THE EFFECT OF LASER PROCESSING PARAMETERS ON THE EFFICIENCY OF MASKING COATING REMOVAL USED IN MILITARY TECHNOLOGY

[1]Norbert RADEK, [2]Renata DWORNICKA, [3]Jacek PIETRASZEK, [4]Marcin SZCZEPANIAK, [5]Łukasz J ORMAN

[1]Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering, Kielce, Poland, EU, norrad@tu.kielce.pl

[2]Cracow University of Technology, Faculty of Mechanical Engineering, Cracow, Poland, EU, renata.dwornicka@pk.edu.pl

[3]Cracow University of Technology, Faculty of Mechanical Engineering, Cracow, Poland, EU, jacek.pietraszek@pk.edu.pl

[4]Military Institute of Engineering Technology, Wroclaw, Poland, EU, szczepaniak@witi.wroc.pl

[5]Kielce University of Technology, Faculty of Environmental, Geomatic and Energy Engineering, Kielce, Poland, EU, orman@tu.kielce.pl

https://doi.org/10.37904/metal.2026.5290

Abstract

A special group of paint systems are paint coatings for military applications, mainly for camouflaging weapon systems and military equipment. Paint coatings are fundamentals of camouflage – they camouflage vehicles/objects in the optical range, both in visible light (VIS) and in the near-infrared (NIR) range.
Numerous research centres all over the world are being involved in the studies of laser surface modification. By controlling laser parameters such as the amount of power, scanning speed, and pulse duration, it is possible to form coatings with different surface properties, including surface geometry, microhardness, stress states or resistance to wear. The paper analyzes the influence of selected parameters of laser processing on the removal of paint coatings used for the purpose of special use of armaments and military equipment. By controlling the laser processing parameters, i.e. power density, feed rate, pulse frequency and duration, the best processing conditions were selected at which masking coatings were removed. In order to clean the surface, laboratory tests were carried out to remove the paint coating using the surface layer cleaning technique using a picosecond laser TruMicro 5325c with UV radiation (343 nm). As part of the research, measurements of the surface geometric structure and as well as observations of the microstructure were made.

Keywords: Mask coating, laser processing, properties, military armament and equipment

1. INTRODUCTION

The production of protective coatings on machine parts is economically justified when their parts or surface layer is worn out and when different characteristics are required from the surface layer than from the core. Currently, there is a dynamic development of coating manufacturing with various surface engineering technologies [1], including applications in bioceramics [2] and energy [3]. This will also influence the organization of production [4,5] and logistics [6,7] for processes involving special coatings e.g. oxide coatings [8]. With particular emphasis on coatings produced by beam technologies using concentrated energy stream [9]. Varnish coating systems account for approximately 50 % of all coating systems. It is estimated that about 95 % of steel structures are protected against corrosion by protective coatings, of which as much as 90 % by paint coatings. The service life of paint coating systems ranges from several months to several years.

Camouflage is a broad concept and can include strategic, operational or direct levels. The subject of the article relates to direct camouflage, and in particular camouflage painting (permanent coating systems), which alongside ad hoc measures such as leaves, branches and camouflage coverings (camouflage nets) forms the basis of modern camouflage. It is one of the cheaper and more effective way of concealing one's own forces from the enemy and thus gain an advantage in both defence and attack. The main task of effective camouflage is to eliminate unmasking features, i.e. those that enable one's own objects to be distinguished from the background terrain, and these may include colour, shape, size, gloss, texture. On the modern battlefield, observed an increasing in the use of multispectral sensors, which enable reconnaissance in many ranges of electromagnetic radiation, but the human eye still remains the basic observation "instrument", where the visible range is assumed to be from 400 nm to 700 nm (**Figure 1**).

