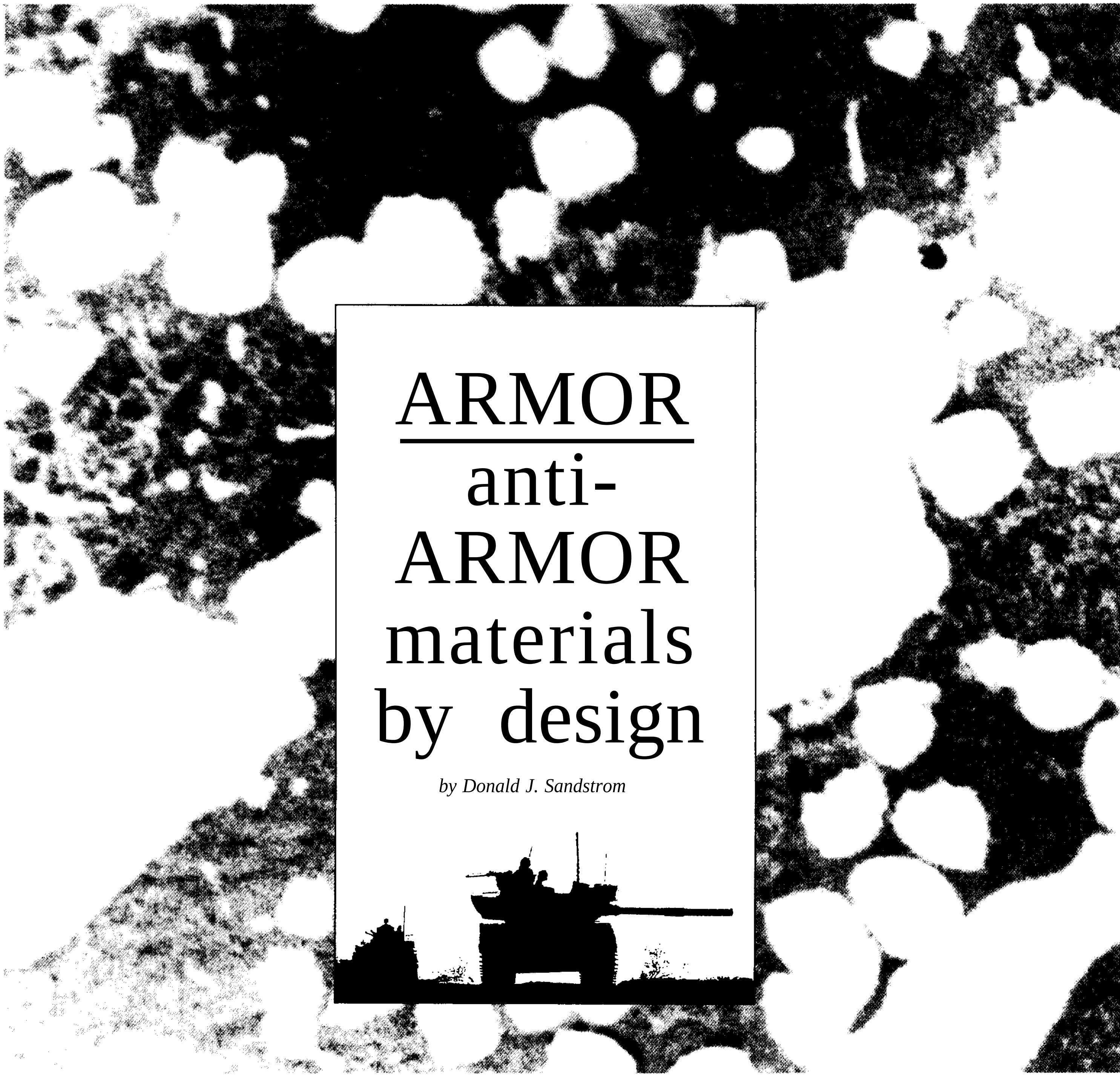


# ARMOR anti-ARMOR materials by design

*by Donald J. Sandstrom*

Imagine tank armor that chews up a high-velocity projectile on impact . . . or composites of tungsten and uranium that lend an antitank penetrator rod the stiffness of the tungsten. the density and py - rophoric property of the uranium, and the surprising strength of their mixture or tiny crystal grains aligned in a sheet of uranium that allow it to stretch into a long, lethal jet of unbroken metal. These examples illustrate how Los Alamos is using its knowledge of materials to design and fabricate new and stronger components for both armor and penetrators of armor.

Our interest in applying ma-

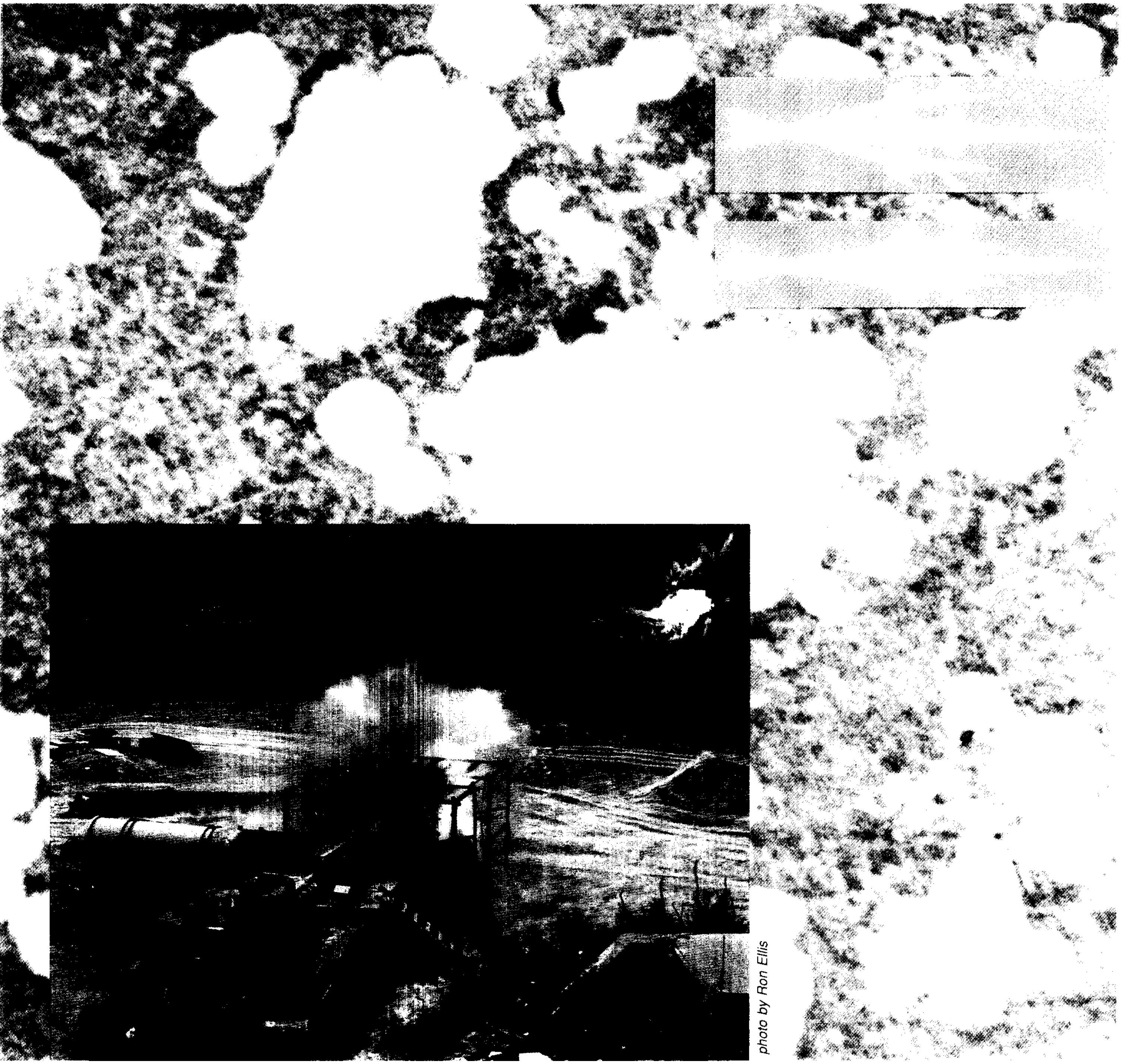


photo by Ron Ellis

terials research to conventional weapons has its origins in the Laboratory's nuclear weapons program. To deal with the unique materials used in nuclear weapons, such as actinides, special ceramics, polymers, and so forth, the Laboratory had to develop significant expertise in materials research. Further, the iterative process of theory, design. fabrication, and testing used to develop nuclear weapons serves as the basis for a similar process in developing conventional ordnance. The attention to detail in material properties required for nuclear weapons is, perhaps, even more important for conventional weapons.

