TUNGSTEN HEAVY ALLOYS

Kennametal Densalloy™

ALLOYS

KENNAMETAL®

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Celebrating more than 75 years as an industrial technology leader, Kennametal Inc. delivers productivity to customers seeking peak performance in demanding environments. The company provides innovative wear-resistant products, application engineering and services backed by advanced material science, serving customers in 60 countries across diverse sectors of aerospace, earthworks, energy, industrial production, transportation and infrastructure.

Kennametal's broad and innovative custom solutions are derived from advanced materials sciences, application knowledge, design expertise, customer support, and commitment to a sustainable environment.

These solutions are all developed to customer requirements:

- **Fabricated and assembled engineered components for wear applications, balance weights, vibration damping, and radiation shielding.**

- **Earth cutting technologies for underground and surface mining and construction products.**

- **Surface technologies such as wear- and corrosion-resistant coatings, claddings, and plates for challenging applications.**

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Contents

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SECTION 1

Tungsten – Metal of the Modern Age

The element name "tungsten" is derived from the Swedish term *tung sten,* meaning "heavy stone." Tungsten has been assigned the chemical symbol W after its German name *wolfram.*

While sometimes regarded as a scarce or even exotic metal, its abundance in nature is actually about the same as that of Sn. The largest known W reserves are in mainland China, though plentiful reserves also exist in North America and elsewhere in the world. W in all its forms used has revolutionized the modern world, making possible such innovations as incandescent lighting, x-ray generation and shielding, and tools for metal forming and cutting that are durable while being very hard.

W has the highest melting point (3420°C or 6188°F) of all metals and one of the higher densities at 19.3 g/cc (0.70 lbs/in^3).

The extremely high melting point of pure W makes the common melt/cast manufacturing approach impractical. Specialized high temperature powder metallurgy (P/M) methods make possible the processing of pure W into rod, sheet, and wire for a wide variety of applications. These specialized operations are restricted in size and shape capability and expensive based on the high process temperatures required.

Nature provides only a limited choice of very dense metals. Using the familiar periodic table as a density map, Figure 1 shows that the very dense (>150% of the density of Pb) elements are centrally positioned.

FIGURE 1

Elements having a very high density of 17 g/cc or greater.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	Se	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	**W**	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Th	Pa	U											

Of these elemental choices, W is the only practical element for use in most density driven applications. U has been used for decades for both counterweights and radiation shielding, but its use has rapidly declined due to its slight radioactivity and high chemical reactivity — leading to rapid corrosion. Au and the Pt-group metals, while having a number of special applications in industry, are precluded from virtually all mass-intensive uses based on their cost. Despite the relatively high cost of W and W-based materials, they offer a unique set of engineering benefits not available from any other material family.

The manufacture of pure W shapes does not lend itself to the production of large cross section parts or relatively complex shapes — nor the attainment of full density without thermomechanical processing. All these factors limit the use of pure W in density-driven applications. Tungsten heavy alloy (WHA) provides many of the advantages of pure W without the extreme sintering temperatures, size/shape limitations, and densification challenges of the latter — making it the practical form of W for mass property applications.

Syringe Radiation Shielding
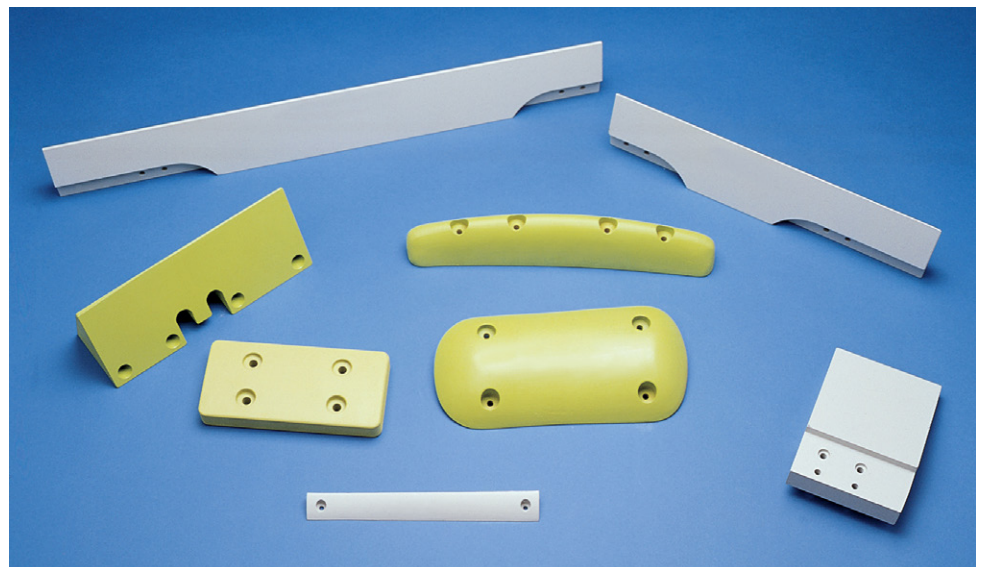
Counter Weights

SECTION 2

Introducing Tungsten Heavy Alloy

Tungsten heavy alloys (WHAs) are not alloys in the true sense,
being more properly classified as metal/metal matrix composites.

Virtually all commercial WHAs are two phase materials, with the principal phase being nearly pure W in association with a binder phase containing transition metals plus dissolved W. As a consequence, WHAs display a unique property set derived from both components — their fundamental properties resulting from those of the principal W phase. The selection of a WHA for a given application is typically made on the basis of very high density — whether gravimetric or radiographic. WHAs are distinctly different from related materials such as pure W and cemented carbides (most commonly WC-Co). Only very rarely could one material be used as a substitute for another. WHA provides many of the properties of pure W, yet in a form that provides:

- Lower fabrication cost due to reduced sintering temperature,

- A greater range of both size and shape can be manufactured due to full density attainment via liquid phase sintering (LPS) as opposed to final densification by post-sinter thermomechanical processing,

- Generally improved machinability, and

- Preservation of desirable properties of pure W.

In difference to pure W however, WHAs are not high temperature materials. Elevated temperature properties of WHA are strongly influenced by the lower melting temperature binder phase. WHAs are not related to "tungsten (T grade) steels."

WHAs were once referred to as "tungsten heavy metals," but that nomenclature has been largely abandoned so as to avoid confusion with toxic heavy metals such as Pb, Hg, and others with which WHAs have no relation.

While primary selection is made on the basis of very high density, WHA offer today's designer/manufacturer a unique set of associated engineering benefits which includes:

- Strength comparable to many medium carbon steels

- Ability to be machined with common shop tools and techniques

- High elastic stiffness

- Low CTE in combination with relatively high thermal conductivity

- Low toxicity, low reactivity surface character

- Ability to be custom manufactured in a wide range of sizes and shapes

- Readily recycled for economy and environmental friendliness

These characteristics position WHA as an ideal material for new mass property applications as well as the replacement of Pb or U in existing applications.

Current uses of WHAs are quite varied, spanning a wide range of consumer, industrial, medical, aerospace, and military applications which include:

- Inertial damping weights for computer disk drive heads and aircraft control surfaces.

- Balancing weights for turbines, crankshafts, and helicopter rotors.

- Center of gravity adjustment weights in aircraft, missiles, boats, and race cars.

- Kinetic energy penetrators for defeating heavy armor and for fragmentation warheads.

- Radiation shielding, radioisotope containers, and collimation apertures for high energy x-ray systems in scientific, industrial, medical, and homeland security applications.

- Pb-free shot for waterfowl hunting and bullets for indoor range shooting.

- Space efficient gyroscope rotors and rotational energy storage.

- High density instrument casings for downhole formation logging in oil/gas wells.

- Rotors for premium grade self-winding watches.

- Weight inserts in premium golf clubs for tailoring mechanical response.

- Low chatter, high stiffness boring bars and toolholders for metalworking.

WHA offers a very high density, as is apparent when compared to other metals, as shown in Table 1. While Pb is generally considered a very dense material, WHAs can easily exceed its density by 60% or more. Pb has been and continues to be the metal of choice for low cost density related applications such as ballast weights and bulk radiation shielding. Pb however is excluded from many uses due to its extremely low strength at room temperature, readily recrystallizing under applied stress. Room temperature creep eliminates any application in which Pb components must be tightly fastened or where thin cross sections must be self supportive. Specialized uses such as precision radiation collimators used in medical imaging benefit greatly from the dimensional stability, higher strength (resistance to handling damage), and sharper cut-on angle provided by WHA.

Many dense material applications necessitate rather large bulk shapes. Such a requirement eliminates all but a few material candidates on the basis of cost, typically reducing the choice of very dense alloys down to either W- or U-based materials. U alloys, like Pb, are eliminated from an increasing number of potential applications based on toxicity considerations, with U-based materials additionally exhibiting both low level radioactivity and extreme corrosion susceptibility.

