OPTOELECTRONICS LETTERS Vol.19 No.5, 15 May 2023

Dynamic response of pulsed laser-irradiated space debris*

LIANG Xiaobo, FENG Tao, QU Junli, SHI Mingdong, TANG Hailiang, and ZHU Chunyan**

Xi'an Modern Control Technology Research Institute, Xi'an 710065, China

(Received 18 October 2022; Revised 6 December 2022)

High-velocity small-sized space debris with a diameter of 1—10 cm can cause huge damage to orbiting satellites and spacecraft. In recent years, the technology of actively removing small-sized space debris by high-energy pulsed laser irradiation has attracted widespread attention from scholars around the world, who strive for giving the maximum protection to the safety of the low-earth orbit environment. This paper focuses on exploring the dynamic behavior of centimeter-sized space debris under space-based pulsed laser irradiation. For this purpose, a fluid-structure-thermal-plasma multiphysics coupling model is built for space debris, and the effect law of plasma plumes produced by space debris after laser irradiation at different time is drawn. The simulation and measurement results are compared for analysis, verifying the validity and reliability of the proposed method and the built simulation model. The findings of this study are expected to provide an important theoretical reference and guidance for the research on the application of pulsed lasers to the active removal of centimeter-sized space debris.

Document code: A **Article ID:** 1673-1905(2023)05-0316-5

DOI https://doi.org/10.1007/s11801-023-2180-4

Since human beings embarked on space exploration, outer space has seen a growing number of man-made objects, such as rocket body debris, abandoned satellites, and parts of disintegrated spacecraft. These failed in-orbit space vehicles and the wastes from spacecraft launch and flight are collectively referred to as space debris[1,2]. Most of them chronically scatter in medium and low orbits and move at an ultra-high velocity, posing severe threats to the safety of in-orbit spacecraft, astronauts, and spacecraft to be launched[1].

Small space debris (1—10 cm) has a large number and scale, various shapes, complex motion state, and it is difficult to track independently in high-speed motion state. It is difficult to achieve this by using conventional mechanical capture, and other methods[3]. However, using the recoil technology of high-energy pulse laser irradiation of space debris to actively remove it is the focus and hot spot of current scholars in various countries[4]. In particular, the centimeter sized small space debris with large kinetic energy in the near earth orbit region is now recognized by the international community as the largest space debris threat to spacecraft. The existing debris mitigation and protection methods can no longer effectively limit the continued growth of the number of such dangerous debris[5]. Since most spacecraft and aerospace activities work in the near earth orbit region, in order to maximize the safety of the near earth space environment, it is urgent to carry out research on the active removal of small space debris by laser irradiation[6].

Studies have shown that the space debris produced by spacecraft disintegration and explosion is mainly made of such materials as aluminum/aluminum alloy, composite materials, and stainless steel. Fig.1 shows the component materials of small-sized space debris as well as their proportions, in which the proportion of aluminum/aluminum alloy exceeded 44%[7].

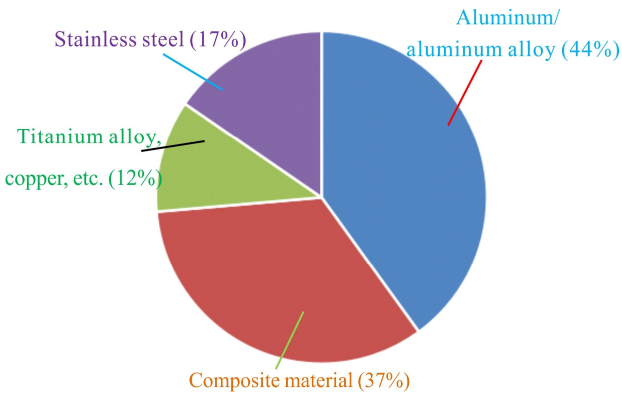


Fig.1 Proportions of component materials of small-sized space debris

Therefore, it is imperative to actively detect and effectively remove small-sized space debris, so as to facilitate the use of space resources and create a good space environment[8]. By far, actively exploring feasible space debris removal strategies has become the consensus among major aerospace countries[9,10]. This paper theoretically

* This work has been supported by the National Natural Science Foundation of China (No.61875231).

