photonics

Article

# Study on the Technology and Mechanism of Cleaning Architectural Aluminum Formwork for Concrete Pouring by High Energy and High Repetition Frequency Pulsed Laser

**Kun Gao [1,2], Jinjun Xu [1,2], Yue Zhu [1], Zhiyan Zhang [3,*] and Quansheng Zeng [1,2,*]**

[1] Aviation Mechanical and Electrical Equipment Maintenance College, Changsha Aeronautical Vocational and Technical College, Changsha 410124, China
[2] Aircraft Coating and Structural Repair Laboratory, Hunan Aircraft Maintenance Engineering and Technology Research Center, Changsha 410124, China
[3] Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
* Correspondence: zyzhang@semi.ac.cn (Z.Z.); zqs_csgx@163.com (Q.Z.)

**Abstract:** In the field of construction, the surface of architectural aluminum formwork for concrete pouring will remain the concrete adhesion layer of heterogeneous composite structures. In view of the difficulty of removing the concrete adhesion layer, we studied the technology and mechanism of removing the concrete adhesion layer by laser cleaning technology in this paper. We analyzed the composition and distribution characteristics of residual concrete on the surface of architectural aluminum formwork, set up a laser cleaning test system, carried out laser cleaning experiments on the concrete layer on the surface of architectural aluminum formwork under different storage times, and analyzed the mechanism of removing the concrete adhesion layer by laser cleaning. The experimental results showed that the residual time of concrete will affect the quality and efficiency of laser cleaning concrete residue on the surface of architectural aluminum formwork for concrete pouring. For concrete residues with short residual time, lasering can achieve efficient and high-quality cleaning. A nanosecond pulsed laser could strengthen the surface hardness of the aluminum alloy template during cleaning, which is helpful in improving the durability of the aluminum alloy template. The main mechanisms of laser cleaning to remove the concrete adhesion layer on the surface of architectural aluminum formwork is that the bubbles and water bubbles in the loose structure of concrete instantly absorb high-energy laser and make the concrete aggregate continuously air-burst. This paper provides technological and theoretical support for the application of laser cleaning technology to remove residual concrete on the surface of architectural aluminum formwork for concrete pouring in the field of construction.

**Keywords:** architectural aluminum formwork; concrete adhesion layer; laser cleaning; cleaning mechanism; process experiment



**Citation:** Gao, K.; Xu, J.; Zhu, Y.; Zhang, Z.; Zeng, Q. Study on the Technology and Mechanism of Cleaning Architectural Aluminum Formwork for Concrete Pouring by High Energy and High Repetition Frequency Pulsed Laser. *Photonics* **2023**, *10*, 242. https://doi.org/10.3390/photonics10030242

Received: 12 January 2023
Revised: 13 February 2023
Accepted: 20 February 2023
Published: 22 February 2023



## 1. Introduction

In the construction of concrete pouring, aluminum alloy formwork has the advantages of a beautiful appearance, high quality, low average single use cost (more than 300 times of reuse), and greatly shortening the construction period. It has become a representative green infrastructure method with low consumption, environmental protection, economy, and practicality, and is widely used in construction engineering [1,2]. However, due to the strong adsorption and poor ductility of aluminum alloy formwork, it is difficult to remove the residual concrete attached to its surface after construction. Traditional methods [3] such as vibration, pickling soaking, shot blasting, and high-pressure water abrasive washing will damage the surface of the aluminum alloy template, reduce the service life, and also produce a lot of dust and waste liquid, resulting in serious pollution. Therefore, we need an environmentally friendly and convenient cleaning method for residual concrete on the surface of aluminum alloy formwork. It is of great significance to improve the efficiency and quality of construction projects, and to eliminate pollution.

Laser cleaning has been widely used by people since its birth. It has the advantages of being green, having high efficiency, and being easy to control [4]. Since the 1980s, laser cleaning has been successfully applied to the cleaning of dirt on the surface of cultural relics and statues, such as marble, murals, buildings, etc. [5]. In recent years, it has solved the problem that it is difficult to remove tiny contaminated particles with strong adsorption on the mask surface [6] in the field of semiconductor precision manufacturing.

The preferred light source for laser cleaning is a high energy (10–500 mJ) and high repetition frequency (kHz) nanosecond (10–100 ns) pulse laser. This is because the nanosecond narrow pulse width laser acting on the pollutant surface can reduce the heat conduction caused by heat accumulation and avoid excessive temperature rise of the substrate [7–9]. The high repetition frequency pulse acts on the surface of the pollutant, which causes the pollutant to quickly reach the separation and removal threshold, and improves cleaning ability and efficiency [10–12]. High-energy laser pulses can use large focused light spots (400–2000 µm) to remove pollutants, it is beneficial to protect the substrate from damage and reduce the difficulty of cleaning process parameters control.

In recent years, with the rapid development of high-energy and high-repetition frequency nanosecond pulse lasers, the laser cleaning efficiency has been greatly improved, and the application field has been expanding. It has been applied in the fields of mold cleaning, metal welding seam de-gluing, and oxide film removal [13,14], as well as aircraft parts and complete machine paint removal [15,16], warship rust removal [17–19], etc. Traditional cleaning methods are being gradually replaced.

