Laser decontamination for radioactive contaminated metal surface: A review

Qian Wang a, Feisen Wang a, Chuang Cai a, Hui Chen a,*, Fei Ji a, Chen Yong b, Dasong Liao a

a Key Laboratory of Advanced Technologies of Materials, Ministry of Education, School of Materials Science and Engineering, Southwest Jiaotong University, Chengdu, 610031, China
b AVIC Chengdu Aircraft Industrial (Group) Co., Ltd., Chengdu, 610073, China

1. Introduction

Surface decontamination of nuclear facilities and various components (reactor pressure vessels, steam generators, pipes, pumps, valves) with respect to radioactive contaminants is necessary to be carried out periodically or irregularly during routine maintenance, overhaul and decommissioning. It is essential for the reduction of occupational exposure, limiting the release and absorption of potential radioactive contaminants and thereby reduction of collective radiation dose of operating personnel to ensure safe operation of nuclear power plants and nuclear application units [1]. Considering the extensive construction of the nuclear power plants, radioactively contaminated metal waste accounts for a large proportion of the nuclear waste generated by nuclear facilities, and the number of components in urgent need of decontamination has soared. Due to very high cost associated with the storage of highly contaminated radioactive substances, decreasing the activity levels of radioactive contaminants is important for reducing the storage cost. In fact, except for the reactor core components which are contaminated as a whole, most of the other metal components which are only surface contaminated, can be recycled and reused. Maintaining contamination levels to a reasonable level and decommissioning of nuclear facilities requires cleaning and decontamination of radionuclide-contaminated surfaces. Development of nuclear power internationally is based on an important strategy of extending the life span of nuclear facilities which has been carried out in significant numbers all over the world.

For large reactors, the removal of radionuclides should be carried out by simple surface decontamination techniques to reach the decontrol level after shutting down the nuclear facility. In-service inspections, periodic tests, and preventive maintenance of nuclear facilities under safe conditions are the preferred strategies [2,3]. Presently, physical and chemical decontamination methods are the most commonly used [4–6], as indicated in Table 1 [7–19]. The above methods have low decontamination efficiencies, generate large volume of secondary radioactive waste. Moreover, most of the operation is carried out manually from close distance, and thus threatening operators’ health. With the rapid development of more convenient fiber lasers [20], the disadvantages of traditional lasers like strong dependency on working environment temperature and humidity, and high cost of use have been overcome. In this regard, laser surface decontamination technology is being widely used in radioactive metal surface due to its non-
contaminant deposition, low secondary waste generation, and easy automation, as shown in Fig. 1.

Laser decontamination is a new surface removal technology of contaminated metal components and equipment of reactors, reprocessing plants and accelerators via laser so as to reach the decontrol level or possible recycling of low-level radioactive metal facilities. Interaction of laser with the substance during laser decontamination includes complex mixture of various physical and

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Table 1
Conventional decontamination of radioactive contaminants.

Fig. 1. (a) Decontamination parts of hot cell [1] (b) Dismantled parts of reactor (c) Laser surface decontamination.
chemical effects. During the irradiation of material surface via laser beam, there will be heating, melting, vaporization in the local microregion [21], in the meantime, the metal vapor is heated further and ionized by the laser to form plasma above the molten pool [22]. Considering the unique characteristics of laser decontamination, there has been a lot of investment in basic research, technology development and engineering prototype development in various countries and regions around the world. There are quite a few articles or reports on the application of laser decontamination technology in the nuclear industry and the obtained results are encouraging. However, due to the lack of theoretical understanding of laser decontamination of nuclear-contaminated components, the application of laser decontamination methods in the nuclear industry is limited.

In this manuscript, the latest research progress on the key technologies of laser surface decontamination of the metal components in nuclear facilities, such as decontamination factor, decontamination thickness, decontamination efficiency and aerosol collection control, are systematically analyzed. The existing problems of the laser decontamination technology for application in the maintenance and decommissioning of nuclear facilities along with future research scope have been discussed.

2. Laser decontamination principle

2.1. Laser decontamination system

Currently, the main types of lasers used in laser decontamination research include CO2 laser [23], fiber laser [24] and excimer laser [25]. However, the fiber lasers are now the spotlight in laser decontamination technology due to their advantages of high coupling efficiency, high conversion efficiency, good beam quality, and so on. The diagram of the laser optical system and beam scan method is shown in Fig. 2. The beam emitted by the laser system passes through the collimating lens for beam shaping, then the shaped beam enters the galvanometer scanner through the mirror. The specimen surface was moved to the focal position of the focusing lens by adjusting the height of the laser head. The laser spot was applied orderly to the simulated specimens by swinging the x- and y-axis mirrors in the galvanometer system, thereby achieving decontamination. There will be inevitable production of radioactive aerosols during laser decontamination of radioactively contaminated surfaces.

