Defence Science Journal, Vol. 74, No. 6, November 2024, pp. 857-866, DOI : 10.14429/dsj.74.19943

Adhesion Characteristics of External Protective Coatings for Combat Vehicle Bodyworks

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ABSTRACT

Special-purpose vehicles are designed to operate reliably for twenty to thirty years in a complex road, climatic, and meteorological conditions, even when stored for a lengthy period. Providing users with maximum protection against enemy paralysing agents, high off-road mobility, and dynamic driving, as well as countermeasures against the enemy, are priorities in the technology of military special-purpose vehicles. This sets high standards for protective materials, mechanical strength, and corrosion resistance used in the bodywork and interior. This article presents the results of an experimental study of the quality of external coatings on the bodyworks of special-purpose vehicles, manufactured at different intervals and operated under challenging conditions, i.e., in mountain landscapes, with large temperature fluctuations during the day and at night and under impact loads. The results presented demonstrate that the materials used for the coatings of special-purpose vehicle bodywork are of high quality and meet expectations.

Keywords: Protective coating; Non-destructive testing; Destructive testing; Special vehicle

NOMENCLATURE

σ_g	: Standard deviation of the thickness measurement
μ	: Mean thickness measurement for data set
σ	: Bonding strength
A	: Surface of the measuring die
F	: Breaking force
g_i	: Thickness of the coating at the i-th point of the surface
n	: Number of measurements
IFV	: Infantry fighting vehicle
MPV	: Multi-purpose vehicle

1. INTRODUCTION

The paper presents the results of selected experimental studies on the quality of external coatings of bodyworks of special-purpose (military) vehicle used in complex operating conditions: terrain, climate, meteorological, and mechanical hazards. External coatings of metallic structures are essential elements that affect their durability, reliability, safety, and service life. In the literature, problems related to the external surface coatings of various structures are described in a very wide range from many different points of view. The results of adhesion tests of acrylic coatings on steel substrates are presented in the article[1]. The conclusion of the research is that there is a significant influence of the surface roughness of the substrate on the strength of its adhesion to the acrylic coating. In[2], the dependence of adhesion and protection on the surface properties of the epoxy primers, aged and unaged prior to the application of the polyurethane topcoat was investigated. It was found that the adhesion of polyurethane systems to aged epoxy is highly dependent on the degree of deterioration of the epoxy interlayer and the value of the internal stress created. Current and future industry trends and innovations in automotive and aerospace materials, along with their protective coatings, are highlighted in the monograph[3]. The paper reviews current developments in coating technology and materials and outlines future trends. A vehicle metastructure coating designed to achieve microwave absorption across the area in civil and military applications is described in[4-5]. A coating for vehicle metasurfaces was proposed to help maintain a smooth surface for improved aerodynamics without compromising the wide-area absorbing performance, which hinders vehicle detection. The study focused on improving both the mechanical durability of coatings and the camouflage capability of military technology was the main topic in[6]. Graphene or graphene oxide was added to the paints. The study showed some increased mechanical durability, but also increased infrared emissivity. Camouflage has attracted a growing interest in thermal applications. In[7] authors proposed a coating solution to demonstrate high-temperature IR camouflage with efficient thermal management. The proposed solution offers transparency in the visible range and high reflection in the whole IR EM spectrum, i.e., low emittance.

The monitoring of a military vehicle coating under exposure to prohesion by embedded sensors according to an established test is presented in the study[8]. The test consists of alternating exposure to wet for 1 hr in salt spray at 25 °C and exposure to dry conditions for 1 hr in air at 35 °C. In addition to visual inspection, ex situ electrochemical testing through

Received : 22 February 2024, Revised : 11 July 2024
Accepted : 23 August 2024, Online published : 25 November 2024

immersion in a suitable electrolyte is used for conventional monitoring of coating properties. In situ monitoring was conducted during the Prohesion® test for the military vehicle coating system using embedded sensors placed between the topcoat and the undercoat. Furthermore, ex situ monitoring was performed to compare with in situ embedded sensor monitoring.

