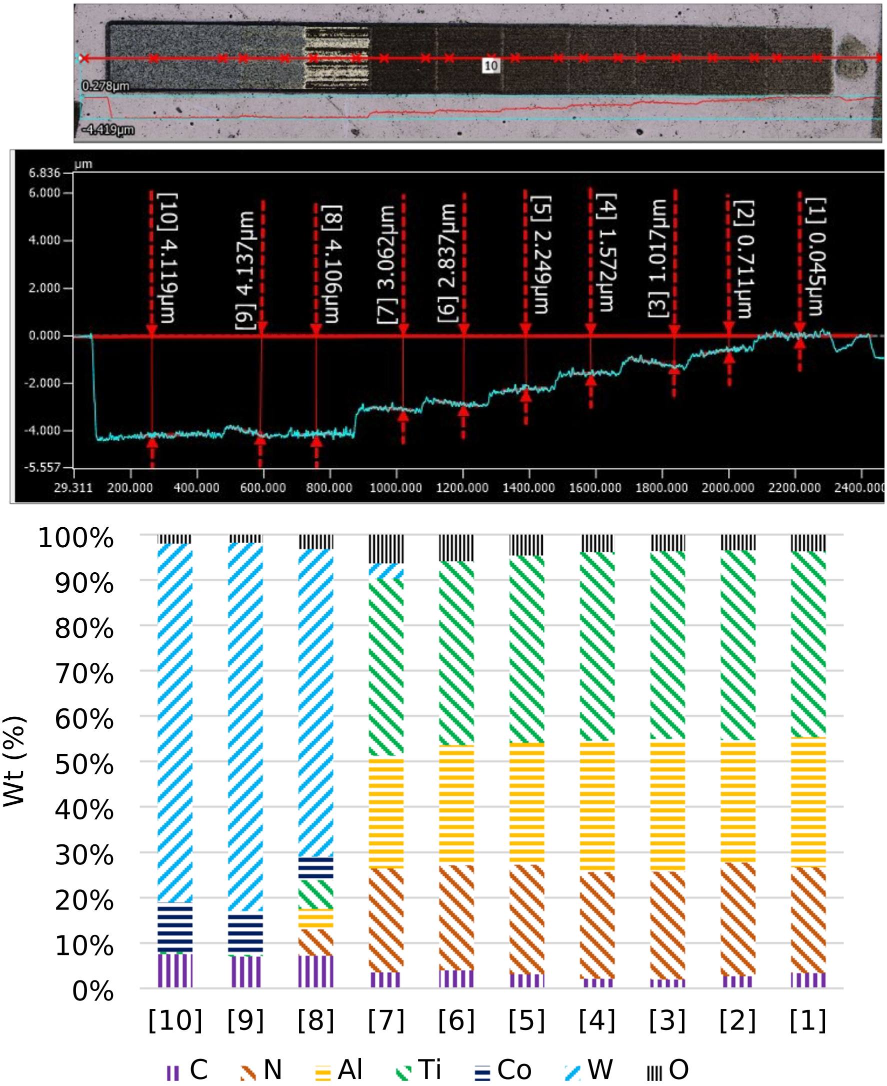


Fig. 4 Results of optical and chemical analysis of the AlTiN coating, for IH and $F/F_{th} = 2.3$

of the ART exhibiting high error bars was affected by many factors, especially the measurement device used, surface roughness, and material properties. Moreover, as proved by EDX analysis, the presence of oxygen after laser processing can cause a change in surface absorption and thus also affect the uncertainty in the selective de-coating process.

