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Army P/M Research and Development Overview

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13. ABSTRACT *(Maximum 200 words)*

The Army uses of powder metallurgy (P/M) extend from the conventional press and sinter to the more exotic processes of liquid phase sintering of tungsten heavy alloys (WHA) and powder injection molding (PIM). Many of the more advanced high performance applications require extensive research and development (R&D) prior to fielding of the application. Examples are the intense research into WHA in the last ten years. This research has led to great understanding of these heavy alloys and application into some kinetic energy systems. The Navy has taken great advantage of WHA by employing them in the phalanx close-in weapon system (CIWS). The Army intends that research will lead to an alloy or composite of tungsten that, when used as a long rod penetrator, will perform as well as, or better than, current depleted uranium (DU) penetrators. This will allow possible replacement of the controversial DU. Powder injection molding of WHA is an area receiving attention because of the potential for producing small and medium caliber projectiles. The drawbacks at this time include the need to develop an alloy that does not require post sinter cold working to develop the strength required for these demanding applications. Other possible problems include producing slender long rod projectiles with desired product straightness. In addition to the work on tungsten alloys, a discussion is underway of other powder metallurgy R&D and is under active investigation within the Army. These topics include aluminum and titanium alloys, intermetallics, and ultrahigh strength steels for structural and propulsion applications, as well as nonequilibrium P/M produced structures.

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Tungsten Penetrator Applications

The most intensive area of research and development (R&D) of powder metallurgy (P/M) within the Army is the tungsten alloys. In particular, the alloy class known as tungsten heavy alloys (WHA) has been examined because of its potential application to long rod kinetic energy penetrators [1]. This application requires a material of high density and high strength combined with good ductility and toughness. The WHAs meet these physical requirements. Unfortunately, these alloys do not perform as well as another high density material, depleted uranium (DU), in ballistic interactions. It is clear from Figure 1 that the DU alloy penetrators perform up to 10% better than the WHA is subscale ballistic testing [2-4]. The resuiting focus of much of the tungsten base research effort was an attempt to improve the mechanical properties through a variety of processing improvements and modifications. This effort led to significant gains in understanding the processing, properties, and microstructure of the heavy alloy system [5]; however, this occurred without concurrent improvement in the ballistic performance. In fact, the ballistic performance of WHA penetrators has since been shown to be insensitive to the mechanical properties in quarter-scale depth of penetration (DOP) testing, as shown in Figure 2 [6,7]. The only apparent driver for ballistic performance in traditional WHA is the density. This is not to imply that the mechanical properties are irrelevant; they are still quite important for launch and flight, as well as in the defeat of oblique targets. It is just that they play no role in the terminal ballistic, target-penetrator interaction.

As previously stated, DU alloys perform much better as kinetic energy penetrators. The reasons for the performance gap between DU and WHA can be seen from the microstructure of recovered penetrator fragments, and the size and shape of the armor target cavity, of each alloy after a ballistic test. The WHA fragments have a mushroom head while the DU alloys have sharp chisel noses. Additionally, the armor targets reveal significant differences; the DU penetrated targets have deep narrow cavities while the WHA penetrated targets have wider, shallower cavities [2,3]. Conservation of energy requires that the two cavities have equal volume. The microstructure of the penetrator fragments is telling. The DU alloy has undergone a shear localization (adiabatic shear) at the nose of the penetrator that maintains the sharp nose while the WHA penetrator has deformed in a ductile manner forming the characteristic mushroom cap. Attaining a shear localization mechanism in a WHA or composite is one of the current foci of the Army's efforts in tungsten P/M for kinetic energy penetrators [5].

Shear Localization in Tungsten Materials

Shear localization, or adiabatic shear, in WHA does not occur in the ballistic event and it has only been observed under the controlled conditions of the laboratory, as shown in Figure 3 [8]. A primary factor for this behavior is the presence of a strong hydrostatic stress field at the penetrator nose during the ballistic event [2]. This stress field delays shear localization so significantly that it cannot occur until the shearing material is unable to play a role in the penetration event. On the other hand, DU penetrator alloys are able to shear localize within the similar hydrostatic stress fields and, thus, retain a sharp nose. In other words, the critical shear strain, for adiabatic shear, of DU is less than that of WHA. Since WHA is a two-phase composite of tungsten, nickel, and iron (see Figure 4), this leads to opportunities that are not typically available in conventional alloys; namely, it may be possible to replace the matrix with one that is more shear prone than the present matrix [5]. Metals that tend to display adiabatic shear tendencies are characterized by a low work hardening rate, high thermal softening, and low strain rate sensitivity. Further, matrix that is highly alloyed, having a low melting point, low crystal symmetry, and a low average atomic number is preferred. These criteria illustrate that there is little hope that an adiabatic shear band will initiate or propagate within the tungsten phase and that this type of failure must, therefore, take place within the matrix phase. These properties also allow a list of candidate materials to be set up for matrix replacement. This list includes: titanium alloys, hafnium, high strength steels, intermetallic compounds, and copper alloys. Each choice of matrix replacement supports a unique processing challenge [5].

