

Features of laser radiation interaction with metals having cryogenic temperature

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Abstract

In this paper we determine the features of the thermophysical processes involved in the interaction of laser radiation with metals that have cryogenic temperature. To do so, we use a one-dimensional model that involves heating a semi-infinite solid by a point thermal source with a constant flux density. Temperature fields, heating and cooling rates in the laser-irradiated zone for iron and titanium at the ambient temperatures of 77 (liquid nitrogen), 293 and 573 K were calculated. The intensity of the laser irradiation enabled the melting temperatures of 1933 K and 1812 K on the Ti and Fe surface, respectively, to be reached. The duration of the laser pulse was 4.5 ms. We show that a drop in ambient temperature from 573 to 77 K leads to a rise in cooling rate from 3.25×10^3 and 6.4×10^6 K/s to 4.25×10^3 and 1.3×10^7 K/s in the Ti and Fe targets, respectively. Agreement was good between the calculated depths of melting and phase transformation isotherms and the experimental depths of the interfaces of melting and heat-affected zones.

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1. Introduction

The two last decades have seen some studies on the laser irradiation of various metals immersed in liquid nitrogen [1–5]. It has been shown that large amounts of nitrogen can be incorporated into the surface layers of iron, titanium and niobium by pulse laser irradiation of the metals immersed in liquid nitrogen. Stable nitrides can be formed on the metal surface. Two ways of heating the metal by laser radiation using cryogenic liquid as the environment exist: one is by partially immersing it in cryogenic liquid and the other is by completely immersing it. If the metal target is partially immersed in the cryogenic liquid when the irradiated surface is not wet, heat transfers to the metal volume with the temperature of cryogenic liquid. If the metal target is completely immersed in the cryogenic liquid, the heat transfers to the cooled metal volume and from the surface of the heated zone due to the boiling of the cryogenic

liquid. In both cases, the drop in environmental temperature (T_0) to the temperature of cryogenic liquid is accompanied by a temperature dependence of the thermophysical coefficients.

In this paper we study the features of the thermophysical processes involved in the interaction of laser radiation with metals partially immersed in liquid nitrogen. Temperature fields, heating and cooling rates in the laser-irradiated zone for iron and titanium at the ambient temperatures of 77 (liquid nitrogen), 293 and 573 K will be calculated.

2. Model

The problem of heating a semi-infinite solid by a point thermal source involves solving the following system of equations [6]

$$\begin{aligned} \frac{\partial T}{\partial t} &= a \Delta T, \\ -K \frac{\partial T}{\partial z} &= q_s(r, t) |_{z=0}, \\ T|_{z \rightarrow \infty} &= T_0, \\ T|_{t=0} &= f(r, z). \end{aligned} \quad (1)$$

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where a , K , q_s and T_0 are the thermal diffusivity, thermal conductivity, adsorbed power density of the point thermal source and ambient temperature, respectively, t the current time, r the radius of the point thermal source (laser spot) and $z = 0$ at the surface of the body.

The solution to this problem is found in Ref. [6]. Assuming that the thermophysical coefficients of the metal target do not change during laser irradiation ($t < \tau$, where τ is the laser pulse duration), and using a thermal source with a uniform distribution of power, in the case of heating the thermal field can be written as:

$$T(z, t) = T_0 + \frac{2q_0\sqrt{at}}{k} \operatorname{ierfc}\left(\frac{z}{2\sqrt{at}}\right) \quad (2)$$

where $\operatorname{ierfc}(x) = \int_x^\infty \operatorname{erfc}(x) dx = (1/\pi) e^{-x^2} - x \operatorname{erfc}(x)$ and q_0 is an absorbed power density of laser radiation.

Differentiating $T(z, t)$ in (2) with respect to t , we obtain a heating rate in the laser irradiation zone:

$$\frac{\partial T}{\partial t} = \frac{q_0\sqrt{a}}{k\pi\sqrt{\tau}} e^{-z^2/4a\tau} \quad (3)$$

Since the end of the laser pulse ($t \gg \tau$), the thermal field can be written as:

$$T(z, t) = T_0 + \frac{2q_0\sqrt{a}}{k} \left[\sqrt{t} \operatorname{ierfc}\left(\frac{z}{\sqrt{4at}}\right) - \sqrt{t-\tau} \operatorname{ierfc}\left(\frac{z}{\sqrt{4a(t-\tau)}}\right) \right] \quad (4)$$

By differentiating $T(z, t)$ in (4) with respect to t , we obtain a cooling rate in the laser irradiation zone:

$$\frac{\partial T}{\partial t} = \frac{2q_0\sqrt{a}}{k} \left[\frac{1}{2\sqrt{\pi t}} e^{(-z^2/4at)} - \frac{1}{2\sqrt{\pi(t-\tau)}} e^{(-z^2/4a(t-\tau))} \right] \quad (5)$$