In[9], the mechanisms of interfacial adhesion in metal and polymer-based composites are described. Hybrid materials with thermoplastic polymer composites in combination with metals are increasingly being used as structural materials in military and commercial transport vehicles. The effect of surface treatment to improve adhesion between organic polymers and steel reinforcement was the focus of the study. The results indicate that the polar groups and free radicals were used to improve the adhesion between the thermoplastic polymer and the metal surface. The authors of the paper[10] conducted laboratory and field tests on a substitute for a protective primer, an electroactive polymer for the coating of military vehicles. Its adhesion and anticorrosion properties were evaluated when applied to steel and aluminium alloys. It was confirmed that the polymer met military requirements in combination with the primer and coating. Field tests have shown that the polymer incorporated into the military coating survived without delamination, with minor corrosion occurring at the spallation points. The adhesion strength of the coatings to different types of primers that were subjected to salt spray and cyclic freeze-thaw cycles was determined and compared. Most of the damage appeared to be due to the poor cohesive or adhesive strength of the zinc-rich primer. In[12], three polyurethane coatings were evaluated using dynamic mechanical analysis to investigate the relationship between dynamic mechanical properties and the durability properties of coated panels. Dynamic mechanical analysis studies showed that a longer curing time at the ambient temperature (6 months or more) could have a negative effect on the mechanical properties of the solvent-based system and could potentially affect the chemical resistance of the water-reducible coating.

Digital camouflage painting of special vehicles[13]. The proposed solution showed that, compared to the traditional spray tool, the strip nozzle can better ensure the uniformity of the film thickness of the digital camouflage spray. The results show that the proposed models are not only effective but also meet practical industrial requirements and are of great practical value, according to a practical spraying experiment.

The available literature provides limited information on the mechanical properties of external coatings on special vehicle bodies. The presented research supplements the knowledge in this area.

The objective of the study is to evaluate the quality of the coatings used in the modern military vehicles. The tests were carried out to the extent allowed by the operator of the equipment. Breaking the structure by cutting and unsealing samples was prohibited. Destructive tests were limited to those that did not require interference with the hull structure, so that the original condition of the hull could be reconstructed after testing.

To achieve research objectives, a multi-phase study was designed and conducted:

- First phase (non-destructive testing) was to determine and compare the thickness of the coating that protects various vehicle hulls;
- Second phase (destructive testing) was to determine the adhesion of the protective coating in terms of standardised cross hatch method;
- Third phase (destructive testing) was to determine bonding strength between the coating and the substrate or between individual coatings of the protective coating was in terms of the standardised pull-off method.

2. EXTERNAL EXPOSURE FACTORS

The technical durability and reliability of special-purpose vehicles over an assumed service life of 25-30 years, and sometimes even longer, is one of the most important requirements in their design. They are subject to high dynamic loads due to the tasks they are expected to perform. However, the mechanical effects on the paint finish of the self-supporting bodywork, the effects of the corrosive environment, and the

