Liquid metal expulsion during laser irradiation

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During laser assisted materials processing such as welding, cutting, drilling, or surface alloying, the processing conditions are adjusted to either achieve or avoid liquid metal expulsion. Currently, there is no theoretical model to determine, from fundamental principles, the operating conditions for the initiation of liquid metal expulsion during laser irradiation. Processing conditions necessary for the initiation of liquid metal expulsion during pulsed laser irradiation have been investigated experimentally and theoretically. Lead, titanium, and stainless steel samples were irradiated by single and multiple pulses of varying pulse durations to investigate conditions for liquid metal expulsion. It is demonstrated that using theoretically computed transient spatial temperature profiles, and by balancing surface tension and recoil forces, the conditions for the initiation of liquid metal expulsion can be determined.

I. INTRODUCTION

When very high power density energy sources such as lasers and electron beams are used for materials processing, intense heating of the material is often accompanied by significant vaporization from the molten pool. In many cases, the escaping vapor exerts a large recoil force and, as a result, the molten material is expelled from the cavity. In laser assisted drilling, cutting, and etching, the operating conditions are adjusted, mostly by trial and error, to achieve liquid expulsion. However, in several important metals processing operations such as welding, surface alloying, and cladding, spatter and weld metal expulsion are unacceptable. Therefore, it is important to know the role of various factors which affect liquid metal expulsion. Currently, there is no theoretical model to predict, from fundamental principles, the operating conditions which lead to liquid material expulsion during laser irradiation.

The liquid pool temperature distribution is influenced by the surface tension gradient driven convection. It is known from recent theoretical[1,2] and experimental[3] research that when a liquid metal is heated by an intense laser beam, the propagation of strong convection currents in the liquid pool, mainly driven by Marangoni force and to a much lesser extent by buoyancy force, is insufficient to eliminate the commonly present strong temperature gradient within the liquid. In laser processing of metals and alloys, the peak temperature reached at the surface is very high and often exceeds the boiling point.[4–10] For example, von Allmen[4] determined molten pool temperatures in excess of boiling point for laser treatment of copper. Batanov *et al.*[5] indicated that temperatures on the surface of a laser irradiated material can be higher than the boiling point. Paul and DebRoy[2] and Zacharia *et al.*[6] have reported theoretically calculated temperatures close to the boiling point for laser welding. Khan and DebRoy[7] arrived at the same conclusion from an analysis of the experimentally determined values of relative vaporization rates of various alloying elements. Chan and Mazumder[8] have also reported temperatures greater than the boiling point during laser irradiation of aluminum, titanium, and a superalloy. Theoretical calculations of the vaporization rates by Knight[9] and Anisimov[10] are based on the premise that the liquid pool surface temperatures are higher than the boiling point. Thus, during laser irradiation, the equilibrium pressures at the pool surface are often higher than the atmospheric pressure and the excess pressure provides a driving force for liquid expulsion. Several investigators have reported experimental results of metal expulsion during laser irradiation. Chun and Rose[11] irradiated an aluminum target with 1 to 30 J laser pulses of duration 1 to 500 μs and observed that as much as 90% of the material lost was removed from the molten pool as liquid. During laser scribing of ceramics with ruby laser pulses, Wagner[12] observed that a conical molten region is formed and all the liquid is expelled. von Allmen[13] suggested that the vapor pressure acts like a piston on the liquid weld pool and forces liquid metal out of the cavity. He proposed a model to calculate liquid metal expulsion rate. The spatial variation of temperature on the weld pool surface, convective heat transfer in the liquid pool, and conduction heat loss in lateral directions were ignored. Furthermore, the spatial distribution of temperature on the weld pool surface was not considered for the calculation of the vapor recoil force. The main difficulty in the application of the melt ejection model[13] to study the critical conditions for the initiation of liquid metal expulsion is that the retarding effect of surface tension is not considered. Thus, a precondition for the application of the model is that the vapor recoil force must be significantly higher than the surface tension force. While such a requirement is not unduly restrictive at very high laser intensities, it precludes application of the model to predict conditions for the initiation of liquid metal expulsion, i.e., when the recoil force just exceeds the surface tension force.