Based on the above background and the development status of laser cleaning technology, laser cleaning technology is applied in the field of construction. In this paper, the laser cleaning technology and mechanism of cleaning the concrete adhesion layer on the surface of aluminum alloy formwork for concrete pouring are studied.

The concrete residue attached to the surface of aluminum alloy formwork is a multi-component mixed structure composed of coarse and fine aggregate (stone, sand) and hydration products of cement. The structural characteristics of the cleaned concrete should be fully considered in the process experiment and mechanism analysis, which are different from the traditional stress stripping and gasification by ablation. Firstly, we analyze the morphology characteristics of the concrete adhesion layer on the surface of aluminum alloy formwork and classify it according to the thickness of the adhesion layer. Secondly, we built a high-energy and high-frequency nanosecond laser cleaning system for aluminum alloy formwork and carried out laser cleaning experiments on concrete adhesion layers with different thicknesses and different residual times. Finally, the cleaning results and the laser cleaning mechanism of concrete with multi-component hybrid structure are analyzed and studied.

## 2. Characteristic Analysis of Residual Concrete on the Surface of Aluminum Alloy Formwork

After the concrete is poured and the mold removal condition is reached, a certain amount of residual concrete layer will be attached to the surface of the aluminum alloy formwork. It is very important to analyze the microstructure and distribution of the concrete residue layer to study the laser cleaning mechanism of aluminum alloy formwork surface concrete, formulate the process method, and clarify the process parameters.

### *2.1. Concrete Composition*

As shown in Figure 1a, from the macroscopic point of view, concrete is a heterogeneous composite structure. It is mainly composed of coarse and fine aggregates (stone, sand) and hydration products of cement. Aggregate accounts for about 70% of the total volume, cement slurry accounts for about 25%, and there are about 5% pores containing water and gas. The quality characteristics of concrete mainly depend on the properties and relative content of aggregate and cement slurry, and the bonding strength of the interface between aggregate and cement. From the submicroscopic point of view, due to the aggregate gap and "bleeding" caused by particle gradation, there are a large number of porous (30–60 μm) and loose interfacial transition zones between aggregate and mud. As shown in Figure 1b, there are micro-cracks and voids containing a lot of water and air in this area, which is the weak link of concrete strength [20].

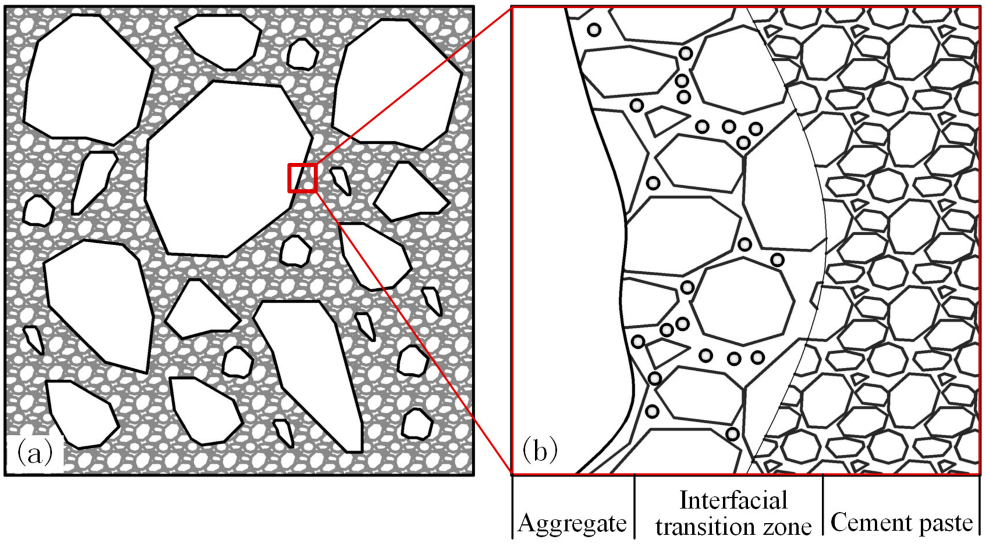


**Figure 1.** Composition of ordinary concrete structure (**a**) macrostructure; (**b**) submicrostructure.

### *2.2. Characteristics of Residual Concrete on the Surface of Aluminum Alloy Formwork*

The aluminum alloy formwork material commonly used in the construction field for concrete pouring is 6061-T6. The attached concrete is the cement cementitious material and sand aggregate naturally attached during disassembly. The physical properties of the two materials are shown in Table 1. As shown in Figure 2, after the aluminum alloy formwork is removed, the coarse aggregate with a larger particle size is left in the pouring wall or falls off with the removal of the aluminum alloy formwork, while the fine gravel is attached to the surface of the aluminum alloy formwork under the action of cement bonding force.

In this paper, according to the distribution of concrete adhesion layer and mud thickness on the surface of aluminum alloy formwork, the disassembled aluminum alloy formwork surface can be divided into three cases: bare area (residual concrete thickness 10~30 μm), thin slurry area (residual concrete thickness 30~100 μm), and thick slurry area (residual concrete thickness >100 μm). The bare area is mainly composed of isolation glue and dust. There are clear boundaries between each area, as indicated by the yellow arrow in Figure 2.