In order to prevent the escape of aerosol which can contaminate the environment, the laser decontamination should be carried out in an acrylic sealed box [26,27] or a stainless-steel sealed chamber [28]. The contaminated specimen was mounted in a sealed chamber. Vacuum pump was connected to the sealed box to ensure that the pressure of the box was below atmospheric pressure. Meanwhile, high efficiency filter was installed at one end of the sealed box for collection of radioactive aerosol particles and to avoid polluting the vacuum pump equipment. As shown in Fig. 2, the specimen was mounted in a Perspex cell, where the laser beam entered through a window. The interior of the Perspex cell was maintained below atmospheric pressure with a filter and vacuum pump to prevent decontaminated ejections from dispersing.

2.2. Absorption of pulse laser

According to the law of conservation of energy, when a laser irradiates the material surface, it is divided into three main parts, which are reflection, absorption and transmission. The optical absorption of laser is mainly dominated by free carrier absorption in materials, i.e. the electrons in the conduction band absorb photons to obtain higher energy [29].

The laser beam is absorbed in an ultrathin metal layer, which increases the thermal motion of free electrons. The kinetic energy of the electrons transforms into the thermal vibration of the lattice due to the collision with the lattice in an ultrashort time \(10^{-11}\)–\(10^{-15}\) s. It results in an increase the material temperature, which propagates through the material according to the mechanism of heat conduction. As a result, the temperature at the spot increases rapidly, causing melting, boiling and vaporization.

The particles of the plasma generated during laser-material interaction absorb laser energy via inverse Bremsstrahlung and photoionization, then its temperature and density rapidly increase [30] to results in the plasma expansion. The expanding plasma absorb, refract and scatter the laser beam to form the plasma shielding phenomenon, which greatly reduces the laser energy that reaches the material surface and the absorption of the laser energy by the material. The theoretical fundamentals of laser decontamination mainly depend on laser pulse duration because it critically determines the physical and chemical process and the dissipation of laser energy into the material. Nevertheless, there is not greatly different between the nanosecond, picosecond and femtosecond pulse laser-induced plasma, and their plasma expansions and shield effects are almost similar [21].

2.3. Characteristics of radioactive contaminants

During the operation of nuclear facilities, the corrosion products of structural materials are deposited on the surface of pipes, valves and water pumps along with the radioactive activation products formed via neutron irradiation of primary coolant. Interaction with high temperature water results in the surface corrosion of the coolant system. Some of the corrosion products which are released
into the coolant are then carried into the reactor core, where they are activated by neutrons and transported back to the coolant system. After a long and high temperature coolant cycle, corrosion products/activation products gradually start depositing on the surface of the reactor coolant system [31], leading to the accumulation of radiation fields around the coolant loop. With increasing service life of the nuclear power plant, increasing level of the radioactive contaminants lead to enhanced radiation field of the system.

The major structural materials of reactor and other nuclear facilities include stainless steel, carbon steel and nickel base alloy. Loose contamination layer along with fixed oxide layer are the usual forms of surface contaminants in the nuclear facilities. Different types of radionuclides become fixed in the oxide layer via chemical reaction and ion exchange [32], where the thickness and structure of the oxide layer are closely related to the operating state of nuclear facilities [33]. In the case of light water reactor, the coolant is generally neutral or alkaline. The coolant forms inner oxide by entering into the micro-pores of the metal surface, and subsequently outer oxide layer is formed due to the outward diffusion of iron ions, thereby the double oxide layers exist on the metal surface in the high-temperature water system [34].

In the case of pressurized water reactor, the oxide layer on the surface is consisted of nickel-rich layer [4,31] and chrome-rich layer [35]. The growth of oxide layer controls the level of radionuclide contamination of the metal surfaces, and the radionuclides are mainly concentrated in the chrome-rich layer. The thickness of surface contaminants will be deeper when the radionuclide diffuses into the interface between the oxide layer and the substrate or due to neutron activation of the trace elements in this area. Around 98% of the radioactive contaminants are accounted in the thickness range of 1–10 μm of the surface layer. In the surface layer having thickness 10–40 μm, the contamination level is less than 2%, while 0.1% of the radionuclides are found in the metal surface layer of 40–50 μm. Thus, a decontamination depth of more than 10 μm can result in the desired decontamination level. Different reactors produce various radionuclides due to the difference in fission fuel, neutron moderator, nuclear reactor coolant, structural materials and auxiliary processes, etc. The radionuclides are mainly 58Co, 137Cs, 60Co, 152Eu, 233U, 232Th and 239Pu, which are widely detected by alpha and gamma ray detectors.

