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Understanding the Richtmyer-Meshkov Instability in the High-Energy-Density Regime

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Fusion, the process that produces thermonuclear reactions in the sun, may someday be a solution to the world's energy problem as a virtually inexhaustible, relatively clean, and cost-effective energy source. For several decades, researchers worldwide have been investigating several approaches to initiate and control thermonuclear reactions. These methods involve the creation of a hot, dense plasma (an electrically conducting fluid composed of freely moving ions and electrons) heated to millions of degrees and held together long enough to produce useful energy through fusion reactions. One method, known as inertial confinement fusion (ICF),[1] implodes a pearl-size spherical capsule (a common geometry used in ICF experiments) that contains fusion fuel: deuterium (D) and tritium (T). Laser energy (or x-rays generated by the lasers) is deposited on the outside of the capsule, which ablates and drives shocks in towards the DT fuel. The fuel is ignited and burns for less than a billionth of a second. Ideally, the inertia of the highly dense plasma should hold it together long enough to produce fusion conditions. But achieving sustained thermonuclear fusion under laboratory conditions is difficult and has therefore become a "Grand Challenge" problem for the United States science community.

As shocks pass through material interfaces, they create Richtmyer-Meshkov Instabilities (RMI)[2,3] that "mix" the different materials. In *high-energy-density* ICF experiments using the Omega laser[4] at the Laboratory for Laser Energetics (University of Rochester), researchers are performing a series of implosion experiments to gain a better understanding of RMI. If not mitigated, the RMI creates "mixing" that introduces impurities into the fusion fuel. Impurities can dilute and cool the fusion fuel and quench the thermonuclear reaction. Although the typical ignition capsule used in ICF experiments is spherical, measuring the extent of mix at target interfaces in a sphere is difficult, if not impossible. For our RMI experiments, we used a cylindrical target that allows us to measure and observe mix axially along the interfaces while they are converging.

Understanding "Mix" in Fusion Reactions

The target assemblies used in our experiments were composed of materials with different densities (Figure 1). In each assembly, a small epoxy cylinder (outer target layer) was filled with polystyrene foam (inner target layer); an aluminum marker band with corrugations (perturbations) in its outer surface was inserted between the epoxy cylinder and the foam (Figure 1). The areas subject to RMI in these experiments involved two regions on the target assembly: (1) the interface between the epoxy cylinder and the marker band and (2) the interface between the marker band and the foam.

Fifty of the 60 Omega lasers illuminate the target assemblies with 18 kJ of energy. This energy heats them to extreme temperatures causing approximately one-half of the epoxy cylinder to vaporize and expand outward (away from the cylinder), while the other half is pushed inward (implodes) by a strong shock wave—a pressure force that travels faster than the speed of sound in the material. The passage of the shock wave through the target assembly heats

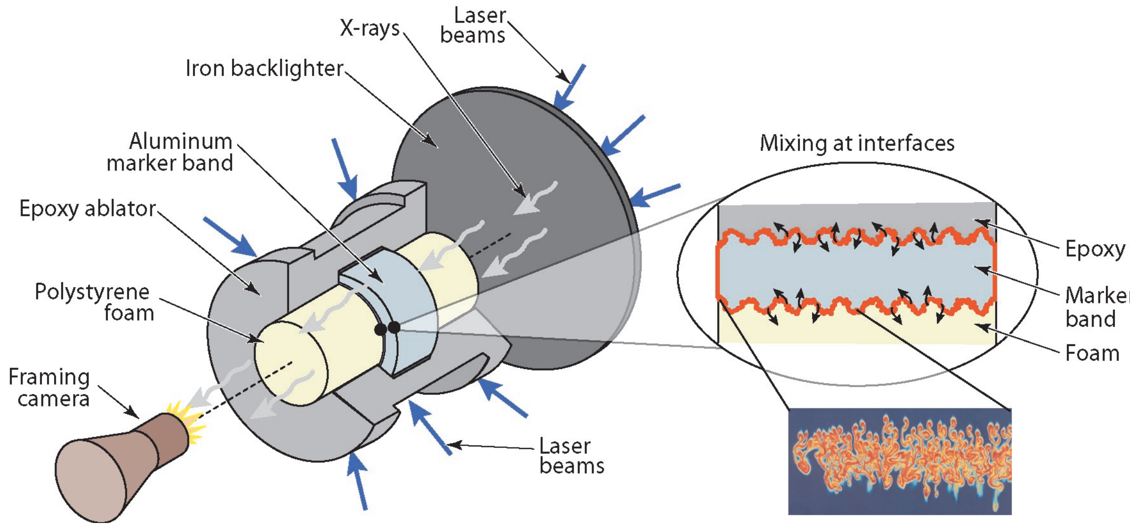
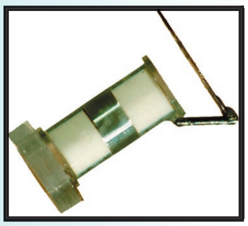