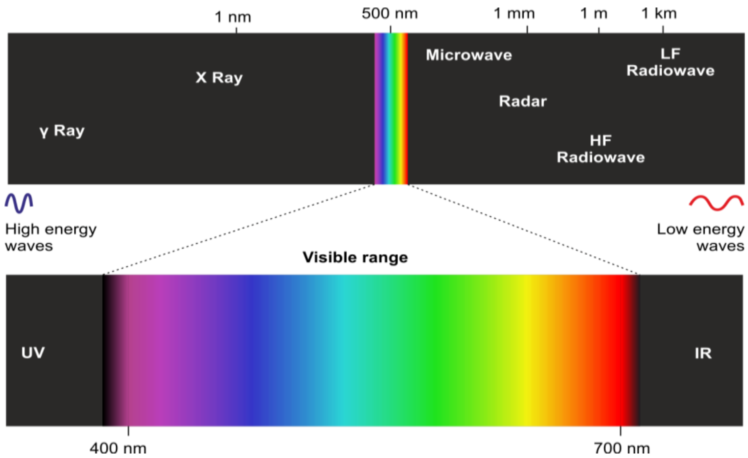

Figure 1 Diagram of the electromagnetic radiation spectrum

The removal of such specialized coatings, especially in military applications, requires high precision to avoid damaging the substrate or underlying functional layers. Conventional mechanical and chemical methods are increasingly being replaced by laser technologies due to their selectivity and environmental benefits. In particular, the use of ultra-short pulse lasers, such as picosecond sources, enables the process of 'cold ablation'. This mechanism minimizes the heat-affected zone (HAZ) and prevents thermal degradation of the remaining coating stack. Recent studies on laser decoating emphasize that by precisely tuning the laser fluence and pulse overlap, it is possible to achieve selective removal of the topcoat while maintaining the integrity of the primer layer [11]. Furthermore, the evolution of surface morphology during the ablation of multi-layer polymer systems is critical for ensuring the adhesion of subsequent camouflage layers in repair processes [12].

The article presents the results of tests on paint systems after laser cleaning intended for military applications. The current research includes analysis of the microstructure and measurements of the geometric structure of the surface.

2. MATERIALS AND PARAMETERS

Samples for the application of coatings were made of S355 structural steel with dimensions of 150 mm x 100 mm x 1 mm. The surfaces of the steel samples were polished using a rotary machine with P80 sandpaper and washed with a solvent. To prepare the surface and apply the paint systems, Festool's rotary polisher with abrasive paper from the same company, SATA GmbH & Co. KG spray guns with nozzles, and a Blowtherm spray booth were used. The cabin had the function of extracting the excess sprayed paint and was covered with foil and secured with a gel preventing dust from settling on the surface of the applied coating. In addition, it was equipped with a thermostat maintaining a constant temperature, with the possibility of increasing it to a temperature of about 60 ˚C, which is required for drying large samples. For drying smaller samples, a WKL 64/70 temperature and climate test chamber with adjustable temperature and humidity by Weiss Umwlttechnik GmbH was used. A coating system for temporary masking was applied to the prepared steel samples by hydrodynamic spraying in the following variants: epoxy primer, interlayer coating (green), masking coating (white). In the technological process, the following parameters for applying the camouflage topcoat (white paint) were used: surface temperature: 24-26 ˚C, working pressure 0.2-0.25 MPa, evaporation time in between layer application: 15 minutes, application technique: hydrodynamic spraying, no. of applications: two layers, drying temperature: 60 ˚C, drying time: 60 minutes. The remaining layers were applied following the technical data sheets provided by the manufacturer of a given paint. The following tests were performed on paint coatings: microstructure analysis and measurements of surface geometric structure.

Laser cleaning of the camouflage topcoat (white paint) was achieved with a Trumpf TruMICRO 5325c laser with average max power 5W, pulse energy up to 12.6 µJ, and beam quality M^2<1.3, maximum pulse frequency 400 kHz and 343 nm wavelength. The following variants of topcoat removal were used: 4 passes with the laser beam (A), 5 passes with the laser beam (B), 6 passes with the laser beam (C), 8 passes with the laser beam (D), 10 passes with the laser beam (E). The following parameters were assumed for the laser treatment: laser spot diameter d = 40 µm, average laser power $P_{śr}$ = 5 W, pulse energy E_i = 12.5 µJ, beam shift rate v = 500 mm/s, pulse duration t_i = 0.62 ps, frequency f = 400 kHz, laser beam stroke S = 50 µm.