In this article, conditions for the initiation of liquid metal expulsion during laser irradiation are examined experimentally and theoretically. Both the pressure and the surface tension forces were taken into account in the theoretical model. The model is useful for predicting operating conditions for the initiation of liquid expulsion in laser

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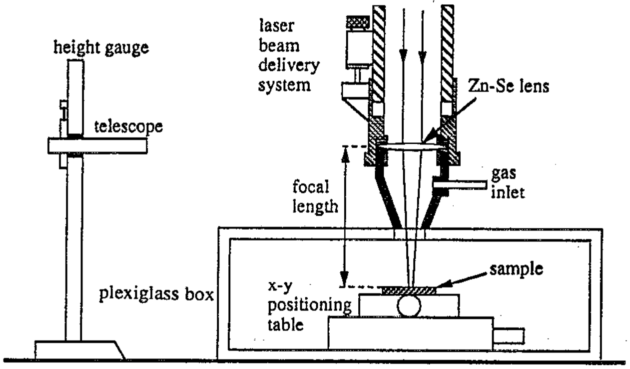

FIG. 1. Schematic diagram of the experimental setup.

assisted drilling and minimizing weld metal spatter during pulsed laser welding. Lead, titanium, and stainless steel samples were irradiated with single and multiple pulses of varying pulse durations. The irradiated regions were then examined by a scanning electron microscope to determine if liquid expulsion had occurred.

II. PROCEDURE

Samples of lead, titanium, and AISI 201 stainless steel were obtained from Aldrich Chemical Company, Milwaukee, WI, Aesar/Johnson Matthey, Ward Hill, MA, and Allegheny Ludlum Steel Company, Brackenridge, PA, respectively. Lead and titanium samples were of 99.9995% and 99.7% purity, respectively. The 201 stainless steel contained 16.34% Cr, 4.87% Ni, 7.15% Mn, 0.073% C, 0.56% Si, 0.035% P, 0.004% S, 0.069% N, 0.004% O, 0.003% Al, and the remainder Fe. The samples were irradiated by carbon dioxide laser pulses of various pulse lengths and frequencies. The CO_2 laser, Coherent model Everlase 525-1, has provision for the adjustments of pulse lengths and frequencies electronically. The shapes of the pulse length versus time plots for the Coherent CO_2 lasers are available in the literature.[14] All samples were finished to 0.5 μm before irradiation and kept in a desiccator. The experimental setup is shown in Fig. 1. The laser was operated in the TEM_{00} mode. The collimated beam was focused on the target with a 12.7 cm focal length Zn-Se lens which had an anti-reflection coating. Stationary samples were irradiated inside a Plexiglass chamber to stop stray radiation. Argon was used as a shielding gas. The sample was kept on a *x-y* positioning table actuated by microprocessor controlled stepper motors. The distance of the sample from the lens was carefully measured because it determines the beam width at the sample surface. A height gage with a telescope attachment was used for the measurements.

III. RESULTS AND DISCUSSION

A. Initiation of liquid expulsion

Micrographs of stainless steel samples irradiated by CO_2 laser pulses of progressively increasing duration are shown in Fig. 2. Melting was observed in each case. However, liquid expulsion did not take place until the pulse length was increased to 1.0 ms.

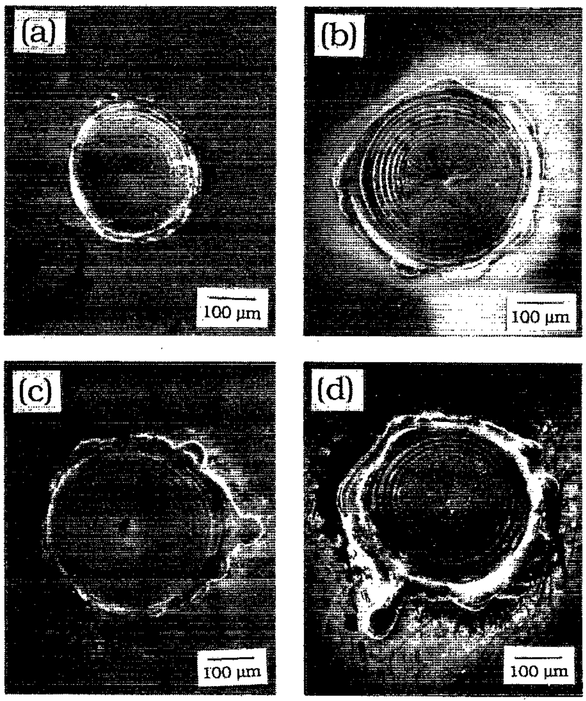

FIG. 2. Micrographs of 201 stainless steel samples irradiated by laser pulses of progressively increasing duration. (a) and (b) represent irradiation with a single pulse of 0.5 and 1.0 ms, respectively. (c) and (d) are for 5 and 10 pulses of 1.0 ms duration, respectively.