3. Results and discussion

For the metal, the relative changes in thermal and physical coefficients, $a(T_{\text{melt}})/a(T_{293})$ and $K(T_{\text{melt}})/K(T_{293})$, are small ($<10\%$) in the temperature range from room temperature (293 K) to the melting temperature of the metal. However, these changes in the coefficients can lead to high corrections in calculations of the thermal fields. To calculate the thermal fields in the laser irradiation zone of the metal target at cryogenic temperature, we must consider:

- an expansion of the temperature range in the area of cryogenic temperatures ($\Delta T = T_{\text{surf}} - T_0$, where T_{surf} and T_0 are the temperatures of the surface and cryogenic liquids, respectively);
- an increase in the relative changes in thermal and physical coefficients by the expansion of the temperature range in the area of cryogenic temperatures ($T_0 < 100$ K).

Fig. 1 shows the changes in thermal conductivity for Ti, Fe and Cu targets as a function of ambient temperature. The figure

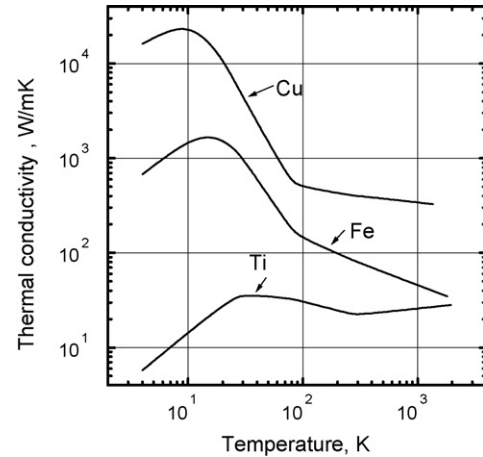


Fig. 1. Change in thermal conductivity for Ti, Fe and Cu targets as a function of ambient temperature. The figure was built on the basis of tabulated data from Ref. [7].

is based on tabulated data from Ref. [7]. In the temperature range $T_{\text{melt}} - T_{77}$, where T_{77} is the temperature of liquid nitrogen, the $K(T_{\text{melt}})/K(T_{77})$ ratios for Ti, Fe and Cu metal targets are roughly 1.6, 5.0 and 2.0, respectively, which are higher than the changes in these parameters in the temperature range $T_{\text{melt}} - T_{293}$. An increase in the relative change in specific heat is also observed [7]. Taking this into account, we averaged the thermal and physical coefficients in the temperature range $T_{\text{surf}} - T_0$.

We used Eqs. (2) and (4) to calculate the thermal fields in the laser irradiation zone for Ti and Fe samples at the ambient temperatures of 77, 293 and 573 K. FORTRAN 90 was used by the calculations. In these calculations, a laser pulse with a rectangular shape and duration of 4.5 ms was also used. Since the adsorbed power density (q_s) of laser radiation needed to achieve the melting temperature on the metal surface depends on the ambient temperature [4], in each case q_s was selected to obtain the melting temperature on the surface of titanium (1933 K) and iron (1812 K). The fields of the heating and cooling rates were also calculated using these conditions.

Fig. 2 shows the evaluation of temperature in the Ti target as a function of ambient temperature, time and depth (z). Line 1 represents the calculated values of temperature on the Ti surface ($z = 0$) as a function of time. We can see that the temperature reaches the melting temperature (1933 K) at the end of the laser pulse ($t = 4.5$ ms). Lines 2–5 represent the calculated values of the temperature in the laser-irradiated zone at $z = 60, 110, 170$ and $210 \mu\text{m}$. At $z = 60 \mu\text{m}$, the maximum of the temperature is reached for $t = 4.51$ ms. This maximum increases as the ambient temperature increases from 77 to 573 K and it has values of 1480 K (Fig. 2a), 1531 K (Fig. 2b) and 1577 K (Fig. 2c) at $T_0 = 77, 293$ and 573 K, respectively. At these temperatures, titanium has a high-temperature β -phase with a body-centered cubic lattice. At $z = 110 \mu\text{m}$, the maximum temperatures are reached for $t = 4.76$ ms: 1170 K (Fig. 2a), 1254 K (Fig. 2b) and 1336 K (Fig. 2c) at $T_0 = 77, 293$ and 573 K, respectively. These temperatures are close to the temperature (1155 K) at which the $\alpha \leftrightarrow \beta$ phase transition takes place. The rise in ambient temperature increases the time

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