There is also a complementarily between the applications of materials in conventional and nuclear weapons-one that has a synergistic effect on both programs, A nuclear weapon releases so much energy so rapidly that materials behave much like isotropic fluids and can usually be described by hydrodynamic equations. In addition, the performance of a nuclear device is more dependent on the nuclear and atomic properties of its constituents than on material properties, In contrast, a conventional munition subjects materials to less severe deformation rates, and the deformation processes are more dependent on the chemistry and prior fabrication history of its constituents. For example, the behavior of an armor-piercing projectile is strongly affected by variations in the chemical composition. processing history. microstructure, and mechanical properties of the materials from which it was formed.

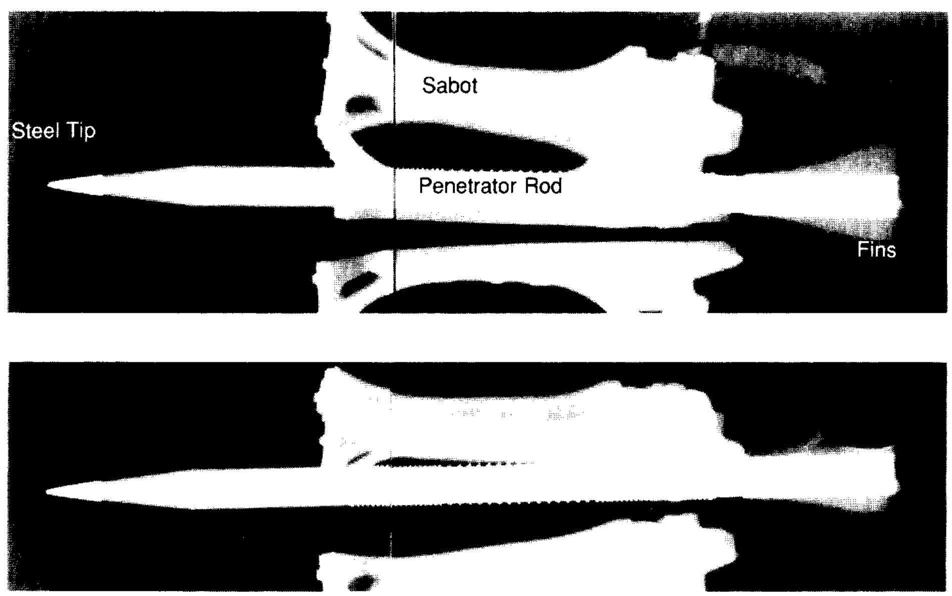
Further, nuclear reaction times are extremely short, whereas the reaction times for conventional munitions are of the order of microseconds-sufficiently long to allow for many types of measurements. And generally. very little, if any, material is recoverable from a test of a nuclear weapon, whereas a test of a conventional weapon frequently leaves a considerable amount of material for post-mortem analysis,

The philosophy underlying the design of nuclear weapons at Los Alamos is traditionally conservative (in the most positive sense), especially in regard to reliability and ease of production. Our approach to conventional weapons follows the same philosophy and pays the same close attention to detail. We strive to use well-characterized, wel1-understood starting materials, we carefully control the synthesis and manufacturing processes. and wc work to develop a complete understanding of the experimental results. Only in this way are we able to relate the performance of armor and anti-armor systems to slight and often subtle variations in material properties or device design and fabrication. I will point out many of' those subtleties as I discuss advances made at Los Alamos in the design of armor penetrators and armor, including some surprising properties of a new type of ceramic armor.

A KINETIC-ENERGY PENETRATOR

**Fig. 1. These x-ray pictures are orthogonal views of the U. S. Army's M-833 standard round (a fin-stabilized, sabot-discarding projectile for tanks) taken after the round had traveled about two and a half meters from the muzzle of the tank gun. The central rod, or core, is a kinetic-energy penetrator made from a dense, hard alloy of depleted uranium and titanium, and the tip is hardened steel. The sabot is a device that allows the pressure of the expanding gas from the burning propellant to accelerate the core and sabot assembly out the barrel of the gun. The sabot is discarded after the core exits. These pictures show the beginning of the sabot-core separation. Also, note that the lower view reveals a bent fin on the core.**

**Two Orthogonal Views**




## Kinetic-Energy Penetrators

Weapons designed to penetrate armor generally fall into two classes: *kinetic-energy penetrators and chemical-energy penetrators.* I will discuss the first class now and return to the second later,

A kinetic-energy penetrator is a solid projectile, usually fired from a gun, that uses high-velocity impact (typically, at about 1 to 2 kilometers per second) to defeat the armor. Examples range from the simple spin-stabilized slug of a 30-mm cannon to fin-stabilized projectiles that consist of a long, steel-tipped penetrator rod and a sabot that falls free of the penetrator after it is tired (Fig. 1 ). If the material strength and kinetic energy of the projectile are sufficient, it penetrates the armor, In addition, the shock wave generated by the impact may travel through the armor plate and blow off a portion of its backside. Fragments both from this *spall* and from the penetrator itself can cause considerable damage to people and equipment behind the armor.

**Depleted uranium.** Materials research has made particularly noteworthy contributions to the design and development of the kinetic-energy penetrator. The most effective armor-piercing material to date is an alloy developed at Los Alamos—an alloy of depleted uranium (most of the fissionable isotope has been removed) and a small amount of titanium (0.75 per cent).

Depleted uranium was considered an attractive material for kinetic-energy penetrators for a number of reasons. Its high density (almost twice that of steel) makes it easy to produce a penetrator that delivers high momentum and kinetic energy to a small volume of target armor. Uranium is highly pyrophoric, and its impact against steel targets at velocities as low as 30 meters per second produces burning fragments that can ignite fuel or propellants. In addition, depleted uranium is readily available in large quantities and is considerably cheaper than alternative materials.

Uranium, however, is more reactive than most other penetrator materials, and its reactivity can result in corrosion problems, particularly in moist air. In addition, some uranium alloys are susceptible to delayed cracking due to residual stresses induced by fabrication and heat treatment of the rods. The cracking can be avoided if care is taken in the heat treatment to reduce such stresses and to reduce entrapped hydrogen gas to levels less than a few parts per million.

Extensive testing at Los Alamos of uranium alloyed with various metals at different concentrations and processed in a number of ways showed that the alloy with 0.75 per cent titanium had the best combination of properties. The alloy has both reasonable corrosion resistance and high penetration effectiveness. It can be heat-treated easily (by water-quenching and subsequent aging in a high-vacuum furnace) to eliminate the cracking problem, and its properties are not sensitive to precise composition. These last two features help give the alloy low manufacturing costs.

The alloy was originally developed and evaluated at Los Alamos for the U.S. Air Force's GAU-8 system, a 30-mm gatling gun system mounted on the A-10 close support aircraft. The gun can fire a thousand armor-piercing penetrator rounds per minute and is said to be the most effective antitank system in the world. The uranium-titanium alloy was so successful that it has been adopted as the standard for large-caliber penetrators (such as the one shown in Fig. 1).

## Dynamic Deformation and Fracture

The penetrating ability of armor-piercing rounds improves with the hardness and strength of the material used. Mechanical properties of this nature are normally determined from the *stress-strain curve* for that material (Fig. 2). Stress is the force per unit area applied to a sample, and strain is the relative deformation of the sample as a result of that stress. Various kinds of deformation can occur (elongation, compression, bending, etc.) depending on the nature of the applied force. If stress to the material is kept below the so-called *yield point,* or proportional limit, the material will spring back to its original undeformed state—in other words, the response is *elastic.* Once this yield strength has been exceeded, however, *plastic flow* occurs, and the material remains permanently deformed. The slope of the initial elastic region, called the *elastic modulus,* is a measure of the material's stiffness; the slope of the later inelastic region is a measure of *work hardening* (since it is the amount of stress needed to achieve a given amount of plastic flow).