3. Laser decontamination technology

The parameters for laser decontamination are variable and difficult to match. Various parameters that affect laser decontamination qualities include laser fluence, spot overlap rate, laser irradiation times, irradiation angles and pulse duration [36], etc. Choice of appropriate laser parameters is very important. The present system diagram of laser decontamination process is displayed in Fig. 3. For laser decontamination of contaminated surface, sufficient technical support and radiation protection preparations must be made in strict accordance with the prerequisite of radiochemical experiments. Therefore, before hot testing of radioactive decontamination, cold testing of the whole process should be conducted.

For simplifying the complex detection process, cumbersome radiation protection, and difficulty in waste disposal during laser decontamination, non-radioactive isotopes were used instead of radionuclides in simulated specimens to improve the analysis. This research methodology is feasible because of similar physical and chemical properties of the radionuclides and their non-radioactive isotopes, which leads to logical conclusion providing theoretical foundation for the subsequent removal of radioactive contaminants.

3.1. Decontamination efficiency and thickness

The radionuclides mainly exist on the oxide layer for some metal equipment, such as steam generators. Carvalho et al. [37,38], firstly sprayed the contaminated solution consisting of Eu and Co on the stainless steel specimens, and then kept it at 600–800 °C to prepare an oxide layer of 0.2 μm – 4.5 μm thickness and then treated the contaminated surface with pulse laser. They studied the effect of laser fluence and spot overlap rate on the decontamination efficiency. With increasing laser fluence, the decontamination efficiency was found to increase. Fig. 4 displays that decontamination efficiency can reach as high as 93% [39] for the spot overlap rate of 80%. The Korea Institute of Atomic Energy used 304 stainless steel contaminated with Cs, Co, Ce, Eu ions solution to simulate the four loose contaminants, and based on the laser ablation method analyzed the influence of various laser parameters such as laser irradiation times and irradiation angles on the decontamination efficiency [40–43]. The results demonstrated that increasing laser irradiation times increased the decontamination efficiency of four kinds of contaminants. However, due to the different physical properties of the four contaminants, the laser irradiations times required for the decontamination efficiency to reach 95% varies greatly. The decontamination efficiency of Cs and Co ions contaminated specimens could reach 95% after 8 times laser irradiation with laser energy density of 13.3J/cm² and the repetition rate of 10Hz, while the Ce and Eu ions contaminated specimens require 32 times laser irradiations [40]. Furthermore, in the range of 0–30°, increasing irradiation angles result in decontamination efficiency of more than 95% for four kinds of contaminants. Further increase of irradiation angles to 45° results in obvious decrease of decontamination efficiency. Therefore, the laser irradiation angle should be less than 30° to achieve satisfactory decontamination effect.

Kumar et al. [44], prepared simulated specimens for hot test by depositing 222Rn on stainless steel, and an optimum combination of laser fluence, scan speed and laser irradiation times could achieve ablation depths from several microns to tens of microns as displayed in Fig. 5(a) and (b). When the surface decontamination thickness was about 50 μm, an alpha X-ray spectrometer was used to test the level of decontamination, and the activity intensities corresponding to before and after decontamination were shown in Fig. 5(c). After laser decontamination treatment, there was significant decrease of the surface activity, and the contaminants were effectively removed. Delaporte et al. [45,46], used XeCl laser to remove metal surface contaminants. The decontamination process was monitored by real-time analysis of the evolution of plasma electric field, considering the interaction between laser and surface materials, especially the surface damage by laser decontamination. In terms of the fixed contaminants, the decontamination factor could be more than 15, whereas it can be greater than 100 for the loose contaminants.

