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EXPLODED BRIDGES

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PULSED LASER STEREO PHOTOGRAPHY OF ELECTRICALLY EXPLODED BRIDGES*

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Abstract

A technique is described for obtaining short exposure (~ 8 ns) high resolution photomicrographs of electrically exploded bridges using a pulsed laser for bridge illumination and band-pass filters to eliminate the intense self light. Two cameras are described, one for a small field of view (~ 1 mm) and one for a relatively large field of view (~ 20 mm). A carbon disulfide cell and a fiber-optic light guide are used to essentially eliminate speckle, which normally limits the resolution of laser photographs of diffuse surfaces. A series of photomicrographs showing the detailed burst characteristics of both flat and round bridges are shown.

Introduction

When a thin conducting wire or foil is pulsed with a very high electric current, it is rapidly heated to extreme temperatures, followed by an explosive expansion of the vaporized conductor. Despite the numerous studies of these exploding bridges, their hydrodynamics remains poorly understood. In our recent investigation of burst phenomena, we have employed framing photography to record the detailed expansion history of the bridge. Conducting wires or foils with dimensions ranging down to ~ 0.04 mm are typically pulsed in a low-inductance capacitor discharge circuit, resulting in substantial vaporization and expansion during periods as short as a few tens of nanoseconds. Consequently, exposure times of a few nanoseconds and spatial resolutions of a few micrometers are needed.

We have developed a special, high-resolution framing camera technique capable of stereoscopic photomicrography of these small bridges. In contrast to the usual electro-optic methods for shuttering a high speed camera, the extremely short exposure times are achieved by modulating the output of a giant-pulse laser that illuminates the bridge. A particular advantage of this technique is that, despite the intense self-luminosity of the bursting bridge, a photograph of the vaporized surface illuminated by an external source can be obtained by using narrow band-pass filters that block most of the self-luminosity, yet transmit the reflected laser illumination.

The standard output pulse from the giant-pulse ruby laser** (~ 20 - 25 ns) is somewhat longer than desirable for these applications. Consequently, an auxiliary, rapidly switched Pockels cell was used in conjunction with the giant-pulse laser to reduce the pulse width to ~ 8 ns. Another drawback in using laser illumination arises from the degradation in photographic image quality by the random speckle pattern associated with the high spatial coherence of the laser beam. This was largely alleviated by passing the laser beam through a carbon disulfide (CS_2) cell and fiber-optic diffuser.

With this framing technique only one exposure is obtained per bridge; therefore, when a sequence of frames is needed, a series of nominally identical bridges must be photographed at different times.

Framing Micrography SystemStereo Optical System

A schematic of the camera system is given in Figure 1, showing the laser components and the stereo optical arrangement.

A number of performance requirements and constraints influenced the camera design. Generally, after establishing the intensity of illumination by the laser pulse (~ 0.20 J in ~ 8 ns), the actual object size and necessary depth of focus dictated the optimum lens aperture and magnification for maximizing the resolution of the system. Two camera systems were developed; a high-magnification (20X-40X) system for viewing small foils and wires (typically 1-mm long by 0.04 -mm diam) and a lower magnification camera (~ 2 X- 5 X) for photographing relatively large (up to about 20-mm square) flat conducting foils. A 16° stereo viewing

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**Model K-1000, manufactured by Korad Corp., Santa Monica, California.

angle was chosen as an acceptable angle for maximizing depth discrimination (which calls for high stereo angles), yet does not substantially exceed the maximum stereoscopic angle of the human eyes (corresponding to viewing an object at the near point of the eye).

Fig. 1. Schematic of pulsed laser stereo photomicrography system.

Fig. 2. Schematic of Stereo camera designs.