A minimal ART in one layer was measured below 0.2 μm for the DLC coating and below 0.3 μm for the AlTiN coating respectively. In addition, lower thicknesses of removed material were found for IH in comparison with IIH. This means that a wavelength of 1030 nm is more suitable for the selective de-coating process of both coatings due to lower ablation rates. A possible explanation of this fact can be found in the absorption properties. Shorter wavelengths are better absorbed by selected coatings [18], which results in better ablation and higher ART in a single layer. This result corresponds with the measured values of incubation factors, but it must be mentioned that there was much more time for the material to relax than when testing the ablation threshold with a larger number of pulses. Lower incubation factors were found for IIH, indicating higher absorption of upcoming pulses, as well as a higher ART per layer for both coatings.

In addition, it was observed that a lower F/F_{th} ratio is required to begin the de-coating process of AlTiN, however, a higher F/F_{th} for DLC W was needed. This can be caused by the higher thermal conductivity of a carbon based upper DLC layer, even if the threshold fluence is lower than for the AlTiN coating. The absolute lowest ART in one layer (0.1 μm) was achieved for the AlTiN coating for IH. Taking into account the total thickness of the AlTiN coating, some coating still remains after 10 passes of the laser beam. On the other hand, the DLC W multi-layer coating has a lower total thickness compared to AlTiN. From the results for DLC W – IIH (Fig. 4-c) the change between top and bottom coating layer can be seen for F/F_{th} = 5–6, which corresponds to an ART ranging from 0.4 to 0.75 μm. In this range, significant changes in material properties were observed. This resulted in high error bars, ranging from 0.2 to 1.3 μm. A higher ART per layer was observed at higher laser fluences. Thus, the effect of the material properties decreased.

The ART per layer for AlTiN is shown in detail in Fig. 4-b). Visible removal was observed from F_{th}=1.5 for IIH and from F_{th}=1.6 for IH, respectively. However, selective de-coating with minimal ART was not achieved for the lowest used fluence. Furthermore, the difference between the thickness of the removed layer decreased with increasing laser power, especially for IIH. As a result of selective de-coating of AlTiN, it can be seen that for IIH the minimal ART = 0.29 μm with very high error bars representing the minimal and maximal removed thickness by laser pass. While controlled ART can be estimated to 0.63 μm due to low difference between minimal and maximal removal for one laser pass. For IH, the AlTiN can be de-coated more precisely, because of the minimal ART is lower than for IIH and has a value of 0.1 μm. However, lower controllability, experesed by higher error bars, was observed for IH in comparison with IIH, although the controlled removal was estimated for ART = 0.25 μm. The trendlines displayed in Fig. 3 exhibit a different behavior depending on the coating used. For the AlTiN coating, a third degree polynomial trendline with smaller progression for higher fluences can be observed, due to a lower ART in the carbide substrate. Thus, for the DLC W coating, high progression (even if for higher fluences) can be seen. This is because of the lower coating thickness which results in faster coating stripping and substrate ablation. which is more common for higher fluences.

In previous work [12], a DLC coating was selectively de-coated by laser radiation using a wavelength of 532 nm. They reported a lower ART per layer of 0.5 μm with high uncertainity, which we also observed. Nevertheless, the main focus of this paper was in in laser stripping of the whole coating. A multi-layer DLC coating was stripped in study [3], but without focusing on minimal removals in one layer.

Moreover, only a static pulse method was used without scanning, which is not useful for industrial applications.

In Fig. 4, the depth profile together with chemical analysis for F_{th} = 2.3 of the AlTiN coating for IH is presented.

The chemical analysis proved the correlation between the identified chemical composition of the surface and color change in the optical images. In such a manner, the extent of AlTiN coating removal can be estimated by the color change, especially when the carbide substrate becomes ablated by the laser. In this case, substrate elements were detected between the 6th and 7th laser pass. While the average de-coated depth was approximately 0.6 µm with high unlinearity, in the carbide substrate this value approaches zero. Consequently, the laser parameters used - corresponding to F/F_{th} = 2.3 (F = 0.45 J/cm^2) - seem to be suitable for complete stripping of the AlTiN coating, as they do not affect the substrate material during removal. On the other hand, the parameters for IIH (F/F_{th}=2 ~ F = 0.45 J/cm^2), presented in Fig. 5, led to significant removal of the substrate material. That said, the ART per layer in the AlTiN coating was 0.6 µm with very low uncertainty.