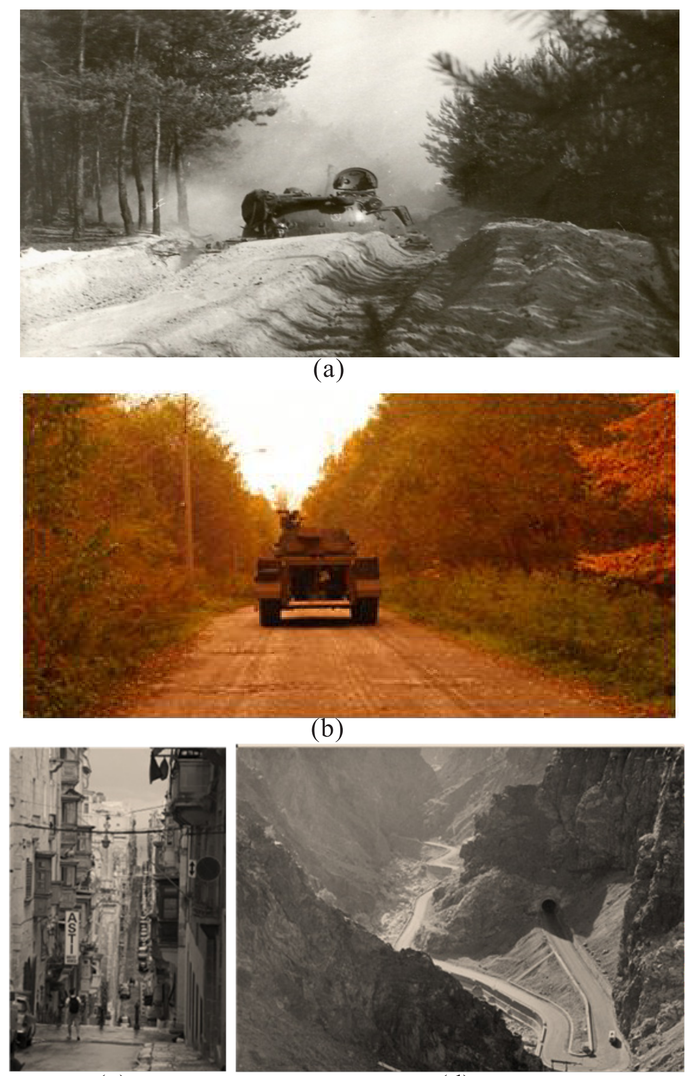


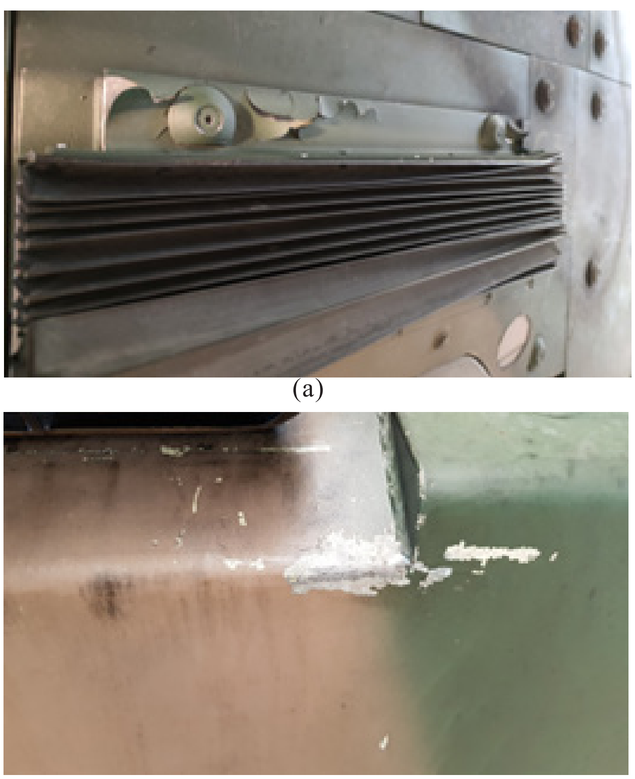
Figure 1. Operating conditions that can cause mechanical damage to special bodywork coatings.

climatic and meteorological conditions are also significant. These affect the quality of camouflage. Mechanical factors that may cause potential paint damage are: a) substrate (i.e., dust, stones, branches) – Fig. 1(a)(b) driving in densely wooded areas – Fig. 1(b)(c) driving in densely built-up urban areas - Fig. 1(c); driving in mountain terrain (e.g. falling stones) – Fig. 1(d).

Special purpose vehicles are in use for a variety of operations, not only in the country, but also abroad, including on other continents. In such cases, they are transported by sea[14], where they are exposed to corrosive environments (Fig. 2).

Complex operating conditions and the effects of numerous factors sometimes cause vehicle coatings to deteriorate or become damaged. Some of these are shown in the Fig. 3.

Figure 2. Military maritime transport[14].



(a)

(b)

Figure 3. Damage from vehicle use; (a) peeling; and (b) mechanical damage.

It should be noted that the vehicles under consideration must be designed to operate in extremely difficult conditions. They must be able to continuously, from equatorial to arctic climates, and under all meteorological conditions. The hulls of these vehicles should also have camouflage features. To meet extreme requirements, vehicles must be equipped with high-quality protective systems. That includes a special camouflage paint geometry that makes it difficult to identify the vehicles by, for example, radio waves.