WHAs are the preferred form of W for most mass/density related requirements in that large components can be easily fabricated from compacted elemental metal powders by the conventional powder metallurgy (P/M) process of liquid phase sintering in H_2 — capable of yielding complete densification at a sintering temperatures far below the melting point of W.

TABLE 1

Property comparison of selected metals and alloys in order of density.

Material	Density (g/cc), [lb/in³]	Solidus or MP (C)	Modulus (GPa)	CTE (ppm/C)	Therm. Cond. (W/m-K)
Mg	1.7 [0.06]	629	44	26	159
Al	2.7 [0.10]	660	69	24	210
Ti	4.5 [0.16]	1670	116	9	17
Fe	7.9 [0.28]	1536	207	12	76
Pb	11.4 [0.41]	328	14	29	33
Ta	16.6 [0.60]	2996	186	7	54
WHAs (typ.)	17.1 – 18.6 [0.62 – 0.67]	1450	310 – 380	~5	~80
U	19.1 [0.69]	1132	160	19	27
W	19.3 [0.70]	3420	410	4	163
Au	19.3 [0.70]	1064	80	14	301
Pt	21.4 [0.77]	1769	171	9	69
Ir	22.5 [0.81]	2443	524	7	147

SECTION 3

WHA Compositions

WHAs typically consist of 90 – 98 wt.% W in combination with some mix of Ni, Fe, Cu, Co, and/or Mo — making possible densities approaching 19 g/cc.

Current alloys in widespread use are typically ternary or occasionally quaternary compositions. The first WHA, developed in 1938, was a W-Ni-Cu composition. This ternary system is still in current though limited use. For several decades, the W-Ni-Fe ternary has become the industry standard for commercial applications — providing generally lower cost, easier pore-free sintering, and most importantly, improved mechanical properties for a given W content.

The 90 – 98 wt.% range of W content covers virtually the entirety of WHA production. WHAs containing less than 90 wt.%W are uncommon due to the quantity of liquid phase that forms during LPS. This results in two practical problems: (1) loss of shape control during LPS and (2) significant density nonuniformity resulting from gravitationally induced settling of the denser, solid W phase within the molten

binder during sintering. Though specialty WHAs have been produced with 99% W, it is rare to find WHA in use with a W content exceeding 97 wt.%. The very small amount of liquid phase that forms during LPS greatly retards pore elimination, slowing the production rate for fully dense sintered parts. Further, the limited amount of ductile binder phase of 97+% W alloys coupled with the increased W-W contiguity of such materials greatly limit their ductility and toughness.

Commercial WHAs are produced in conformance to industry standard specifications such as MIL-T-21014D (superseded by AMS-T-21014) and ASTM B777, as well as one aero-structural oriented specification AMS 7725E. The current revision of all of these specifications define 4 density classes of WHA as shown in Table 2. Nominal WHA contents have been established based on these density classes.

TABLE 2

Commercial WHA density classes and corresponding Kennametal Densalloy™ grades.

Class	Nom. W (wt.%)	Spec. Density (g/cc)	Densalloy™ Grade	Theo. Density (g/cc)
1	90	16.85 – 17.25	SD170	17.15
			Dens21	17.19
2	92.5	17.15 – 17.85	SD175	17.65
			Dens23	17.70
3	95	17.75 – 18.35	SD180	18.16
			Dens25	18.20
4	97	18.25 – 18.85	SD185	18.60

Table 2 allows for a considerable range in sintered density. Well sintered WHAs achieve 99.5% or greater of the theoretical density as calculated by rule of mixtures. Such material contains no interconnected porosity and is impermeable to liquids and suitable for vacuum applications.

Further, with the exception of AMS 7725E, material certification is based on the testing of coupons — not actual parts. These general specifications allow a rather wide range of property variation that may not be sufficient for all WHA applications. In such cases, end users having need for more precise knowledge of the density, tensile, and other properties of full size parts should consider an application specific destructive testing plan in addition to these industry standard material specifications when purchasing WHA for such uses. Supplemental material specification becomes essential when WHA is purchased in mechanically processed forms or when special post-sinter heat treatments have been applied. In contrast to typical commercial practice, military material specifications for WHA typically define a specific alloy, post-sinter processing, and a testing plan.

The composition of the matrix (or binder) phase influences attainable mechanical properties, phase stability, alloy magnetic response, corrosion behavior, and alloy thermal response. Table 3 provides a comparison of several alloy systems that have been commercialized to date. The ratio of alloying elements is very influential on resultant WHA characteristics. Table 4 summarizes the effects of the Ni/Fe ratio in this widely used alloy system. For general purpose WHAs intended for use in the as-sintered state, it is important that their compositions be chosen so as to avoid the formation of embrittling intermetallics on cooling at commercial rates. Taking the widely used W-Ni-Fe system as an example, many past studies have identified the $2 \leq Ni/Fe \leq 4$ range as ideal, with $6 \leq Ni/Fe \leq 7$ for low magnetic permeability grades. There is a likelihood of Fe_7W_6 formation when Ni/Fe<1. Once formed on cooling from sintering, the thermochemical stability (to ~1640C) of mu-phase makes resolutionization impractical. For Ni/Fe>7, there is a greater tendency to form Ni_4W on cooling. In that Ni_4W is stable only to ~1000C, resolutionization is straightforward. While Kennametal has the capability to produce any of the alloy systems listed in Table 3, the commercial focus has been W-Ni-Fe alloys because of a variety of advantages.

TABLE 3
Comparison of commercialized WHA alloys.

| Type	System	Advantages	Disadvantages
Ternary	W-Ni-Cu	Lowest lps temperature, lowest magnetic permeability, highest thermal conductivity	Lower mechanical properties
	W-Ni-Fe	Generally lowest cost to manufacture, large part size enabled by freedom from intermetallics	(Standard for comparison)
	W-Ni-Co	Highest mechanical properties for demanding applications	Resolution/quench required to control intermetallics
Quaternary	W-Ni-Fe-Co	Slightly better mechanical properties than w-ni-fe	Potential for co activation in certain radiation environments
	W-Ni-Fe-Mo	Higher as-sintered hardness	Increased sintering sensitivity

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TABLE 4
Significance of Ni/Fe ratio in W-Ni-Fe ternary WHAs.

Ni/Fe Ratio	Alloy Characteristics and Applications
≤ 1	The probability of brittle mu-phase (Fe_7W_6) formation at W-matrix interfaces increases as Ni/Fe ratio is decreased. Once formed, mu-phase cannot be effectively resolutionized. Such brittle alloys can be used when intentional stress-induced fracture is desirable.
1.5 to 2	Used in many older alloy formulations. Sintering is more sluggish due to lower W solubility in the molten binder during LPS. These alloys offer equivalent mechanical properties in the as-sintered state as higher %Ni alloys but slightly lower post-sinter processed properties than the latter.
2.33 (or 7/3) to 4	Preferred composition range of commercial W-Ni-Fe alloys, offering best overall properties in the as-sintered and vacuum annealed states and freedom from intermetallics over a wide range of cooling rates.
6 to 7	Increased %Ni causes substantial drop in magnetic permeability of the binder, achieving a µR as low as 1.01. This alloying option provides a useful alternative to W-Ni-Cu in applications where a "non-magnetic" alloy is required. Slow cooling rates from sintering should be avoided.
≥ 8	Very high Ni/Fe ratio WHAs require resolutionization/quench for control of the Ni_4W intermetallic. While not commercialized, such WHAs are capable of providing mechanical properties exceeding that of lower Ni/Fe ratio alloys.

Starting with basic W-Ni-Fe formulations, property sets can be customized for specific end uses. The as-sintered hardness of WHA is relatively low at 24 – 29 HRC. For special applications requiring greater hardness (such as for use as dies or parts subject to wear) without post-sinter deformation processing, Mo can be used as an alloying addition. During LPS, Mo dissolution acts in competition with W, resulting in a greatly refined W phase grain size. As an illustration, a WHA containing 83% W and 12% Mo in combination with a relatively high Ni/Fe ratio binder can provide a vacuum annealed hardness of ~36 HRC, a corresponding 0.2% OYS of ~130 ksi, ~5% EL, and a sintered density of ~16.5 g/cc. For these special alloys, optimum tensile property development is highly dependent on strict control of sintering.