On varying the frequency and the pulse length for a total exposure time of 1.0 s, a similar behavior was observed in both lead and titanium samples. For example, in Fig. 3, the transition from melting to liquid expulsion can be observed with increasing pulse length in both lead and titanium. A summary of the frequency and pulse length combinations, necessary for initiating liquid metal expulsion in lead, titanium, and stainless steel, is presented in Fig. 4. When irradiated with single pulses, metal expulsion was observed only for large values of pulse length. For multiple pulses, short pulses led to liquid metal expulsion only at high frequencies when the irradiated region could not cool sufficiently between pulses. It will be established subsequently in this article that the peak temperature must exceed a critical temperature for liquid metal expulsion to occur. Furthermore, it will be demonstrated that the transition from melting to expulsion can be understood from the fundamental principles of transport phenomena.

B. Irradiation with a single pulse

When a laser beam strikes the surface of the sample, melting occurs almost instantaneously. Velocity and temperature fields in laser melted pools can be estimated from the numerical solution of the equations of conservation of mass, momentum, and energy.[15,16] The computed[1] steady state velocity and temperature fields during laser irradiation of iron and titanium are presented in Fig. 5. The data used for the calculations are presented in Table I. The

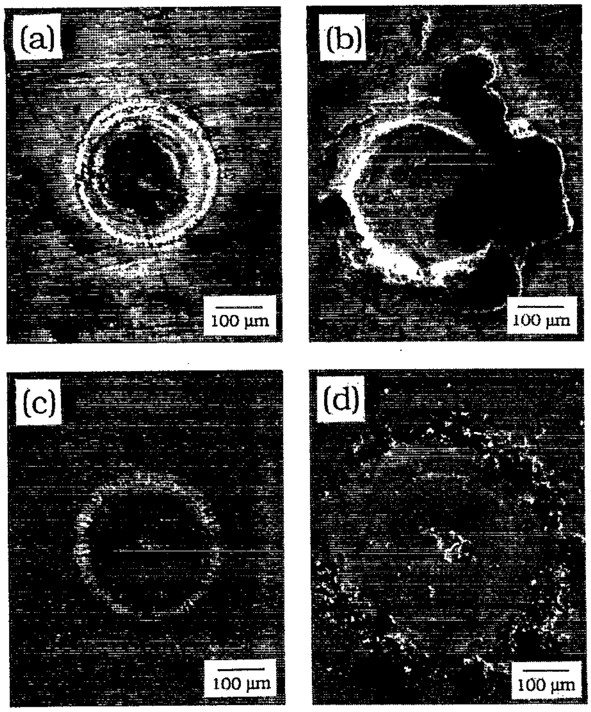

FIG. 3. Micrographs of lead and titanium irradiated by laser pulses of increasing duration, leading to liquid expulsion. Lead irradiated by single pulses of (a) 0.05 ms and (b) 0.10 ms durations. Titanium irradiated by single pulses of (c) 0.5 ms and (d) 1.0 ms durations.

velocity distribution is typical where Marangoni force, resulting from the spatial gradient of surface tension, is the main driving force for convection. The negative values of the temperature coefficient of surface tension for pure met-