** E-mail: liangxiao_bo@126.com

looks into the dynamic behavior of small-sized space debris in low-earth orbit under space-based pulsed laser irradiation, and explores the dynamic response of space debris under nanosecond pulsed laser irradiation using the finite element-based numerical simulation method, with the goal of providing theoretical guidance and reference for the application of the space debris active removal technology by space-based pulsed lasers.

In the process of nanosecond pulsed laser irradiation, the metal target absorbs the laser energy and converts it into heat energy that diffuses rapidly inside the target owing to thermal conduction. Consequently, the target undergoes such physical processes as melting, vaporization, and plasmaization[11,12].

In the process of pulsed laser irradiation of space debris, the surface of the target debris began to melt when the intensity of the pulsed laser was less than 10^5 kW/cm^2, and the corresponding mathematical model can be expressed as[13]

$$\rho C\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_s\frac{\partial T}{\partial x})+Q(x,t)\quad (0<t<t_1). \tag{1}$$

The initial condition is

$$T(x,0)=T_0. \tag{2}$$

The boundary conditions are

$$-k_s\frac{\partial T}{\partial x}\bigg|_{x=0}=Q_s(t), \tag{3}$$

$$-k_s\frac{\partial T}{\partial x}\bigg|_{x=l}=0, \tag{4}$$

where ρ is the density of the solid material of the target debris, C and k_s are the specific heat capacity and thermal conductivity of the target debris material, l is the thickness of the target debris, Q is the laser energy emitted by the pulsed laser, Q_s is the laser energy incident on the surface of the target debris, x is the distance from the incident direction of the laser to the target surface, and t_1 is the time taken for the surface material of the target debris to melt.

With the increase of the irradiation time, the pulsed laser energy continuously accumulates on the surface of the target debris. When the pulsed laser energy reached 10^8 kW/cm^2, the material on the target debris surface began to vaporize. When the energy came to 10^9 kW/cm^2, it was further ionized into high-temperature, high-pressure plasma jet plumes, and the corresponding mathematical model is given by[13]

$$\rho_1 C(\frac{\partial T}{\partial t}-u(t))\frac{\partial T}{\partial x}=\frac{\partial}{\partial x}(k_s\frac{\partial T}{\partial x})+Q(x,t)\quad (t_1<t<\tau). \tag{5}$$

The initial condition is

$$T(x,t_1)=T(t_1). \tag{6}$$

The boundary conditions are

$$-k_s\frac{\partial T}{\partial x}\bigg|_{x=0}=Q_s(t)-\rho_1[L_m u_m+L_v u(t)], \tag{7}$$

$$-k_s\frac{\partial T}{\partial x}\bigg|_{x=l}=0, \tag{8}$$

where ρ_1 is the density of the liquid material of the target debris, C and k_s are the specific heat capacity and thermal conductivity of the target debris material, l is the thickness of the target debris, Q is the laser energy emitted by the pulsed laser, Q_s is the laser energy incident on the surface of the target debris, x is the distance from the incident direction of the laser to the target surface, τ is the duration of the laser beam for irradiation, L_m and L_v are the latent heat of fusion and vaporization of the target debris, respectively, u_m and $u(t)$ are the melting and vaporization rates of the surface material of the target debris.

A two-dimensional geometric model for the target debris irradiated by nanosecond pulsed lasers is constructed, and the initial conditions are assumed to be as follows.

(1) The material of the irradiated target debris is isotropic and homogeneous.

(2) The viscous resistance change of the material during the action process is neglected.

(3) The relative positions between the incident laser and the target debris are assumed to be in a vertical relationship, i.e., the laser is irradiated vertically to the surface of the target debris, and their geometric centers completely coincide.

(4) The target debris used herein is small-sized flake structures with a radius of 1—10 cm made of aluminum material.

Based on the above analysis and the assumed conditions given, a two-dimensional geometric model of laser-irradiated space debris is built with aluminum debris as an example. Fig.2 is the schematic diagram of the geometric model that is simplified. As illustrated, the built target debris geometric model is in the rectangular coordinate system O_{xy}, and the origin of coordinates is at point O, the geometric center of the upper surface of the aluminum target. In the figure, l and r are the thickness and geometric radius of the target debris, the red arrow represents the incident laser, the blue area represents the background gas, and the white is the target debris.