The addition of Co to W-Ni-Fe alloys boosts both the attainable strength and ductility levels of W-Ni-Fe for applications requiring higher mechanical properties, with 5 – 15% substitutions being common. The presence of Co in the binder provides solid solution strengthening and increased strength at W-matrix interfaces — increasing both quasi-static and higher strain rate properties. The incorporation of Co in WHA formulations also increases the amount of W retained in metastable solid solution in the binder. In general, the greater the extent of retained W, the greater the attainable tensile properties. Cooling rate from sintering must also be considered, as the faster the rate, the greater the retention of W in solution. For substitutions of ~20% and higher of Co into the Ni-Fe binder, post-sinter

resolution/quench will typically be required (dependent also upon Ni/Fe ratio) to control mu-phase, which in this case will be $(Fe,Co)_7W_6$. For highest mechanical property uses such as long rod kinetic energy penetration of armor, the Fe-free W-Ni-Co ternary provides the highest known property set thus far developed. Table 5 illustrates the typical gain in combined strength, ductility, and toughness obtained from the use of W-Ni-Co. These gains are very significant for WHA that will be subsequently cold worked. The usable Ni/Co ratio spans from 2:1 to 9:1, and post sinter heat treatment is mandatory in every case to control intermetallic formation (Co_3W and others). It is important to note that whenever resolution/quench is required for any reason, there is a part size limitation imposed by the ability to both achieve the required cooling rate through-thickness as well as the avoidance of quench cracks.
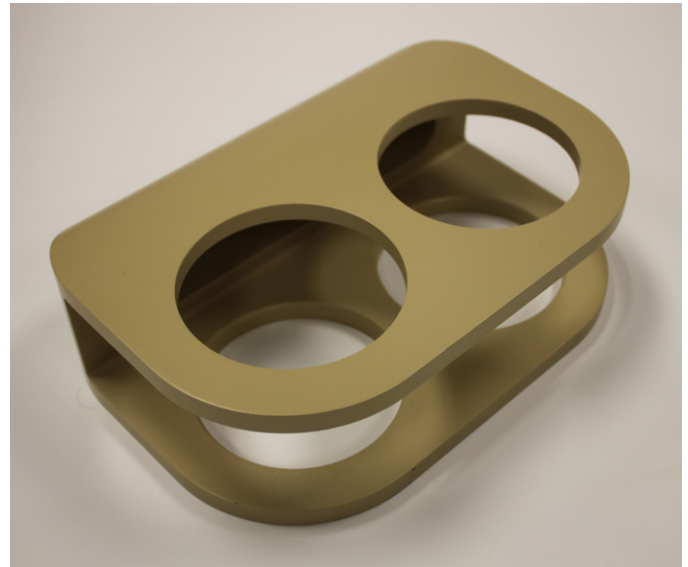
Vibration Dampening Weight

TABLE 5

Metastable W retained in matrix solid solution from sintering and resultant properties.

Alloy	Sintering	W (wt.%)	UTS (ksi)	EL (%)	HRC	Charpy (ft – lbs)*
91W – 6.3Ni – 2.7Fe	solid state	~18	too brittle	–	–	–
91W – 6.3Ni – 2.7Fe	liquid phase**	~23	135	35	28	220
91W – 6Ni – 3Co	liquid phase**	~40	140	40	31	300+

Standard unnotched 1 x 1 cm bars
** Resolutionized & quenched condition

SECTION 4

WHA Production

Although a variety of possible fabrication technologies exist and may be utilized for very specific applications, virtually all WHA manufacture worldwide utilizes the conventional powder metallurgy (P/M) approach of press and sinter.

This manufacturing approach is favored for two principal reasons. First, the previously mentioned very high melting point of W (3420C) precludes the effective use of a melt and cast approach due to the energetics involved, limitations on melt containment, and the boil-off of alloying elements. Secondly, P/M provides economy through the ability to form net shape parts or near net shape blanks.

> The goal of P/M fabrication is to capture as much shape detail as possible in oversize tooling — accounting both for the volumetric changes resulting from powder compaction during pressing and from subsequent densification during sintering — and preserving that geometry through the sintering process.

As opposed to making standard cross section mill shapes as is common with steel, the P/M manufacturing approach conserves the high value metal W — using only the amount that is required to produce the desired shape. This saves not only material cost but also conserves the time/cost involved in machining away the excess material that would otherwise be present from use of a standard cross section bar. This poses a limitation however in that WHA is not commercially available in very long lengths or wide area sheet as are other common metals such as steel and aluminum.

This is rarely a true limitation on design however in that large assemblies are typically constructed in modular fashion to better accommodate the weight buildup that is inescapable when handling very dense metal parts.

While HIP, thermal spray, and rapid consolidation techniques are also available fabrication options, their use is very rare in that the short processing times generally yield inferior mechanical properties due to trapped oxide films and other impurities, and often at a higher cost as well. Problems with residual porosity, common in many solid state sintered (SSS) P/M materials, is virtually nonexistent in WHAs provided LPS is correctly executed using high quality raw materials.

The manufacturing sequence for a typical commercial WHA part can be summarized in the following steps:

- Raw materials selection
- Powder blending – mechanical mixing to form a homogeneous blend.
- Pressing – high pressure powder compaction in shaped tooling.
- Sintering – liquid phase sintering (LPS) in H_2 at T>1460C.
- Optional post-sinter processing for enhancement of specific properties.
- Machining of shape to final configuration.
- Application of any required finish via painting, plating, or other.

A typical 95WHA will start with a blended powder having a bulk density of ~3.7 g/cc. Powder will be compacted to ~10 g/cc and subsequently sintered to ~18 g/cc. Press tooling must be considerably oversize to accommodate the extent of both powder compaction and consolidation (shrinkage) during sintering.

Starting Powders

The W metal powder (and additionally any Mo) used in WHA is produced by H_2 reduction of an oxide of the parent metal. Transition metal powders used are typically of carbonyl origin. All powders are very fine — typically in the 1.5-8 µm FSSS size range. The use of very pure powders is critical for attaining high mechanical properties in the sintered state.

Blending

Selected metal powders are weighed out to yield the correct alloy formulation and subsequently mixed in a rotating shell type blender. Such blenders are routinely fitted with a high speed agitator which aids in powder deagglomeration and blend homogenization. A suitable process window must be established to avoid underblending (poor homogenization) and overblending (excessive bulk density increase, loss of "green strength").

Pressing/Green Shaping

Cold isostatic pressing (CIP) allows the use of dry blended powder, and is used whenever possible due to versatility, economy, process simplicity, and resultant green strength of the pressed part. CIP pressures on the order of 30 ksi are used. CIP utilizes specifically shaped elastomeric tooling, allowing slabs, rods, blocks, and even hollow cylinders to the compacted in the same press cycle. The deformable tooling is not capable of providing exacting geometric form, such that parts pressed using CIP typically require either

green shaping (milling, sawing, or waterjet profiling) in the pressed state or machining to the required configuration once sintered. Excess material removal is ideally performed in the as-pressed state due to more favorable economics of recovery.

For more precise shaped pressings, conventional punch-and-die hard tooling is necessary. In many cases, depending on part geometry and pressing technique to be used, additives are introduced into the blend for enhancement of specific characteristics:

- Increase the handling strength of the part in the pressed condition ("green strength")
- Addition of paraffin and/or other organics to permit the formation of a granulated, free-flowing feedstock for automated presses
- Introduction of compounds to serve as pressing lubricants

High green strength is essential when pressing thin, large area parts to prevent breakage during handling. Additives are to be avoided whenever possible, as they represent added cost in terms of additional process steps to introduce them and also remove them prior to sintering. Any additive used must be capable of both clean and nondestructive removal from the pressed part prior to sintering. Otherwise, interfacial embrittlement (contamination from residual C) and/or cracked parts out of sintering (internal gas pressure) will almost certainly result. Attention must be given to die filling in order to avoid uneven pressed density and locally undersized parts in the sintered condition.

In the as-pressed state, compacts are held together primarily by plastic welding of particle asperities and the interlocking of irregular shaped particles that occurred under high imposed pressure. Compact strength is therefore relatively low in the absence of the sound metallurgical bonding that will occur later during sintering.

Given the density (up to ~11 g/cc [or ~0.38 lb/in^3]) yet friability of WHA pressings, nondestructive handling becomes a prime consideration in the production of large shapes.

Sintering

Powder compacts are subjected to sintering in a H$_2$ atmosphere furnace, as shown in Figure 1. Commercial production of WHA components most commonly utilizes continuous pusher-type furnaces in that such designs offer high throughput rates and are capable of excellent sintered quality. While this photo shows a commonly used stoker type furnace. As the temperature of a compact increases, the metal oxide layer on each metal particle is reduced by the reactive H$_2$ atmosphere, forming water vapor as a reaction product. Optimum heating rate is determined by part section thickness, with massive sections requiring slower heating so as to avoid surface pore closure before the deoxidation process can approach completion. Batch type metallurgical furnaces are ideal for the sintering of very large parts requiring very slow temperature ramps. Thermally activated surface diffusion drives inter-particle neck formation in the vicinity of 1000C. Particle rearrangement and slow densification occur as this process continues. As the temperature climbs to ~1400C, the part will have achieved near full density while still in the solid state. Depending on initial pressed density, linear shrinkages up to ~20% may occur. Although with sufficient time essentially full density can be achieved in the solid state condition, resultant mechanical properties would be too low for practical use.

As the sintering temperature for a W-Ni-Fe alloy is increased to ~1450C, the formation of a liquid metal phase occurs, with the shape of the part being maintained by both liquid metal surface tension and an evolving W skeleton. The solidus temperature for a given WHA is obviously dependent on the combination of lower melting temperature elements. Any remnant porosity is virtually eliminated. Commercial LPS is performed ~30C or greater above the solidus temperature of the alloy, as this additional temperature promotes a greater volume fraction of molten binder phase to form (via increased W solubility), thus aiding spheroidization of the W phase. Within the size distribution of W particles present in the compact, the finer, higher surface energy W particles dissolve preferentially.