Figure 1. Rendering of a typical target used in the RMI experiment. These targets are about 2.25 mm long and 1 mm in diameter. A rough surface is machined into the outside of the aluminum marker band. The inset shows mixing at the interfaces. The target below (oriented in the same position as the rendering of the target) and an image of "mix" obtained from an advanced simulation are shown.



the target materials and causes them to become plasmas. As a result, the interfaces along both sides of the marker band are accelerated, and the materials mix over time. The danger of RMI is that if the mixing becomes severe enough in an ignition capsule, fusion reactions end, and thermonuclear ignition—the ultimate goal of all ICF experiments—fails. To measure the amount of mixing, 5 additional laser beams from Omega strike an iron foil at one end of the cylinder after a small time delay. X-rays are emitted, travel lengthwise through the cylinder, and are collected by a framing camera that records 16 images through a pinhole. Each image spans approximately 60 ps, and the 16 images are distributed over 1 ns.[5]

Richtmyer-Meshkov Instability

The Richtmyer-Meshkov instability is a hydrodynamic instability driven by the passage of a strong shock past an interface between two fluids. Any perturbation present at the interface will grow proportionately with time. Most previous research into RMI has been done with intentionally seeded, simple perturbations in a flat geometry. Our recent high-energy-density RMI experiments[6,7] had several distinct features over these other RMI experiments. We imploded a cylindrical target to capture the same effects of a *convergent* geometry as those in an ICF capsule implosion. The target material in our RMI experiment was *compressible*—that is, the density increased when the shock passed through it. In addition, the materials that comprised the composite target in our experiments were *miscible* and could therefore mix freely into one another. Moreover, we were interested in studying the effects of shock waves in the *strong-shock* regime where Mach (supersonic) numbers are greater than 10. With such strong shocks, the RMI grows in proportion to the Mach number. Finally, the Reynolds number was about 1 million, which placed the fluid flow well into the turbulent fluid regime. (In fluid mechanics, the Reynolds number is the ratio of inertial to viscous forces. A high Reynolds number means that the flow can become turbulent because the viscosity of the fluid does not damp the effects of any local disturbance.) Currently, no accepted theoretical or computational model exists for explaining such complex environments. Experimental data in such regimes are needed if controlled thermonuclear fusion energy is eventually to become a reality.

The critical measurement and signature of the RMI in this experiment is the expansion of the interfaces of the radiographically opaque marker band into both the foam and epoxy. A typical datum is displayed in Figure 2a in which the transmissive inner foam, the opaque marker band, and the translucent epoxy outer layer are visible. Data in these experiments were azimuthally averaged to make quantitative comparisons with advanced computer simulations. The width of the marker layer is defined as the difference between the inner and outer 50% transmission points (Figure 2b), and systematic parallax effects are removed. By analyzing each of the 16 images obtained in one experiment and then repeating the experiment with different measurement timing, we can record an entire implosion history (Figure 3).

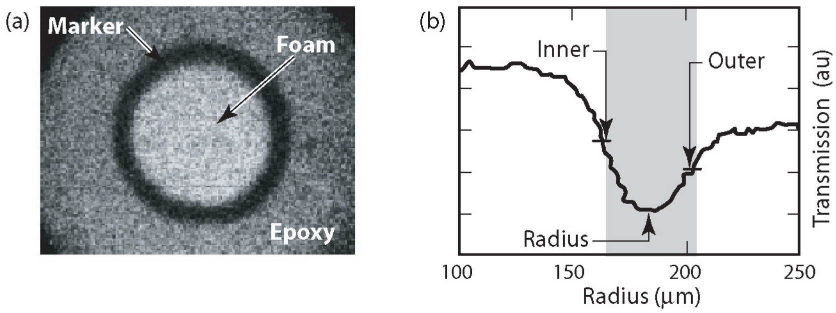


Figure 2. A radiographic image of a smooth aluminum marker (a). The average radial profile (b) is obtained from an azimuthal average of the transmission.

The computer modeling used in the RMI experiments excellently reproduced the marker widths and the position of the marker bands with initially very smooth marker surfaces. Both the experiment and the code show a steady increase in the marker width as the cylinder implodes, reaching a maximum width when the cylinder has reached minimum volume. As the cylinder "bounces" or expands, the marker width decreases.