The concept of matrix replacement is based on the idea that other materials could shear localize in a manner similar to DU; however, it is in question as to whether or not it will shear localize as a matrix in a tungsten composite. To test this, research at Los Alamos National Laboratory (LANL) made a tungsten composite using DU as the matrix [9,10]. The ballistic test results indicated that this composite maintained a chisel nose and performed in a manner similar to a monolithic DU alloy. With this proof-of-principle others are moving forward with matrix replacement efforts.

Hafnium

Some of the physical properties; e.g., thermal diffusivity, of hafnium are similar to DU, which leads to the belief that it may have similar behavior at elevated strain rates. To date, efforts to form hafnium-tungsten composites has been unsuccessful due to an inability to obtain fully dense structures [11]. Attempts to liquid phase sinter led to a highly brittle product resulting from oxygen pickup. The two phases also reversed their roles with the tungsten phase acting as the matrix and the hafnium acting as the reinforcement. This also contributed to the brittle behavior [12].

An alternative approach is where the hafnium is coated onto the tungsten powder prior to consolidation. This is accomplished by chemical vapor deposition (CVD) in a fluidized bed. Powder produced by this process is shown in Figure 5. This process, along with solid state consolidation, could result in a composite with a desirable microstructure where the hafnium is forced to act as the matrix. Preliminary work has indicated that hafnium, as a monolithic material, will shear localize under laboratory conditions. Shear localization behavior of the CVD coating composite is still unproven due to an inability to obtain thick deposits of hafnium [11].

Intermetallics

Conventional metallic materials typically display decreasing strength and increasing ductility with increasing temperature. Some intermetallic compounds exhibit an opposite dependence on temperature which is called anomalous strengthening; i.e., the strength increases and ductility decreases with increasing temperature. Examples of intermetallic compounds that behave in this manner are the $L1_2$, structured Ni_3Al, and $L1_2$ + FCC Ni-12Al-40Fe. These intermetallics have each been incorporated as the matrix of a tungsten composite with varying degrees of success. The most successful has been the W-7%NiFeAl composite which sintered to greater than 98% theoretical density. In dynamic testing this composite indicated the possibility of shear localized failure and was attributed to the two-phase nature of the NiFeAl matrix. Study is continuing in this area to identify other candidate intermetallic compounds and develop enhanced processing techniques to attain full density [13].

Titanium Alloys

Adiabatic shear has been previously observed in titanium alloys, particularly when used as armor. This prior observation of adiabatic shear due to ballistic interaction is encouraging since it indicates that shear localization will likely occur at the loading rates of interest. The greatest problem with using titanium alloys as the matrix is their low density (4.5 g/cc). As a comparison, the density of the nickel/iron matrix is typically 8.6 g/cc, and the density of hafnium is 13.1 g/cc. Low density is a drawback that makes titanium alloys a low priority for this application [5].

High Strength Steels

Similar to the titanium alloys, adiabatic shear has been observed in high strength steels, including armor steels. A matrix that had the composition of a high strength steel could shear localize under ballistic conditions. Unlike the heavy alloys using a steel matrix, this leads to significant problems due to the formation of brittle intermetallic phases. Recent work has indicated that it is possible to apply solid state consolidation to a tungsten 4340 steel composite and achieve 96% theoretical density. This consolidation was achieved without the formation of intermetallic phases when the temperature was held at 1050°C. Further process optimization is required in order to obtain full density [14].

Powder Injection Molding (PIM)

Powder injection molding (PIM) offers the opportunity to form complex components to net- or near net-shape through the use of manufactured feedstocks composed of metallic (or ceramic) powder and a polymer/wax vehicle (binder). The process employs an injection molding machine to form the powder plus polymer component in a mold. Upon molding, the polymer has served its function and is removed from the "green" part through the use of solvents, heat, or a combination of the two. The polymer compositions and debinding procedures are usually closely held, proprietary information. After debinding, the "brown" part is then sintered according to normal procedures. This type of processing allows for considerable cost savings for the manufacture of high volume, complex components.