When photographing wires (in contrast to large flat foils), the objective lenses are aligned perpendicular to their respective optic axes, as illustrated in Figure 2(a). The bridgewise axis is then aligned along the intersection of the two viewing-direction focal planes, i.e., perpendicular to the plane of the paper in Figure 2(a), so that the entire length of the wire is equally in focus. For these high-magnification framing pictures, a matched pair of 59-mm focal length, f/8 microscope objectives were used for the objective lenses, resolving ~ 130 lines/mm at the object plane.

When photographing large flat foils, it is necessary to align the lens' symmetry plane parallel to the foil surface as shown in Figure 2(b), to keep all parts of the conductor surface in focus. Because of the generally poorer performance of a lens when used in an off-axis orientation, high quality, wide angle objective lenses (Goerz Dagor f/6.8) were used at a magnification of $\sim 4\times$, with a resolution of ~ 40 lines/mm.

A high resolution, red sensitive film* was used to record the camera images. The magnification was made sufficiently large so that the resolved detail projected onto the film is large compared to the film resolution, thus minimizing the resolution degradation due to the film.

A pair of 36-mm diam, ~ 1.5 -nm band-pass filters, centered on the 694.3-nm ruby light, were positioned on the long focal length side of each objective lens, as shown in Figure 2. The location of these filters has an important effect on their performance; they are designed for approximately collimated light so they must be located on the longer focal length side of the lens; and if not positioned some distance from the film plane, secondary off-axis interference fringes generated by the filter are superimposed on the image. Consequently, they were positioned as near as possible to the objective lenses.

Laser Pulse Chopper

In its standard configuration, the giant-pulse laser consists of a ruby laser oscillator (that incorporates a Pockels cell switch) and a laser amplifier section. It typically produces a 1- to 4-J, 694.3-nm pulse with a beam diameter of ~ 10 mm. Shortening the laser pulse is accomplished with the arrangement depicted in Figure 3. The polarization of the linearly polarized ~ 25 -ns pulse from the oscillator section is rotated with a quarter-wave plate and transmitted through an unactivated Pockels cell and onto a Glan prism. The quarter-wave plate is not essential to the operation of the pulse chopper; it merely allows the laser to be easily converted from the chopped to unchopped mode. The Glan prism is

*Kodak Linagraph Shellburst #2476, manufactured by Eastman Kodak Co., Rochester, NY.

oriented so that the polarized beam is totally reflected out of the laser optic axis, and focused onto one electrode of a nitrogen-filled spark gap.

The initial portion of the oscillator laser pulse, when focused near the spark gap electrode, is sufficient to cause electrical breakdown of the gap, switching the high voltage of the charge line onto the Pockels cell. When activated by this voltage, the Pockels cell rotates the beam polarization by 90° so that it is now transmitted by the Glan prism into the amplifier section of the laser.

Fig. 3. Schematic of laser pulse chopper.

The "on-time" of the Pockels cell is determined by the duration of the electrical pulse, i.e., by the length of the charge line. By selecting an appropriate charge line length, and introducing a short delay line between the spark gap and Pockels cell, a central 8-ns portion of the oscillator output pulse can be selected for amplification.

Laser Speckle Reduction

Laser speckle, which normally limits the resolution of laser illuminated photographs of diffuse surfaces, was largely eliminated by passing the beam from the amplifier section through a CS_2 cell and fiber-optic light guide. The intense electric field of the laser pulse produces a time dependent change in index of refraction of the CS_2 , which in turn produces a nonuniform frequency shift that reduces the beam coherence. The unaligned fiber-optic light guide provides mixing of the beam and allows for illumination of the entire object with a relatively broad-band light source.

Experience has shown that both the CS_2 cell and fiber-optic light guide are necessary to eliminate the laser speckle; however, either one produces some reduction, as shown in Figure 4. Figure 4(a) shows the speckle without either the CS_2 cell or the light guide, 4(b) shows some speckle reduction with the light guide only, 4(c) shows the reduction with the CS_2 cell only, and 4(d) shows the improvement with both the CS_2 cell and the light guide. It is seen that the spatial coherence was sufficiently destroyed with the beam configuration in 4(d) so that no discernible degradation in resolution resulted from laser speckle. A more complete description of this technique is given in Reference 3.