**Table 1.** Physical performance parameters of architectural aluminum formwork and its attached concrete.

| Materials | Elastic Modulus (MPa) | Coefficient of Linear Expansion ($K^{-1}$) | Poisson's Ratio ($\upsilon_a$) | Thermal Diffusivity ($m^2/s$) | Thermal Conductivity (W/(m·K)) | Melting Point (°C) |
|---|---|---|---|---|---|---|
| Aluminum formwork 6061-T6 | $7 \times 10^4$ | $23 \times 10^{-6}$ | 0.3 | $2.3 \times 10^{-5}$ | 155 | 580~650 |
| Concrete C15~C80 | $2.20$~$3.80 \times 10^6$ | $4.76$~$12.1 \times 10^{-6}$ | 0.2 | $1.34 \times 10^{-3}$ | 1.28 | 1800~2500 |

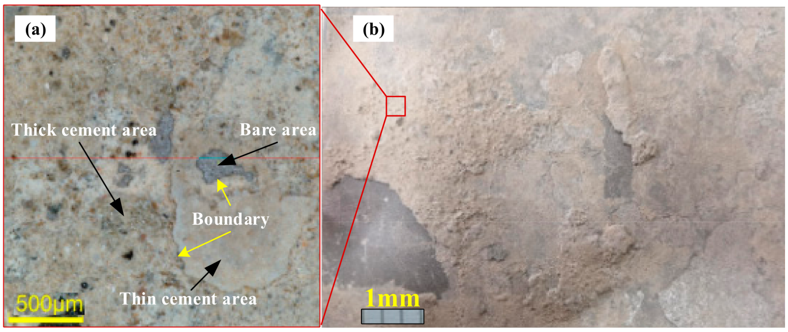


**Figure 2.** Morphology characteristics of concrete adhered to the surface of aluminum formwork (**a**) microstructure; (**b**) structure.

## 3. Laser Cleaning Experiment of Residual Concrete on Aluminum Alloy Formwork Surface

### 3.1. Laser Cleaning Experiment and Testing System

As shown in Figure 3, the laser wavelength of the laser cleaning experimental system is 1 μm, the maximum output power is 600 W, the output frequency is continuously adjustable from 20 kHz to 50 kHz, the pulse width is 100 ns, the maximum single pulse energy is 30 mJ@20 kHz, the diameter of the tail fiber core for laser flexible transmission is 400 μm, and the numerical aperture is 0.2. The two-dimensional motion platform is used to drive the aluminum alloy formwork to translate at a fixed speed, and the positioning accuracy is less than ±20 μm. The paint film thickness gauge (QNIX, 4500, Manufactured by QuaNix in German) is used to detect the thickness of residual concrete on the surface of the aluminum alloy formwork. The measuring range is 0~3000 μm, and the accuracy is ±(3% + 2) μm. The surface cleanliness of aluminum alloy formwork after cleaning is tested by Olympus Digital Microscopy system (OLYMPUS, DSX1000, version: 1.2.2.36). The surface hardness of aluminum alloy formwork after cleaning is tested using an indentation Wechsler hardness tester (HV-1000Z); the measuring range is 0~3000 HV. To accurately detect the change in the thickness of the concrete layer on the surface of the aluminum alloy formwork before and after cleaning, we install a positioning fixture on the moving platform to ensure the positioning accuracy of the repeated installation of the aluminum alloy formwork. The thickness gauge is fixed on the guide slider. It can move along the guide rail perpendicular to the truss to measure the thickness of the concrete layer on the surface of the aluminum alloy formwork.

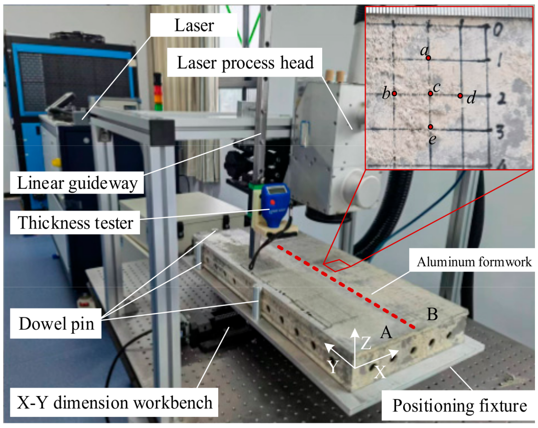


**Figure 3.** Laser cleaning test and detection system.

### 3.2. Experimental Sample

In this paper, the laser cleaning experiment is carried out by using the planar aluminum alloy formwork with a concrete layer attached to the surface. The grade of aluminum alloy formwork material is 6061-T6, the size specification is 650 × 300 × 65 mm (L × B × H), and the type of residual concrete on the surface of aluminum alloy formwork is C30.

### 3.3. Experimental Method

First of all, in order to fully simulate the actual working conditions, the aluminum alloy formwork is divided into two areas, and concrete samples with different residual time are respectively prepared. As shown in Figure 3, the residual time of the concrete residue on the surface of the aluminum alloy formwork in area A is 72 h, and that of concrete residue in area B is 4 weeks.

Secondly, the test area of the residual concrete on the surface of the aluminum alloy formwork is gridded, and the grid size is 10 mm×10 mm. Each grid is numbered and the coordinate direction is marked to form a cleaning interval with three different types of residual concrete layers: thick, thin, and bare. After each positioning, we timely measure and record the height values of four coordinate points a, b, d, and e before and after laser cleaning. The four measuring points are near the center point c, as shown in the aluminum alloy template in Figure 3.