The color change, supported by chemical analysis and the depth profile, allows for the coating thickness to be verified. For IH, the substrate elements were detected between 3 and 4 µm, for IIH the substrate elements were detected in the range 3.8–4.2 µm. Thus, the thickness of the AlTiN coating can be estimated to sit within the narrow range of 3.8-4 µm.

With both profiles (AlTiN – IH, AlTiN – IIH) analysed by EDX, the surface roughness can be expressed by the arithmetical mean height (Sa) in the relation to the depth of coating removed. Results are shown in Fig. 6. Higher Sa values were observed for the IH harmonic, although a lower ART per layer was obtained for this wavelength. This caused the need for more energy to ablate the AlTiN coating, resulting in significant melting, ultimately leading to less material being removed and a higher surface roughness. Moreover, the decrease of initial surface roughness (Sa = 0.12 µm) was observed for both harmonics even if the coating had not been removed. The first de-coated layer caused a significant reduction in surface roughness, which makes this process interesting for laser polishing of a coating surface after deposition. Meanwhile, the transition between coating and substrate resulted in a significant increase in surface roughness due to a different interaction with the laser beam. Negligible substrate removal was observed for the laser parameters used. Instead, there was a thermal effect which caused melting of the material, leading to an increase in surface roughness.

In study [17] similar experiments to those presented here were made, however, the experimental set up allowed for a scanning speed in the range of 0.3–0.4 mm/s, which yielded an ineffective process. In addition, the reported surface roughness was higher than that achieved by our process. Some similar conclusions were found, especially that low power leads to a lower etch rate.

For the DLC W coating, the observable start of the de-coating process was for F/F_{th} = 5. When analyzing the height profiles of the measured data, selective removed layers were wavy and rough (Sa approx. 0.11 µm, Sz approx. 2.6 µm). As an example, the profile for F/F_{th} = 5.7 is presented in Fig. 6. Removals were detected only in the coating up to the sixth layer, while for more laser passes the