3. RESULTS AND DISCUSSION

The microstructure observations were carried out using the HITACHI S-3500N (SEM) scanning electron microscope equipped with the NORAN 986B-1SPS EDS X-ray spectrometer. The SEM photograph (**Figure 2**) shows an exemplary microstructure of a coating system for temporary camouflage change. Based on the obtained results, it was found that the minimum thickness of the masking coat was approx. 125 µm, while the maximum thickness was approx. 160 µm. The SEM analysis showed that the thickness of the interlayer coating was in the range of 70÷80 µm. The epoxy primer had a thickness in the range of approx. 60 µm to 70 µm. There are clear boundaries between the individual layers (**Figure 2**). In addition, **Figure 2** shows a clear boundary between the three-layer coating system and the base material. We can also observe that varnish coatings are free of pores and microcracks.

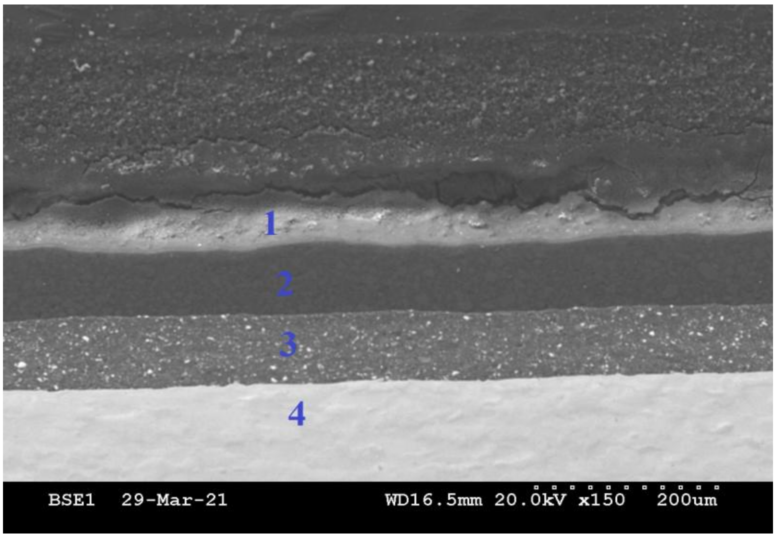

Figure 2 SEM microstructure of the cross-section of the coating system: 1 - top coat, 2 - interlayer, 3 - epoxy primer, 4 - base material (S355 steel)

Figure 3 Topcoat of the masking coating system before and after laser cleaning (variant A)

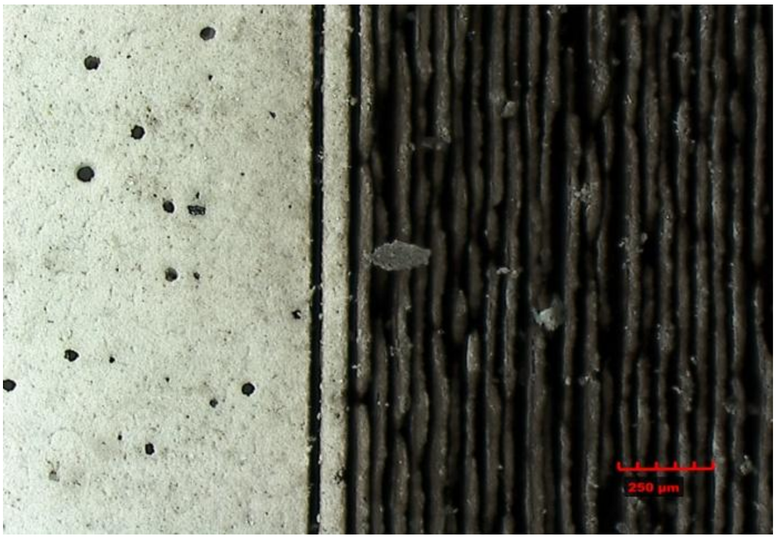

Figure 4 Topcoat of the masking coating system before and after laser cleaning (variant E)