To achieve the highest efficiency of laser cleaning in the practical application of aluminum alloy formwork in concrete pouring, we use the highest power P that the laser can provide. The residual concrete on the surface of the aluminum alloy formwork with a residual time of 72 h or 4 weeks was cleaned by laser. The process standard is to completely remove the concrete layer of a certain state, and the specific process parameters are shown in Table 2. The evaluation indexes are cleaning quality and cleaning time of a single piece, to verify the feasibility of the laser cleaning technology in aluminum alloy formwork cleaning.

**Table 2.** Technological parameters of laser cleaning experiment.

| Laser Power P (W) | Frequency f (kHz) | X-Axis Scanning Width D (mm) | X-Axis Scanning Speed Vx (mm/s) | Y-Axis Speed Vy (mm/s) | Spot Diameter (mm) |
|---|---|---|---|---|---|
| 600 | 20 | 50 | 2000 | 10 | 0.8 |

The laser energy density and energy value of the high repetition frequency pulse laser acting on the unit area of concrete surface per unit time can be calculated by Equation (1). It is used to formulate the process standard of laser cleaning to remove concrete from the surface of the aluminum alloy mold.

The number of pulses per unit scale of two-dimensional scanning cleaning is:

$$P_n = \frac{n \cdot N}{D}, \tag{1}$$

where $N$ is the number of pulses output by the laser in a single scanning process:

$$N = f \cdot \frac{D}{V_x}, \tag{2}$$

$n$ is the average overlap rate in the $Y$ direction:

$$n = (d/V_y)/(D/V_x), \tag{3}$$

$V_x$ is the one-dimensional scanning speed in the $X$ direction of the galvanometer, $V_y$ is the translation velocity in $Y$ direction of the substrate, $D$ is the scanning range of the galvanometer in the $X$ direction, f is the repetition frequency of pulsed laser, and $d$ is the diameter of the spot.

By substituting the parameters of Table 2 into Equations (1)–(3), we determine that the laser energy per unit area and unit time used in this paper is 114 mJ.

## 4. Experimental Result

### *4.1. Effect of Residual Time of Concrete on Cleaning Efficiency*

The laser cleaning process parameters in Table 2 are used to clean the surface of aluminum alloy formwork in area A and B, respectively. The two areas A and B have different concrete residual times.

#### 4.1.1. Comparison of the Macroscopic Morphology

The cleaning results are shown in Figure 4a, and the enlarged observation of ①~④ areas in A and B are shown in (b)~(e). Among them, the surface of the aluminum alloy formwork substrate in region A is completely exposed and shows metallic luster. The total cleaning time of area A is about 195 s. The cleaning result of area ① is shown in Figure 4b.

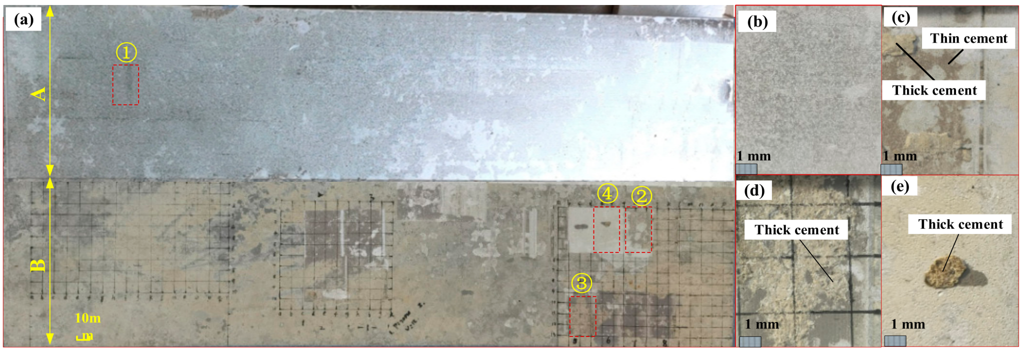


**Figure 4.** Macroscopic morphology and local magnification of cleaning surface: (**a**) Overall appearance of aluminum formwork; (**b**–**e**) ①~④ area enlargements.

However, under the same cleaning process parameters, the concrete adhesion layer in area B cannot be completely removed, and there are still more concrete adhesion layers in thin slurry area ② and thick slurry area ③. Area ④ is the surface of thin slurry area ② after repeated cleaning with the same cleaning parameters for five times. Its surface is different from that of area ①. The color of the surface is yellowish and some residual blocks with a black color and a thickness of 300~400 μm are not removed.

#### 4.1.2. Comparison of the Thickness of the Residual Layer on the Cleaning Surface

Table 3 shows the measured values of concrete layer thickness at five specific points before and after laser cleaning on the surface of the aluminum alloy formwork. At position ① in area A, the concrete residue on the surface of both thin and thick slurry areas is almost completely removed, and the thickness of the residual concrete layer is less than 5 μm. The concrete layer at ② and ③ of area B was removed about 20~50 μm after being cleaned by laser for a single time. At position ④ of area B, after repeated cleaning five times, the thickness of the residual block is about 453 μm, and the yellowing layer still has a relatively thick concrete layer, with a thickness of about 8.6~15.6 μm.