FIGURE 1

Pressed WHA shapes are positioned on ceramic slabs prior to insertion into a pusher type furnace for LPS in a flowing ambient pressure H$_2$ atmosphere.

W dissolution into the molten phase continues as equilibrium concentration is eventually reached, at which point continued dissolution is accompanied by W precipitation on larger pre-existent W particles. W particles typically undergo substantial volumetric growth from initial faceted crystallites to much larger spheroids during this solution-reprecipitation growth sequence (Ostwald Ripening). On cooling from sintering, a typical commercial W-Ni-Fe exhibits a spheroidized, nearly pure W phase in combination with a matrix phase containing typically 20 – 25 wt.% W in metastable solid solution. The Ni-rich matrix retains a highly ductile face-centered cubic (FCC) crystal structure which in combination with the rounded W phase contribute to the ductility and machinability of WHA.

Sintering and post-sinter processing of WHAs must be performed in furnace environments that prevent diffusional contamination from C, which would result in embrittlement. Continuous furnaces (stoker or screw fed) with flowing ambient pressure H_2 atmosphere produces the highest mechanical properties as water vapor and other volatiles are efficiently moved from the vicinity of the parts being sintered. It is possible to use standard metallurgical furnaces with graphite hot zones provided the manufacturer correctly engineered the furnace for correct directional H_2 flow. While uncommon in commercial practice, it is possible in modern cold wall sintering furnaces equipped with high efficiency blower quench to combine H_2 sintering, vacuum annealing, and quenching into a single energy and time efficient cycle.

Sintered Quality

While unimportant to density driven interests alone, having a well spheroidized microstructure is essential for high mechanical properties.

> Tensile elongation (%EL) is generally regarded as the most important single measure of WHA quality.

It indirectly measures both structure and interfacial microchemistry. High elongation can only be obtained from high purity, well spheroidized WHA. No amount of post-sinter processing can compensate for lack of LPS structure development. It is also important to note that when sintering in a reactive atmosphere, it is generally not possible to achieve the same level of structure/property development in large cross section parts as in smaller cross sections due to differences in both time/temperature history and rate dependencies involved in diffusion driven oxide reduction and water vapor escape prior to interconnected pore closure. This reality likewise implies that in thick section parts, the near-surface region will exhibit higher mechanical properties than material near the center of the cross section. This is an important awareness for scale-up of component designs that were developed subscale.

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SECTION 5

Post-Sinter Processing

For the majority of commercial mass property end uses of WHA, as-sintered properties as addressed by specifications such as AMS-T-21014 and ASTM B777 are sufficient.

There are however many applications that require greater mechanical properties in some application driven aspect, either greater ductility and toughness for durability or greater strength and hardness for stress applications. In such cases, post-sinter processing is required. For strength enhancement, deformation processing is required as there are no known transformational strengthening mechanisms in conventional WHA systems. With proper post-sinter processing, WHAs can be processed for maximum ductility exceeding 40% EL or for maximum strength levels exceeding 250 ksi with associated hardnesses up to ~50 HRC.

Aileron Weight

Post-Sinter Heat Treatment for Ductility/Toughness

W, like Fe in the ferritic state, possesses a body-centered cubic (BCC) crystal structure. As such, it similarly exhibits a susceptibility for hydrogen embrittlement. In that sintering is performed in a H_2 atmosphere furnace, WHAs supplied in the as-sintered commercial state have mechanical properties limited by the presence of interstitial H. While this is not problematic for the majority of mass property applications of WHA, it is not a desirable condition for material that will be used in stress applications or for mobile components susceptible to impact damage. Hydrogen embrittlement of WHA can be essentially eliminated by a post-sinter anneal in vacuum or inert gas atmosphere that provide sufficient thermal activation for H outgassing, greatly reducing the interstitial H content of the material to a low ppm level. Annealing time and temperature are determined by section thickness, with times 4 – 15 hours and temperatures 900 – 1100C being common. Material so treated typically exhibits a doubling of tensile elongation, thus promoting "bend before break" type behavior that is needed in critical applications.

Further mechanical property enhancement (specifically fracture toughness) is available via a resolution/quench sequence. For W-Ni-Cu alloys and W-Ni-Fe alloys with $2 \leq$ Ni/Fe ≤ 7, the principal benefit of this treatment is to reduce segregation induced embrittlement of grain boundaries caused by the presence of trace level contaminants of small atomic radii species such as B, C, S, and P. For very high Ni/Fe ratio ternary alloys and all W-Ni-Co alloys, resolution at ~1200C in an inert atmosphere followed by water quench is performed not only to reduce segregation induced embrittlement but more importantly to control embrittling intermetallics that would otherwise severely limit mechanical properties. Quenched WHAs typically exhibit another 5% gain in UTS, 10 – 30% gain in elongation, and ~200% gain in fracture toughness (as evaluated with unnotched Charpy impact) over vacuum annealed material. It is important to note that effective resolution/quench is limited to relatively small cross sections and cannot be performed on all sizes and shapes of WHA parts.

Post-Sinter Deformation for Enhanced Strength

Deformation processing of WHA is performed either to: (1) efficiently manufacture a specific shape or (2) to increase the strength and hardness of the alloy. (The former will be addressed later under "Forming," as this section deals only with the latter.) For the goal of alloy strengthening by strain hardening, deformation operations are typically performed at room temperature or only slightly above the DBTT.

High strength is rarely required in commercial applications but very common for military uses such as long rod kinetic energy penetrators. The most commonly used means of increasing the strength and hardness of WHA is by rotary swaging, in which the diameter of a bar is reduced by rapid short stroke hammering using contoured dies. This cold (or occasionally "warm") working additionally results in an increase in bar length and imparts an axial orientation to the microstructure. Cold working of WHA serves to sharpen the "knee" of the stress-strain curve. Whereas undeformed WHA typically has a 0.2% offset yield strength ~70% of the UTS, material worked to "~20% reduction in transverse cross sectional area (RA) or greater typically exhibits a yield strength >97% of the UTS.

The extent of swaging possible for a given alloy is a function of its initial ductility and toughness. Prior to swaging, WHA blanks must be subjected to H outgassing and resolution/quench treatment so as to possess sufficient ductility and toughness to survive the swaging operation. The strength and hardness of swaged material can be further increased by performing a strain aging heat treatment. The worked stock is then subjected to an isothermal heat treatment — typically 1 – 2 hours at 350-550C. This gives rise to signifi-cant strain aging in both the binder phase and the W phase as dislocation rearrangement occurs. Attempts at aging in the range 700 – 1000C may cause embrittlement in some alloys due to intermetallic precipitation. As W content of the WHA and/or starting bar diameter increases, the limiting value of %RA in swaging must be decreased.

There is a continuous set of mechanical properties available via the tradeoff in ductility and toughness for strength and hardness that occur on deformation processing WHA, as shown in Figure 2. An advantage presented by Co-containing WHAs, and in particular the W-Ni-Co ternary, is the ability to start with a higher combined property set, thus enabling the generation of higher strength and hardness levels for a given minimum ductility level.

Although swaging is the most commonly used deformation processing technique for WHAs, alternative methods of working include extrusion, rolling (conventional or Kocks mill), or upsetting. Hydrostatic extrusion is capable of successfully achieving very high reduction ratios, producing a fibrous microstructure. Upsetting, a commonly used practice for introducing work into short rods, differs from other techniques in terms of direction of material flow.

FIGURE 2

Property map for Ni-Fe and Ni-Co binder WHAs illustrating the greater processing options for the latter.
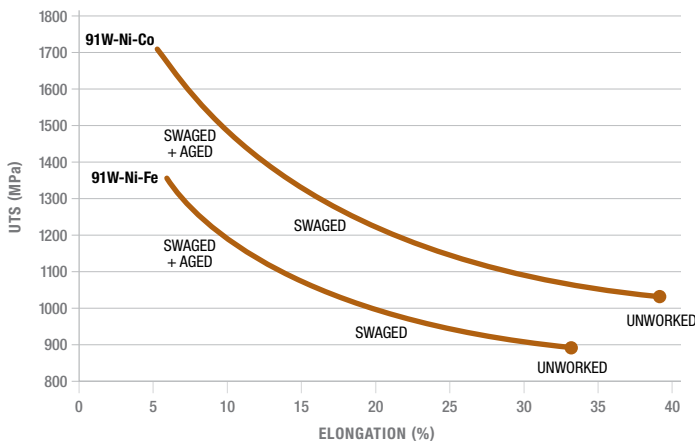
SECTION 6

Sintered Microstructure

With the exception of some specialty ordnance alloys, all commercial WHAs are two phase metal/metal matrix composites in which the W phase is almost always present in a spheroidized form for maximum part ductility/durability.

WHA is a true composite in that its set of key properties are derived from characteristics of each component, as illustrated in Figure 3.