Measurements of surface geometric structure (SGS) were carried out at the Laboratory of Computer Measurements of Geometric Quantities of the Kielce University of Technology. Measurements of surface stereometry were made using the Talysurf CCI optical profiler using the method of coherent correlation interferometry, enabling measurement with a z-axis resolution of up to 10 pm. The measurement result is saved in a matrix of 1024 x 1024 measurement points, which, with the lens used with a magnification of x50, gives the measured area of 0.33 mm x 0.33 mm and a horizontal resolution of 0.33 µm x 0.33 µm. Measurements were made using the function of numerical combination of nine measurements into a single surface (stitching). 10 measurements were made on each sample with paint systems and S355 steel, which allowed to average the test results. The analysis of the obtained surface stereometry using the TalyMap Platinium software allowed for the assessment of the geometric structure of the tested surfaces. **Figures 5** shows exemplary isometric images of the S-L surface geometrical structure (roughness) of the masking coating systems (variant A) obtained after applying the Gaussian filter 0.08 mm x 0.08 mm. **Figure 6** shows the isometric image of the wavy surface painting system (variant A). The tested coating system after laser cleaning had averaged values of the arithmetic mean deviation of the surface roughness from the average surface *Sa*=18.432-26.114 µm, while before laser cleaning *Sa*=0.748-0.893 µm. The samples of S355 steel after grinding with P80 grain sandpaper, on which the coatings were applied, had *Sa*=1.194-1.421 µm. The *Sa* parameter is the basic amplitude parameter for quantitative assessment of the condition of the analyzed surface. A similar tendency in the measurement results of paint systems and S355 steel was observed for the mean square deviation of the surface roughness *Sq*, which was characterized by a strong correlation with the *Sa* parameter. As a result of the application of the masking topcoat, the surface roughness significantly increased. Supplementary information on the shape of the surface of the tested elements is provided by the amplitude parameters: the coefficient of skewness - asymmetry *Ssk* and the coefficient of concentration - kurtosis *Sku*. These parameters are sensitive to the presence of local elevations or depressions on the surface, as well as defects (e.g. scratches, delaminations). The obtained kurtosis values close to *Sku*=3 prove that the distribution of ordinates for all samples is close to the normal distribution. Analysis of the SGS measurement results shows that only variants A, B, D have a positive value of the surface asymmetry coefficient *Ssk* (skewness), which proves that we are dealing with a surface without deep scratches. Other variants of laser processing (C and E) have negative values skewness factor. The smallest values of the *Ssk* parameter measured for the temporary masking coating system indicate numerous elevations and depressions on its surface, which is the result of the laser cleaning.

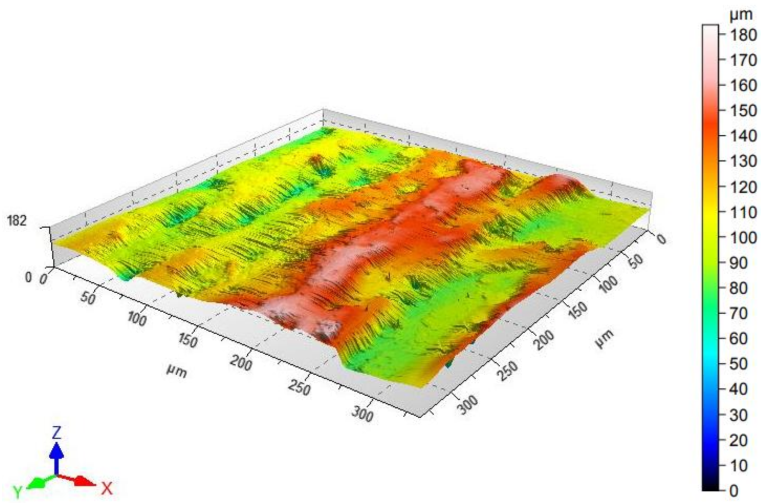

Figure 5 Isometric view of the surface roughness of paint coating systems (variant A)

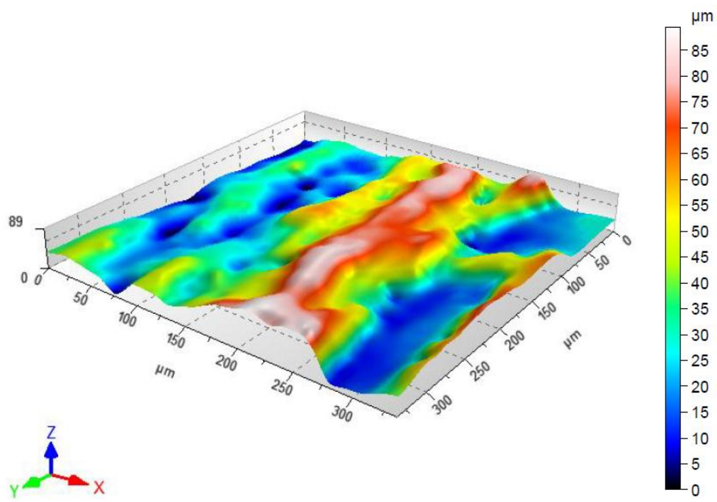

Figure 6 Isometric view of the waviness surface of paint coating systems (variant A)