As a result of the considerations, it is evident that the bodywork coating of the vehicles under analysis must satisfy a range of complex criteria. These criteria include:

- Quick and easy application to metals, plastics, rubber, and other paints;
- Quick drying after applying;
- High adhesion to the bodywork surface;
- Good protection of the surface against corrosion;
- Resistance to rain, hail, snow and abrasion by tree limbs, stones, etc.;
- Non-toxicity;
- Incombustibility;
- Having radiation absorbing (scattering) properties.

3. METHODOLOGY

Multi-phase testing, both non-destructive and destructive one, was planned. The purpose of the non-destructive tests was to determine the thickness of the coatings that protected the hull of the vehicles. The purpose of destructive tests was to determine the quality of the protective coating. The coating is a multi-layer structure consisting of the following elements: substrate, primer, interlayer and top layer. In the second phase, two types of destructive tests were conducted: a single-stage test to determine the quality of the protective coating application using a cross hatch test and a multi-stage test using the pull-off method.

3.1 Non-Destructive Testing

Measurements were taken using a Blue Technology MGR-11-S-AL coating thickness gauge. The gauge was equipped with a flat probe on a cable. This gauge measures the thickness

Figure 4. MGR-11-S-AL coating thickness gauge.

of the paint film on steel and aluminium substrates with an accuracy of 10 µm, with the type of substrate automatically detected. The accuracy of the readings can be self-checked using the supplied calibration plates. A view of the gauge is shown in the Fig. 4.

Three measurements were taken at four points located at the corners of the rectangle, with each side not exceeding 100 mm, for each bodywork section under consideration. The Tables 1-5 show the results of the measured values of the paint film thickness of the vehicle bodyworks tested and the calculated standard deviations σ in accordance with the Eqn. (1).

$$g = \sqrt{\frac{\sum_{i=1}^{n}(g_i - \ )^2}{n}} \quad (1)$$

where: µ - mean value of the coating thickness from the measurements in the examined area, g_i – thickness of the coating at the i-th point of the surface, n - number of measurements in the examined area.

3.2 Destructive Testing

One of the most important properties and critical factors in the durability of exterior bodywork coatings is adhesion. Two methods, the cross hatch method and the pull-off method, were used to test the adhesion of the coating.

3.2.1 Cross Hatch Method

This method is used for coatings with a thickness of up to 250 microns. The tests were conducted using a set of knives with multi-cutter wheels. A perpendicular grid of notches was made in the coating up to the substrate. The blades used to make the grid have six parallel blades, the distance between the blades depending on the thickness of the coatings being tested. Figure 5 shows a set of test devices and a view of the knife used directly in the test. The view of the cracked edges of the cuts and the detachment of the coating from the individual segments was visually assessed according to the standards[15-18].

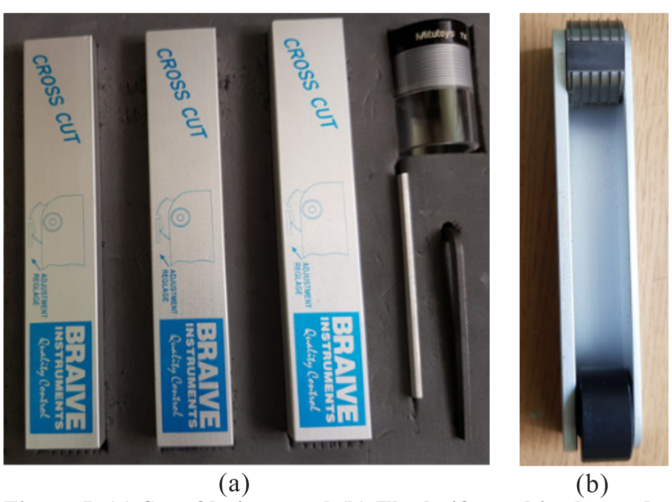


Figure 5. (a) Set of knives; and (b) The knife used in the study.

3.2.2 Pull-off Method

Adhesion tests were performed on the outer surface of the special-purpose vehicle using the pull-off method with the Elcometer 106/4. Figure 6 shows a view of the pull-off adhesion tester. The device measurement range is 0-22 N/mm^2 (0-22 MPa) and a die diameter of 20 mm. The test procedure was conducted according to the standards[19] recommendations. The tests were carried out outdoors (field tests), in the first phase at the ambient temperature of 20 °C and humidity of 55 %, and in the second phase at the ambient temperature of 28 °C and humidity of 31 %.