Fig. 4. Photomicrographs of a USAF resolution test chart for four laser illumination configurations: (a) without either the CS_2 cell or light guide, (b) with the light guide only, (c) with CS_2 cell only, and (d) with both the CS_2 cell and the light guide.

Applications

Photomicrographs of Flat Foils

Typical photomicrographs of flat bridges are shown in Figures 5 and 6. Times shown under each frame are referenced to the "burst time", which is taken to be the time of maximum electrical resistance of the bridge. The maximum resistance ordinarily occurs at about the time of complete vaporization of the bridge, just prior to arc breakdown in the vaporized metal.

Fig. 5. Typical photomicrographs of flat bridges. The three frames in (a) are of a 10-mm square aluminum bridge and the four frames in (b) are of a 1-mm square aluminum bridge.

The three frames in Figure 5(a) are of a 10-mm square aluminum bridge and were photographed with the low-magnification camera. For comparison, Figure 5(b) shows four frames of a 1-mm aluminum bridge, that were taken with the high-magnification camera. Considerable detail of the burst dynamics are shown for both cases: the black vapor clouds first appear near the sharp corners and then envelope the entire bridge.

Figure 6 shows a series of photomicrographs for a 0.5-mm long by 0.18-mm wide by 0.025-mm thick gold/glass bridge. For this inhomogeneous material, the burst characteristics are somewhat different. Vaporization commences in the cracks and micropores of this irregular material, spreads across the conductor, and not until well after burst time is the entire surface vaporized.

Fig. 6. Typical photomicrographs for an inhomogeneous gold/glass bridge.

Stereo Mapping

Standard stereo mapping techniques, using a stereo comparagraph, (4) can be used to determine the surface uniformity of metal foils being driven by an exploding bridge. Figure 7 shows a typical contour plot and the photomicrograph of an aluminum flying foil being driven up a cylindrical barrel (1.1-mm long by 1.5-mm diam) by a 1-mm square bridge. A center line on the near surface of the barrel was used as a zero reference for all of the contours. (The vertical reference lines in Figure 7 show the barrel surface to be slightly tilted away from the viewer from left to right.)

Fig. 7. Photomicrograph and corresponding stereo contour plot for an aluminum flying foil being driven up a cylindrical barrel (1.1-mm long by 1.5-mm diam) by a 1-mm square bridge.

Photomicrographs of Bridgewires

A sequence of photomicrographs showing burst phenomena for 0.039-mm diam by 1-mm long gold wires is shown in Figure 8. The upper frames in each figure were taken using a shadowgraph technique, i.e., by backlighting the wire with the laser light and using a single channel of the stereo camera. The lower frames were taken by reflected illumination. Some nonuniformity in burst is seen as early as -66 ns, with a small quantity of vapor appearing at the wire surface. A striated character of the expanding material is developed quite early (-47 ns) and persists to the late time of +82 ns.

Figure 9 shows a series of 0.039-mm diam by 1.0-mm long gold wires exploded in water. Compared to wires bursting in air, the expansion in water is seen to be relatively uniform. A distinct shock wave is visible at about 27 ns before burst and becomes more prominent at about the time of burst. Care must be exercised in determining expansion diameters of these wires due to the lens effect of the shocked water.

a

b

Fig. 8. Typical photomicrographs for 0.039-mm diam by 1-mm long gold wires. Upper frames are shadowgraphs and lower frames were taken with reflected laser light.

Fig. 9. Typical photomicrographs for 0.039-mm diam by 1-mm long gold wires exploded in water.

Conclusions

With the careful consideration of camera design, elimination of laser speckle, and pulse shortening, a pulsed laser stereo photomicrography technique provides sufficient time and spatial resolution to reveal detailed expansion characteristics of relatively small electrically exploded wires and foils.

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