**STRESS-STRAIN CURVE**

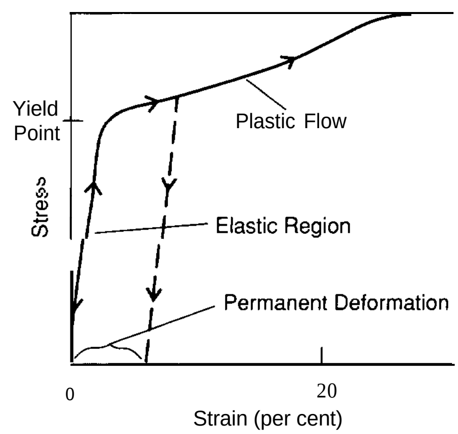



**Fig. 2. Many material properties, such as hardness and strength, are determined from the relationship between stress (the force per unit area applied to the material) and strain (the resulting deformation of the material). The initial, approximately linear part of a stress-strain curve is called the elastic *region* because material stressed in this region will not suffer any permanent deformation when the stress is relaxed (in other words, the stress-strain curve returns to the origin). The point at which the curve leaves the elastic region by bending toward the horizontal indicates the onset of permanent deformation and is a measure of the material's *yield strength.* Beyond that point is the inelastic, or *plastic-flow,* region of the curve. The slope of the curve in the elastic region is the *elastic modulus,* a measure of the material's stiffness. The slope in the plastic-flow region is a measure of *work hardening* since a steeper slope means more stress must be applied to create a given amount of deformation.**

Generally, it is desirable for a penetrator to have a high elastic modulus (high stiffness), high yield strength, and high work hardening. For instance, any energy lost to plastic flow in the penetrator is unavailable for destruction of the armor. Similar considerations are also true of armor materials.

The values of these material properties, however, depend on the *rate* at which the material is strained, and realistic analyses of armor-penetrator impact require knowing both static and dynamic material properties. Static properties are easily measurable. Moreover, they can serve as a starting point for an analysis of the material since dynamic properties often scale in the same direction as the static properties. Nevertheless, it is the dynamic deformation and failure processes that are of paramount interest, and these can only be understood by measuring properties at high strain rates.

The Materials Science and Technology Impact Facility at Los Alamos includes a wide variety of test equipment for determining material properties over a broad range of extreme conditions. Several gas guns are used for high-velocity impact research, and two split Hopkinson pressure bars (Fig. 3), measure the stress-strain behavior of materials at strain rates up to 104 per second.

Figure 4 is illustrative of the influence of strain rate on the strength and behavior of a material—in this case, of depleted uranium. Comparing the high (dynamic) and low (static) strain-rate curves of Fig. 4 shows that at high strain rates the material has significantly higher yield strength and higher *initial* work hardening. But as strain increases the material thermally softens—the slope of the curve, in this case, actually becomes negative, Such factors, of course, must be well characterized if one is to fully understand the performance of a material during ballistic impact.

**Shock waves.** Another factor of great interest for the design of armor and penetrators is the response of materials to imposed shock. It turns out that shock waves generated by the ballistic im-

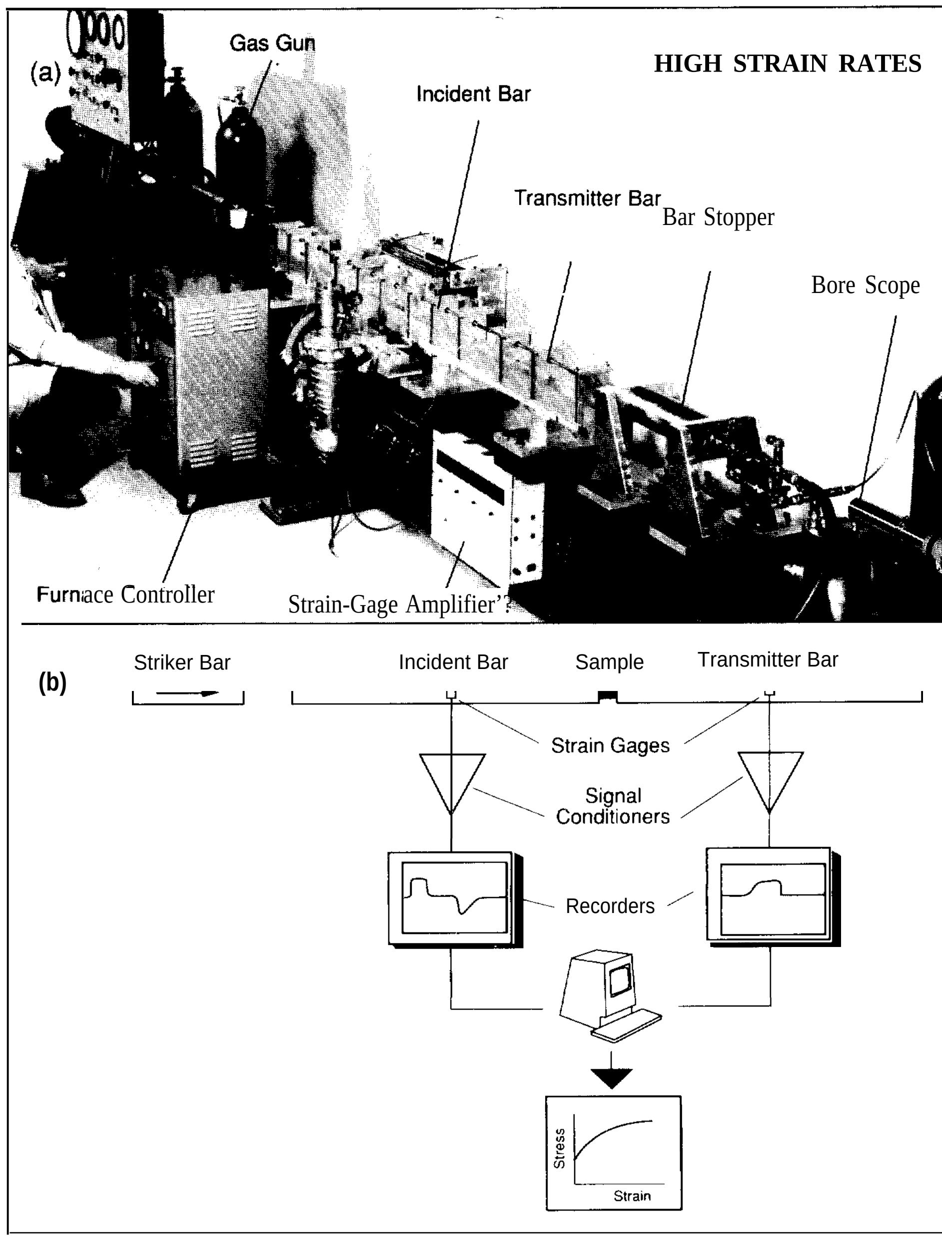



**Fig. 3. (a) The split Hopkinson pressure bar can measure the stress-strain behavior of materials up to strain rates of about 104 per second. Such measurements are performed, as shown schematically in (b), by placing the sample between two pressure bars made from high-strength steel, then firing a striker from the gas gun on the left. The impact of the striker with the incident bar generates an elastic compression wave that travels into the sample, causing plastic deformation of the softer material. A strain gage in the incident bar measures the strain due to the incident and reflected waves, and another gage in the transmitter bar measures strain due to the wave that passed through the sample. These measurements are used to calculate the strain rate within the sample and the stress-strain curve, such as the one show** in red in **Fig. 4. This Hopkinson bar facility is unique in that it can test samples at temperatures as high as 1000°C.**

**DYNAMIC VERSUS STATIC**

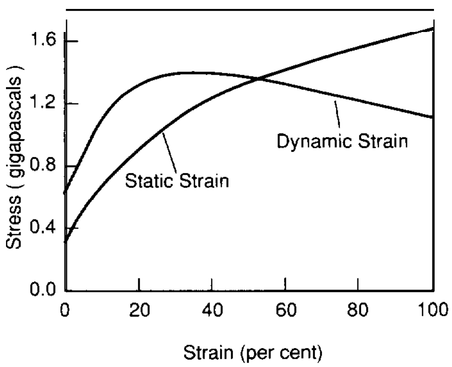



**Fig. 4. Stress-strain curves for depleted uranium at strain rates of 5000 (red) and 0.001 per second (black). The dynamic, or high-strain-rate, curve shows a higher yield point and, initially, higher work hardening, followed by lower work hardening as the material thermally softens. As such, the curve illustrates the influence of strain rate on the strength and behavior of the material. Both samples were initially at room temperature (300 kelvins), but the dynamically deformed specimen reached a temperature of 470 kelvins at 100 per cent strain.**

pact affect the microstructure and the strength of the components—that is, the "as fabricated" properties of the materials are altered by the passage of the shock waves. The massive structural deformations that occur during armor penetration take place in *shock-deformed* material with transformed properties.