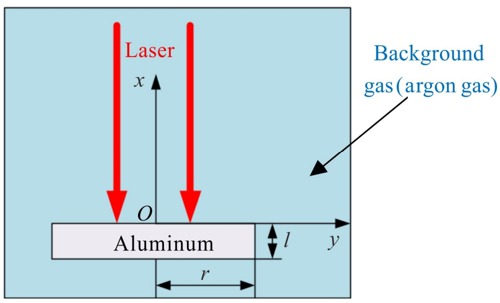


Fig.2 Two-dimensional geometric model of the aluminum target debris irradiated by pulsed lasers

The boundary conditions of the aluminum target debris are set as shown in Fig.3. The pulsed laser beam vertically irradiates the upper surface of the target debris from the top, and the radiation area is set as the heat flux boundary. The surface of the aluminum target debris transfers heat that comes from the absorbed laser energy. Since the simulated environment is supposed to be vacuum, this paper mainly considers heat conduction and heat radiation on the upper surface, with other surfaces set to have insulating boundaries.

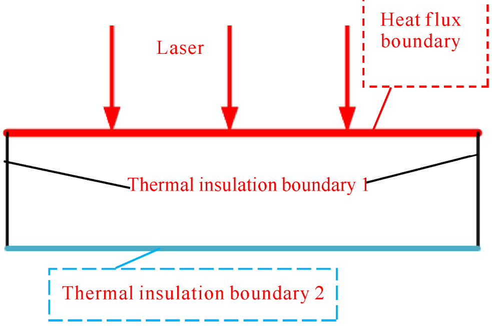


Fig.3 Schematic diagram of the set boundary conditions

For the heat flux boundary, the governing equation is[14]

$$-K\frac{\partial T(x,y,t)}{\partial x}\Big|_{x=0}=P(x,y,t). \quad (9)$$

For insulating boundary 1, the governing equation is

$$-K\frac{\partial T(x,y,t)}{\partial y}\Big|_{y=\pm r}=0. \quad (10)$$

For insulating boundary 2, the governing equation is

$$-K\frac{\partial T(x,y,t)}{\partial x}\Big|_{x=-l}=0. \quad (11)$$

Since irradiating the aluminum target debris with pulsed lasers is a transient heat conduction process and the aluminum target debris is isotropic, the heat conduction equation can be drawn according to Fourier's law. Before the surface of the target starts to vaporize, the equation can be written as[14]

$$\rho_{\mathrm{A}}C_{\mathrm{pA}}\frac{\partial T(x,y,t)}{\partial t}=\frac{\partial}{\partial x}(k_{\mathrm{A}}\frac{\partial T(x,y,t)}{\partial x})+\frac{\partial}{\partial y}(k_{\mathrm{A}}\frac{\partial T(x,y,t)}{\partial y})+P(x,y,t). \quad (12)$$

The initial conditions is

$$T(x,y,0)=T_0=293.15\ \mathrm{K}, \quad (13)$$

where ρ_{A}, C_{pA} and k_{A} are the density, specific heat capacity, and thermal conductivity of the material of the target debris, respectively, P is the laser source, l is the thickness of the target debris, and x is the distance from the incident direction of the laser to the surface of the aluminum target debris.

Based on the built models, the expansion plume generated by space debris irradiation at different time and under different laser parameters is simulated for analysis. Fig.4 shows the jet velocity interface of the plasma plume produced by the 50 μs irradiation of a 150 kW pulse laser on the aluminum target debris.

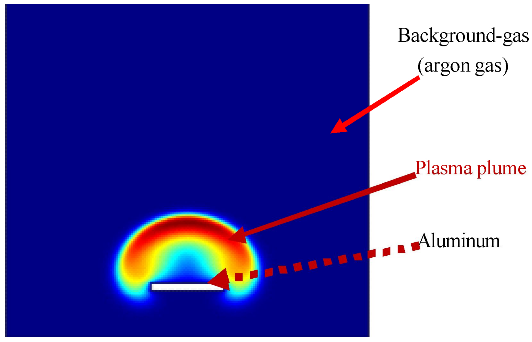
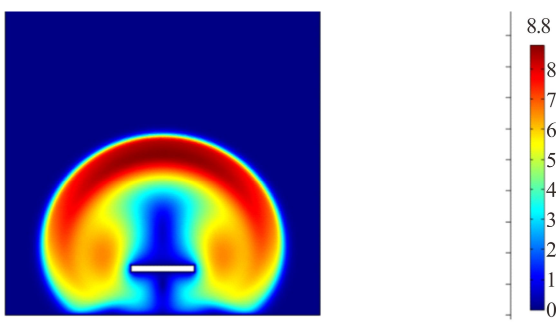