For loose contamination, laser decontamination mainly relies on the rapid thermal expansion between the substrate and particulates [47], which generates mechanical stresses and inertial forces on the metal surface. Consequently, the particulates escape from the surface to achieve the decontamination effect [48] provided the mechanical stresses and inertial forces are able to overcome the van der Waals force, capillary force and electrostatic force on the surface. Roberts et al. [49], studied the surface decontamination of stainless steel contaminated with uranyl nitrate (UO2(NO3))2⋅6H2O) and uranium dioxide (UO2) by pulse laser, and the uranium activity was found to decrease significantly after laser treatment. Kumar used laser decontamination to remove loose contaminants such as uranium dioxide particulates (UO2), thorium dioxide particulates (ThO2) [23,50] from the surface of stainless steel and plutonium.
Fig. 3. System diagram of laser decontamination process.

Fig. 4. Laser decontamination efficiency [38,39].

Fig. 5. Laser decontamination using hot test [44] (a) Effect of laser fluence on ablation thickness (b) Effect of scanning speed and irradiation times on ablation thickness (c) Alpha spectra of $^{232}$U contaminated specimen.
experiences pitting corrosion, intergranular corrosion, and stress corrosion when it is used in water at high temperatures and pressures [56]. Microstructure and composition of laser-decontaminated surfaces are essential parameters affecting the corrosion resistance. Therefore, it is particularly significant to study the thickness, composition and structure of oxide layer on the metal surface after laser decontamination.

The surface microstructure and properties are related to the laser fluence [24], pulse duration [36,57], and laser absorption rate [58] during laser decontamination. The ablation depth increases with the increase of laser energy density [59]. For nanosecond and picosecond laser, the pulse duration is of the same order or longer than the energy relaxation time, the ablation efficiency of nanosecond laser is higher than that of picosecond pulsed laser [60]. On the contrary, for femtosecond laser, its pulse duration is too short for the single photon process, electron-phonon interaction process, and thermal diffusion process [21], and the laser terminates before the energy is completely redistributed in the solid material. Thus, the ablated depth is nearly independent of the pulse duration [61]. The influence of laser fluence and pulse duration on the surface morphology and crystallographic structure of substrate has been investigated by Greifzu et al. [24]. The short pulse duration minimizes the thermal damage to the substrate, inhibits the formation of the molten pool, and reduces the extent of the heat-affected zone. When the pulse duration is 105 ns, the grain structure of the ferritic steel surface remained unaltered, as shown in Fig. 8. Chen et al. [62], studied the influence of laser power on surface roughness. With increasing laser power, the oxide layer on the surface of stainless steel gradually started to decompose and peel off. When the laser power was increased to 500 W, laser-based decontamination caused partial damage to the substrate with consequent great increase of the roughness. Tong et al. [63], studied the effect of various parameters of laser on the surface roughness and morphology during surface decontamination. For optimized parameters, a fine surface structure at the micro-and nano-scale was found to form and the surface hardness also increased under the condition of excellent decontamination effect.

Laser decontamination was accomplished by ablation during the nanosecond irradiation of a small area of the surface [64,65], and submicron remelting layer is formed on the material surface after...
laser decontamination. High-energy laser modified the crystallographic structure during laser irradiation, the strain-induced martensitic transforms to $\delta$-ferrite phase. As shown in Fig. 9(a), the oxide layer on the surface of stainless steel after laser melting has a double layer structure [66–68]. The upper layer is polycrystalline Fe(Fe,Cr)$_2$O$_4$, and the lower layer is chromium-rich FeCr$_2$O. There are two main reasons for improving the corrosion resistance of laser surface treatment [69], as shown in Fig. 9(b): (1) the recast layer was redistributed after laser irradiation, which reduced the number of Mn–S inclusions (2) the chromium-rich oxide layer served the protective function after the dissolution of the passivation film in the treatment surface, the passivation film and chromium-rich oxide layer acted as a double separator that prevents the corrosion of the substrate.

In conclusion, laser energy and pulse duration are the critical factors affecting surface quality. The structure and composition of the specimen surface are changed combined with laser surface melting technology. Due to the rapid development of laser technology and the significant demand of the extend reactor life, laser decontamination has become an effective removal technology of radioactive contaminants from the surfaces of various components in nuclear facilities. Nonetheless, the interaction between highly concentrated laser energy and surface contaminants modifies the crystallographic structure and surface properties, the interaction mechanism is still not widely explored. Under the premise of effective decontamination, it is urgent to improve the mechanical properties, chemical properties, physical properties and radioactive properties of decontaminated surface, which is one of the major problems that need to be solved.

3.3. Concentration and size distribution of aerosol particles

The concentration and size distribution of aerosol generated during the laser decontamination process are influenced by laser wavelength [70,71], pulse duration [72–74] and laser fluence [75–77]. Moreover, filtration process of radioactive waste is also closely related to aerosol distribution. Therefore, concentration and size distribution of aerosol particle is an important study direction of laser decontamination.