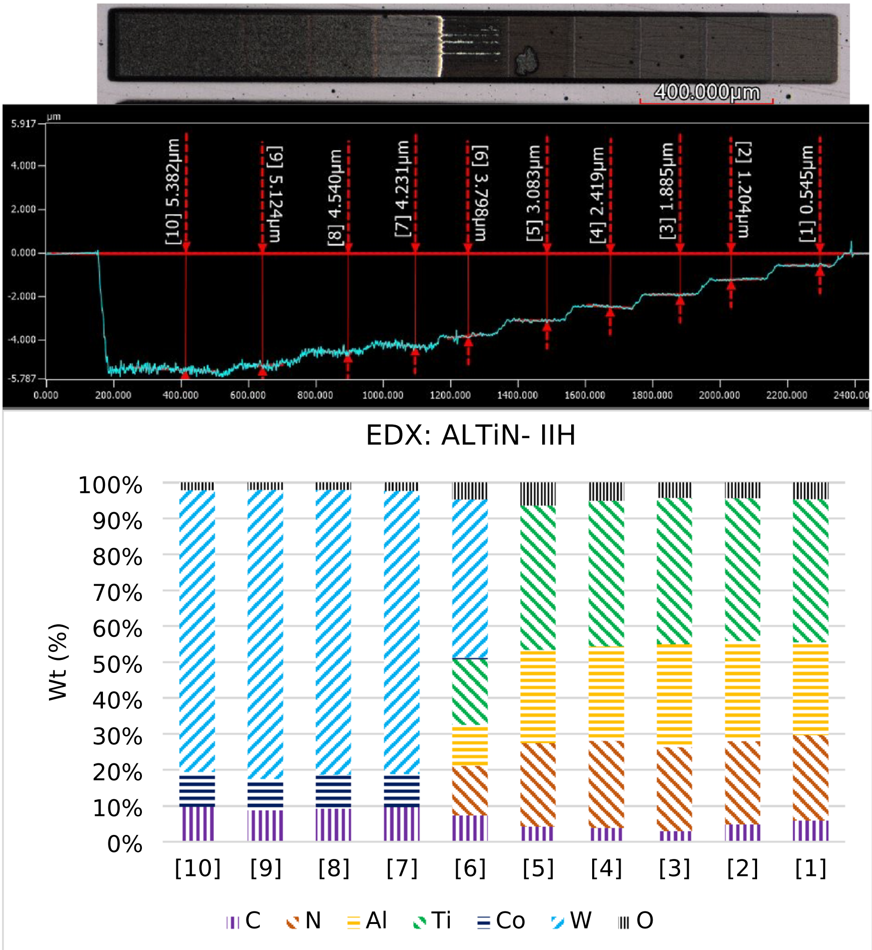


Fig. 5 Results of optical and chemical analysis of the AlTiN coating for IIH and $F/F_{th}=2$

carbide substrate was affected and partialy removed. This fact is indicated by the change in the surface profile, depth and surface roughness, since carbide (especially binder cobalt) melts and evaporates more readily under the conditions used. From the color change in the optical image, the change of elements for different de-coated depths can be estimated. Simultaneously, this change was validated by the chemical analysis, where the change from the upper carbon layer to the lower CrN layer was identified. Hence, the average coating and interlayer thickness can be calculated. The upper carbon DLC coating thickness was calculated to be approximately 0.7-1 µm. The thickness of the CrN interlayer was found to be 1-1.3 µm, and the total DLC W thickness was calculated to be approximately 1.75-2 µm. The average removal on this profile was 0.16 µm, but with a high uncertainity caused by low coating thickness and observed surface roughness. According to this analysis, complete

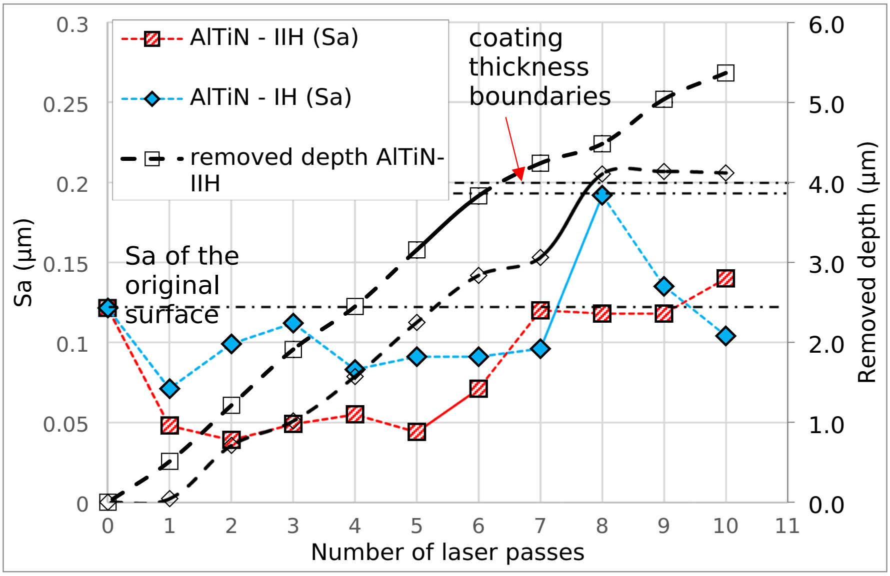


Fig. 6 Comparison of surface roughness (Sa) in relation to the removed depth for AlTiN coating removed for a different number of laser passess equal to de-coated layers

selective de-coating was done. It was confirmed that the CrN substrate coating appeared in the seventh layer, at a depth of 0.74 µm. The transition between the CrN interlayer and the substrate was observed in the eighth layer (depth of 1.2 µm). The first layer probably caused only thermal damage, resulting in difficulties when measuring the height (tens of nanometers) (Fig. 7).