Fig.4 Interface of the plasma plume's jet velocity

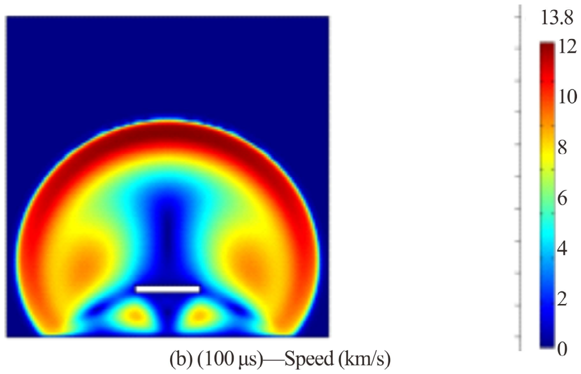
To verify the dynamic response model of the pulsed laser-irradiated space debris, simulation is carried out using the aluminum target debris parameters in Ref.[15]. In Ref.[15], an experimental platform for laser irradiation of aluminum target debris was built to simulate the action process of the irradiation in a vacuum environment. The results showed that when the laser power density was 12.7 J/cm^2 and the laser ablation diameter was 1 mm, the velocity of the plasma jet generated on the surface of the aluminum target debris was 17 km/s, given by the numerical calculation method in Ref.[15] that utilized the mathematical relationship between time and displacement.

The action process of lasers irradiating aluminum target debris is simulated. Fig.5 presents the velocities of plasma jets generated by laser irradiation on the surface of aluminum target debris at different time. Fig.6 is the comparison between the test results when the action time was 100 ns and those in Ref.[15].

As illustrated, when the laser action time was 50 μs and 100 μs, the maximum jet velocities of the plume on the surface of the aluminum target debris were 8.8 km/s and 13.8 km/s, respectively. It can be seen that with the increase of the laser action time, the jet velocity of the plume was also rising. Further, the comparison between the simulation and experimental results in Fig.6 showed that under the condition of the same parameters, the distribution of the plume on the surface of the aluminum target debris was basically consistent with the experimental results. In particular, at the moment of 100 μs, the plasma jet velocity generated on the surface of the aluminum target debris reached a maximum of 13.8 km/s, while the value in Ref.[15] was about 17 km/s.



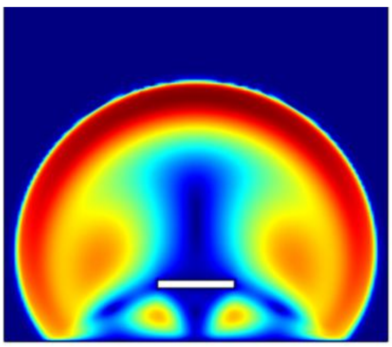
(a) (50 μs)—Speed (km/s)



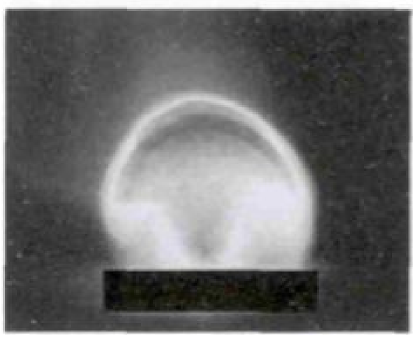
(b) (100 μs)—Speed (km/s)

Fig.5 Plasma jet produced by pulsed laser irradiation of aluminum target debris at different time

The research results showed that the simulation and experimental values were relatively consistent, which verifies the validity of the model built herein. There is a certain error between the simulation and experimental results, which is primarily because the test wasn't conducted in a complete vacuum state owing to the limitation of the test equipment while the simulation could achieve the vacuumization of the surrounding environment of the target debris through the filling of the background gas. In addition, errors might also occur in the calculation of the jet velocity, which was based on the features of the plume extracted by the image processing method. However, in the numerical simulation process, the jet velocity of the plasma plume was mainly obtained by fluid mechanics model simulation based on finite elements, which may be a source of errors as well.