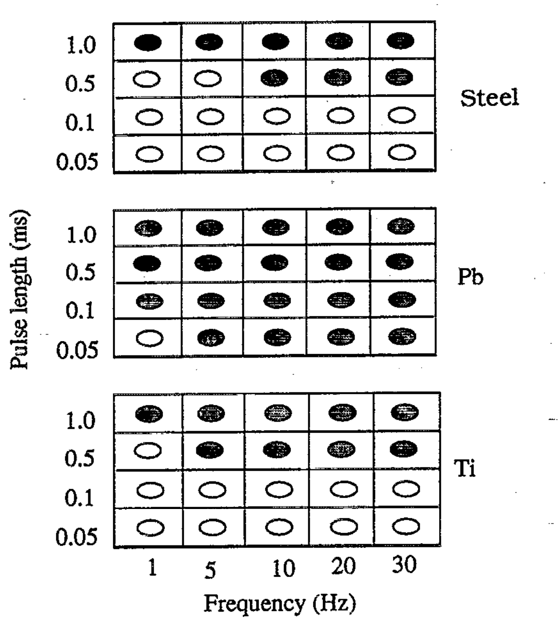

FIG. 4. Combinations of pulse length and frequency which lead to liquid metal expulsion. Cross hatched circles indicate liquid expulsion and open circles indicate melting but no expulsion. Laser power: 500 W and focal length: 0.127 m.

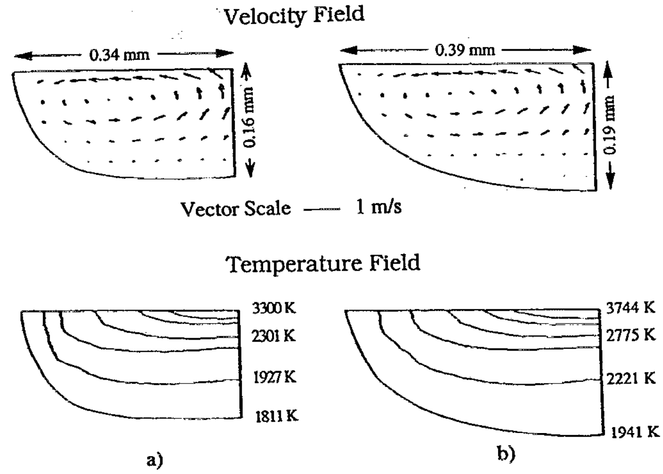

FIG. 5. Numerically calculated temperature and velocity fields (see Ref. 1) for (a) steel and (b) titanium.

als lead to radially outward velocities. Because of the intense energy density of the laser beam, the temperature in the molten pool is very high and the peak surface temperature exceeds the boiling point of the metal. For large pulses, the temperature distribution can be estimated from a steady state numerical solution of the equations of conservation of mass, momentum, and energy. However, the calculation is a complex, time consuming, and expensive task. A practical, much simpler, and marginally less accurate description of the weld pool surface temperature distribution can be stipulated if the peak temperature and the radius of the molten pool can be prescribed.[17] The temperature distribution at the surface of the molten pool irradiated by a laser operating in the TEM_{00} mode can be expressed as:

$$T=T_0\, e^{-a_1 r^2}, \tag{1}$$

where T is the temperature at the weld pool surface at a distance r from the axis and T_0 is the temperature at the center of the weld pool. The value of a_1 in Eq. (1) can be prescribed from the measured value of the weld pool radius when the liquid expulsion is just initiated.

TABLE I. Data used in calculations.

Property	Stainless steel	Lead	Titanium
Molecular weight (kg/kg mole)	55.8	207.2	47.9
Density (kg/m^3)	7800.0	11300.0	4500.0
Melting point (K)	1811.0	600.0	1941.0
Boiling point (K)	3135.0	2013.0	3562.0
Latent heat of vaporization[4] (kJ/kg)	6330.0	858.0	8816.0
Thermal conductivity[19] (W/m K)	41.84	19.66	20.50
Specific heat[19] (kJ/kg K)	0.418	0.151	0.782
Surface tension coefficient[20] (N/m)	1.872	0.468	1.650
Emissivity[14]	0.10	0.10	0.10
Critical weld pool radius (mm)	0.18	0.16	0.19
Laser beam radius: 0.16 mm			

