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FLUID FLOW INSTABILITY AND MICROSTRUCTURE EVOLUTION IN THE INCLINED LASER PROCESSING OF METAL SURFACE COMPRISING IMPURITIES

S. Lugomer[1], A. Maksimović[2], G. Peto[3], A. Karacs[4], A.L. Frenkel[5 §]

[1,2]Material Physics Department
"Rudjer Bošković" Institute
Bijenička, c. 54, Zagreb, 10001, CROATIA
[1]e-mail: lugomer@irb.hr
[2]e-mail: maks@irb.hr

[3,4]Research Institute for Technical Physics and Material Sciences
Hungarian Academy of Sciences
P.O. Box 49, Budapest, H-1525, HUNGARY
[3]e-mail: peto@mfa.kfki.hu
[4]e-mail: karacs@mfa.kfki.hu

[5]Department of Mathematics
University of Alabama
Tuscaloosa, Alabama, 35487-0350, USA
e-mail: frenkel@hotmail.com

Abstract: We have shown that laser surface processing under an angle generates surface morphology which comprises localized structures analogous to gravitationally caused nonlinear instabilities on the inclined plate. The presence of the low and the high melting (boiling) point metal and nonmetal impurities causes instability evolution at the rate much higher than on the pure metal. The fluid surface dynamics influenced by impurities causes formation of irregular long-range structures in the peripheral regions, and irregular short range ones in the central regions of the spot. Thus, chaotic dynamics appears in the whole interaction space, indicating the loss of memory of the initial conditions.

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[§]Correspondence author

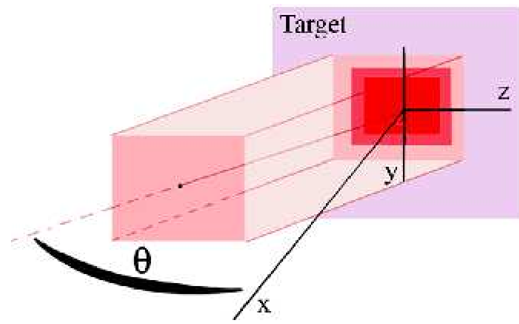

Figure 1: Schematic view of the laser irradiation of Ti sample under $\theta = 20^o$. The x axis of the coordinate system is normal to the target surface; the y axis is directed spanwise, and the z axis streamwise and in the target surface.

1. Introduction

Modification of surface properties by pulsed laser-matter interactions (LMI) is a well established process, based on the nonlinear and nonequilibrium dynamics and surface self- organization. Such processes change the surface morphology by generation of capillary waves, nonlinear solitary waves, breaking waves, coherent structures and localized surface phenomena [3]. Evolution of surface structures depends on the laser and the material parameters, and on the interaction configuration as well. The configuration of technological interest is the inclined LMI which causes flow instability in the molten layer due to the transfer of laser shock-momentum to the fluid layer. The emerging nonlinear flow instability [6] which is similar to the gravitational flow instability on the inclined plate [11, 9, 7, 5, 10] , is qualitatively well described by the the Frenkel model [1, 2, 4, 6]. A laser pulse of Gaussian power profile causes the formation of an inhomogeneous pattern of surface structures [6]. These structures on pure titanium take the form of long-range parallel stripes (indicating regular dynamics) in the peripheral regions, and of the short-range intermittent ones (indicating chaotic dynamics), in the central regions of the spot [6]. However, the influence of material composition, the presence of surface particles and impurities on the structure evolution which was experimentally observed [8] was not studied yet.

In this paper we present for the first time, the influence of metal and nonmetal impurities of the low and the high melting (boiling) points, on the evolution of surface structures in LMI.