As an illustration of the importance of the extent of sintering, Figure 4 provides a microstructural and tensile property comparison between two extremes — that of solid state sintering (SSS) and full LPS. SSS WHAs can possess full density and therefore could serve well in both mass property (counterweight, etc.) and radiation shielding applications if

it were not for brittleness. In a mature LPS condition, W spheroids are well rounded and are all approximately the same diameter (typically 30 – 60 µm). The presence of a noticeable population of smaller spheroids, or especially non-rounded W phase features, indicates a less than fully LPS alloy state. Uniform spheroid diameter is the basis for this determination — not spheroid size — as the latter is a function of the sintering temperature employed, which is commonly increased for sintering higher W content alloys.

FIGURE 3

Illustration of the phase composition of a typical LPS WHA.
Phase contrast provided by relief polishing and selective focus in brightfield, eliminating the need for chemical etching.

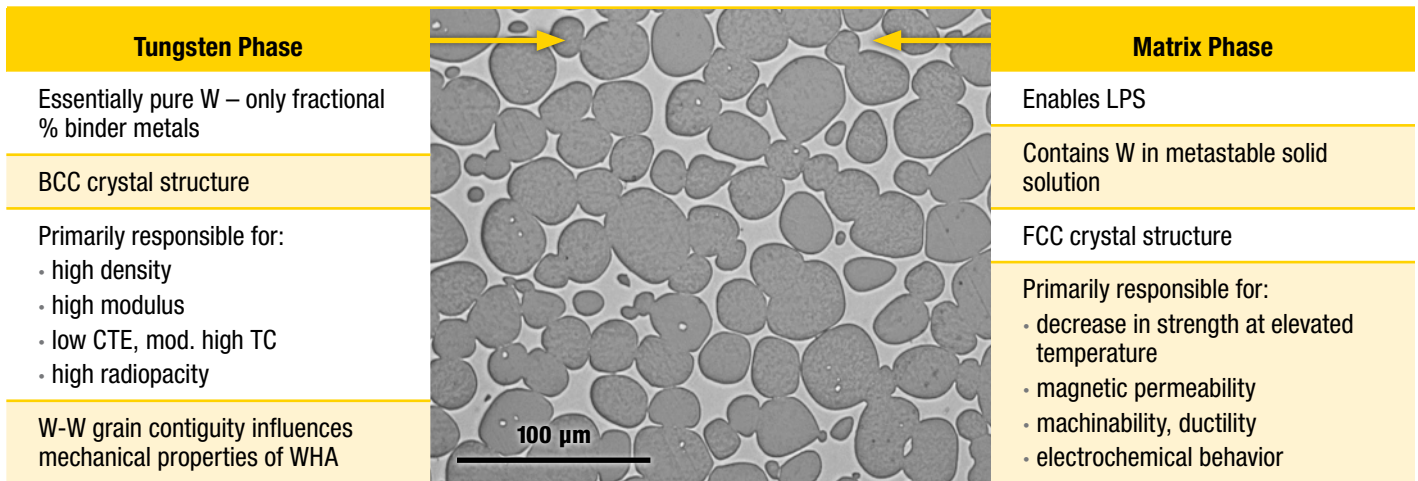| Tungsten Phase	Matrix Phase
Essentially pure W – only fractional % binder metals	Enables LPS
BCC crystal structure	Contains W in metastable solid solution
Primarily responsible for: • high density • high modulus • low CTE, mod. high TC • high radiopacity	FCC crystal structure
W-W grain contiguity influences mechanical properties of WHA	Primarily responsible for: • decrease in strength at elevated temperature • magnetic permeability • machinability, ductility • electrochemical behavior

100 µm

FIGURE 4

Illustration of the extremes in full density sintering of a Class 1 WHA.

While either extreme would provide equivalent density and x-ray attenuation, the SSS condition would offer poor durability whereas the LPS condition would provide high ductility and respond well to post-sinter heat treatment. The sensitivity of tensile elongation to overall quality is evident.
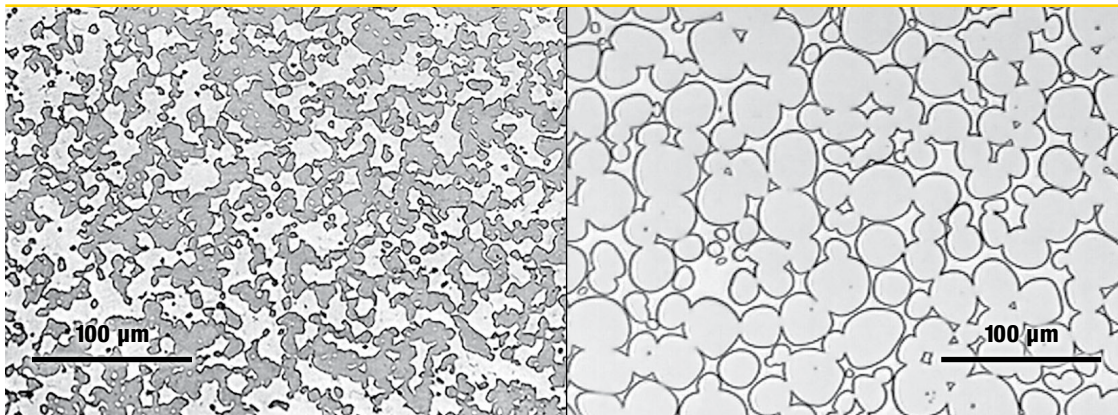
Solid State Sintered	Condition	Fully Liquid Phase Sintered
Full	Sintered Density	Full
Poor	Durability/Machinability	Good
<1	Typ. %EL in Tension (as-sint)	~12
~1	Typ. %EL in Tension (vacuum annealed)	~25

The nature and cause of the common surface-to-centerline microstructural variation has been discussed previously. This is only one of several gradients that may be present. As most commercial WHA production is performed with directional (pusher or continuous stoker) sintering furnaces, a front-to-back variation in W content, density, and tensile properties exists in LPS material. Highest tensile properties will most commonly be found in the front of the part. Such gradient effects are more pronounced in longer parts.

Batch sintering eliminates this front-to-back structure/ property gradient. Regardless of sintering method, in lower W content alloys there will be a top-to-bottom density gradient resulting from gravitational settling of the W phase during LPS. All other factors equal, a tensile specimen from the top of such a part will exhibit greater attainable elongation than one from a lower region — the latter having a slightly higher W content and density.

There are therefore 3 distinct gradients — sensitive to both alloy and part geometry — that can be present in LPS WHA parts that directly affect attainable properties in that region: (1) surface-to-centerline, (2) front-to-back, and (3) top-to-bottom. The presence of such structure/property gradients has the following implications for tensile (as well as other quality) testing:

- The location from which a sample is taken from a large or long WHA part can make a significant difference in tensile properties.

- Large cross section parts cannot be expected to yield the same level of tensile properties as smaller cross section WHA parts.

- Users with demanding applications needing specific property information for parts must develop a supple-mental quality plan that specifies where destructive test samples are to be excised.

As part geometry affects the rate of heat up in sintering, the testing of smaller but equivalent thickness coupons may not provide results representative of actual parts.

The existence of these factors explain why the general purpose commercial specifications for WHA are based on the testing of coupons and not actual parts. It would be impossible to specify a universally applicable destructive test plan and required property minima as there are too many variables involved. Destructive testing of full size WHA parts is in many cases very expensive due to the cost and quantity of W involved, but remains the only option to truly measure actual part properties.

Optical metallography provides the most convenient means of examining the sintered structure of WHA. Due to the mechanical differences between the W and matrix phases, an accurate rendering of WHA microstructure can be made using the relief polishing technique, in which an oxide polish slurry is used to selectively erode the softer matrix phase. If chemical etching is desired, Murakami reagent is the most widely used microetchant. Figure 5 shows the typical appearance of a LPS Class 1 WHA. Figure 6 presents a comparative image of a polished LPC Class 4 WHA. Of immediate recognition is the larger grain size resulting from the need to sinter this lower binder content alloy at a higher temperature to achieve full density in an acceptable time. Because of the temperature sensitivity of W solubility in the binder, spheroid size tends to be a function of LPS temperature.

The scanning electron microscope (SEM) is preferred for the examination of interphase boundary details. (All SEM images shown were taken in the SE mode.) The image shown in Figure 7 is representative of material that has been H outgassed by vacuum annealing. The fracture mode has transitioned to predominant cleavage. This transgranular fracture mode is indicative of high mechanical properties. In contrast, Figure 8 shows the typical appearance of the fracture of an embrittled WHA. No cleavage is present. The intergranular fracture path produced separation of the W/matrix interfaces, with only minimal suggestions of matrix deformation prior to failure.

FIGURE 5

Relief polished 90WHA specimen pictured in reflected light brightfield.