Tungsten Heavy Alloys (WHA)

A recently completed preliminary investigation of injection molding WHA was very successful [15-17]. It demonstrated the isotropic nature of debinding and sintering shrinkage which is an important aspect in mold design (see Figure 6). Additionally, the sintered strength and ductilities of the alloys investigated were at least equivalent to commercially produced material indicating that the PIM process did not degrade the mechanical properties through contamination or induced defects, as shown in Figure 7.

It is envisioned that PIM of WHA could lead to cost savings in the production of small and medium caliber projectiles. Technical hurdles to be overcome include: (1) holding dimensional tolerances, particularly straightness in long, slender rods; and (2) increasing the strength of the as-sintered heavy alloy to a level that is acceptable for launch and terminal ballistics. Since the thrust for using PIM is its net-shape capability, the second point is quite important as there will be no opportunity for cold working as a means to raise the strength level. It is expected that this will require a significant alloy development effort to achieve the needed strength levels.

Other Materials

Intermetallic compounds have great potential for application at high temperature but can present great difficulty in fabrication. PIM offers the opportunity to manufacture these materials to net-shape by using powder produced by an inexpensive technique. Plasma initiated self-propagating high temperature synthesis (PSHS) has demonstrated the production of NiAl irregularly shaped 5 μm powder, as shown in Figure 8. Compositional control of the PSHS process is very good, and in the case of NiAl a single phase product was the result. A single pressureless sintering experiment (1550^{o}C/four hours) of this powder resulted in 96% density. This result is encouraging since there was no attempt at optimization of the sintering variables. This powder is expected to be reasonably priced in the $10 to $50 per pound range [18,19].

Cathode arc transport is a process originally developed for application of surface coatings. This technique was modified to induce gas phase nucleation of powder particles of intermetallic compounds. Specifically, the following compounds have been investigated: Ni-10Al-30Fe, Fe-40Al-1Hf, and Ni-50Al (all atomic percent). This process typically produced 0.3 μm to 1 μm powder with excellent compositional control. It is particularly noted that the 1% hafnium was retained in the Fe-40Al-1Hf compound. The production of powder in this submicron size powder is quite exciting as very fine consolidated grain sizes are expected to result in intermetallics compounds of very high ductility without the need for microalloy additions [18].

The Army is also interested in the production of noncritical parts for small arms applications. As could be inferred, these applications require high performance materials that are consolidated to full density by processes including hot isostatic pressing (HIP). Materials for these applications include maraging and precipitation hardening stainless steels. The Army's Benét Laboratory at Watervliet Arsenal in New York is dedicating an effort to develop the maraging steel feedstock for these parts [20].

Aluminum Alloys

The Army is engaged in several programs involving P/M aluminum alloys. Recent work by Alcoa Corporation and Allied Signal has resulted in the development of several new P/M aluminum alloys for elevated temperature applications. A round robin program is conducted to measure a number of the mechanical properties for inclusion in MIL-HDBK-5. The composition of the alloys under study are given in Table 1.

Table 1. Composition of P/M high temperature aluminum alloys

	Fe	V	Si	Ce	Al
Al 8009 (Allied Signal)	8.5	1.3	1.7	---	Bal.
Al 8019 (Alcoa)	8.3	---	---	4.0	Bal.
CZ 42 (Alcoa)	7.1	---	---	6.0	Bal.

The alloys were produced as powder and then extruded. The average ultimate tensile strengths (UTS) of the Al 8019 are 206.9 MPa (30.0 ksi) at 316°C (600°F) and 322.7 MPa (46.8 ksi) at 232°C (450°F). These values compare favorably with the UTS for conventional aluminum alloys; e.g., Al 5083 or Al 7075-T6. Creep, stress rupture, and fracture toughness tests are in progress and extensive correlation studies of microstructure and fracture mechanisms are planned on these alloys.

The Army is also interested in aluminum-lithium alloys for a number of potential applications. The addition of lithium in aluminum alloys both increases the modulus and decreases density, resulting in alloys with higher specific strengths. These properties suggest application in armor plate, bridging, and certain helicopter components. To investigate the role of Ti and Zr on the ductility and fracture toughness of Al-Li alloys, a number of P/M compositions were produced, gas atomized, and extruded to rectangular bars. The Ti and Zr were added at two concentrations; singly and in combination. These additions were made to promote the formation of desirable intermetallic compound precipitates that, in turn, alter the localized shearing mechanisms [21].