The profile for $F/F_{th} = 3.7$ was chosen as an example of DLC W selective de-coating for IIH, as shown in Fig. 8. From chemical analysis it can be seen that up to fourth layer only de-coating of the upper carbon layer occurs. Hence, a composition change from carbon to chromium was detected, which is indicative of inter-layer stripping. The thickness of this CrN layer was calculated to be 1.05–1.3 µm. Only substrate elements were detected after lasering of the seventh layer. According to the profile measurement, the total thickness of the DLC W coating was calculated as 1.75-2 µm. The ART per layer for this profile was 0.167 µm, with high uncertainity caused by chemical composition changes and surface roughness. The lowest removal was observed in the first layer, probably only by thermal damage without significant ablation and de-coating.

The surface roughness (Sa) was analysed from both DLC W profiles, previously analysed by EDX. The relation between Sa and removal depth can be seen in Fig. 9. After the first pass of the laser beam, the surface roughness increased in comparison to the original. Moreover, a significant change in surface roughness was observed at a depth of 0.9 and 1.8 µm. Both points correspond to a change between coating layers, as found by EDX analysis. A similar surface roughness was measured for both harmonics, however the first harmonic (IH) led to a more linear tendency with low uncertainty in comparison to the second harmonic (IIH).

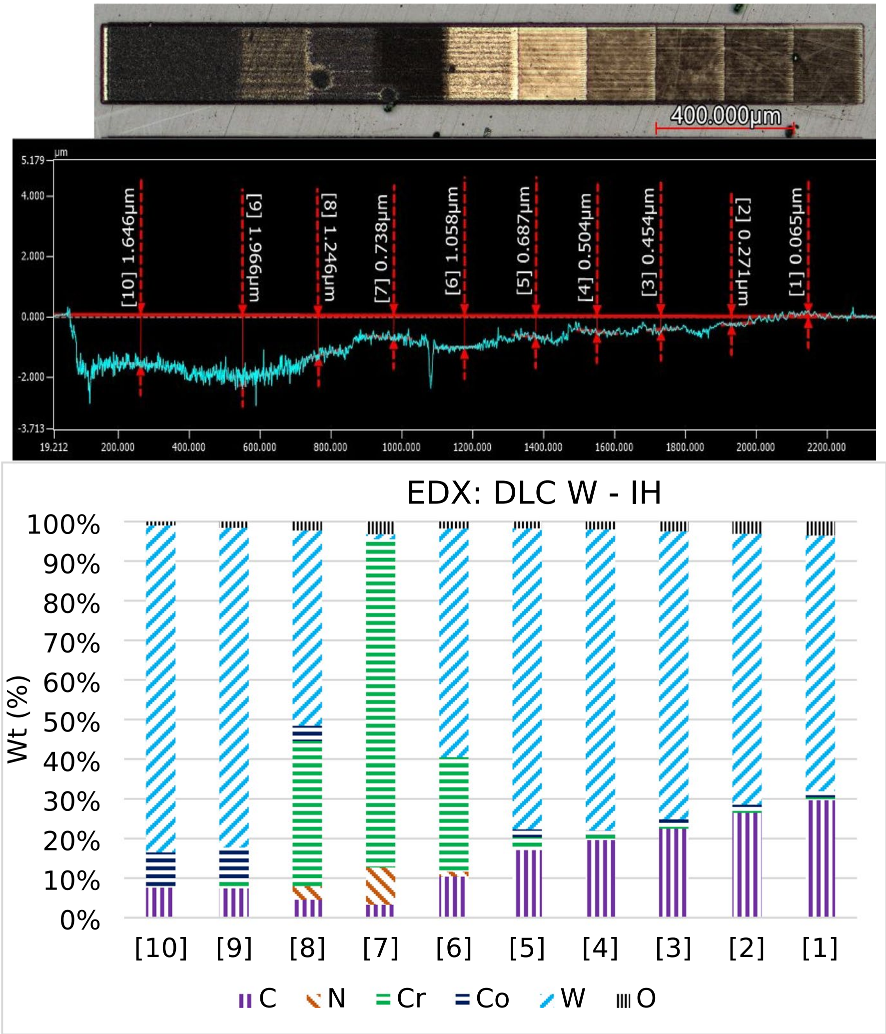


Fig. 7 Results of optical and chemical analysis of the DLC W coating for IH and F/F_{th}=5.7

From all chemical analyses, a significant increase in oxygen content was observed. This can cause differences in absorption of the laser beam, resulting in different removal depths, as reported elsewhere [12].

Conclusion

In this paper, two different coatings, namely AlTiN and DLC W, were studied by means of a newly developed process of precise selective laser de-coating using two harmonic wavelengths of 1030 and 515 nm. First, the ablation thresholds of

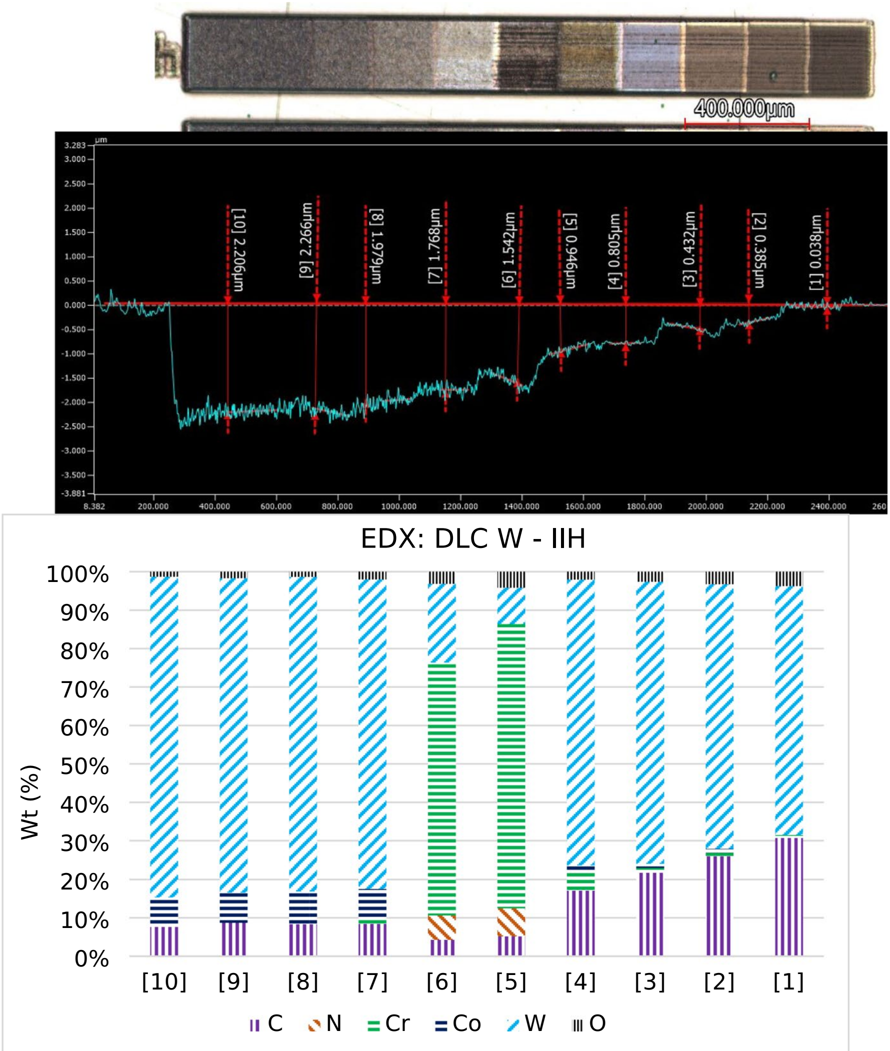


Fig. 8 Results of optical and chemical analysis of the DLC W coating for IIH and F/F_{th}=3.7