**Table 3.** Concrete height values before and after cleaning in each area (μm).

| Area | Measuring Time | a | b | c | d | e |
|---|---|---|---|---|---|---|
| ① | before | 38.7 | 27.8 | 57.1 | 243 | 47.9 |
| | after | 1.3 | 2.3 | 2.1 | 4.8 | 1 |
| ② | before | 46.9 | 57 | 47.4 | 13.9 | 54.5 |
| | after | 13.4 | 6.4 | 21.5 | 2.3 | 8.7 |
| ③ | before | 780 | 923 | 849 | 408 | 582 |
| | after | 724 | 892 | 792 | 384 | 342 |
| ④ | before | 54.3 | 241 | 470 | 68.2 | 34.6 |
| | after | 10.2 | 211 | 453 | 15.6 | 8.6 |

Through comparative analysis, it can be determined that when the concrete remains on the surface of the aluminum alloy formwork for a short time (<72 h), whether in the thick or the thin slurry areas, using a laser to clean the residual concrete on the surface of aluminum alloy formwork can achieve a better removal effect. However, when the concrete remains on the surface of the aluminum alloy formwork for a long time (4 weeks), laser cleaning of residual concrete on the surface of the aluminum alloy formwork cannot achieve a good removal effect in both thick and thin slurry areas. It specifically shows a low cleaning efficiency and more surface residue after cleaning. From the perspective of engineering application, the residual time of 72 h selected in this paper can meet the time requirements of laser cleaning at the construction site. The selected time also meets the time requirements for transferring it back to the aluminum formwork factory for laser cleaning. Under the experimental conditions of this paper, it is estimated that the cleaning time for one aluminum alloy formwork is 6.5 min, which has high feasibility in engineering application. This cleaning efficiency has high feasibility in engineering application.

### *4.2. Comparison of Micro-Morphology*

#### 4.2.1. The Surface Morphology of Area A after Being Completely Cleaned

Figure 5a shows the typical surface micro-morphology at ① in area A after complete cleaning. The surface concrete is almost completely removed, and the metallic luster of the aluminum alloy formwork substrate is completely exposed. As shown in Figure 5b, the microscopic surface of the aluminum alloy formwork is covered with micro-pits of different sizes and depths. The maximum depth of the pits is about 40 μm, which is the surface damage caused by concrete gravel extrusion and early high-pressure water abrasive washing during the application of the aluminum alloy formwork. Figure 5c shows the exfoliation collected after laser cleaning. The exfoliation is a micro flake structure containing fine aggregate. After absorbing a high-energy laser, the temperature of concrete sharply rises, which forms a higher temperature gradient with the aluminum alloy substrate, and forms thermal stress. However, the isolation agent between concrete and aluminum alloy has no bonding effect, and the connection strength is much less than the thermal stress, which leads to a regular peeling off of the exfoliation.

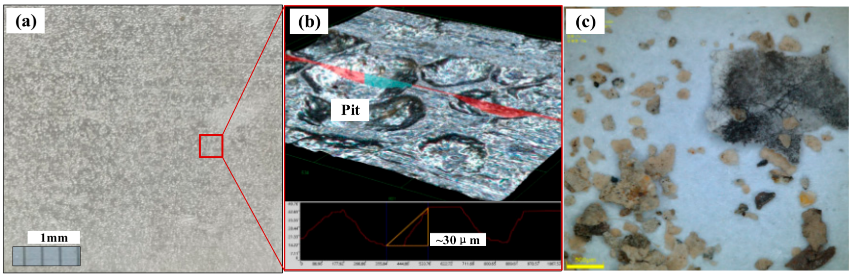


**Figure 5.** Typical surface micro-morphology after cleaning at ① in area A: (**a**) 2D view; (**b**) 3D view and measured value; (**c**) the exfoliation collected after laser cleaning.

#### 4.2.2. The Surface Topography of Area B That Cannot Be Cleaned

Figure 6 shows the surface morphology at ②~④ in area B that have not been completely cleaned. By observing Figure 6a,b, it can be found that before the surface residue of the thin slurry area ② is cleaned, some of the metal substrate is exposed (indicated by the red dot arrow), and the attachment layer in some areas is not completely peeled off. Due to the isolation agent, the residue showed warped scales. The micro-morphology after removal of the residue shows that the thin residual layer with cement as the main body is still attached, and the exposed metal area and the residual area are intertwined and distributed. According to Figure 6c,d, it can be found that no obvious cleaning exfoliation can be found on the surface of the concrete layer in the thick slurry area ③, and there are a large number of pits (indicated by the yellow arrows) and semi-exposed tiny aggregate (indicated by the red arrows) on the surface. The depth of the deeper pit is about 110 μm.

However, in the range of visual distance, there is one fresh pit, and the surface color of the other pits is the same as that of the protruding surface. According to Figure 6e,f, it can be found that the height of the residual block at ④ in area B after repeated cleaning is about 360~480 µm, and its surface color is darker. There is one fresh pit (indicated by the yellow arrow) within the visual range, while the other pits have a similar surface color to the protruding surface.