The Army Research Office (ARO) is sponsoring research on the synthesis of new glassy and quasicrystalline metallic materials and the study of their stability, transformation behavior, and structural properties. This work has potential relevancy in the development of high strength, lightweight materials for Army aircraft and ground vehicles. It is also relevant to Army transformer materials, permanent magnets, and recording media applications. The thermal stability and formation is being studied to investigate the unusual formability of these new materials. The strongest glass tested had an ultimate tensile strength of 1280 MPa (186 ksi) and a modulus of 74 GPa (10.7 x 10^6 psi), comparable to commercial heat treated alloys. Also, work has recently started at the University of Virginia on the formation of amorphous phases in aluminum alloys by mechanical alloying near room temperature. Some results of these studies may be found in References 22 through 24. The U.S. Army Benét Laboratories in Watervliet, New York are also starting a program in mechanical alloying and is directed by Dr. S. K. Pan. Initial work on aluminum alloys is being conducted, leading to R&D on WHA and refractory metals for a number of potential armament applications.

Titanium

The Department of Defense (DoD) is now using a number of titanium alloy components made by the blended elemental powder approach. These include parts such as the Army's Stinger missile warhead casing and the dome housing and seeker housing for the Navy's Sidewinder and AIM-9P4 missiles. More than 33,000 Stinger warhead casings, as shown in Figure 9, have been shipped. Near-net shapes are produced by cold isostatic pressing (CIP) of blended powders, followed by sintering and possible subsequent HIP to full density. The process has resulted in considerable savings compared with the same parts machined from forgings. However, because of the high chloride content of the starting titanium powder, fatigue properties are not as good as those obtained on wrought product. Previous work had shown that the use of very low chloride powder, produced by the hydride/dehydride process, resulted in much improved fatigue properties. Therefore, to take advantage of the P/M approach, an ongoing program is aimed at determining the cost/property relationship of various ratios of low cost/high chloride powder and the higher cost/low chloride material. Details of this work are given in a separate paper in this conference [25].

In support of the Army's efforts on the integrated high performance turbine engine technology (IHPTET) initiative, a P/M super α_2 titanium aluminide alloy (Ti-25Al-10Nb-3V-1Mo) prepared by rapid omnidirectional compaction (ROC) of prealloyed powder was evaluated at the Army Research Laboratory (ARL) in Watertown, MA. This alloy shows superior mechanical properties compared with similar HIP material. The ultimate tensile strengths attained at room temperature and at 427°C (800°F) were 1174.9 MPa and 1139.1 MPa (170.4 ksi and 164.2 ksi), respectively, for a specimen heat treated at 1140°C (2084°F) for one hour and aged at 816°C (1500°F) for four hours, plus air cooling. The elongation was 2% and 6.7%, respectively. The alloy also showed good stress rupture resistance. In general, the plate-like α_2 phase provides the best combination of ductility and strength [26].

Steels

The Army uses ultrahigh strength steels in a number of helicopter structural applications such as rotor actuators, rotor retention nut, bolting, etc. These components must have good ballistic tolerance for aircraft survivability, as well as being thoroughly reliable from a structural viewpoint. Past work has shown that ballistic performance most closely correlates with steel hardness; i.e., strength. However, the fracture toughness and stress corrosion cracking (K_{Iscc}) resistance of ultrahigh strength steels decrease with increasing hardness. Recently, a new steel, AerMet 100, has been introduced. This high nickel, high cobalt grade is a martensitic, controlled recovery, secondary hardening steel and has a K_{Iscc} about twice that of existing alloy steels in the same hardness range.

Another promising approach to developing alloy steels with improved K_{Iscc} involves P/M processing. A martensitic alloy steel was designed from first principles in which the embrittling impurities (S and P) are gettered by lanthanum. After an analysis of thermodynamic data, lanthanum was selected to react with phosphorous to form $LaPO_4$ and also an oxysulfide La_2O_2S. Previous work had shown that rapid solidification processing produces a finer dispersion of the oxysulfide and phosphorous solidification processing produces a finer dispersion of the oxysulfide and phosphorous compounds. A steel was then formulated with the composition Fe-0.40C-2.0Ni-1.5Mo-0.066La with all other elements kept as low as possible, particularly Mn, Cr, and Si [27]. A subsequent attempt was not successful because of silicon contamination from the refractory crucible; lanthanum combined with silicon rather than P or S. Additional heats of material are currently being evaluated. Examination of one heat shows that La combined with P and Zr. Results from stress corrosion cracking tests showed significant improvement over AISI 4340 steel heat treated to the same strength level [28]. Successful completion of this effort remains desirable because the cost of this alloy will be less than that of AerMet 100.