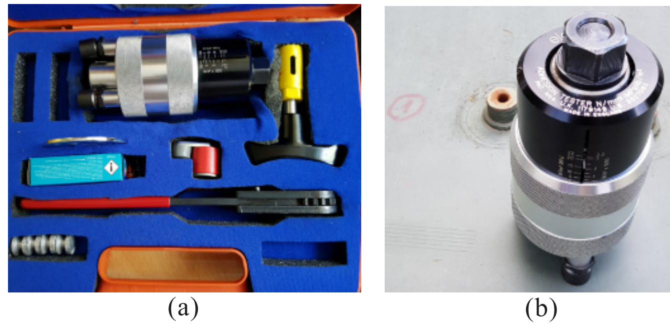


Figure 6. (a) Elcometer 106/4 tester with accessory; and (b) Tester before adhesion test.

The measure of adhesion of the coating to the bodywork is the lowest tensile stress that causes the weakest boundary surface (adhesive), or the weakest point of the tested coating system (cohesive) to break[18]. During tests, both types of debonding may occur simultaneously. The test result shall be the value of the tensile stress and the area (in %) of each type of detachment.

The adhesive bond strength of the coating to the substrate shall be calculated for the entire die area[19] according to the Eqn. (2) as follows:

$$\sigma = \frac{F}{A} \quad (2)$$

where:

F – breaking force [N]; A –surface of the measuring die [mm^2]; σ – bonding strength between the coating and the substrate [MPa].

3.3 Research Objects

The measurements of the paint coatings on the bodyworks of special-purpose military vehicles were made. These are the Vehicle 1 - 8x8 wheeled vehicle hull; the Vehicle 2 - medium

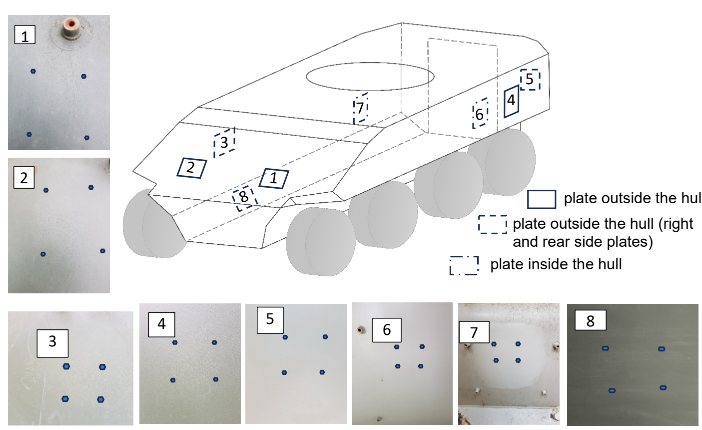


Figure 7. Distribution of the measurement areas and the points within them for the Vehicle 1.

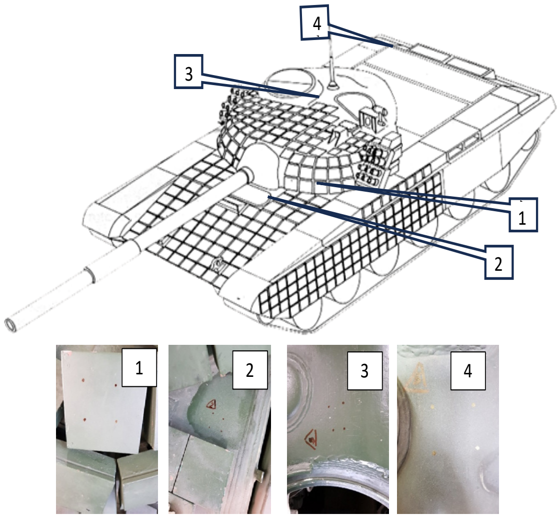


Figure 8. Distribution of the measurement areas and the points within them for the Vehicle 2.