To study those changes, we use an 80-mm-diameter gas gun (Fig. 5) to shoot a projectile called a flyer plate at a target of the same material. After impact the shock-deformed sample is recovered, examined for microstructural changes with a transmission electron microscope, and tested for changes in material properties.

Figure 6 displays static stress-strain curves for an aluminum alloy in its as-received state and after being shock deformed at 2, 8, and 13 gigapascals. All four curves were measured using a slow strain rate (0.001 per second). The data show that yield strength increases with increasing shock deformation, but work hardening decreases. By the time the sample has been strained 20 per cent, the decrease in work hardening has compensated for the higher yield strength, and the curves for as-received and shock-deformed material intersect.

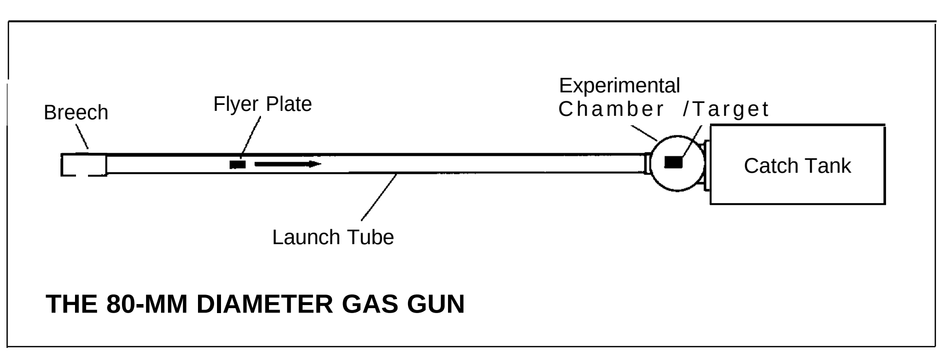
As it turns out, the effect of shock deformation on this alloy is relatively small. Other materials, such as uranium and copper, show much larger changes in their stress-strain curves. In general, we find some materials are very rate and shock sensitive, whereas others are not. Shock-induced changes to materials properties illustrate why it is important to characterize materials carefully and thoroughly.

**Dynamic fracture.** Fracture at high strain rates is another important consideration in armor and anti-armor performance. Although fracture is generally detrimental to penetrators, certain types of armor may, in fact, turn fracture to an advantage.

Because dynamic fracture is a complex process dependent on structure, processing history, strain rate, and stress state, it cannot be fully characterized by a single parameter or measurement. Our approach to a more fundamental understanding is a combined experimental and theoretical effort based on computer modeling. We incorporate into the models the factors influencing dynamic fracture, and then compare code predictions of deformation and fracture with those that actually occur during armor penetration (see "Modeling Armor Penetration").

We are currently studying the dynamics of how voids are initiated, how they grow, and how the generation of such voids leads to ductile fracture—for example, span failure in armor plate. Using the 80-mm-diameter gas gun, the span strength of a material can be determined from axial stress (measured by noting changes in the resistance of manganin gages embedded in the back of the target) or from particle motion at the back surface of the target (by measuring Doppler shifts with a recently installed laser interferometer). Several metals have been studied, including copper, rolled homogeneous armor, and carbon steel. Now that we have mastered the experimental techniques, an investigation of dynamic brittle fracture in ceramic materials is under way.

**Fig. 5. One of the teat devices of the Materials Science and Technology Impact Facility at Los Alamos, an 80-mm-diameter, single-stage, gas gun. In this gun, pressurized gas shoots a projectile, or flyer plate, down the launch tube at a stationary target in the experimental chamber. The flyer plate and target are typically made of the same material, which is the material being tested for changes due to imposed shock.**



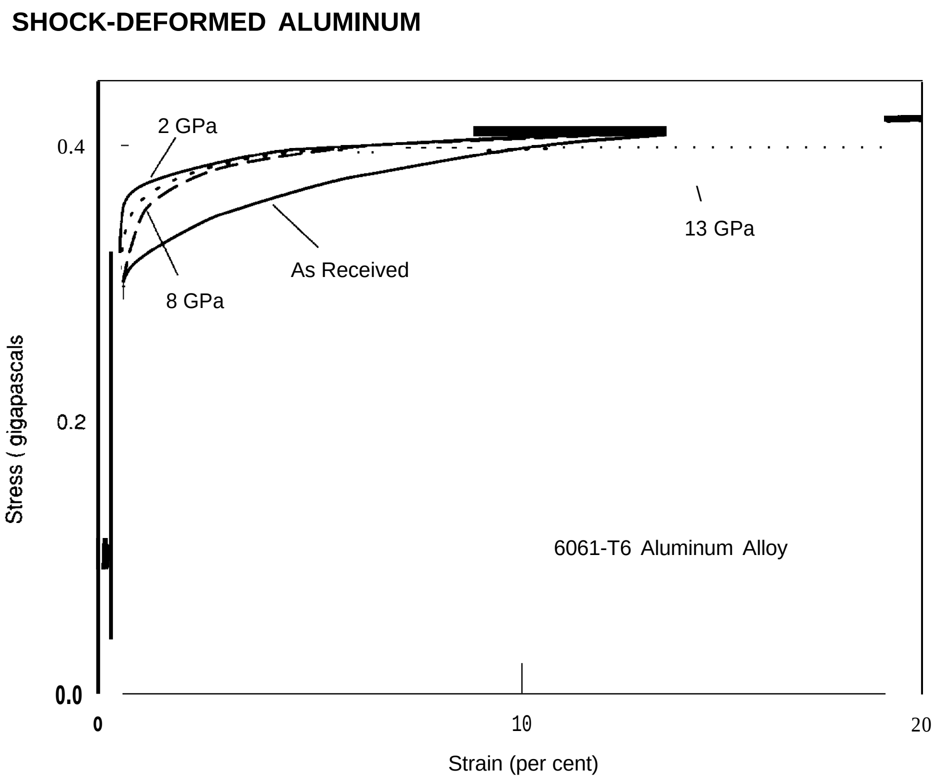



**Fig. 6. The static stress-strain curves of 6061-T6 aluminum alloy as received (black) and after having been shock-deformed (red) at 2, 8, and 13 gigapascals with the gas gun in Fig. 5. The shock-deformed samples show higher yield strengths but less work hardening. The strain rate for ail samples was 0.001 per second.**

One of our main goals in the work on dynamic processes is to develop constitutive relations that describe the stress-strain behavior of materials over a wide range of strain rates, strains, and temperatures. Such relations will increase our ability to predict the behavior of particular systems at a variety of conditions.

As an example, to model deformation and plastic flow we need relations for yield stress and work hardening. The yield stress $\sigma_Y$ at any instant can be described by using an equation of the form

$$\sigma_Y = s(\dot{\epsilon}, T, p)\hat{\sigma},$$

where $s$ is a function of strain rate $\dot{\epsilon}$, temperature $T$, and pressure $p$ and $\hat{\sigma}$ is a parameter (or combination of parameters) that represents the current state of the material. This equation reflects the fact that a material's yield stress *changes,* both because of what is happening to the sample (s) and because of the state of the material ($\hat{\sigma}$), which can have been affected, say, by the previous history of stress loading.

We can then go further by describing work hardening $d\hat{\sigma}/d\epsilon$ with an equation of the form

$$\frac{d\hat{\sigma}}{d\epsilon} = \theta_0 \left[1 - F\left(\frac{\sigma_Y}{\hat{\sigma}_s(\dot{\epsilon}, T)}\right)\right]$$

where $\theta_0$ is an initial work-hardening rate and $F$ is a function of the ratio of the current yield stress to a *saturation* value $\hat{\sigma}_s$ that would be obtained by considerable working of the material at a particular strain rate and temperature. In other words, the slope of the stress-strain curve beyond the yield point depends, among other things, on the current stress history of the sample compared to a state in which further stress loading of a particular type has no effect.

The advantage of the above type of analysis is that the kinetics of work hardening are separated from the conditions that determine the yield stress for a given state. This procedure allows predictions for complex strain-rate and temperature histories, such as are typically found in dynamic impact events. We have developed constitutive relations for model metals and are now extending this work to armor and penetrator materials.