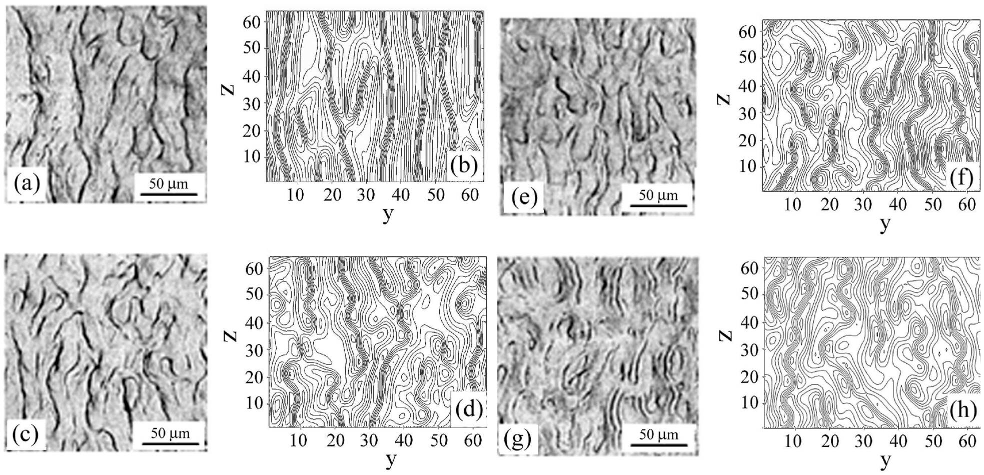

Figure 2: Comparative view of the optical micrographs of surface flow structures in various regions of the spot on Ti comprising impurities and of numerical simulation. a) Periphery region (PR). Remnants of the long-range periodic (z-oriented) instabilities. b) Numerical simulation of the structures in Figure 2a.(t = 52). c) Near periphery region (NPR). Periodic z-oriented structures, perturbed by transversal oscillations in the y-direction. d) Numerical simulation of the structures in Figure 2c.(t = 91). e) Near central region (NCR). Intermittent structures. f) Numerical simulation of intermittent structures in Figure 2e (t = 112). g) Central region (CR). Chaotic, short-range structures. h) Numerical simulation of chaotic short-range structures in Figure 2g (t = 202–210).

2. Experimental Details

The experiments were performed on the plates of $\geq 95\%$ Ti comprising impurities. By the Auger electron spectroscopy, the presence of Na, Fe, Sr, and Mo metals, and of Se as the nonmetal element, was identified. The Ti target of $\sim$ 1mm thickness was irradiated in vacuum of 10^{-3} Pa by a rectangular Gaussian pulse of a Nd:YAG laser (Es 8.5 J/cm^2, $\tau = 40$ ns), in the inclined position under $\theta = 20^o$, as shown in Figure 1.

A laser pulse has generated thin fluid layer on the target which was accelerated in the z-direction (collinearly with the beam direction), showing the flow instability. At the end of the pulse fast solidification occurs so that the fluid structures stay frozen permanently thus making a posteriori study possible.

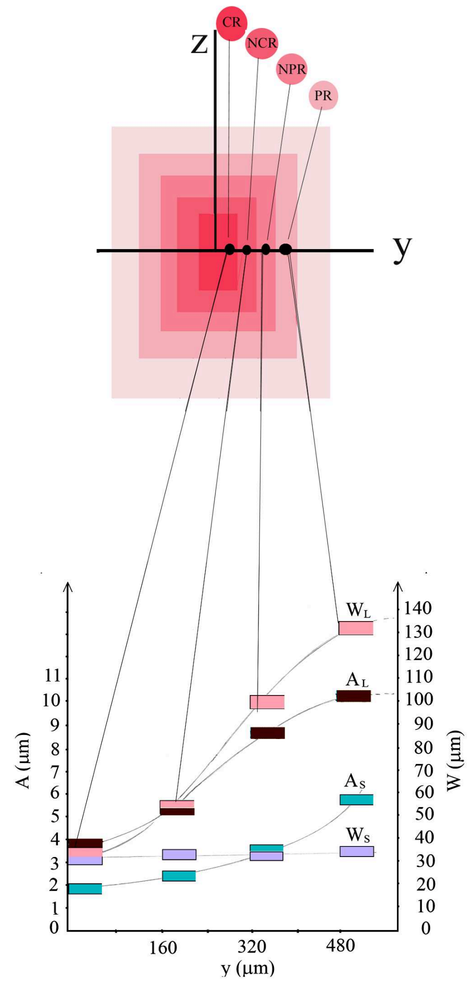

Fig. 3

Figure 3: Diagram of the wavelengths, W_L and W_S, and of the amplitudes A_L and A_S, of instabilities in the PR, NPR, NCR and CR of the spot. [Subscripts L and S relate to the long and the short wavelengths (amplitudes), respectively].

3. Results, Numerical Simulations and Discussion

Laser irradiation of target generated an inhomogenous pattern of surface flow structures which can be divided into four characteristic regions: the central region (CR), the near-central region (NCR), the near-periphery region (NPR), and the periphery region (PR) of the spot, respectively. Figure 2. The analysis of the structures in these regions is based on their juxtaposition with the structures obtained by numerical simulation. Assuming the small-amplitude regime ($u = h - 1 \ll 1$; $u =$ amplitude, $h =$ film thickness), the 3D Navier-Stokes equations can be reduced to the single 2D evolution equation, which after rescaling can be transformed into 2D canonical form with only two input coefficients (Frenkel)[1, 4, 6]:

$$u_t + u\,u_z + u_{zz} - \kappa u_{yy} + \nabla^4 u + \lambda \nabla^2 u_z = 0\,, \tag{1}$$

where $\kappa = \cot\theta/\delta$ and $\lambda = 3/(We\delta)^{1/2}$. By definition $\delta = (4Re/5 - \cot\theta)$ is a positive constant, Re and We are the Reynolds and the Weber numbers, respectively. [$Re = h_0 U/\nu$], and [$We = \sigma/2\rho\nu U$], and h_0 is the average fluid film thickness, $U =$ fluid velocity ($U = U_0 \sin\theta, \nu =$ kinematic viscosity, $\rho =$ fluid density and $\sigma =$ surface tension). The second term stands for nonlinearity, the third represents instability, the forth and fifth ones are due to surface tension, and the last term represents dispersion generated by viscosity [1, 4, 6].