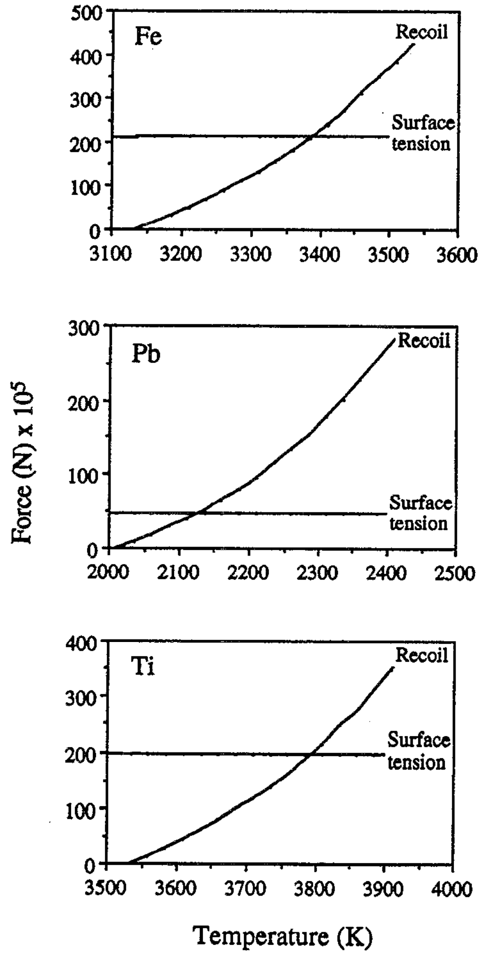

FIG. 6. Recoil force as a function of peak surface temperature and the surface tension force at the melting point.

$$a_1=\frac{1}{r_0^2}\ln\,(T_0/T_m)\,, \qquad (2)$$

where T_m is the melting point of the material. Therefore for an assumed value of T_0, the temperature distribution at the weld pool surface can be determined. The value of the maximum weld pool surface temperature just before the initiation of liquid metal expulsion can be determined from the following criterion. Liquid expulsion takes place when the vapor recoil force overcomes the surface tension force of liquid metal at the periphery of the weld pool. For an assumed value of T_0, the recoil force, R, is calculated from the relation:

$$R=2\pi\int_0^{r_b} r\Delta P(r)dr, \qquad (3)$$

where r_b is the radial distance at which the surface temperature is equal to the boiling point and $\Delta P(r)$ is the difference between the local equilibrium vapor pressure and the atmospheric pressure and is a function of radial distance from the beam axis. The calculated values of the surface tension force at the periphery of the weld pool, $2\pi r_0\sigma$, where σ is the surface tension at the melting point, and the recoil force for various values of T_0 are shown in Fig. 6. It is observed that the recoil force is a strong function of the peak temperature. The value of T_0 for which the recoil and surface tension forces are equal is the critical temperature for liquid expulsion. Liquid expulsion from stainless steel can take place when the temperature at the center of the pool, T_0, exceeds a critical temperature, T_{cr}, which is 3380 K. The values of T_{cr} for lead and titanium are 2120 and 3780 K, respectively.

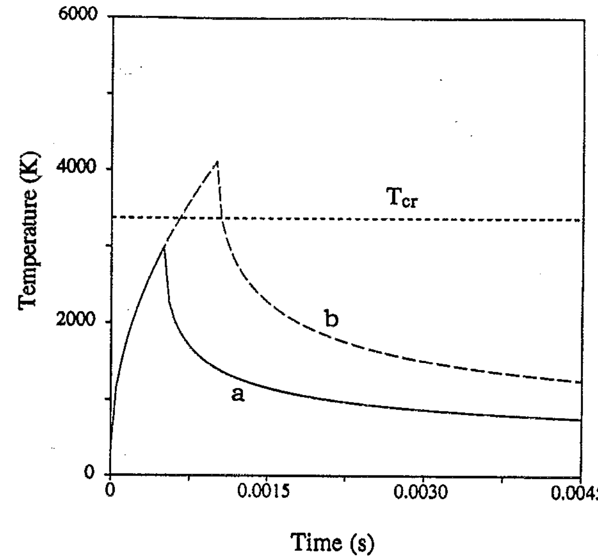

FIG. 7. Peak temperature vs time for a stainless steel sample irradiated by single pulses of (a) 0.5 and (b) 1.0 ms durations.

