Three-Dimensional Velocity Field Characterization in a Bridgman Apparatus: Technique Development and Effect Analysis

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Abstract

The integrity of crystal structures is strongly influenced by the existence of thermally-induced flows as well as local nucleation and growth in the melt, which may act in a detrimental manner. In both ground-based and microgravity material processing, these velocity and particle fields need to be measured to identify their effects on the processing. In spite of the efforts to alleviate these problems, their influence cannot be completely eliminated. Consequently, providing means for detecting three-dimensional (3-D) three-component (3-C) velocity or particle fields and characterizing pertinent solidification parameters is very important for crystal growth experiments in optimizing production parameters. It is also vital to validation and improvement of numerical process modeling. In this effort, two complementary optical techniques have been developed and tested for the measurement of 3-D 3-C particle or flow motions, which reflect the peculiar aspects of restricting experimental conditions in crystal growth. One, termed Holographic Diffraction Image Velocimetry (HDIV), utilizes double-reference-beam off-axis recording and reconstruction of two independent time-sequence images of a particle field. The other, called Stereoscopic Imaging Velocimetry (SIV), is based on dual solid-state camera observation. These two techniques are believed to meet a broad range of experimental requirements, being complementary with respective strengths and limitations. The HDIV technique offers velocity extraction of an extended area with high spatial resolution and dynamic range from a single observation direction but it does not provide a real-time capability. It is also complex in setup. In contrast, the SIV technique is appropriate for observing a restricted area with limited resolution and dynamic range but it allows continual real-time detection. It can also provide a simple experimental configuration.

A breadboard setup for HDIV has been built and testing of the technique has been conducted for evaluation of the concepts, data acquisition systems, and processing algorithms. The testing has proven HDIV to be a viable candidate for the accurate measurement of 3-D 3-C flow velocities of a particle field, intentionally seeded or formed by natural nucleation. The strengths of the technique include greater experimental freedom in volumetric field illumination and observation, both of which can be arbitrary in direction and shape. These features are very necessary in conducting crystal growth experiments. Conventional two-dimensional (2-D) particle image techniques require sheet-beam illumination normal to the observation direction. Three-dimensional in-line holographic techniques require direct forward illumination, which demands large particle seeding to produce a sufficient reference/object beam ratio. The HDIV approach can thus allow the capture of smaller particles with lower laser power for improved detection of motions with higher resolution and miniaturization of the setup. Unlike conventional 2-D techniques, no specific particle focusing is required during the recording of velocity and particle size information. The use of cross-correlation for in-plane measurements eliminates the problem of velocity sign ambiguity associated with the conventional auto-correlation based on photographically-superimposed-image methods. The HDIV technique is tested in various situations and operational modes. The effects of emulsion shrinkage, wavelength change, and plate mispositioning in recording and reconstruction are also investigated for remedial solutions to minimize the effects. In-plane displacement measurements show that the accuracy is limited only by the finite pixel size of the image digitizer. For the out-of-plane measurements, motions on the order of fractional depth of focus of the image acquisition system have been detected based on image correlation. If the approach of comparing intensity variances is adopted, they can further be improved even though the computation processing is very intensive. The HDIV method has been applied to measure a

flow around a sphere for its performance assessment under a practical environment since the flow characteristics have been very well understood.

The SIV approach is based on the quantitative measurement of 3-D particle fields by using two CCD sensors that record data from different vantage points. The SIV measurement consists of camera calibration, particle identification through image-superposition decomposition and centroid detection, particle tracking for each camera image, and stereoscopic 3-D matching of individual particle tracks. Images of individual particles or equivalently data points are not completely recoverable during the process of centroid identification of individual particles and the optimization phase of particle tracking. In order to maximize the data recovery and to enhance the measurement accuracy, neural networks are implemented in these two phases of processing. For tracking, the back propagation neural network has proven to be very useful in particle identification and overlap decomposition because of its ability and efficiency in pattern recognition and classification. The test results demonstrate higher efficiency and speed in identifying single or superimposed particles as compared with conventional models. The tracking algorithm takes as its input the particle positions found in the particle identification process. It then provides the output of particle image track assignments across time-sequence image frames. The utilization of the Hopfield neural network has proven to be very successful in attaining potentially valid tracks, that is, identifying those that correspond to a global optimization scheme. The developed Hopfield neural network is a purely global technique that not only consider all possible track combinations but also consider the effects of all the other tracks competing for an assignment. For the approach, experimental measurements have been conducted with the developed prototype hardware and software to assess the performance of the technique.

With current investigations focusing on the improvements to processing speed and achieving yet higher resolution and dynamic range, it is believed that these 3-D 3-C techniques can become an viable tool for applications to flow velocity and particle size characterization in crystal growth. Future investigation will be focused on the applications of these techniques to the crystal growth investigations including microgravity experiments. These involve miniaturization of the experimental systems and further refinement of the processing algorithms.