## Composite Penetrators

The Department of Defense has a need for gun-launched kinetic-energy penetrators with length-to-diameter ratios sufficiently high that the rods will penetrate modern armor steel configurations. However, such rods must have high stiffness (that is, high elastic modulus) to resist bending during launch and flight because slight bending may lead to yaw during flight and a glancing blow off the target. The uranium-titanium alloy described above is a marginal candidate for use in the proposed penetrator rods because its elastic modulus is not high enough. Design analysis shows that *composites* of depleted uranium and of tungsten (whose elastic modulus for bending is three times that of uranium) improve the stiffness of the rod and thus, potentially, its performance. The stiffness of the composite rod is directly related to the geometric placement of the high-modulus material in the rod. It is possible to arrange the composite so that maximum stiffening is achieved with the least change in penetrator density.

Early in the development of the composite penetrator, we realized that the difference between the coefficients of thermal expansion of the two materials was sufficiently large that the tungsten either fractured or buckled slightly, causing it to lose collinearity with the penetrator axis. Both these effects, of course, are detrimental to the properties of the composite as a penetrator. We added various metal powders to the uranium component and found, for some. that the coefficients were matched more closely. In fact, both the thermal-expansion coefficient and the elastic modulus were altered according to the "rule of mixtures" (the value of a property of a mixture is the sum of component values, each weighted by the relative concentration of the component).

We tested tungsten-uranium composite rods in which the uranium was reinforced with metallic particles. There was both an expected slight increase in elastic modulus (25 per cent) and an unexpected but significant increase in yield strength. For example, the *tensile* (stretching) yield strength increased from the 25,000 psi (pounds per square inch) typical of cast unalloyed uranium to 110.000 psi in the cast composite, an increase of more than 400 per cent.

The significant jump in yield strength was an exciting bonus. Penetrators cast from the uranium-titanium alloy are brittle and therefore must be heat treated. but heat treatment is expensive, time consuming, and prone to formation of voids in the uranium. Composite penetrators can simply be cast without heat treatment, producing rods with yield strengths in the same range as for uranium-titanium alloy penetrators that have been heat-treated. The results to date have identified an optimum composition of metallic powders that produces rods with both high strength and high stiffness.

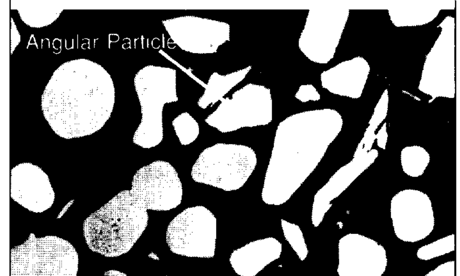
**Another alloy.** Our research on these composites has concentrated on developing material with the highest strength compatible with a low enough powder content to preserve ease of casting. Optical micrographs of both the original powder and a cast uranium-metallic powder material (Fig, 7) show that part of' the powder, after casting, is present in the uranium as a dispersion of coarse particles. However, the particles are smaller and less angular than those found in the starting powder itself, which indicates that part of the metal dissolves in the uranium, forming another alloy. Significantly,, regions of fine particles are also observed: apparently. some of the dissolved metal reprecipitates during the cooling process. Our studies indicate that the precipitation is the principal cause of the strengthening of the material.

The addition of metallic powder to uranium has been so effective in minimizing the mismatch of thermal expansion coefficients in the composite that fabrication of full-scale penetrators have yielded crack-free rods that require no further heat treatment before rnachining (Fig. 8). The simplicity of processing is a significant advantage for manufacture, Further. subscale ballistic tests have shown that uranium-tungsten composite rods can penetrate targets at relatively low velocities, whereas pure uranium rods failed to penetrate the same targets at *any* velocity.

Our work to date on the mixtures of uranium and metallic powder also hints at the possible development of a new high-strength uranium alloy with other highly desirable features not possessed by, say, the heat-treated uranium-titanium alloy. Weldability of' the material is quite good, and bend tests show it to have significantly enhanced ductility' (the ability to be deformed without fracture).

**METAL-POWDER MORPHOLOGY**

Starting Metal Powder




Cast Uranium-Metal Powder

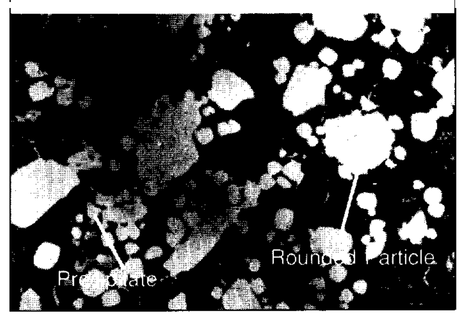


**Fig. 7. These optical micrographs show the changes in morphology that occur when metallic powder is mixed with uranium and then cast at about 1350°C. The fact that the occasional sharply angular regions in the original powder have disappeared in the cast material indicates that part of the metal dissolved in the uranium, and the presence of finer particles in the cast material indicates that part of that dissolved metal reprecipitated on cooling.**

Among the many aspects of the alloy that we of interest and that need to be studied are the following:

- confirmation of the alloy phase diagram. especially the solid volubility of the metal in uranium:
- determination of the precipitation mechanism;
- variation of the metal grain size with thermomechanical processing;
- effect of size and size distribution of

particles in the powder on mechanical properties:

- dependence of fracture toughness and other mechanical properties on temperature;
- large-strain behavior and work-hardening characteristics:
- resistance to chemical and stress-illduced corrosion; and
- relationships between the microstructure and material properties.

**I.ow-pressure plasma spray.** Cost is a major consideration in the development of any armor or anti-armor component. Generally. but not always, the cost of the raw material is only a small fraction of the overall cost of a component. and significant savings can be realized by reducing fabrication costs. In general, we have found that simple materials coupled with reliable engineering and assembly lead to cost-effective components. With that approach in mind, we have investigated low-pressure plasma spraying as a possible fabrication technique for such things as composite penetrators.

The plasma-spray process that we have developed uses a DC-arc plasma-spray torch in a chamber filled with inert gas at a low pressure (Fig. 9). A high-velocity stream of high-temperature plasma melts injected powder particles and propels the molten droplets against a substrate. The result is a rapidly solidified deposit of fine-grained material.

Our facility features a single DC-arc plasma-spray torch with *two* powder-feed inlets. The two inlets allow us to deposit two materials simultaneously. Four axes of manipulation are available between the spray torch and the substrate. Plasma spraying should prove to be faster and cheaper than any other means of fabricating composite penetrators.

## Chemical-Energy Penetrators

As mentioned earlier, the second class of penetrators is the chemical-energy penetrator. This weapon defeats armor by using the chemical energy of a shaped explosive charge, ignited on impact, to propel a metal liner at the target, Typically, the liner is a conical shell bonded to a machined hollow in the charge opposite the detonator with the base of the cone pointing outward toward the target (Fig. 10). The shape of the charge focuses much of its explosive force onto the metal liner. turning it inside out and stretching it to form a long jet of solid material, (In other versions of the weapon, a compact, high-velocity slug is formed.) In effect, the liner becomes a kinetic-energy penetrator but with typical impact velocities of about 7 kilometers per second compared to 1 or 2 kilometers per second for normal kinetic-energy penetrators. Although a kinetic-energy penetrator travels from gun to target at high velocity. a chemical-energy weapon can work even if the device is simply *placed* against the armor and ignited.

Los Alamos has applied much of its knowledge about materials to the development of liners for the chemical-energy weapon, find liners made from unalloyed uranium represent the most effective such penetrator currently available. The fact that the physical and mechanical properties of materials are important determinants of the performance of a munitions component is nowhere more evident than in the case of those liners. For example, the ability of a liner to form a long, stable jet depends in an extraordinary way on both the physical properties of the material and the process-induced mechanical properties.

To achieve ideal performance, a precisely fabricated shell of depleted uranium bonded into the machined cavity of high explosive must, upon detonation. produce a long, thin, *unbroken* jet of metal traveling at a high velocity. The jet elongates in flight and must have sufficient dynamic ductility to prevent breakup before striking the target, Such ductility depends strongly on the metallurgical history of the liner.