The key scientific question that we are trying to answer is how do surface imperfections—that is, the initial conditions—affect the evolution of the RMI? We addressed this question by machining surface features (like the thread of a screw) along the length of the outer surface of the aluminum marker band. Surface perturbations like these produce a much wider marker band than do initially smooth bands (Figure 2). Randomly rough surfaces are not seen to mix any more than initially smooth surfaces.

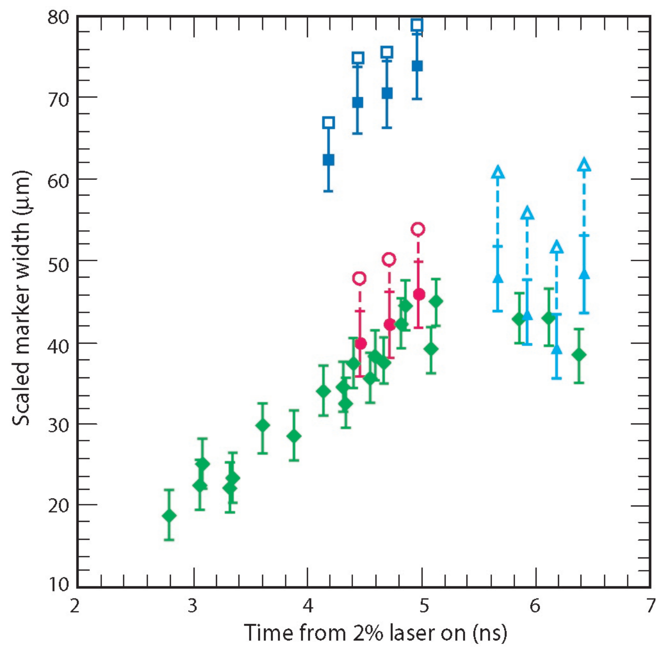


Figure 3. The measured marker-width evolution shows that the marker increases in width until about 5 ns when the cylinder reaches maximum compression. The data points at even larger marker widths are for targets that had the marker surface prepared in a particular manner (i.e., screw thread) to enhance mixing.

A conceptually much simpler outer surface is an azimuthally varying sinusoidal surface, like a tube with corrugations running the length of the tube.[8] This direct analog to numerous planar experiments is readily simulated with several different advanced computational codes and is potentially tractable theoretically. Such targets have been manufactured and experimentally tested. Figure 4 shows the experimental data from three experiments where the number of oscillations was 8, 16, or 28. The initial peak-to-valley size of the perturbation (6 μm) was the same for each experiment. Based on measurements and modeling of planar experiments, we expected that the size of the perturbations in our experiments would be directly dependent on the number of initial perturbations. In other words, we expected the growth in the 28-perturbation target to be 3.5 times larger than the 8-perturbation target at the same time. However, as shown in the data of Figure 4, this did not happen. In fact, the perturbations in all three cases (the 8, 16, or 28 perturbation targets) have approximately the same amplitude. Simulations using complex codes actually predicted the same trend. We are still determining the physical reason for these results in ongoing work.

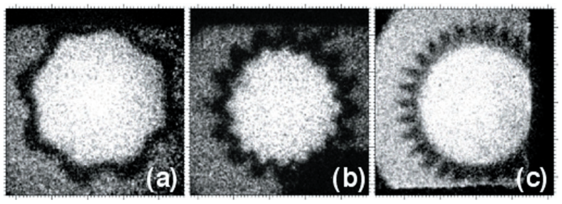


Figure 4. Axial radiographs of single-mode sinusoidally perturbed targets with mode numbers of 8 (a), 16 (b), and 28 (c).

Conclusion

The fundamental physical explanation for these results—that some types of surfaces grow whereas others do not when a strong shock is applied—is not known. Our experiments found that the type of perturbation at the interface affected the subsequent level of instability growth. Computer simulations were able to reproduce some of the results (Figure 4) but not others (Figure 3). We are pursuing experimental and computational lines of inquiry to understand the physics and modeling of these simplified experiments. Computational modeling is using features of the advanced codes, such as modern mix models and three-dimensional simulations, to address these issues. Experimentally, we implemented improvements to the framing-camera diagnostic to improve its spatial resolution. These improvements seem to have increased the quantitative accuracy of these experiments. We are also pursuing focused experiments on the effect of perturbation wavelength. Besides full-surface perturbations, the effects of material defects, like those seen at the joint of a beryllium capsule during implosion, are being investigated. Finally, we are measuring the effect of a second shock on the marker layer. Future experiments in convergent, compressible fluid instabilities in the presence of strong shocks are being planned for the National Ignition Facility.[9] These cylinders will be imploded by soft x-ray radiation, which will allow faster implosion velocities, the use of larger cylinders, and better relative resolution of the mixing zone.

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