the coatings were determined for different numbers of pulses. Thus, an incubation effect was described. Subsequently, the main experiment focused on finding the limits of average removed thickness (ART) per layer. Finally, surface roughness and chemical composition of de-coated areas were inspected. The following conclusions can be drawn according to our findings:

- A new method of selective de-coating of industrial coatings was succesfully developed and demonstrated for two different coatings.

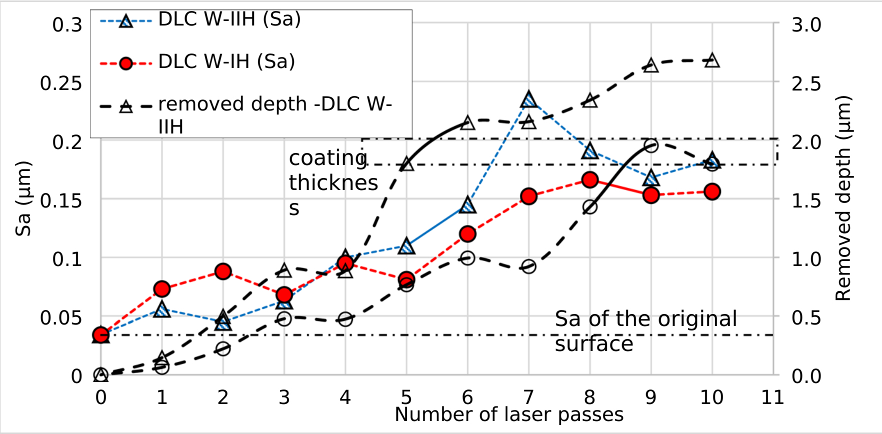


Fig. 9 Comparison of surface roughness (Sa) in relation to the removed depth for the DLC W coating, for different number of laser passess equal to de-coated layers

- The ablation thresholds for different numbers of pulses were estimated and incubation coefficients were calculated. Higher values of the incubation coefficient were found when the IH harmonic was applied, meaning a lower absorption for a higher number of pulses, resulting in less material removal in comparison with IIH.
- Limits of average removed thickness (ART) per single layer were found for both harmonic wavelengths. Moreover, it was observed that the first harmonic (1030 nm) led to more precise de-coating with lower ART per layer cf. the second harmonic (515 nm) used. ART was found to be lower than 0.15 µm for both coatings, with certain unlinearity caused by material properties, surface roughness and the measurement devices themselves.
- It was proved by the experiment and chemical analysis that the presented method can be used for the selective de-coating of multi-layer coatings, for inspection of interlayer coatings, or for very precise laser structuring to improve coating properties. In addition, the high precision of this method can be used for complete laser stripping of coatings with little or no effect on the substrate.
- The measurement of surface roughness (Sa) on de-coated areas shows differences between both coatings and the harmonic used. For the AlTiN coating, the surface roughness decreased when removal only occurred in the coating, and increased exponentially at the interface between the coating and the substrate. For the DLC W coating, two changes were observed in the increase in surface roughness, indicating transitions in the multilayer coating. A possible next step in this research could be to investigate changes in coatings as a function of changes in surface roughness.
- Finally, a high repetition rate and scanning speed were used in the experiments presented herein, resulting in a very high process efficiency, ultimately bringing the developed method closer to industrial applications.

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Data Availability All data and materials have been published in the text of the manuscript.

Declarations

Ethical Approval Not applicable.

Competing Interests There is no conflict of interests.

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