When we recognized that jet breakup was highly dependent on the material"s process history as well as on its physical properties, we undertook a program. sponsored primarily by the Air Force Armaments Laboratory at Eglin Air Force Base, to gain a better understanding of how metallurgy affects jet formation. To achieve this understanding, we studied uranium and other metals with different crystal structures. A number of metallurgical factors emerged

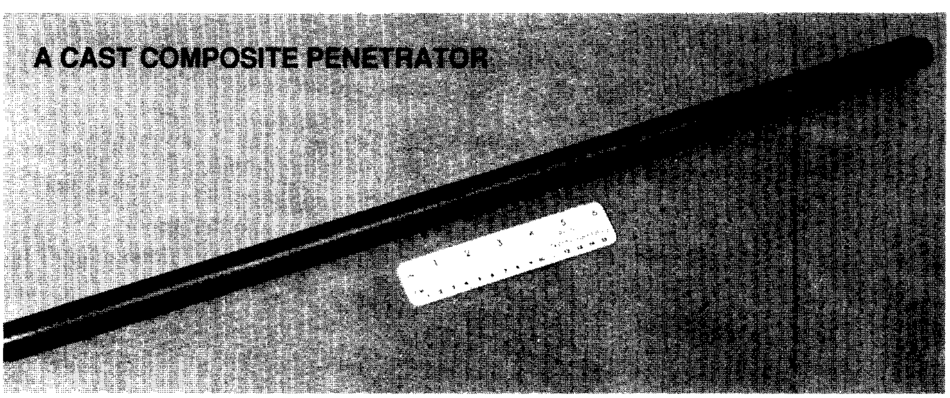



**Fig. 8. Crack-free composite penetrator rods of tungsten and uranium have been successfully formed by more closely matching the thermal coefficients of the two materials. The match was achieved by adding metal powder to the uranium.**

that have an important bearing on liner performance.

The key to these desired mechanical properties is the production of an appropriate crystalline microstructure in the formed liner blanks. To achieve the correct microstructure, we first select a material whose properties are highly sensitive to mechanical deformations and then subject that material to a series of carefully manipulated deformations and heat treatments. To learn more about formation of the preferred microstructure, we monitor our materials carefully during the various stages of deformation. Mechanical properties of the fabricated sheet are measured in three orthogonal directions in the material, crystallographic orientation of the grains are determined using x-ray diffraction, and the development of the microstructure is followed using various metallographic techniques.

In addition to our success with depleted-uranium jets, we have shown that liners with reproducible characteristics can be formed from other metals. In fact, some of our experimental metal liners produce particularly long ductile jets with very late breakup times. The same careful attention to processing history and development of the appropriate crystalline microstructure are critically important for these metals also.

**PLASMA-SPRAY DEVICE**

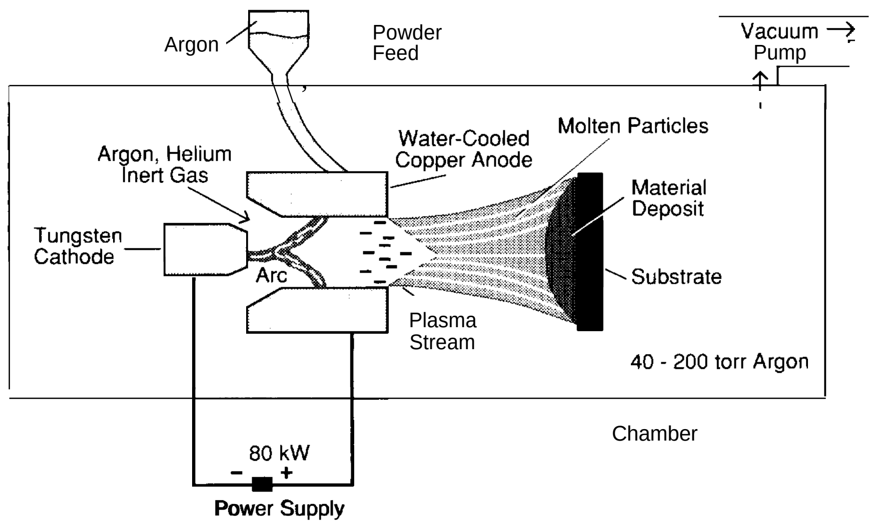



**Fig. 9. This schematic depicts the major components of a low-pressure plasma-spray device being used at Los Alamos to explore the low-cost fabrication of such objects as composite penetrators. An 80-kilowatt arc is generated in a mixture of argon and helium gases by applying a DC voltage across the gap between a tungsten cathode and a cylindrical water-cooled copper anode. The arc creates a high-temperature, high-velocity plasma stream moving to the right. Powder fad into this region collides with the stream, melts, and is propelled as molten droplets onto a substrate,** where it **quickly solidifies, producing a fine-grained deposit. A second powder feed (not shown) allows one to run the feeds simultaneously, producing a layer of mixed material. The whole device operates under a reduced pressure of argon, and the powder feeds operate by being pressurized with argon.**

## Ceramic Armor

The opposite side of the coin from penetrators, of course, is armor. Here also knowledge of material properties is of critical importance to the design of armor packages that will defeat a wide range of penetrators.

Any material used to defeat a high-velocity projectile must deal with the kinetic energy and momentum of that projectile with some combination of three mechanisms: 1) absorption of the energy as heat and deformation in the *target* material, 2) rebound of the projectile, which is how steel armor deals with a steel projectile, and 3) gross deformation of the *projectile.* The last mechanism is the most efficient way for armor to defeat projectiles because most of the kinetic energy is absorbed in the destruction of the projectile itself and, with little rebound of the projectile, momentum transfer to the armor is minimized. Unfortunately, conventional steel armor is not capable of defeating high-hardness projectiles, such as armor-piercing bullet cores and tungsten rods. in this way.

As a result, a variety of armors have been developed, including multilayered composites and *reactive* armor. (Reactive armor has a layer of explosive material that ignites on impact, blowing a facing plate outward to deflect or destroy the projectile. ) However, one of the key problems facing armor designers is weight—a well-armored tank may, in the end, be too heavy to move. As a result, there is a need for armor systems that are light but difficult to penetrate.

One approach to weight reduction has been the use of ceramics, which offer exceptional protection for very light weight. Some of the relevant ceramic materials are aluminum oxide ($Al_2O_3$), silicon carbide (SiC), boron carbide ($B_4C$), and titanium diboride ($TiB_2$), all of which have high hardness with an associated abrasiveness, high compressive and tensile strengths, and good elastic properties to high stress values.

**Microwave processing.** High cost is currently one of the disadvantages of ceramic armor, and, as pointed out earlier, cost is a major consideration in the development of' any weapons component. A significant portion of the cost of ceramic armor lies in the fabrication of monolithic ceramic plates with the required high density. Here, again, we have attempted to reduce fabrication costs—in this case, by using microwave radiation to process the ceramic,

The ceramics of interest for armor materials are currently processed using hot pressing (in which graphite dies apply high uniaxial pressure while the material is slowly heated) or using hot isostatic pressing (in which an inert gas applies high isotropic pressure to the material in a heated chamber). These techniques generate the high densities needed for ceramic armor but are expensive and slow.

Microwave processing, using the commonly employed frequency of commercial [microwave ovens (2.45 gigahertz), achieves the required high densities by starting with cold-pressed ceramic powder and rapidly *sintering* it (heating without melting until the material forms a dense homogeneous mass). Microwave processing is much faster, and therefore less energy-consumptive. than conventional hot pressing, and the equipment needed is considerably less expensive.

Microwave processing also produces a superior material because the heating occurs rapidly throughout the entire volume of material. Traditional processing methods, which depend upon conduction from surface to interior, promote growth of large crystal grains in the material because of prolonged heating, much as overbaking creates a rough, crumbly texture in bread. Microwave sintering couples energy rapidly throughout the material and thereby favors densification of the material over grain growth. The end result is a ceramic with a finer grain size, fewer voids, and fewer stress cracks and thus better mechanical properties, such as greater strength and higher resistance to ballistic penetration.

Microwave processing also offers advantages in the final fabrication steps. Hot pressing can produce only simple shapes that must then be machined into the desired forms. Depending on the density and eventual application of the ceramic, the machining may require many extra hours and the use of expensive diamond-tipped cutting tools. Microwave processing can be applied to shapes close to those required for the ultimate use.

Although microwave sintering of ceramics is not new, we took the process a step further by combining precise positioning in the microwave oven with insulation techniques that reflect and concentrate the radiated energy on the sample. much as snow or sand reflect sunlight back to the skin. The resulting greater thermal efficiency of the process improved the sinterability of difficult materials such as aluminum oxide. boron carbide, and titanium diboride. We have. for example, been able to sinter boron carbide to 95 per cent theoretical density (Fig. 11). The time required to heat the material from room temperature to over 2000 degrees centigrade is under 12 minutes. whereas conventional hot pressing takes several hours. The capital costs for the Los Alamos microwave facility were less than $35,000, whereas a 3-inch-diameter hot press, the equipment needed to density a boron carbide sample of the same size, costs between $120,000 and $200,000. Further, energy costs were cut about 18 per cent.