During laser irradiation, the rise and decay of the peak temperature at the surface of a metal can be determined[18] from Eqs. (4) and (5), respectively.

$$T_0-T_0^0=2I\sqrt{\frac{t}{\pi k\rho C_p}} \quad \text{for} \quad t<t_p\,, \qquad (4)$$

$$T_0-T_0^0=2I\left(\sqrt{\frac{t}{\pi k\rho C_p}}-\sqrt{\frac{t-t_p}{\pi k\rho C_p}}\right) \quad \text{for} \quad t\geqslant t_p\,, \qquad (5)$$

where T_0 and T_0^0 are the peak temperature at time t and just prior to irradiation respectively, I is the local intensity of absorbed laser radiation, k, ρ, and C_p are the thermal conductivity, density, and specific heat of the metal, respectively. The temporal temperature profile calculated from Eqs. (4) and (5) neglects the effects of phase change, variable material properties, and weld pool convective heat transport but allows rough estimation of the changing peak temperature on the surface.

The temporal surface temperature profiles for stainless steel irradiated by single pulses of length 0.5 and 1.0 ms are presented in Fig. 7. It is observed that for a pulse length of 0.5 ms, the peak temperature reached is significantly lower than the minimum peak temperature, 3380 K, required for liquid expulsion to occur. However, for a pulse length of 1.0 ms the peak temperature exceeds the critical temperature. The results are consistent with the experimental data shown in Figs. 2 and 4. Similarly for lead and titanium the peak temperature reached in a single pulse could be used to rationalize the experimental observations presented in

Figs. 3 and 4. It should be noted that, although there is good agreement between the predicted and the observed condition for expulsion, the equations employed are not exact and the computed temperatures provide dependable trends but not rigorously computed temperature data.

C. Irradiation with repeated pulsing

In several experiments the samples were irradiated repeatedly with short pulses of length t_p. The rise and decay of the peak temperature,[18] T_0, during the nth cycle are given by Eqs. (6) and (7), respectively.

$$T_0=T_{(n-1)/f}+2I\sqrt{\frac{t-(n-1)/f}{\pi k\rho C_p}}$$

$$\text{for} \quad \frac{n-1}{f}\leqslant t<\frac{n-1}{f}+t_p, \tag{6}$$

$$T_0=T_{(n-1)/f}+2I\left(\sqrt{\frac{t-(n-1)/f}{\pi k\rho C_p}}-\sqrt{\frac{t-t_p-(n-1)/f}{\pi k\rho C_p}}\right)$$

$$\text{for} \quad \left(\frac{n-1}{f}+t_p\right)<t<\frac{n}{f}, \tag{7}$$

where f is the pulse frequency, $T_{(n-1)/f}$ is the peak temperature at the end of the $(n-1)$th cycle. During repeated pulsing, at the frequencies used in this study, the sample does not have sufficient time to cool to ambient temperature between successive pulses. As a result, the maximum surface temperature increases progressively. The calculated peak temperature versus time for a stainless steel sample irradiated by pulses of 0.5 ms each at frequencies of 5 and 10 Hz are presented in Fig. 8. It is observed from Fig. 8(a) that at a frequency of 5 Hz the peak temperature does not satisfy the criterion for liquid expulsion. However, at a frequency of 10 Hz, the peak temperature exceeds the critical temperature as shown in Fig. 8(b). The results are consistent with the experimental observations presented in Fig. 4. Thus, for a given energy distribution, the pulse length and frequency can be varied to control liquid metal expulsion. The net force responsible for the liquid expulsion is the difference between the recoil force and the surface tension force. The acceleration of the liquid metal, expressed in a dimensionless form, serves as a useful factor for examining liquid metal expulsion from the melt. The dimensionless acceleration, f^*, of a mass contained in a hemispherical volume of liquid of radius r_0 is given by:

$$f^*=\frac{\int_0^{r_b}2\pi r\Delta P(r)dr-2\pi r_0\sigma}{(2/3)\pi r_0^3\rho g}. \tag{8}$$

The numerator in the above expression gives the difference between the recoil force and the surface tension force while the denominator represents the gravitational force. The variation of f^* with the temperature difference, $\Delta T=T_0-T_{cr}$ is shown in Fig. 9. It is observed from the figure that f^* is a sensitive function of the peak temperature. Thus,