Composition and properties of materials influence the size and concentration of aerosol particle generated during laser decontamination [78], but the aerosol particles have similar characteristics irrespective of the materials. Laser ablation results in the generation of two main structures for aerosols: spherical nanoparticles and chain structures formed by agglomeration of nanoparticles. Cooling rate affects the size and concentration of nanoscale particles, larger cooling rate results in smaller size of aerosol particle. The chain structure [79] is composed of dozens or even hundreds of nanoparticle aggregates formed by collision and coalescence [80,81], as shown in Fig. 10(a) and (b). The cooling process begins as soon as the laser pulse ends, with high temperature collision and coalescence of primary particles. During the
cooling of aerosols, the coalescence process stops and at this time the colliding particles tend to form aggregates, which continue to grow in clusters [82], as displayed in Fig. 10(c).

Meanwhile, the types of radioactive contaminants present on the surface of materials also affect the particle size and concentration of aerosol. The Korea Atomic Energy Research Institute [83] studied the concentration and size distribution of aerosol particles generated after laser decontamination of metal surfaces contaminated with radionuclides using laser ablation method. To simulate radioactive contaminants, the non-radioactive isotope of Co, Cs, Eu and Ce, were deposited on the surface of stainless steel to generate surface contaminants with uniform distribution of the radionuclides. For STS 304 substrate and the contaminated specimens with Co and Cs, the concentration and size distribution of aerosol induced by laser ablation were found to be almost the same, having average particle diameter of 80 nm. However, the particle concentration was higher for Eu and Ce contaminated specimens compared to that of Co and Cs contaminated samples, as shown in Fig. 11.

Moreover, the laser decontamination mechanisms also affect the particle size and shape of aerosols. During laser decontamination of stainless steel, the aerosol particle size generated by evaporation was less than 100 nm. The phase explosion and cavitation cause a large number of contaminates on the material surface to be ejected as droplet particles [84], and the aerosol particle size ranges from 100 to 1000 nm. However, few studies have been conducted based on the generation of radioactive aerosols by vibration and stripping mechanisms. Since laser decontamination process may consist of one or multiple mechanisms, the related research becomes more complicated. As a result, the interaction between different laser decontamination mechanisms and aerosol needs further study.

4. Mechanism of laser decontamination

The laser decontamination of metallic surface is a transient heating-cooling process. The laser decontamination efficiency is greatly influenced by the composition of metallic component and
the characteristics of surface contamination layer. Due to the presence of relatively large temperature gradient on the metallic surface during the laser irradiation, and rapid rate of cooling and solidification, the mechanism of laser decontamination of contaminated metal surface is more complicated. Therefore, surface decontamination of metallic structural materials in nuclear power plants is a challenge.

As displayed in Fig. 12, preliminary studies of surface decontamination by pulse laser suggest that the laser-material interaction is a very localized and transient process. There are three main mechanisms involved in the material removal: laser ablation effect, elastic vibration effect and thermal expansion effect.

4.1. Laser ablation effect

When the laser beam is concentrated by the optical system, there will be high-energy which will result in generation of very high temperature (several thousand degrees or even tens of thousands of degrees) near the focus, leading to instant vaporization or stripping of the contaminants attached to the surface. The ablation mechanism includes vaporization, phase explosion [85,86] and cavitation [87-89]. When the high-energy pulse laser irradiates the material surface, the material surface absorbs the laser energy resulting in rapid increase of the temperature which goes above the melting and boiling point, and thus the vaporization effect occurs. With rising temperature, the material surface reaches a super-heated liquid state in the central region of the spot due to the Gaussian distribution of spatial profile of the laser beam. In the local micro-region, there is bubble nucleation due the fluctuation of thermodynamic properties. There is exponential increase in the rate of bubble nucleation and growth until the bubbles confluence leads to unstable growth, with final explosive ejection of liquid droplets [90-92]. In the edge areas of the light spot, the bubbles present in the interface area of solid-liquid collide, merge, and grow to form cavitations. As a result, foam structure is formed instantly in the connected liquid region, which separates from the matrix and produces cavitation. The thickness of cavitation increases with laser fluence, as shown in Fig. 13. In the central area of laser spot, laser ablation depth is the largest, and the ablation depth gradually decreases with the increase of distance from the center of the laser spot. At a given pressure, when the molten pool temperature exceeds the boiling point, the escape of metal vapor from the surface is the main driving force for laser ablation decontamination. The expanding and escaping metal vapor plume produce recoil pressure on the molten pool below [93], resulting in the redistribution of the molten pool and flow along the edge of the laser spot [94–96] to re-solidify to form a new edge profile [97,98].