We are also working on a new com-

**THE CHEMICAL-ENERGY PENETRATOR**

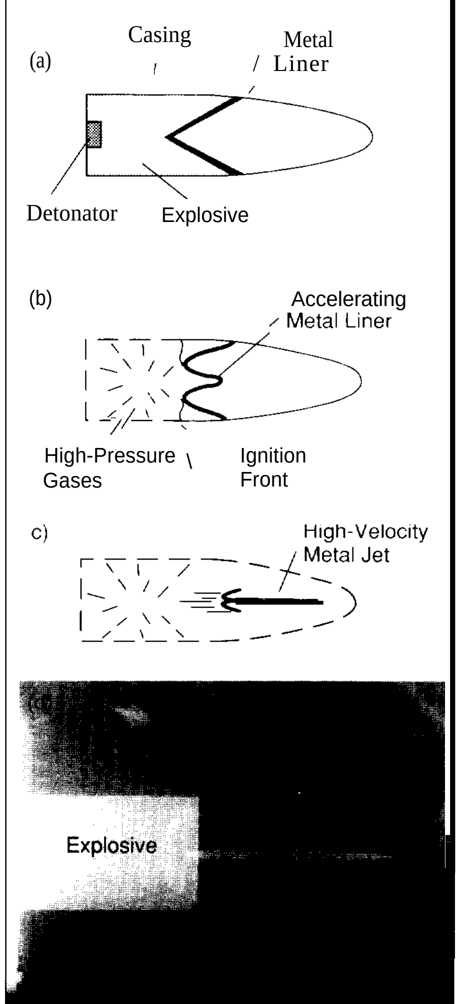
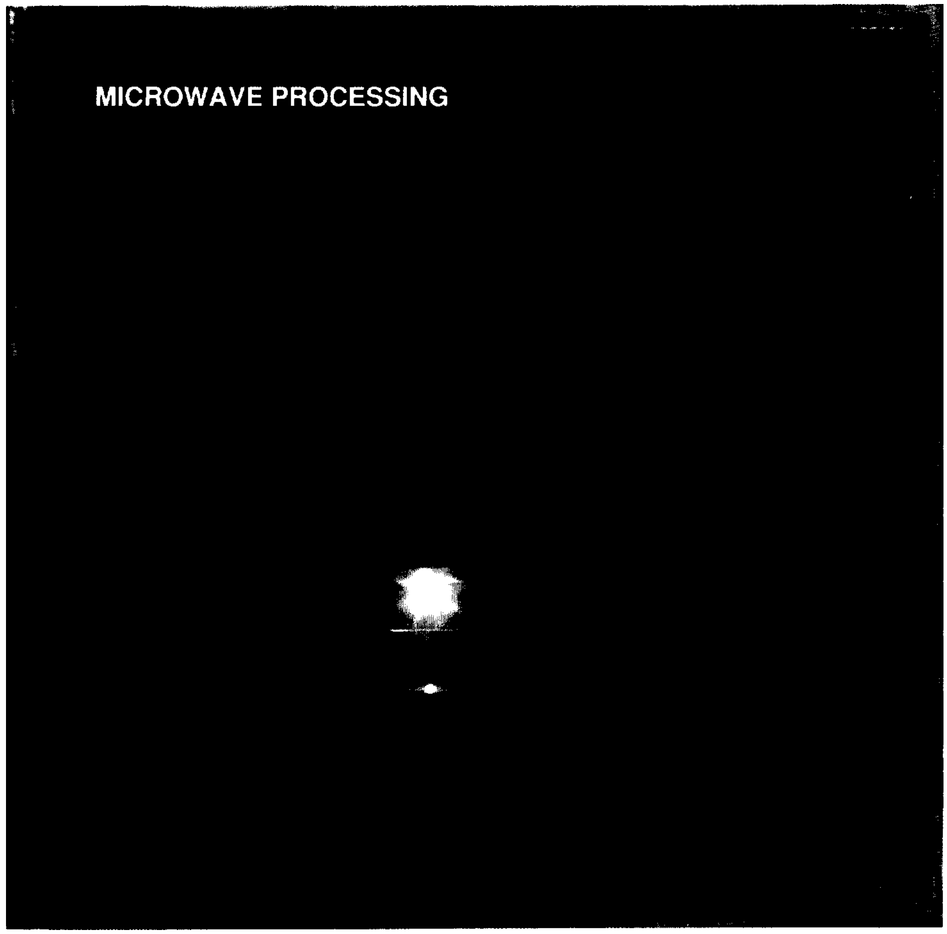



Fig. 10. (a) The conical shape of a typical chemical-energy penetrator is designed to focus the explosive energy of the charge onto a metal sheet (red) that lines the conical hollow. (b) Because the explosive force in the charge reaches the center of the liner first, this region is accelerated before the outer regions. (c) As a result, the liner turns inside out, stretching into a long jet of material. If the metal liner has the proper materials properties, it will form an unbroken jet and will impact the target at a velocity much higher than that of a typical kinetic-energy penetrator. (d) This doubly exposed radiograph of a chemical-energy penetrator shows the shaped charge on the left with, in this case, a hemispherical liner. The image to the right is the solid jet formed when the charge was fired.

posite material for armor applications—aluminum oxide reinforced with platlets of silicon carbide. The platlets, being single crystals, have exceptional tensile strength and can be used to increase the fracture toughness of ceramics, metals, and perhaps even polymeric. Less than 10 minutes of microwave processing are required to produce the new composite at 94 per cent of theoretical density, and we expect that material to have very good resistance to ballistic penetration.




## Ceramic-Filled Polymer Armor

Ceramic armor for, say, lightweight fighting vehicles and armored personnel carriers currently consists of an outside layer of high-density ceramic tile bonded to a backing plate. Conventional wisdom about such armor had suggested that the ceramic should have high impact strength and hardness so it can help break up a sharp, hard projectile. That requirement implies the ceramic should possess high elastic impedance combined with high hardness and high compressive strength.

Another property that had been felt to be important for ceramic armor is high tensile strength. The impact load transmitted through the ceramic produces compressive stress on the backing plate and a corresponding tensile stress on the rear surface of the ceramic tile. The result is plastic yield in the ceramic and the development of a fracture conoid. A ceramic with high tensile strength would resist such fracture.

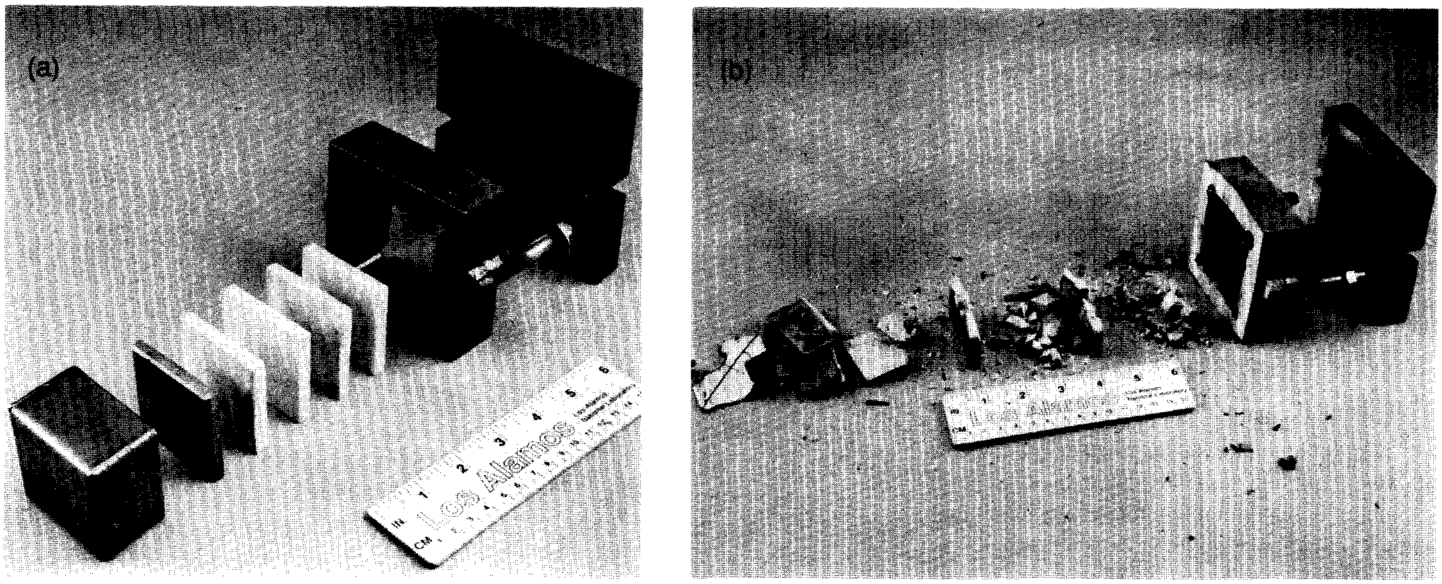
However, research by Mark Wilkins at Lawrence Livermore National Laboratory indicates that the most important mechanism for defeat of a projectile by ceramic armor is abrasion. The fracture conoid in the ceramic spreads from the point of impact and generates sharp fragments that are instrumental in helping to abrade or erode the projectile.

