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Real-Time Measurement of Materials Properties at High Temperatures by Laser Produced Plasmas

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Determination of elemental composition and thermophysical properties of materials at high temperatures, as visualized in the context of containerless materials processing in a microgravity environment, presents a variety of unusual requirements owing to the thermal hazards and interferences from electromagnetic control fields. In addition, such information is intended for process control applications and thus the measurements must be real time in nature. We will describe a new technique which we have developed for real time, in situ determination of the elemental composition of molten metallic alloys such as specialty steel. The technique is based on time-resolved spectroscopy of a laser produced plasma (LPP) plume resulting from the interaction of a giant laser pulse with a material target. The sensitivity and precision have been demonstrated to be comparable to, or better than, the conventional methods of analysis which are applicable only to post-mortem specimens sampled from a molten metal pool. The LPP technique can be applied widely to other materials composition analysis applications.

The LPP technique is extremely information rich and therefore provides opportunities for extracting other physical properties in addition to the materials composition. The case in point is that it is possible to determine thermophysical properties of the target materials at high temperatures by monitoring generation and transport of acoustic pulses as well as a number of other fluid-dynamic processes triggered by the LPP event. By manipulation of the scaling properties of the laser-matter interaction, many different kinds of flow events, ranging from shock waves to surface waves to flow induced instabilities, can be generated in a controllable manner. Time-resolved detection of these events can lead to such thermophysical quantities as volume and shear viscosities, thermal conductivity, specific heat, mass density and others.

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Determination of elemental composition and thermophysical properties of meterials at high temperatures, as visualized in the context of containerless experimentation in a microgravity environment, presents a variety of unusual requirements owing to the thermal hazards and interferences from electromagnetic control fields. In addition, such information is transient in the sense that the target specimen is undergoing a change of state either due to material processing or it is stimulated for certain responses, and thus the measurements must be real-time in nature. We describe a new technique developed for real-time, in-situ determination of the elemental composition of molten metallic alloys such as specialty steel. The technique is based on time-resolved spectroscopy of a laser produced plasma(LPP) plume resulting from the interaction of a giant laser pulse with a material target. The sensitivity and precision have been demonstrated to be comparable to, or better than, the conventional methods of analysis which are applicable only to post-mortem specimens sampled from a molten metal pool. The LPP technique can be applied widely to other materials composition analysis applications.[1-5]

The basic concept is to determine elemental composition by time- and space-resolved spectroscopic analysis of a plasma plume, as produced by a high power laser pulse incident on molten metal, under real-time in-situ conditions. Analysis of molten metal composition by laser produced plasmas(LPP), as conceptualized above, represents a creation of completely new technology from the very fundamental level physics of laser-matter interactions. As such, the research program has had to deal with the extraordinary challenge of making an efficient connection between the newly gained knowledge of the dynamical properties of laser produced plasmas and the task of design and construction of applications hardware for a physically brutal environment of metals production furnaces.

The question then boils down to how to produce the LPP plume off the molten metal surface such that elemental abundances can be determined in a highly reproducible manner, uninfluenced by the variabilities in the thermodynamic and environmental variables. It is understood that each full anlysis is carried out with a single laser pulse. Each LPP plume must consist of elemental consitituents in exact proportion to the elemental composition in the condensed phase of the target material. This has required extensive experimental and theoretical studies on laser-matter interaction and the lessons from them have indeed been reduced to a rule of thumb.

The LPP analysis concept has been implemented in the form of a prototype sensor-probe.

In order to make a connection between the new LPP methodology and the long-standing analysis establishment, we have first directed attention to analysis of solid alloy specimens. The elemental composition data from the LPP method have been successfully compared with the results for the same specimens analyzed by the conventional analytical techniques such as spark discharge emission spectroscopy and X-ray fluorescence.

Extensive studies have been made of the various issues of LPP analysis of molten metals using a number of different sources. Combining the experimental investigation with our own numerical code studies, we have developed a general picture of the differences between the response to a laser excitation when an alloy specimen is in a liquid form and that when in a solid form. We have also confirmed that all the requisite spectroscopic properties for elemental analysis exist of the LPP plume off the molten metal surface. The prototype LPP sensor-probe has been successfully demonstrated as a survivable real-time analysis tool under full exposure to a steelmaking furnace.

It is worth stating that the LPP method opens up new opportunities for materials analysis because of its very information-rich nature. It is possible to make a strong connection between the microscopic morphology of an alloy, as can be interrogated by the LPP mehtod, and its macroscopic performance properties, such as resistance against wear, corrosion or fracture. It is also possible to explore the interface properties of composites by the LPP method because, on one hand, an LPP event can lead to a thermal pulse, acoustic pulses or a shock wave, which can be used for diagnostics, and, on the other, the interfaces can influence the growth of the LPP plume.

From the standpoint of the containerless experimentation under microgravity, the LPP methodology can play many useful roles. The case in point is that it is possible to determine thermophysical properties of the target materials at high temperatures by monitoring generation and transport of acoustic pulses as well as a number of other fluid dynamic processes triggered by the LPP event. By manipulation of the scaling properties of the laser-matter interaction, many different kinds of flow events, ranging from shock waves to surface waves to flow induced instabilities, can be generated in a controllable manner. These phenomena are in themselves of considerable interest in the microgravity context. In addition, time-resolved detection of these events can lead to such thermophysical quantities as

viscosity
thermal conductivity
specific heat
mass density
surface tension
latent heat of melting
critical properties
elastic properties and others.

Of particular interest is the fact that the LPP method can create a supercritical state of the target, which can be studied at the same time.

The LPP method can play a crucial role in unravelling the near-the-surface density profile and chemical reactions at high temperatures because of its intinsic ability to interogate sub-nanosecond and micron-size features.

On the other end of the possibilities, the LPP method can provide an extremely effective means for exacting manipulation of the target specimen for rotation and translation, without requiring any materials injection.

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