Assuming the solution $u \propto \exp\left[i\left(k_z z + k_y y\right)\right]$, the equation 1 can be expressed as a combination of the F-modes. Simulations were performed in the square cell of the size $L \times L = [64 \times 64]$ using the Runge-Kutta scheme, and assuming the initial condition [6]:

$$u(z, y, 0) = A\,\left[\cos(Mky) + \frac{1}{4}\mathrm{randn}(L)\right] \tag{2}$$

where M is the number of periods ($M = 4$) , $A =$ perturbation amplitude ($A \sim 10^{-3}$), and $k = 2\pi/L$ [6]. Estimating the fluid velocity $U_0 \sim 5000$m/s, kinematic viscosity $\nu \sim 10^{-6}\mathrm{m/s}^2$ [6], and the average liquid metal film thickness $h_0 \sim 4\mu$m, one finds $Re \sim 7000$, $We \sim 36443$, $k \sim 0.00049$, $\delta \sim 5597$, and $\lambda \sim 0.00021$.

The juxtaposition of numerically generated structures shows a very good agreement with the experimental ones (see Figure 2). Irregular remnants of the long-range instabilities in the z- direction disturbed by mixing with the background fluid are observed in the PR (see Figure 2a). These structures can be favorably compared to the numerically simulated ones in Figure 2b, obtained for t = 53. The irregular structures in the NPR (Figure 2c), can be compared to those obtained by simulation for t = 91 (see Figure 2d). The intermittent NCR structures that show tendency to chaos (Figure 2e), can be compared to those obtained for t = 112 (see Figure 2f). Finally, the short-range CR chaotic structures in Figure 2g can be compared to those obtained for t = 202–210 which show tendency to the solitarylike organization at some attractor

[4, 10, 6] (see Figure 2h).

The analysis of the evolution rate of structures indicates different fluid dynamics in various domains during the same pulse of 40 ns. The short-range chaotic structures that appear at longer times have much higher evolution rate than the irregular long-range ones appearing at short times. Therefore, by the end of pulse, the structure evolution in the PR and the NPR is stopped in the late phase, while in the NCR and the CR structures reach very late phase of evolution. It is surprising that the evolution rate of structures in the CR and the NCR is $\sim$ 3–4 times higher-than the evolution rate in the corresponding regions on very pure titanium.

The analysis of the wavelength and the amplitude of instabilites has shown nonlinear variation over the spot (see Figure 3). The wavelength, W_L of the long-range instability increases from about 37 μm in the CR and the NCR, up to the largest value in the PR where it reaches the saturation level off $\sim$ 136 μm. The corresponding amplitude A_L which is $\sim$ 3.8 μm in the CR, increases up to 9.8 μm in the PR, where it also reaches the saturation level. The wavelength, W_S of the short-range instability of $\sim$ 35 μm is constant in all regions of the spot, while the corresponding amplitude, A_S increases exponentially from $\sim$ 1.8 μm in the CR to $\sim$ 5.5 μm in the PR (see Figure 3). The wavelength of the long-range instabilities, W_L is about an order of magnitude larger-than W_L on very pure titanium, see [6].

4. Conclusion

Irradiation of titanium comprising imputrities of very low and very high melting (boiling) points, by a Gaussian laser pulse under $\theta = 20^o$ has generated an inhomogeneous pattern of structures. Random variation of surface melting and boiling rates as well as of vaporization of low-boiling-point elements, represents an additional random perturbation that accelerates the transition of instabilities into irregular and chaotic structures. While the irregular long-range structures are for $\sim$ 150–200 μm shorter, their wavelength, W_L and amplitude, A_L are many times larger-than the corresponding ones on very pure titanium [6]. The tendency to saturation of W_L and A_L indicates the limit for the shock momentum transfer to the fluid layer with increasing distance from the center of a Gaussian spot. It is surprising that the evolution rate of chaotic structures is 3–4 times higher than that on very pure titanium. The qualitative agreement of instabilities and numerically generated ones, indicates that initially regular states are strongly perturbed in all regions of the spot. Thus, both, the irregular long-range and the chaotic short-range structures indicate the loss of memory about the initial conditions. The observed effects indicate the existence of a deeper connection with the funadamental physical aspects of the phenomenon, which require an additional study.

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