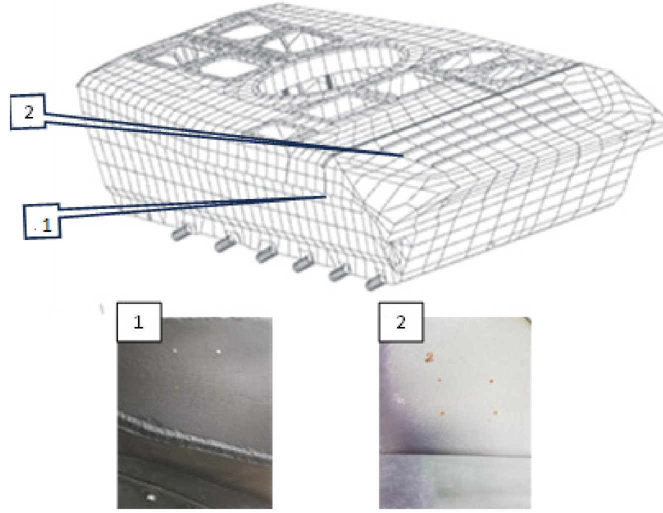


Figure 9. Distribution of the measurement areas and the points within them for the Vehicle 3.

Table 1. Summary of the coating thickness measurements [µm] for the measurement areas of the Vehicle 1

Area	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
x̄ ± SD	216.7±16.1	225.8±10.0	175.8±7.4	214.2±9.2	174.2±5.0	220±14.2	160±11.5	133.3±2.7
Point	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD
1	193.3±5.8	236.7±5.8	173.3±5.8	223.3±5.8	170±0.0	203.3±5.8	170±0.0	133.3±5.8
2	230±10.0	213.3±5.8	173.3±5.8	203.3±5.8	176.7±5.8	230±0.0	150±10.0	130±0.0
3	223.3±5.8	223.3±5.8	186.7±5.8	210±10.0	170±0.0	233.3±11.5	150±0.0	133.3±5.8
4	220±0.0	230±0.0	170±5.8	220±0.0	180±0.0	213.3±5.8	170±0.0	136.7±5.8

Table 2. Summary of the coating thickness measurements [µm] for the measurement areas of the Vehicle 2

Area	**1**	**2**	**3**	**4**	**5**
x̄ ± SD	395.0±16.0	425±25.7	289.2±15.0	194.2±6.8	375.0±20.4
Point	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD
1	410±0.0	453.3±11.5	310±10.0	193.3±11.5	376.7±5.8
2	406.7±5.8	440±17.3	280±0.0	193.3±5.8	360±10.0
3	386.7±25.2	400±17.3	276.7±11.5	186.7±11.5	403.3±25.2
4	376.7±11.5	406.7±20.8	290±0	203.3±5.8	360±0.0

tracked vehicle hull and bodywork panels; the Vehicle 3 - light tracked vehicle hull (IFV); the Vehicle 4 - light tracked vehicle hull (MPV); the Vehicle 5 - 4x4 vehicle bodywork.

Figure 7 shows the location of the measurement areas in the self-supporting bodywork of the 8x8 vehicle (1st vehicle). Figure 8 shows the location of the measurement areas of the Vehicle 2 and the Fig. 9 shows the location of the measurement areas of the Vehicle 3.

Table 3. Summary of the coating thickness measurements [µm] for the measurement areas of the Vehicle 3

Area	1	2
x̄ ± SD	258.3±5.8	266.7±13.0
Point	x̄ ± SD	x̄ ± SD
1	253.3±5.8	250±0.0
2	256.7±5.8	280±0.0
3	266.7±5.8	273.3±5.8
4	256.7±15.3	263.3±5.8

In the case of the Vehicles 4 and 5, coating thickness measurements were taken on their bodyworks in areas like the Vehicle 3, i.e. front and side faces. Mechanical hazards are more likely to occur in these areas.