In other P/M steel R&D, the Army is collaborating with Syracuse University to evaluate new Crucible Particle Metallurgy (CPM) high speed steels for bearing applications. A progress report on this work is presented in another paper in this conference [29].

Summary

The Army and other services use P/M components in a wide variety for weapons and vehicle systems. Many of these are made by conventional P/M production techniques that take advantage of the cost savings of net shape or near-net shape parts. Many of these were discussed by Sanderow at the previous conference in this series [30].

In this paper the Army's ongoing R&D activities in P/M materials and rapid solidification technology is discussed. The majority of this work is on WHA for kinetic energy penetrators; however, significant efforts are underway on aluminum and titanium alloys and intermetallics with the goal of improving the specific properties of these lightweight structural materials.

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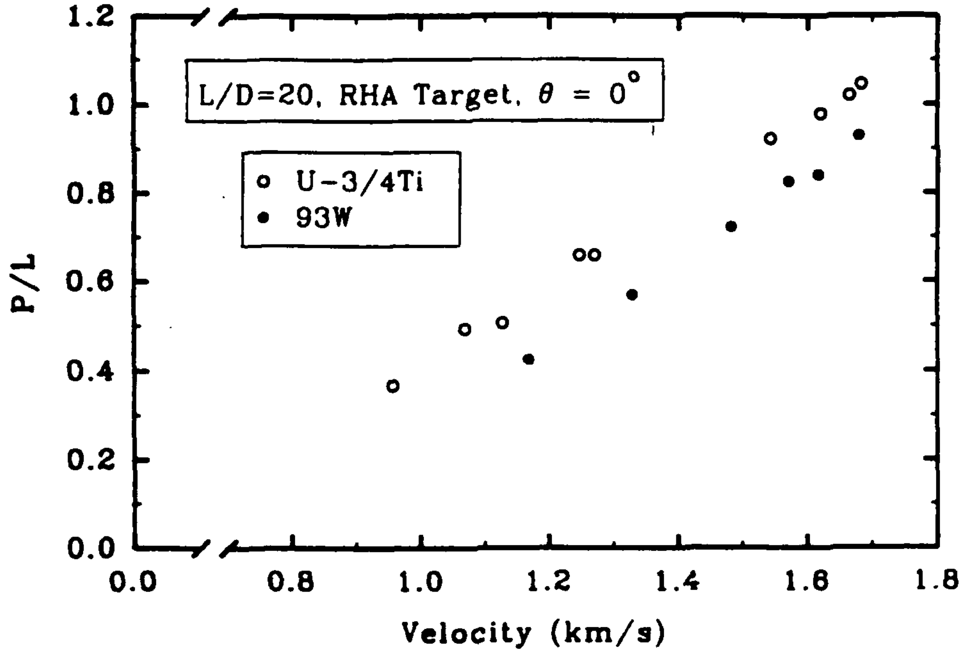

Figure 1. Penetration efficiency versus impact velocity for DU and WHA penetration. P/L is the normalized penetration of the projectile where P is the penetration anr' L is the original penetrator length (see Reference 4).

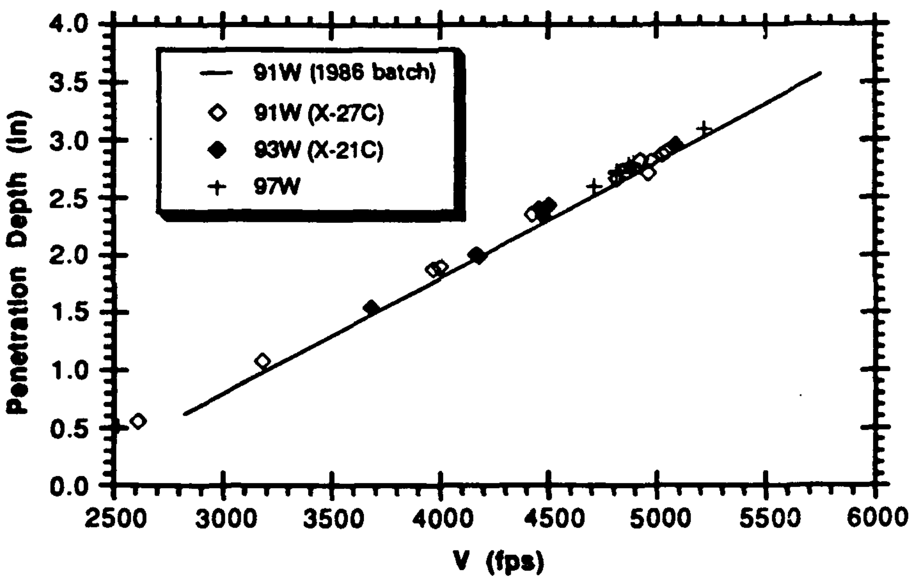

Figure 2. Depth of projectile penetration versus projectile velocity for WHA penetrators. The target was a monolithic block of semi-infinite rolled homgeneous armor struck at 0° obliquity (see Reference 6).