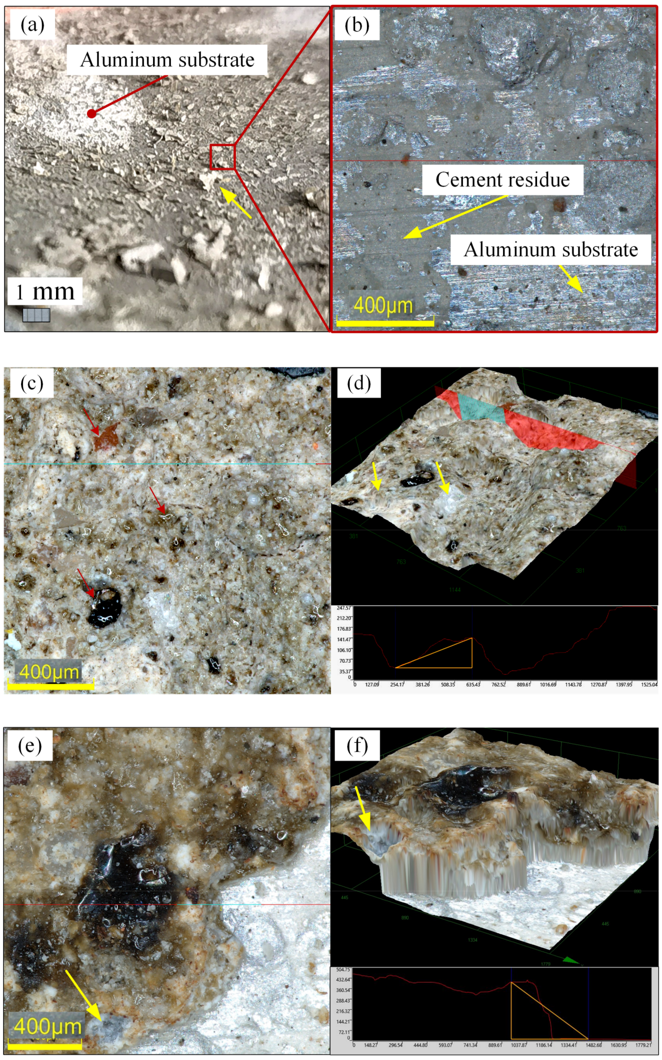


**Figure 6.** Typical micro-morphology at ②~④ in area B: (**a**,**b**) morphology at ②; (**c**,**d**) morphology at ③; (**e**,**f**) morphology at ④.

By comparing the above results, it can be concluded that the laser can effectively clean the concrete on the surface of the aluminum alloy formwork for architectural concrete pouring that has been dismantled in a short period of time. However, when the concrete remains on the surface of the aluminum alloy formwork for a long time, the removal efficiency and quality of laser cleaning are low.

### *4.3. Surface Hardness Test of Aluminum Alloy Formwork after Laser Cleaning*

As shown in Figure 7a, the surfaces adjacent to areas A and B are selected to test the hardness of the cleaned and uncleaned but completely exposed aluminum alloy formwork substrate. The measured values are shown in Figure 7b. The results show that under the action of instantaneous thermal shock of the pulsed laser, the surface of the aluminum alloy template is hardened to a certain extent, and the surface hardness is slightly improved. It is beneficial to improve the wear resistance and service life of the aluminum alloy formwork.

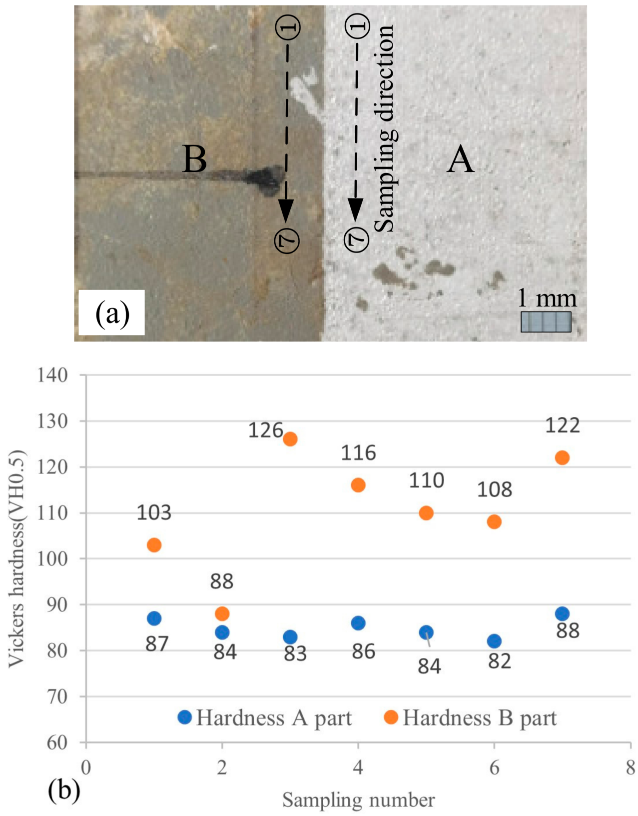


**Figure 7.** (**a**) Vickers hardness test sample; (**b**) Hardness test result.

## 5. Mechanism Discussion

### *5.1. Laser Cleaning Mechanism of Thick Concrete Slurry Layer*

As shown in Figure 8, when the laser hits the surface of the concrete layer, the tiny aggregates and cement compounds in the concrete absorb the laser energy at the same time. The thermal conductivity of concrete is poor, and the local temperature of the irradiated area rapidly rises. However, it is not enough to make high temperature resistant aggregate (main component $SiO_2$) and cement slurry ablation and gasification. Therefore, concrete cannot be removed by ablation and gasification as easily as paint and other organic matter. However, there is an interface transition zone between concrete aggregate and cement slurry, and its structure is loose and there are many air bubbles and water bubbles. Their volume violently expands under high temperature, which leads to explosions and impact peeling. The tensile strength of concrete is only 1/10 of the compressive strength. Under the above impact, the tiny aggregate and mud all break away and fly out, forming fine dust to achieve the purpose of cleaning and removal.