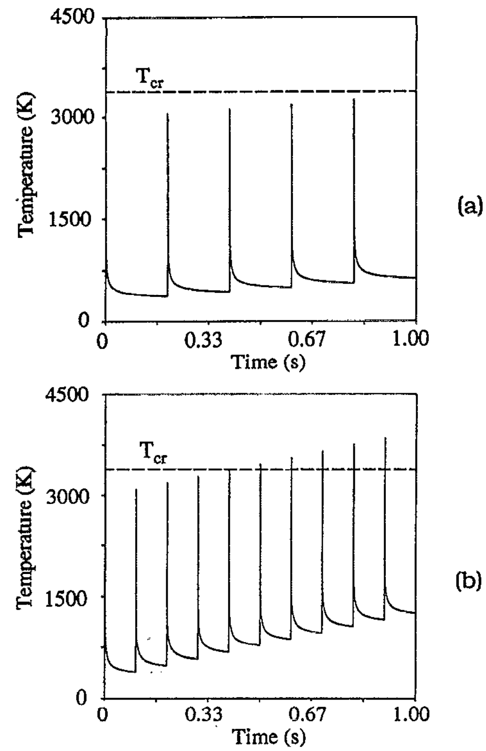

FIG. 8. Peak temperature vs time for a stainless steel sample irradiated by multiple pulses of 0.5 ms duration at (a) 5 and (b) 10 Hz.

even for a small increase in temperature above the critical temperature for metal expulsion, T_{cr}, the liquid experiences a large acceleration and is immediately expelled. This conclusion is supported by the observation that after the expulsion of liquid metal commences, no residual liquid metal is observed in the cavity.

When the peak temperature at the center of the pool exceeds the critical temperature, T_{cr}, liquid expulsion takes place. When molten metal is expelled from the weld pool, the laser beam gets defocused resulting in a decrease in the heat flux. As a result, the peak temperature may drop below the critical value and no further expulsion may take place. Thus, the extent of melting at the time when the critical temperature is reached determines the amount of

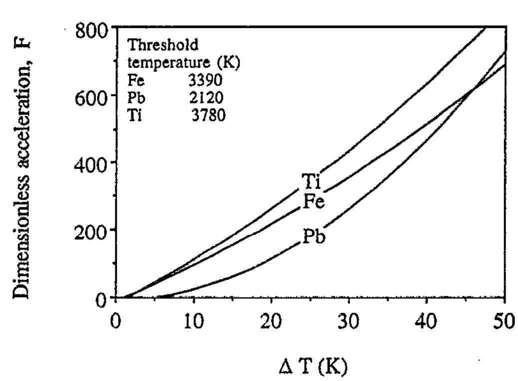

FIG. 9. Dimensionless acceleration of liquid metal as a function of the difference between the peak surface temperature and the critical temperature for expulsion, $\Delta T=T_0-T_{cr}$.

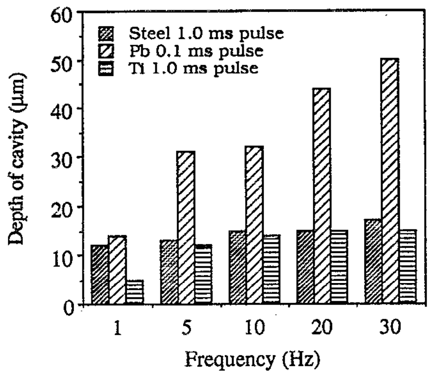

FIG. 10. Experimental observations of depth of crater formed with increasing pulse frequency.

liquid metal expelled. Figure 10 shows the experimentally determined depth of the crater formed in lead, titanium, and stainless steel samples under conditions where liquid expulsion occurred. When the material is irradiated with repeated pulses, several cycles may be required before the critical temperature is reached. Thus, although the total amount of liquid expelled increases with the number of cycles, the rate of increase slows down. This is observed from Fig. 10. The pool depth increases with frequency for all metals but the increase is not linear.

IV. CONCLUSIONS

During pulsed laser irradiation of metals, the processing conditions for the initiation of liquid metal expulsion have been examined both experimentally and theoretically. A dimensionless acceleration factor, which takes into account the processing conditions, the physical properties of the metal, and the theoretically computed transient spatial temperature profiles, can be used to understand the initiation of liquid metal expulsion. Experimentally observed trends in liquid metal expulsion during laser irradiation of lead, titanium, and stainless steel samples with single and multiple pulses were consistent with the calculated results. The conditions necessary for the initiation of liquid metal expulsion from laser irradiated metals can be determined by balancing the vapor recoil force with the surface tension force at the periphery of the liquid pool.

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