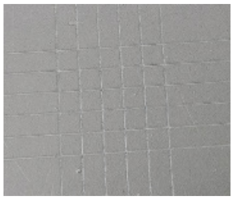
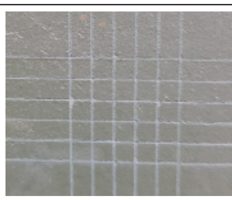
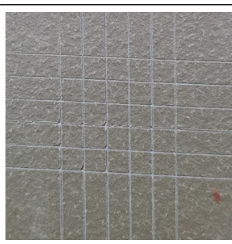
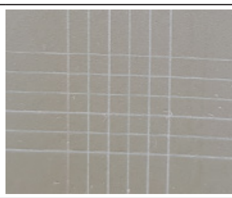
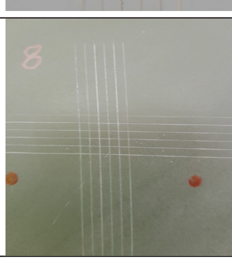
4. RESULTS AND DISCUSSION

The areas of the vehicle selected for coating testing were

Table 4. Summary of the results of the coating thickness measurements [µm] in the specified areas of the Vehicles 4 and 5

	Vehicle 4		**Vehicle 5**	
Area	**1**	**2**	**1**	**2**
x̄ ± SD	344.2±38.3	338.3±17.6	353.3±22.3	475.8±23.3
Point	x̄ ± SD	x̄ ± SD	x̄ ± SD	x̄ ± SD
1	300±52.0	356.7±11.5	343.3±5.8	480±10.0
2	390±0.0	323.3±5.8	343.3±5.8	463.3±5.8
3	356.7±5.8	323.3±5.8	340±0.0	506.7±5.8
4	330±10.0	350±0.0	386.7±5.8	453.3±15.3

Table 5. Summary of the results of the adhesion test of the coating by means of the notch grid method

Surveyed region	View of notch grid	Description of visual inspection of the notch grid of the coating	Degree of adhesion
1		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
2		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
3		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
4		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
5		No peeling off the coating, smooth cut edges	1
6		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
7		Slight peeling of the coating from the substrate at the edges of the notches does not exceed 5 % of the area of the notched mesh.	2
8		No peeling off the coating, smooth cut edges	1

those that, in the authors' opinion, were the most exposed to external influences. The tests were conducted in two stages, non-destructive and destructive ones.

Non-destructive coating tests were conducted on the Vehicles 1-5 (wheeled and tracked special-purpose military vehicles). The thickness of the coating varied between 133 and 225 µm, depending on the area examined. The standard deviation did not exceed a value of 16.1. The results of the thickness measurements for the Vehicle 1 are summarised in the Table 1.

In the case of the Vehicle 2, the coating thickness varied between 194 and 395 µm, depending on the area examined. The standard deviation did not exceed a value of 25.7 µm. The results of the thickness measurements for the Vehicle 2 are summarised in the Table 2.

In the case of the Vehicle 3, the thickness of the coating was approximately 260 µm. The standard deviation did not exceed a value of 13. The results of the thickness measurements for the Vehicle 3 are summarised in the Table 3.

In the case of the Vehicles 4 and 5, the coating thickness exceeded 300 µm. The standard deviation did not exceed a value of 28.3 µm. The results of the thickness measurements for the Vehicles 4 and 5 are summarised in the Table 4.

For all vehicles, the average thickness of the coating in the areas examined is greater than 170 µm, which is an indication of two layers covering the individual bodies. It is noticeable that in the tested areas there are thickness differences at the measuring points (even several percent). This is a result of the geometry of the coated surface. This should not be interpreted negatively, as in addition to camouflaging against detection, it may scatter or absorb radiation from external radio and optoelectronic devices. In vehicles 2 to 5, the thicknesses are much greater, so it can be assumed that there are several layers of paint in addition to the primer. Therefore, the Vehicle 1 was further investigated.

Table 6. Summary of the results of the external coating adhesion test

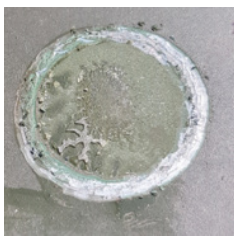
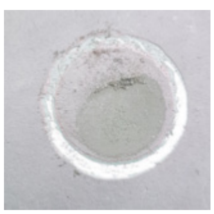
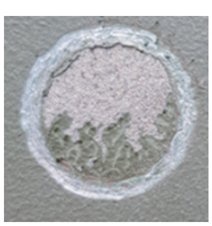
Surveyed region	View of the test footprint	View of the die stamp after the test	Breaking strength [MPa] type of fracture
1			4.5 60 % B, 40 % Y cohesion
2		No photo available	4.5 40 % B, 60 % -/Y cohesion
3			2.5 60 % B, 40 % Y cohesion
4			2.5 80 % B, 20 % Y cohesion
4'			2.5 70 % B, 30 % Y cohesion