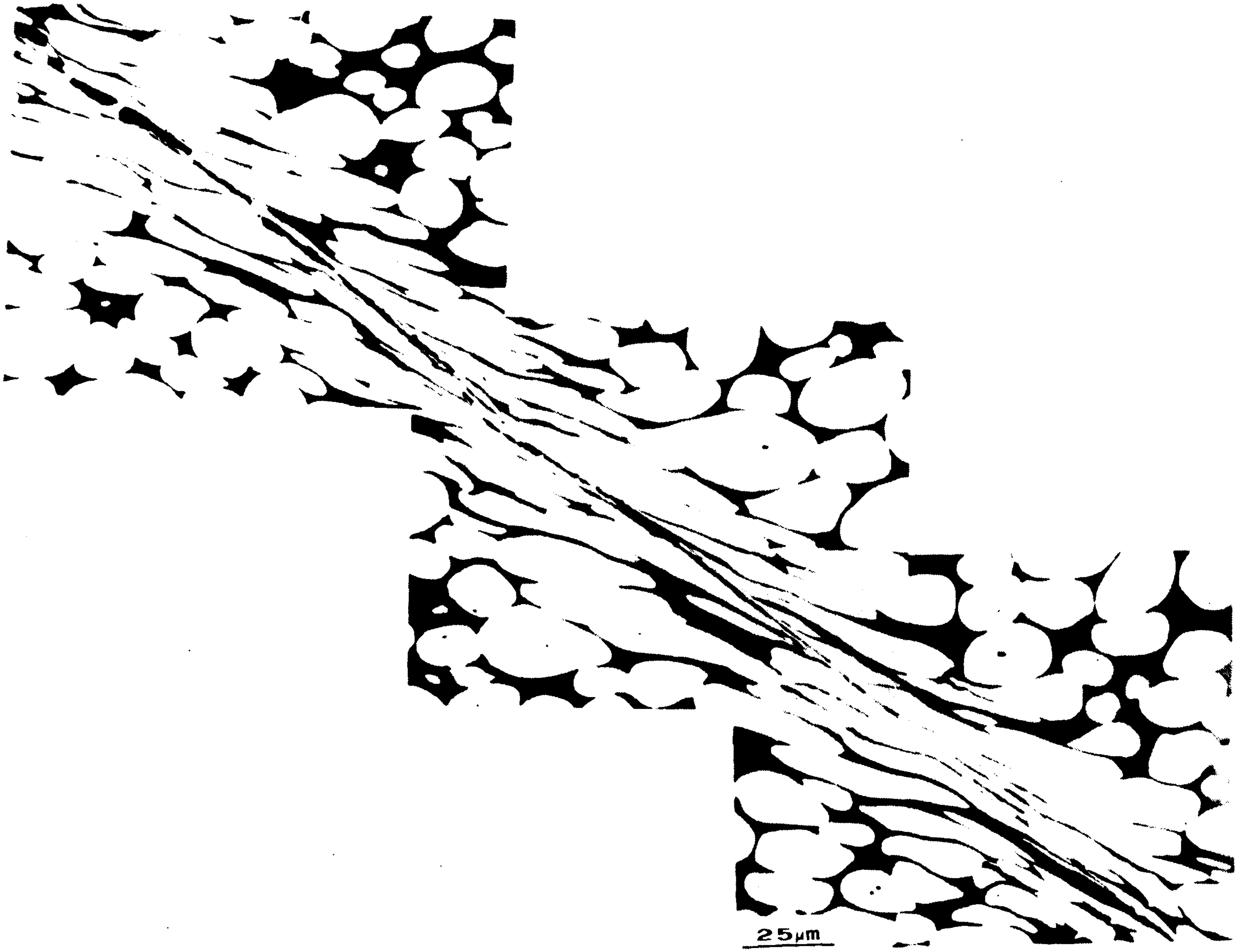

Figure 3. Shear band in a 20% swaged 91W-4.4Ni-1.9Fe-2.7Co WHA tested in compression at 5000 sec^{-1}.