4. CONCLUSIONS

The following are the conclusions drawn from the experimental data:

1. Analyzing the microstructure, it can be concluded that the thickness of the paint system is in the range of 125-160 µm. In addition, the paint system is free of pores and microcracks.
2. A very important factor affecting the geometric structure of the coating system is the proper preparation of the base material. The painting system is characterized by a lower *Sa* parameter in relation to the base material (about 2 times).
3. The high values of the slope coefficient of the surface of the *Sku* (kurtosis) indicate the low dispersion of the ordinate surfaces. The positive values of the asymmetry coefficient of the surface *Ssk* (skewness) show that making faces with a smooth surface without deep crack.

REFERENCES

[1] BURAKOWSKI, T., WIERZCHOŃ, T. *Inżynieria powierzchni metali.* Warszawa: WNT, 1995.

[2] DUDEK, A. Surface properties in titanium with hydroxyapatite coating. *Optica Applicata*. 2009, vol.39, pp.825-831.

[3] OPYDO, M., DUDEK, A., KOBYLECKI, R. Characteristics of solids accumulation on steel samples during co-combustion of biomass and coal in a CFB boiler. *Biomass & Bioenergy*. 2019, vol. 120, pp.291-300.

[4] PACANA, A., CZERWIŃSKA, K. Improving the quality level in the automotive industry. *Production Engineering Archives*. 2020, vol. 26(4), pp.162-166. https://doi.org/10.30657/pea.2020.26.29

[5] PACANA, A., SIWIEC, D. Method of Determining Sequence Actions of Products Improvement. *Materials*. 2022, vol. 15, art. 6321. https://doi.org/10.3390/ma15186321

[6] ULEWICZ, R., CZERWIŃSKA, K., PACANA, A. A Rank Model of Casting Non-Conformity Detection Methods in the Context of Industry 4.0. *Materials*. 2023, vol. 16, art. 723. https://doi.org/10.3390/ma16020723

[7] NOWICKA-SKOWRON, M., ULEWICZ, R. Quality Management in Logistics Processes in Metal Branch. In: *METAL 2015 24th Int. Conf. on Metallurgy and Materials*. Tanger, Ostrava, 2015, pp. 1707-1712.

[8] KORZEKWA, J., GĄDEK-MOSZCZAK, A., ZUBKO, M. Influence of the Size of Nanoparticles on the Microstructure of Oxide Coatings. *Materials Science*. 2018, vol. 53, pp. 709-716. https://doi.org/10.1007/s11003-018-0127-x

[9] ŻÓRAWSKI, W., CHATYS, R., RADEK, N., BOROWIECKA-JANROZEK, J. Plasma sprayed composite coatings with reduced friction coefficient. *Surface & Coatings Technology*. 202, 2008, pp. 4578-4582. https://doi.org/10.1016/j.surfcoat.2008.04.026

[10] SEE, T.L. et al. A comparison of the DPSS UV laser ablation characteristic of 1024 and H10F WC-Co. *Optics and Laser Technology*. 2017, vol. 92, pp. 101-108. https://doi.org/10.1016/j.optlastec.2017.01.018

[11] ZIVELONGHI, A. et al. Laser decoating of DLC films for tribological applications. *International Journal of Advanced Manufacturing Technology*. 2017, vol. 93(5-8), pp. 1715-1724. https://doi.org/10.1007/s00170-017-0482-z

[12] DU, R. et al. Mechanism of Continuous Laser Cleaning of Composite Paint Layers on Aluminium Alloy Surfaces. *Zhongguo Biaomian Gongcheng/China Surface Engineering*. 2025, vol. 38(4), pp. 324-334. https://doi.org/10.11933/j.issn.1007-9289.20241008001