We recently performed a series of ballistic tests on a new type of armor, *ceramic-filled polymer* armor, and the results were exceptional. Our new material typically consists of a ceramic aggregate (about 85 per cent ceramic by weight) mixed with a binding polymer or other carrier. Such a material possesses essentially none of the mechanical properties deemed important for ceramic armor. In fact, the *primary* mechanism for defeat—erosion of the penetrator—depends upon the tendency of the new material to fragment fully.

**Design and fabrication.** The ceramic-filled polymer serves to illustrate the importance of the entire design of an armor package. One of the important properties of this material may be its *dilatancy,* that is, its tendency to readily expand into any free volume when fractured. But whether dilatancy works to advantage in the erosion process may depend critically on how the material is confined.

The effect of packaging on dilatancy can easily be demonstrated by using rice to represent the ceramic-tilled armor and a pencil to represent the projectile. If a pencil is pressed down into a beaker filled with rice, resistance will be slight.

## TESTING CERAMIC-FILLED POLYMER




But if the rice is confined to a flask with a narrow neck, resistance to the pencil will be much larger because the rice is unable to move out of the way of the pencil. Free volume is available for expansion in the first case but not in the second.

Although a complete explanation of the excellent results of ceramic-filled polymer armor has not yet been obtained. it appears that dilatancy is involved, A chunk of unconstrained polymer simply blows away on impact with little or no effect on the projectile. A properly designed armor package, however, totally constrains the ceramic-filled polymer (Figs, 12 and 13), say with a backplate and surrounding layers of a high-performance polymeric fiber like Kevlar©. On impact the only free volume is the hole generated by the projectile itself' as the armor is hit and fractures. The resulting expansion of the ceramic-filled composite generates a very large number of highly erosive ceramic particles that may be forced out between the sides of the hole and the penetrator, eroding the projectile.

These properties, of course, are quite different from those usually thought of as ideal for ceramic armor. In fact, the ultimate tensile strength of' ceramic-filled polymer armor is limited by the strength of the polymer binder, which typically is much lower than that of monolithic ceramic, Another property of the aggregate limits compressive strength—the polymer bonding agent becomes fluid at low applied

**Fig. 12. The before and after of a test of the stopping power of ceramic-filled polymer. (a) The various pieces of the test configuration in the order in which they are put together, including polymer plates (white), the target holder that constrains the polymer (the metal pieces on the left and at the center), and the armor plate being protected by the polymer (the metal piece on the far right). (b) The same pieces after the plates have stopped a projectile without significant damage to the armor plate.**

## CERAMIC-FILLED POLYMER ARMOR

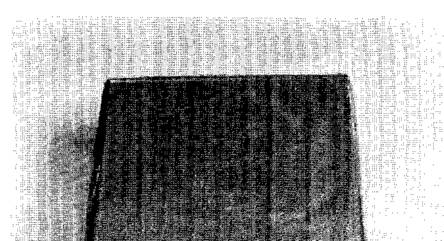



**Fig. 13. This sample of polymeric armor has been cut open to reveal the various layers of ceramic-filled polymeric plates confined beneath Kevlar©. The ceramic used in the front plate (black) is boron carbide; the ceramic used in the other plates (white) is aluminum oxide.**

shear stress. This phenomenon, called *thixotropy,* can be capitalized on during manufacture or repair of the armor because the aggregate-filled polymer will flow under a constant applied forming pressure, allowing the armor to be cast or molded at low temperatures.

Lightweight armor systems are currently made of high-density ceramic tiles—a very expensive process because the ceramic requires high-temperature fabrication and extensive finish grinding. The polymeric armor requires no high-temperature fabrication or expensive finishing steps and can be easily formed to any required shape, including very large and thick or very geometrically complicated shapes. Additionally, monolithic ceramic suffers from a limited ability to withstand multiple hits because of its propensity to break up, whereas polymeric armor, although highly fractured by the impact, mostly remains in place.

Ballistic tests on an armor package containing ceramic-filled polymer tiles have shown exceptional results. On an equal-volume basis the polymer-bonded material is almost equal to a high-density, high-purity aluminum oxide ceramic tile. On an equal-mass basis the ceramic-filled polymer is better!

Ceramic-filled polymer armor can offer four important advantages over conventional ceramic armor:

- a reduction in weight of about 10 per cent since more than 10 per cent of the ceramic is replaced with low-density polymer bonding agent;
- a reduction in manufacturing cost of greater than 50 per cent due to low-temperature fabrication and elimination of expensive grinding steps;
- greater ease of in-field repair since either prefabricated, lightweight tiles or the ceramic and polymer constituents can be stored on board the vehicle; and
- greater ease of accommodating design improvements, such as incorporation of very hard boron carbide plates in the modular package to increase the capability of the armor to break up penetrators.

We are currently exploring in greater detail both the abrasion-erosion mechanism of defeat and the exact contribution of packaging constraints on armor effectiveness. Those effects must be studied systematically if we are to exploit ceramic-filled polymers for fabricating inexpensive, reliable, lightweight armor for mobile fighting vehicles (see "ATAC and the Armor/Anti-armor Program").

A variety of other research on armor and anti-armor materials takes place at Los Alamos. Those studies range from investigation of other alloys for penetrators to the use of chemical vapor deposition to infiltrate "open mesh" composite materials. The latter has a particularly high potential for improving the properties of ordnance components such as gun barrels and sabots.

We believe that materials technology is the enabling—or limiting—technology for virtually all conventional weapons systems. Materials science and technology has progressed to the point that "tailored" properties of materials are a reality. The effects of microstructure on liner performance for chemical-energy weapons, the adjustment of the coefficient of thermal expansion and the accompanying improvements in mechanical properties of the tungsten-uranium composite penetrators, and the exceptional protection offered by ceramic-filled polymer armor are examples of rather straightforward applications of developments in materials. These developments, though seemingly simple, are grounded in a thorough understanding of materials science and technology. We believe the surface has barely been scratched and that the future in conventional munitions belongs to innovators and designers of new materials. ■

## Further Reading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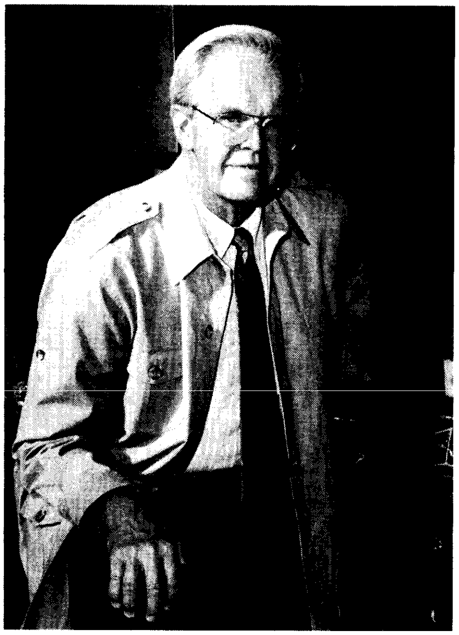

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Some of the people responsible for the work described in this article include (from left to right ) Anna Zu rek ( high-strain properties of materials), Joel Katz (microwave processing), Phil Armstrong (materials properties and characterization). Noel Calkins (development of composite aroms), Pete Shalek (ceramics processing), Paul Dunn (development of composite kinetic-energy penetrators), Paul Stanek (development of low-pressure plasma spraying), Don Sandstrom, Billy Hogan (Program Manager for the kinetic-energy penetrators), and Robert Reiswig ( chemical-energy penetrators and materials char acterization).