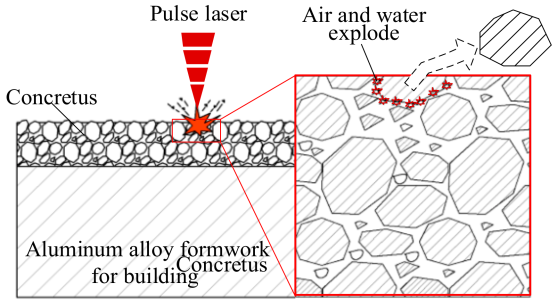


**Figure 8.** Laser cleaning mechanism of thick concrete slurry layer.

After the concrete layer is placed for a long time, the water content of the loose tissue of the transition layer decreases or evaporates. The insufficient energy of steam explosion caused by air bubbles heating can only cause a small amount of aggregate with a weak binding force to explode, crush, and peel, as shown in Figure 6c–f.

Therefore, the air bubbles and water bubbles in the transition interface layer between the concrete aggregate and the cement slurry instantly absorb high-energy laser gasification explosion and form an impact pressure wave. This is the main mechanism of laser cleaning to remove the thicker concrete slurry layer.

### *5.2. Laser Cleaning Mechanism of Thin Concrete Slurry Layer*

As shown in Figure 9, the residual thin paste layer of concrete is mainly composed of cement paste and smaller aggregates dispersed in it. After laser irradiation, the main cleaning mechanism of aggregate and cement slurry is that the air bubbles and water bubbles in the interface transition zone are gasified at a high temperature, and finally the smaller aggregate is removed by blasting impact. Because the cement layer is thin, the impact of blasting will cause cracks in the thin cement layer and transfer along the surface of the aluminum alloy substrate. It can force the cracked cement layer to leave the surface of the aluminum alloy substrate with the isolator, forming a flake cleaning material collected from Figure 5c.

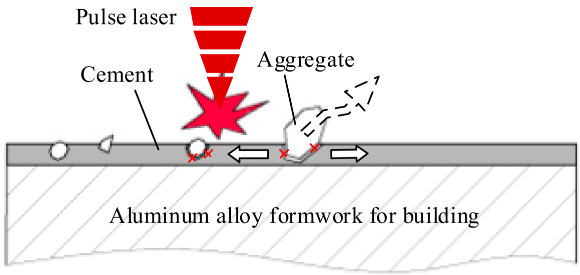


**Figure 9.** Laser cleaning mechanism of thin concrete slurry layer.

However, the thin slurry layer, which has been placed for a long time, has less water content and insufficient impact force of an air steam explosion, so it is difficult to produce enough cracks in the thin slurry layer. At the same time, the cement layer is resistant to high temperatures and cannot be directly removed by gasification after laser action. The poor thermal conductivity of cement leads to the deterioration of laser thermal vibration, which can only form the incomplete separated scale residue shown in Figure 6a.

In summary, the concrete layer mainly consists of aggregate and cement, and their interface transition area has a loose structure and low strength. The shock wave formed by the gasification explosion of air bubbles and water bubbles in this area after absorbing high-energy laser is the main mechanism of cleaning architectural aluminum alloy formwork by laser.

Figure 10 is a mechanism diagram of the laser cleaning and removal of multi-component structure materials represented by concrete structures. The multi-component structure substances contain materials with low vaporization temperature or high thermal expansion coefficient, which rapidly expand and deform or form a blast after absorbing a high-energy laser. Therefore, based on this effect, we can add water and other substances that are easy to vaporize and form explosions when cleaning some materials, so as to improve the cleaning efficiency and ability.

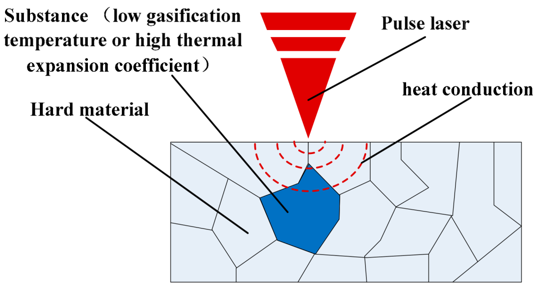


**Figure 10.** Mechanism diagram of laser cleaning materials with multi-component structures containing substances with low vaporization temperatures or high thermal expansion coefficients inside.