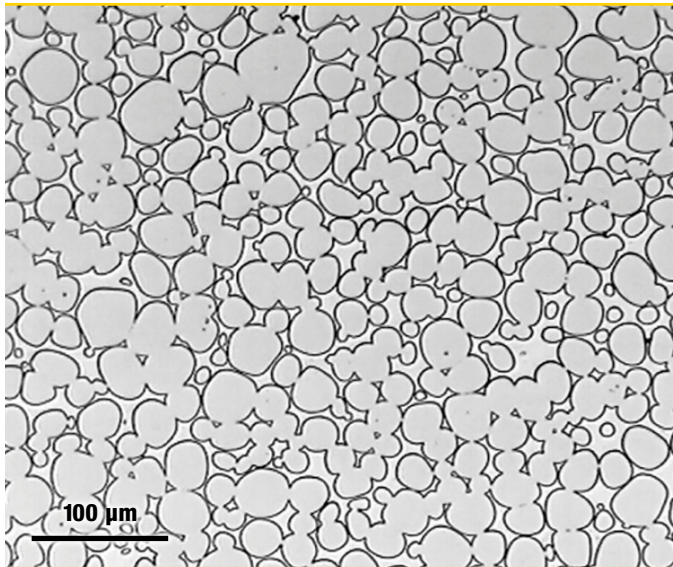Focus adjustment selectively gray shades W phase.

FIGURE 6

Equivalent magnification image of 97WHA showing larger spheroid diameter resulting from higher sintering temperature.
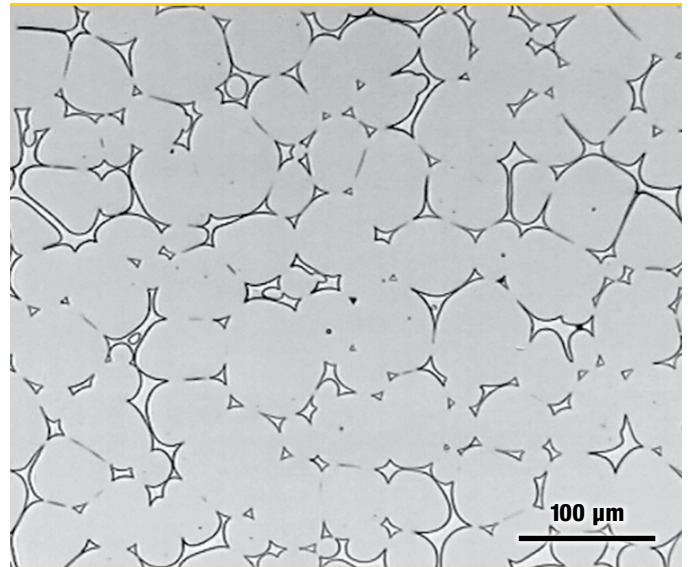
FIGURE 7

SEM fractograph of high ductility in 90WHA (vacuum annealed state).

Fracture mode was virtually all transgranular, with the classic appearance of W cleavage prominent. Matrix exhibited ductile "knife edge" fracture.
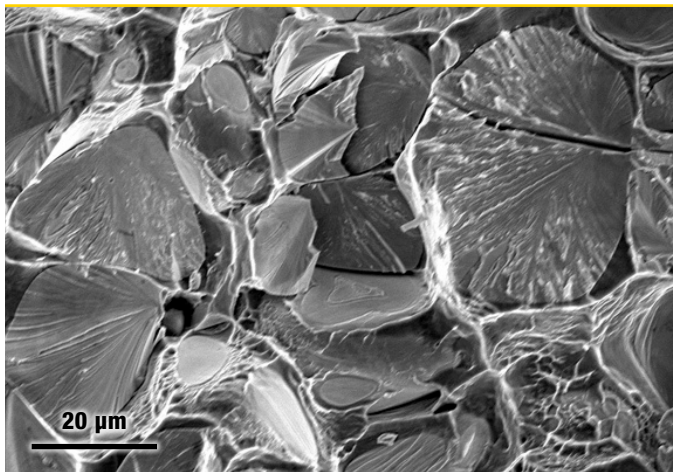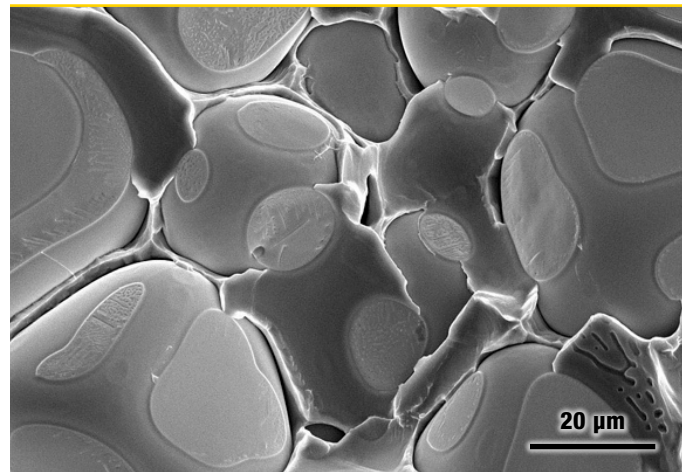

FIGURE 8

SEM image of an embrittled WHA.

W-matrix interfaces were too weak to transfer sufficient stress to induce cleavage. The matrix simply detached from the W spheroids under the applied stress.

SECTION 7
WHA Properties

Tensile Properties

Differences in testing speed will sometimes make direct comparison of published values difficult due to the strain rate sensitivity of the W phase, such that higher rates result in slightly higher strength and slightly lower ductility indications. Various gauge aspect ratios of tensile specimens (ASTM E8 specifies 4:1) further affect calculated ductility measurements. Attainable tensile properties vary with:

- W content;
- metallurgical state [as-sintered, vacuum annealed, resolutionized/quenched, or deformed]; and
- binder phase composition.

The offset yield strength of as-sintered WHA increase slightly with increasing W content, whereas ductility decreases. Tensile properties of W-Ni-Fe alloys are also sensitive to the binder Ni/Fe ratio, and typically undergo a maximum in both strength and ductility as shown in Figure 9A for two post-sinter processed conditions. Kennametal can supply any desired Ni/Fe ratio in custom blends.

FIGURE 9

Variation of mechanical properties of a 93W-Ni-Fe alloy with Ni/Fe ratio for hydrogen outgassed (VA) and additionally resolutionized and quenched (VA+Q) states.
Effects on quasi-static tensile behavior shown in Figure 9A and on medium strain rate unnotched Charpy energy shown in Figure 9B. Property maxima were revealed in all cases.

FIGURE 9A

FIGURE 9B
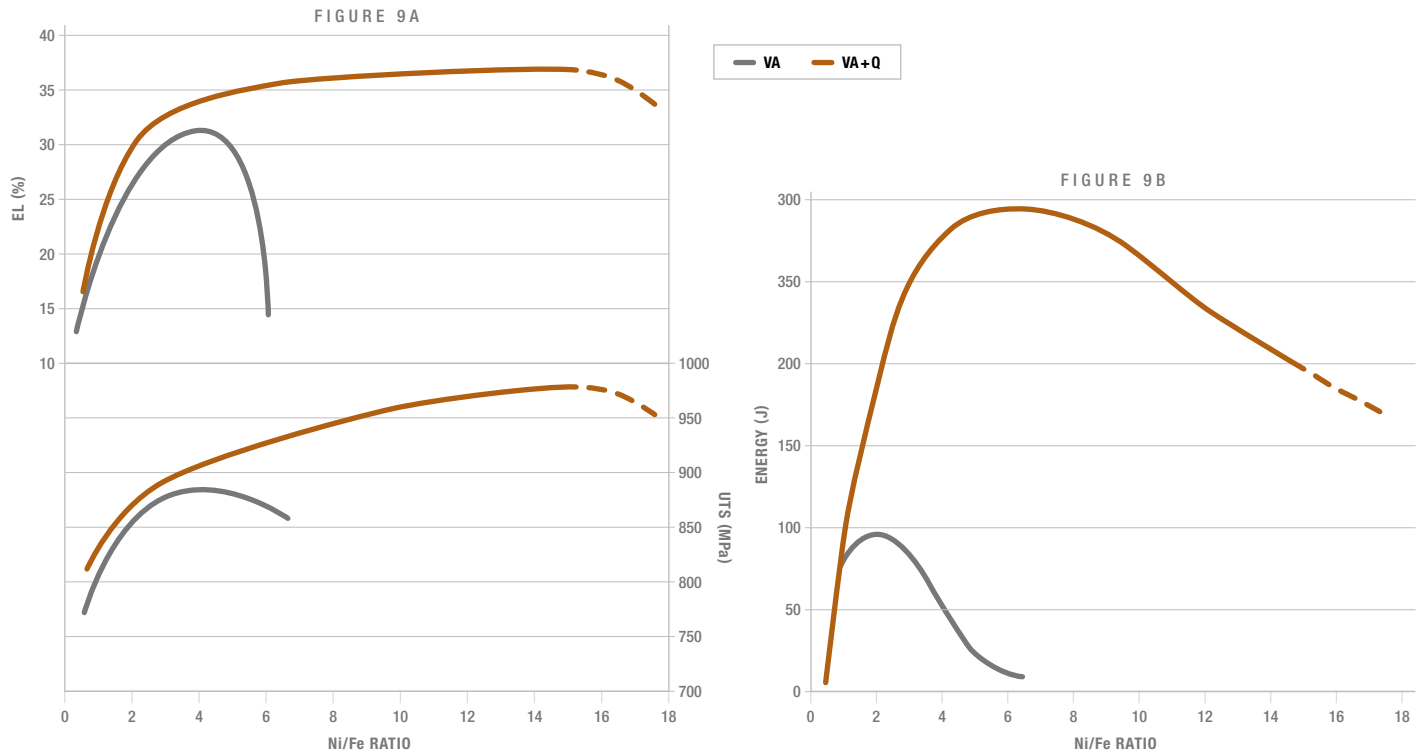
MIL-T-21014D, AMS-T-21014, and ASTM B777 all call out a similar set of as-sintered minimum tensile properties for commercial grades. W-Ni-Fe alloys are capable of providing much better properties than these minima suggest. However, given the various size and shape influences previously described, it is impossible to compile a table of tensile properties that would be representative of a given WHA part. Generally speaking, strength values for small sintered cross sections are on the order of 15% higher than the minimum specified values. Tensile elongations can be ~4 times minimum values. Further, the ductility of a given grade can then be essentially doubled by a post-sinter vacuum annealing treatment. Thus, while the minimum elongation for a Class 1 WHA is given as 5%, 15 – 20% is common and ~40% can be obtained in practice from vacuum annealed material. Such material would typically provide ~85 ksi in 0.2% offset yield strength and a UTS of ~130 ksi.