Table 7. Summary of the results of the interlayer adhesion test

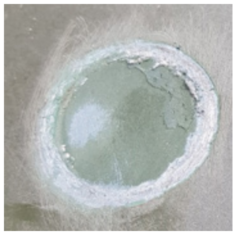
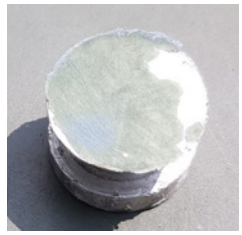
Surveyed region	View of the test footprint	View of the die stamp after the test	Breaking strength [MPa] type of fracture
1			2.5 30 % B/C, 50 % Y, 20 % Y/Z adhesion
2			3 90 % B/C, 10 % Y/Z adhesion

Table 8. Adhesion test of the primer coat

Surveyed region	View of the test footprint and die stamp (P) after test	Breaking strength [MPa] type of fracture
P		4.5 50 % B, 50 % Y/Z cohesion

Destructive tests were conducted on the Vehicle 1, which had been removed from service after intensive use under varied and complex conditions, characterised by a high temperature gradient, humidity, dynamic loads, and exposure to mechanical damage to protective coatings. However, it is still used as a training vehicle. Interfering with its structural integrity, such as cutting out samples for testing, was not feasible.

The coating is a multi-layer structure consisting of the following elements: substrate, primer, intermediate and top layer. The primer is epoxy, and the top layer is polyurethane. Protective coatings are applied to the hull surfaces by spraying. Large parts are applied pneumatically, while smaller parts are applied hydrodynamically. The process starts with shot blasting. A zinc and epoxy primer is then applied to the steel components, followed by light grinding top layer is applied. All products used for coating (NOVOL, Barwa) and technological processes comply with the NO-80-A200 normative document. During the process, the joints are sealed with a sealant, while the profiles are sealed with a special profile compound.

The cross hatch method was used in the second phase of the single-stage study. In most of the areas tested, the peel was marginal, and the peel size did not exceed 5%. The degree of adhesion was described as good or very good. The detailed results are summarised in Table 5.

Several pull-off tests were conducted in the third phase. Examining the outer layer was the first step. The scale of the photographs is not the same for the footprint and stamp views. The results of the first step are summarised in the Table 6. Tensile strength values were in the range of 2.5 to 4.5 MPa. Cohesion was found to be the main mechanism that prevents delamination. Increased external adhesion values of coatings are found on the hull surfaces that are most exposed, for example, when driving through clumps of bushes, breaking through copses, hitting gates, fences, and ramming natural or artificial barricades. Examining the inner layer was the second step. Tensile strength values were in the range of 2.5 to 3 MPa. Adhesion was found to be the main mechanism that prevents delamination. The results of the second step are summarised in Table 7. Examining the primer coat was the third step. The tensile strength was 3 MPa and cohesion was found to be the main mechanism of delamination. The third step result is shown in the Table 8.

Adhesion tests according to the methods used and the results obtained confirm that the type of coating chosen and the method of applying it to the surfaces of the special-purpose vehicle were conducted correctly.

5. CONCLUSIONS

As a result of the tests, it was found that when measuring the thickness of the coating, the differences in thickness at the measuring points were as follows:

- 16.1 % for the Vehicle 1;
- 25.7 % for the Vehicle 2;
- 13 % for the Vehicle 3;
- 38.3 % for the Vehicle 4;
- 23.3 % for the Vehicle 5.

Adhesion tests on paints showed the following:

- Tests with the cross hatch method - in most cases the degree of adhesion according to[18] is 2, and in some cases, it is higher and is 1, indicating a good or very good adhesion;
- Pull-off test - the adhesion value ranges from 2.5 to 4.5 MPa. Peeling of the stamp coating was observed mainly in the first layer.

Due to the nature of the vehicle, the test results presented are qualitative and not quantitative.

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ACKNOWLEDGEMENT

This work was financed/co-financed by Military University of Technology under research project UGB 22-832/2023.

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