(a) Simulation result



(b) Experimental result

Fig.6 Comparison of simulation and experimental results

After the analysis of space-based pulsed laser irradiation of space debris, a fluid-structure-thermal-plasma multiphysics coupling model of pulsed laser-irradiated space debris was built based on the geometric model of the irradiation, and the propagation of plasma plumes produced by pulsed laser irradiation of target debris was explored. The coupling model built was analyzed and verified. By analyzing the physical process of pulsed laser irradiating space debris, this paper constructed a corresponding multi-physics coupling model based on the geometric model of plasma plume production by laser irradiation, and discussed the material parameters, meshing, and boundary conditions involved in the modeling. The dynamic response model of pulsed laser irradiated space debris was verified. The simulation analysis of flow field characteristics was carried out using the relevant parameters in Ref.[15]. The simulation results were found to be basically consistent with the plasma plume test results in Ref.[15], so did the maximum jet velocity. Hence, the validity of the dynamic response model built was verified.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

References

[1] DU J L. Research on space-based monitoring system for space debris cataloging[D]. Wuhan：Wuhan University, 2018：1-7. (in Chinese)

[2] LI M, GONG Z Z, LIU G Q. Space debris monitoring and removal frontier technology and system development[J]. Science bulletin, 2018, 63(25)：2570-2591.

[3] YUTA E, HIROHISA K, PAVEL T. New formulation for evaluating status of space debris capture using tether-net[J]. Advances in space research, 2022, 70(10).

[4] WEN Q, YANG L W, ZHAO S H, et al. Removing small scale space debris by using a hybrid ground and space based laser system[J]. International journal for light and electron optics, 2017, 141：105-113.

[5] TSURUTA H, DONDELEWSKI O, KATAGIRI Y, et al. Ablation spot area and impulse characteristics of polymers induced by burst irradiation of 1 μm laser pulses[J]. Acta astronautica, 2017, 136：46-54.

[6] KATSUHIKO T, SATOSHI W, TAKAYO O, et al. Laser ablation induced impulse study for removal of space debris mission using small satellite[J]. Applied physics A, 2022, 128(10)：932.

[7] FANG Y W, ZHAO S H, YANG L W, et al. Study on the interaction law of small-scale space debris in low earth orbit irradiated by ground-based laser[J]. Infrared and laser engineering, 2016, 45(2)：15-20.

[8] BATTISTON R, BURGER W J, CAFAGNA A, et al. A systematic study of laser ablation for space debris mitigation[J]. The journal of space safety engineering, 2017, 4(1)：36-44.

[9] CHANG H. Nanosecond laser ablation impulse coupling characteristics and its application in space debris removal[D]. Beijing：Equipment Institute, 2014：1-5. (in Chinese)

[10] DENG Y, JI X L, LI X Q, et al. Optimal momentum coupling between the ground-based laser impulse and space debris[J]. Applied physics B, 2022, 128(8)：138.

[11] FANG Y W. Space-based pulse laser removal of near-earth small debris[J]. International journal for light and electron optics, 2021, 226(1)：165898.

[12] MURTAZA A, PIRZADA S, XU T, et al. Orbital debris threat for space sustainability and way forward[J]. IEEE access, 2020, 8(99)：1.

[13] ALI M, HENDA R. Modeling of plasma expansion during pulsed electron beam ablation of graphite[J]. MRS advances, 2017, 2(16)：905-911.

[14] WEI Y. Research on numerical simulation method of laser matter interaction based on finite element analysis[D]. Jilin：Changchun University of Technology, 2017：17-23. (in Chinese)

[15] CHANG H, JIN X, YE J F, et al. Analysis of propulsive flow field characteristics of nanosecond pulsed laser ablation of typical materials in vacuum environment[J]. Propulsion technology, 2017, 38(6)：1427-1433.