Due to their composite microstructure, all WHAs are notch sensitive. Tensile specimens must be prepared without impact and cleanly machined with minimal surface smearing/tearing, which would result in localized cold working and reduced ductility. The reduced section of a test specimens must also be free from circumferential tool marks from turning — otherwise they may prompt premature failure. While ductile, lower W content alloys may be more tolerant of such surface conditions, higher %W alloys and deformation processed WHAs will exhibit strong sensitivity. The use of scratches or indents to set extensometer placement during testing should be strictly prohibited.

The stress-strain curve for WHA is basic, with linear elasticity making a smooth transition into the plastic work hardening region. The 0.2% offset yield strength is commonly ~67% of the ultimate strength. The work hardening exponent has been determined to vary over the range of 0.51 – 0.58 for the 90 – 97 %W compositional range. Tensile specimens of WHA in a high ductility state exhibit noticeable necking prior to failure. Ductile failure is exemplified by transgranular (cleavage) fracture of the W spheroids in association with knife-edge failure of the binder (or matrix) phase. WHAs having tensile properties limited by the presence of interstitial H or small atomic radii impurities at the boundaries typically fail by intergranular W/matrix parting.

Elastic Modulus

Due to their high W content, WHAs offer high elastic stiffness, exceeding steel by ~50%. The Young's modulus is sometimes measured in tension, but more commonly in compression or by ultrasonic means. There is considerable variation in published values, no doubt in part due to different testing methods. While by no means a linear trend, the Young's Modulus for a given WHA can be approximated by:

$$E(\text{x}10^6 \text{ psi}) = 59.5 - (100\text{-W})$$

where W is the %W content (the elastic modulus for pure W is generally stated as 59.5E+6 psi (410 GPa). WHAs provide a large percentage of this elemental stiffness, yet with much greater part size and shape flexibility in manufacturing.

Impact Properties

Due to their composite microstructure and strain rate sensitivity, all WHAs are sensitive to impact loading. Notch sensitivity makes for easy crack initiation and the reduced ductility on higher rates of loading contribute to easier crack propagation. These two factors — notch sensitivity and strain rate sensitivity — must be considered in all stress intensive uses of WHA to ensure maximum material performance.

The most common measurement of WHA impact toughness is by the Charpy test (ASTM E23). Due to the high notch sensitivity of WHAs in both the unworked and work conditions, Charpy testing is most commonly performed using unnotched specimens. The use of specimens with "V" or "U" notches greatly lowers the sensitivity of the test to variations in metallurgical condition. As an example, standard 1 cm^2 Charpy bars of W-Ni-Fe exhibiting unnotched failure energies of ~150 ft-lbs and ~50 ft-lbs will both fail at ~6 ft-lbs if tested with the standard Charpy V-notch present. Charpy fracture energies obtained with subscale specimens cannot be scaled proportional to area in that the span between test anvils remains constant.

Absorbed energy to fracture of WHA decreases with increasing W. It is highly dependent on metallurgical state — increasing in the order of: as-sintered, vacuum annealed, to resolutionized/quenched. Quenched 90W-7Ni-3Fe can exhibit a Charpy energy of ~250 ft-lbs, decreasing to ~60 ft-lbs for 97W-2.1Ni-0.9Fe. Cold working lowers the fracture energy. Swaging a 93W-4.9Ni-2.1Fe alloy to 25%RA will reduce its Charpy energy from ~150 ft-lbs to ~70 ft-lbs. Within the industry standard W-Ni-Fe system, Charpy energy also exhibits a maxima relative to binder element composition as shown in Figure 9.B for given metallurgical states.

Hardness

The hardness of WHA is most commonly measured according to ASTM E18, using the Rockwell C scale. For unworked WHAs, hardness is a generally uninformative measurement, as material character can vary widely and yet display only a very minimal, if any, change in hardness. Hardness will increase, though only slightly so, with decreased W spheroid diameter and/or increased W content. For the industry standard W-Ni-Fe system, hardness can be varied over a range of ~27 HRC for as-sintered material to a value of ~45 HRC for the swaged and aged condition.

Magnetic Properties

WHA industry standards use a relative magnetic permeability (μR) value of 1.05 as the threshold of magnetic character — "magnetic" to imply attraction by a magnet (capture of flux lines) rather than the WHA itself exhibiting substantial magnetization. For simplicity, magnetic permeability of WHA is typically measured using a Severn Gauge as described in ASTM A342. W-Ni-Fe alloys with Ni/Fe<6 exhibit a weak ferromagnetic response. As can be seen in Table 6, alloys with Ni/Fe=7 exhibit only very feeble ferromagnetism — comparable to that of some austenitic stainless steels and easily satisfying the requirement for "nonmagnetic" classification. Even the highest permeability WHA is far less magnetic than common steels. For the very few applications that require true paramagnetic character, W-Ni-Cu alloys must be chosen. Any significant amount of Fe contaminant in W-Ni-Cu will slightly compromise their paramagnetic behavior.

TABLE 6

Magnetic permeability comparison.

| WHA Composition	AMS-T-21014 Class	Permeability (μ_R)
Mumetal (ref.)	na	20000
1010 ferritic steel (ref.)	na	>1000
Densalloy™ SD170 (Ni/Fe = 2.5)	1	5.0 – 5.5
Densalloy™ Dens21 (Ni/Fe = 7)	1	~1.01
90W-Ni-Cu	1	1.00
Densalloy™ SD175 (Ni/Fe = 2.5)	2	4.5 – 5.0
Densalloy™ Dens23 (Ni/Fe = 7)	2	~1.01
Densalloy™ SD180 (Ni/Fe = 2.5)	3	4.0 – 4.5
Densalloy™ Dens25 (Ni/Fe = 7)	3	~1.01
Densalloy™ SD185 (Ni/Fe = 2.5)	4	1.6 – 2.0
Pure W	na	1.00

Acoustic Properties

Reported values for the sound speed of pure W are typically 5180 m/s for a longitudinal wave and 2870 m/s for a shear (transverse) wave. Even for WHAs as low as 93% W, these values do not significantly change — attributable to the internal W skeleton that formed during LPS. While the sonic velocity for W is not exceptional, given the other properties of W, its acoustic impedance is the highest of any common material at ~100 (10^6 kg/m^2-s). Accordingly, WHAs also offer high acoustic impedance in a readily machinable form that facilitates use in transducers and similar applications that involve mechanical wave reflection or scattering.

Thermal Properties

While primarily comprised of the highest melting point metal, WHAs are not high temperature materials *per se.* While the W phase strongly influences CTE, thermal conductivity, and specific heat, elevated temperature behavior is influenced by the binder phase. WHA service temperature is limited by the decreased strength of the lower melting temperature binder phase, the onset of objectionable (as determined by application) surface oxidation, and the decrease in yield strength with increased temperature. Further, in the case of advanced alloys, there is the service temperature limitation posed by the precipitation of intermetallics. C hanges in mechanical properties with service temperature are very important in some applications in which a wide variation of temperature is routinely experienced (such as aerospace counterweights and certain nuclear shielding scenarios). Figure 10 illustrates the change in tensile properties that can occur over a >400C variation in temperature. The drop in ductility at lower temperatures must be considered in applications such as mobile radiation shielding to be used in severe winter temperatures.

FIGURE 10

Tensile property variation trends in large cross section Class 3 WHA.