Figure 4. Backscattered electron micrograph of a 91% WHA from a commercial source

Figure 5. SEM micrographs of hafnium coated 5.0 μm tungsten powder (see Reference 11).

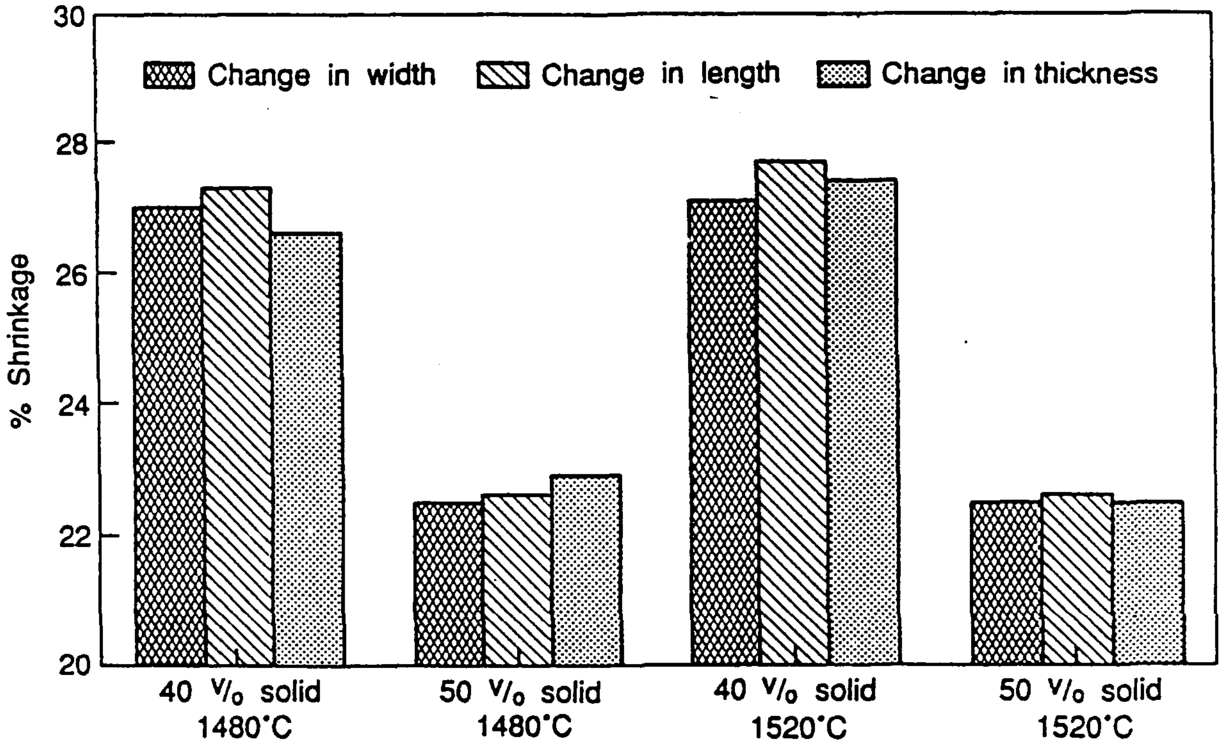

Figure 6. Shrinkage of powder injection molded test bars after sintering of injection molded 95% WHA (see Reference 15).