4.2. Elastic vibration effect

Elastic vibration effect refers to the formation of plasma on the material surface due to the surface irradiation by high energy laser, and the expansion of plasma generates of shock wave. When the laser shock wave interferes with the laser incident wave, high-energy resonance occurs, resulting in micro-rupture, fragmentation and separation of surface contaminants from the specimen surface.

4.3. Thermal expansion effect

Adhesion forces between the contaminants and substrate surface include mainly van der Waals force, capillary force and electrostatic force, as shown in Fig. 14. van der Waals force, $F_v$, is responsible for the adhesion of contaminant particles with a diameter less than 50 μm to the substrate surface, which can be expressed as follows [101]:

$$F_v = \frac{h r}{8 \pi Z^2} + \frac{h r_c^2}{8 \pi Z^3}$$ (1)

where, first term is the van der Waals force between the spherical particle and substrate surface at point contact, the second item is the additional force when the particle or substrate surface deforms leading to enhanced contact area, $h$ is the Lifshitz-van der Waals constant related to the material, $r$ is the particle radius, $r_c$ is the radius of the particle at the contact surface, and $Z$ is the atomic separation.

When the atmospheric water condenses in the micro-light gap between the particles and substrate, the resultant capillary force $F_c$ between contaminant particles and substrate as described as follows [101]:

$$F_c = 4 \pi r \gamma$$ (2)

where $\gamma$ is the surface tension.
For contaminant particles with diameters more than 50 μm, electrostatic force is the main adhesion force. Due to the excess electrical charge on particle surface, there is coulomb attraction \( F_i \) between the particle and substrate. However, when the contaminant particles and substrate materials are different, the contact potential difference caused due to the difference of local energy states and work functions will produce double electrostatic force \( F_d \).

The particles are fixed by two types of electrostatic forces, which can be expressed as [101]:

\[
F_i = \frac{q^2}{4\pi \varepsilon e \varepsilon_0 l^2} \tag{3}
\]

\[
F_d = \frac{\pi e r U l^2}{Z} \tag{4}
\]

where \( q \) is the electrical charge, \( \varepsilon \) is the free space permittivity, \( e \) is the dielectric constant of the medium between the particle and the surface, \( l \) is the distance between the charge centers, and \( U \) is the electric potential.

Due to laser irradiation of the material surface, the contaminants on the surface expand due to resulting thermal effect. The thermal stress \( P_a \) generated by thermal expansion can be expressed as:

\[
P_a = \frac{mq_m}{\tau_p} \left( \frac{\alpha_s A_{s}}{\rho_s C_s} + k \frac{\alpha_p A_p}{\rho_p C_p} \right) \tag{5}
\]

where, \( q_m \) is the maximum power density of the laser, \( \tau_p \) is the pulse duration, \( m \) is the mass of contaminated particle, \( \alpha_s \) is the thermal expansion factor of the substrate material, \( A_s \) is the absorption coefficient of the substrate material, \( C_s \) is the heat capacity of substrate material, and \( \alpha_p \) is the thermal expansion factor of the contaminated particle, \( A_p \) is the absorption coefficient of contaminated particle, and \( C_p \) is the heat capacity of the contaminated particle.

The surface contaminants separate from the substrate surface under the condition that the thermal stress is greater than the binding force between the surface contaminants and the substrate [100].

In previous work, the application of laser surface treatment on oil stains, epoxy paint and oxide layers on metal surfaces was investigated. The interaction between laser and substrate material during the irradiation process show that ablation, vibration and thermal expansion are the main mechanisms. However, for the particularity of physical and chemical properties and the variation of contaminated depth of the radioactive contaminants on various metal surfaces of nuclear facilities, the laser decontamination process for is quite different from that of the ordinary metals. Therefore, based on the decontamination mechanism of non-radioactive metals, combined with the physical and chemical properties of the nuclides of radioactive contaminants, it is significant to study the chemical metallurgy and physical metallurgy of radionuclides during laser decontamination for studying the future mechanism.

5. Conclusions

(1) The surface of various metallic components in nuclear facilities is contaminated by the radionuclides \(^{137}\text{Cs}, {^{60}\text{Co}}, {^{152}\text{Eu}},\)
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