## 6. Conclusions

In this paper, based on the laser cleaning device built by a high-energy and high-frequency nanosecond pulse laser, we carried out laser cleaning experiments on the residual concrete layer on the surface of the aluminum alloy formwork with different thicknesses and disassembly times. Finally, the following conclusions were obtained:

(1) The residual time of concrete residue on the surface of aluminum alloy formwork for concrete pouring will affect the quality of laser cleaning. For concrete with a short residual time, lasering can realize high-efficiency and high-quality cleaning. Using the experimental system and process parameters in this paper, the cleaning rate was 6.5 min per formwork, which has high engineering application feasibility. However, for concrete with a long residual time, the efficiency and quality of laser cleaning were poor.

(2) The nanosecond pulse laser will not cause secondary damage to the surface of the aluminum alloy formwork. It can strengthen the hardness of the surface of the aluminum alloy formwork. After laser cleaning, the surface hardness of the aluminum alloy formwork is slightly improved, which helps to improve the durability of the aluminum alloy formwork.

(3) The air bubbles and water bubbles in the loose concrete structure instantaneously absorb the high-energy laser, causing the concrete aggregate to continuously explode. This is the main mechanism for laser cleaning to remove the concrete adhesion layer on the surface of aluminum alloy formwork.

**Author Contributions:** Conceptualization, Q.Z. and Z.Z.; methodology, K.G.; investigation, J.X.; writing—original draft preparation, Y.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by "Hunan High-Tech Industry Science and Technology Innovation Leading Plan, grant number 2020SK2027" and The Laser system was funded by "National Key R&D Plan, grant number 2022YFB4601501".

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Wang, Y.H.; Li, Q.Z. Application of Architectural aluminum formwork in Some Super Tall Building. *Constr. Technol.* **2011**, *40*, 35–37+75.
2. Zhang, A.Q. Research and Application of Aluminum Formwork Technology in Super Tall Building. Master's Thesis, Changchun Institute of Technology, Changchun, China, 2016.
3. Li, Y. A pass-through cleaning system of aluminum alloy template. *Clean. World* **2019**, *35*, 10–11.
4. Song, F.; Liu, S.J. Principle and application research on laser cleaning. *Clean. World* **2005**, *21*, 1–6.
5. Pleasants, S.; Kane, D.M. Laser cleaning of aluminum particles on glass and silica substrates: Experiment and quasistatic model. *Appl. Phys.* **2003**, *93*, 8862–8866. [CrossRef]
6. Cooper, M.; Larson, J. The use of laser cleaning to preserve patina on marble sculpture. *Conservator* **1996**, *20*, 28–35. [CrossRef]
7. Qiu, T.W.; Yi, J.L. Characteristics of Nanosecond Pulse Laser Cleaning Paint Coatings on 2024 Aluminum Alloy Surface. *Laser Optoelectron. Prog.* **2021**, *58*, 0514001.

8. Guo, L.; Li, Y. Numerical and experimental analysis for morphology evolution of 6061 aluminum alloy during nanosecond pulsed laser cleaning. *Surf. Coat. Technol.* **2022**, *432*, 128056. [CrossRef]
9. Zhang, D.; Xu, J. Removal mechanism of blue paint on aluminum alloy substrate during surface cleaning using nanosecond pulsed laser. *Opt. Laser Technol.* **2022**, *149*, 107882. [CrossRef]
10. Qi, X.S.; Ren, Z.G. Study on effect of laser derusting technology on properties of high speed train collector ring. *Laser Technol.* **2019**, *43*, 168–173.
11. Shi, S.D. Researches on Theoretical Model, Numerical Simulation and Application of Painting Removal by Laser Cleaning. Doctor's Thesis, Nankai University, Tianjin, China, 2012.
12. Zhang, Z.Y.; Wang, Y.B. Removal of Low Thermal Conductivity Paint with High Repetition Rate Pulse Laser. *Chin. J. Lasers* **2019**, *46*, 148–156.
13. Lei, Z.; Tian, Z. Laser Cleaning Technology in Industrial Fields. *Laser Optoelectron. Prog.* **2018**, *55*, 60–72.
14. Zhang, G.; Hua, X. Investigation on mechanism of oxide removal and plasma behavior during laser cleaning on aluminum alloy. *Appl. Surf. Sci.* **2020**, *506*, 144666. [CrossRef]
15. Zhu, G.D.; Wang, S.R. Corrosion and wear performance of aircraft skin after laser cleaning. *Opt. Laser Technol.* **2020**, *132*, 106475. [CrossRef]
16. Ünaldi, S.; Papadopoulos, K. Towards selective laser paint stripping using shock waves produced by laser-plasma interaction for aeronautical applications on AA 2024 based substrates. *Opt. Laser Technol.* **2021**, *141*, 107095. [CrossRef]
17. Gao, K.; Zeng, Q.S. Adhesion of Residual Primer Paint After Laser Cleaning Aircraft Aluminum Alloy Skin. *Laser Optoelectron. Prog.* **2021**, *58*, 296–302.
18. Zheng, G. Study on Laser Paint Stripping of Aircraft Surface. Master's Thesis, Institute of Electrics, CAS, Beijing, China, 2005.
19. Li, J.M. Development, Trend and Application of High Average Power Diode Pumped Lasers. *Laser Optoelectron. Prog.* **2008**, *45*, 16–29.
20. Zhang, F.Q. *Concrete Material*; Chemical Industry Press: Beijing, China, 2015.