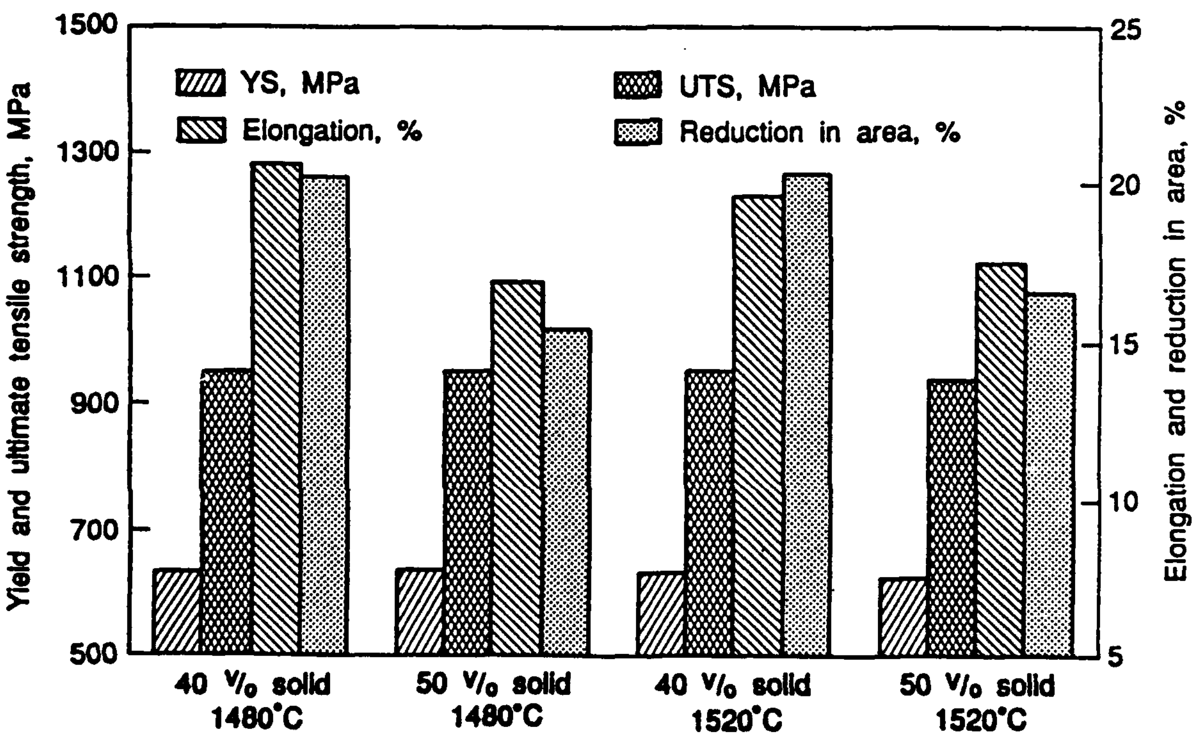

Figure 7. Mechanical properties of powder injection molded 95% WHA. The properties compare favorably with as-sintered commercial material (see Reference 15).

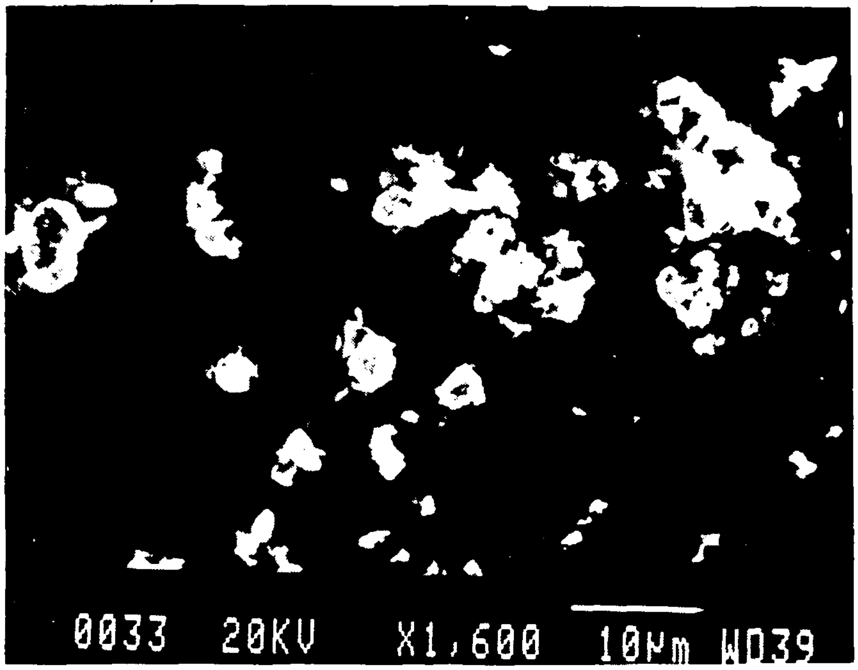

Figure 8. SEM micrograph of PSHS produced intermetallic aluminide powder.

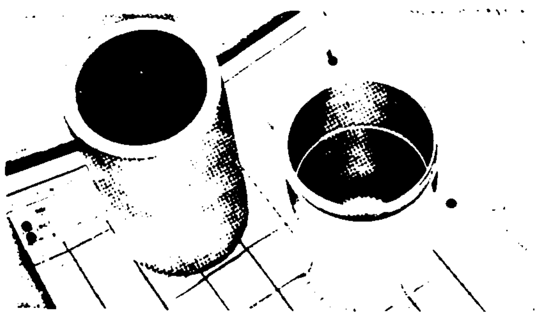

Figure 9. Stinger warhead casing made from blended elemental powders (Ti-6Al-6V-2Sn) by a cold and hot isostatic pressing (CHIP) process. Courtesy Dynamet Technology, Inc.

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