All tensile testing was performed in open air.
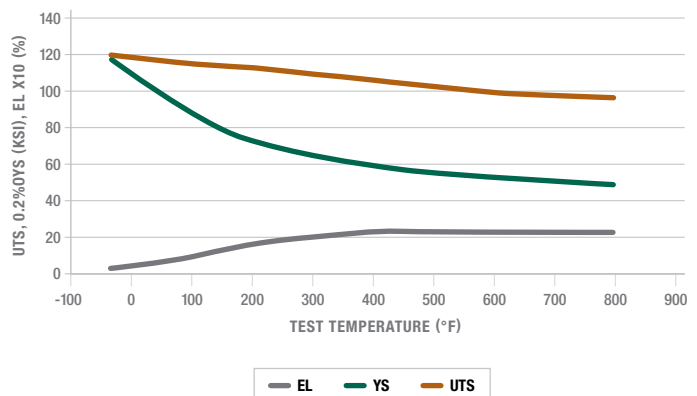
Under ambient conditions, surface oxidation will become noticeable at a temperature of ~350C. Protective atmospheres (N_2, Ar, etc.) are recommended for prolonged use at higher temperatures. Even if a protective atmosphere is employed, service temperatures ~600C and higher are to be avoided as these composite materials exhibit "hot short" behavior. If service temperature of a W-Ni-Fe alloy reaches ~1450C, a liquid phase will begin to form. Maximum service temperature is a matter of what is important to the end use, and WHAs have been successfully employed at temperatures on the order of ~1200C, but such instances are rare special cases.

While the coefficient of thermal expansion (CTE) of pure W is very low at 4.2 ppm/C (for 20 – 200C), the CTE for common WHAs is slightly higher. While not a linear dependency, the near ambient CTE can be approximated by:

$$CTE\ (ppm/C) = 4.2 + 0.155\ (100\text{-}W)$$

where W is the %W of the given WHA. The CTE of a typical WHA is generally three or more times that of other transition metals in mechanical contact. For applications involving large temperature change, this becomes a very important design consideration to maintain configurational integrity.

Figure 11 shows smooth trend lines. In reality, if a greater number of tensile tests were performed between 20 – 200F, inflection points would have been revealed due to ductile-to-brittle transition resulting from the W phase response (BCC crystal structure). This behavior is even more apparent in fracture toughness tests such as Charpy. Depending on the metallurgical condition of the material, the DBTT for a given WHA part may be slightly above or below ambient temperature.

The thermal conductivity of pure W is given as ~160 W/m-K. The lower W content of WHA coupled with the composite microstructure and alloying effects in the binder reduce the thermal conductivity of commercial W-Ni-Fe alloys to roughly half this elemental value (~70-100 W/m-K for Class 1 to 4), though reported values vary considerably. Corresponding values for W-Ni-Cu alloys are ~35% higher for a given W content. Reported values for specific heat decrease slightly with increasing W content, ranging from approximately 0.037 cal/g-K for 90WHA to 0.032 cal/g-K for 97WHA.
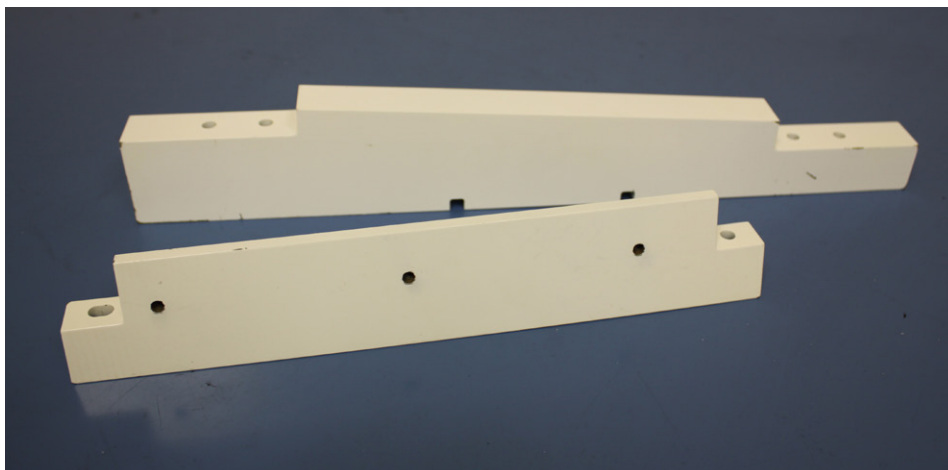
Wing Weights

Corrosion Behavior

WHAs are reasonably resistant to corrosion and are not susceptible to stress corrosion cracking (SCC) as is DU. Although their ambient corrosion resistance is good, long term corrosion resistance becomes a concern in applications presenting persistent exposure to harsh environments. Such uses would include marine environments and exposure to reactor or holding pool water. On exposure to extreme humidity, salt spray, or the presence of strong electrolytes, surface corrosion of WHA can occur. This is driven by the electrochemical difference between the matrix and the W phases, which sets up micro-scale galvanic cells on the exposed surface. All commercialized WHA compositions exhibit this behavior. Figure 11 shows an example of a corroded WHA surface, in this case resulting from ambient temperature exposure to a reactor emergency cooling water simulant. An etching type surface attack occurred. Galvanic contact with other dissimilar metals — especially of greater surface area and/or passivated surfaces — provides an additional drivers for WHA corrosion. The matrix phase is most readily attacked by acidic solutions whereas the W phase is most rapidly dissolved by alkaline solutions. Corrosion films that form on WHA do not offer further protection to the substrate. In cases where such harsh exposure is anticipated, a variety of protective finishes can be applied.

Perhaps one of the most easily applied metallic coatings for corrosion inhibition is electroless Ni. Most electroless Ni platings bond well to WHA, although plating chemistries with high P should be avoided. In corrosion applications additionally requiring wear or erosion resistance, a hard Cr plating may offer better protection of the WHA shield element. Both Ni and Cr platings can form a strong bond to a WHA surface. Conversion coatings such as "black oxide" commonly applied to steels are inappropriate for the corrosion protection of WHA.

FIGURE 11

Example of the aqueous corrosion response of a representative Class 1 W-Ni-Fe alloy.

A polished sample was immersed in a 40 g/L boric acid solution for 90 hours. Corrosion occurred preferentially to the binder phase as expected, with slight orientation sensitive etching of the spheroidized W phase. On the macro scale, this level of corrosion appeared as a very slight surface roughening and discoloration. Image shown in reflected light brightfield illumination.

20 µm
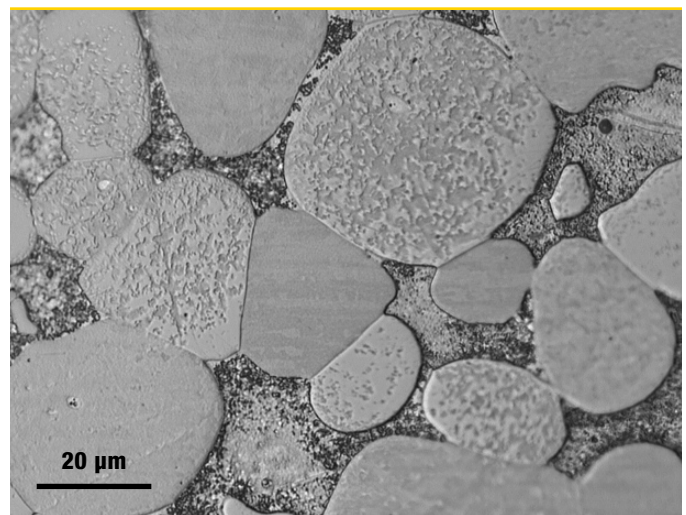
In many cases, adequate corrosion protection can be provided simply by a strongly adherent polymeric film. A variety of polymeric finishes, including epoxy and acrylic based paints, may be effectively used for corrosion protection. Paints additionally allow convenient color coding and ID marking of components when required, often simplifying cask assembly and QA verification. Organic coatings also provide a dielectric layer, useful in preventing the formation of a galvanic couple. For optimum bond strength, organic coatings should be dried by baking at the recommended temperature to ensure the full set of curing reactions occur.

SECTION 8
Radiation Attenuation

The shielding of penetrating radiation is one of the principal uses of WHA due to a number of its characteristics:

- Offers high attenuation of photonic radiation for a given mass and thickness
- Possesses (and maintains) sufficient mechanical properties for durability with a yield strength comparable to many medium carbon steels
- High thermal conductivity for efficient dissipation of decay heat from high activity sources
- Minimum susceptibility to undesirable photonuclear reactions
- Low in toxicity, chemical reactivity, and susceptibility to corrosion
- Available in a wide range of sizes and shapes

WHA is never required for the shielding of alpha or other charged particle radiation, as many cheaper material solutions are readily available. Likewise, WHA is not a good solution for attenuation of beta radiation, and its use for such is in fact

Syringe Radiation Shielding

counterproductive due to the efficiency of Bremsstrahlung that would be created due to the relatively high atomic (Z) number of W. The resultant energetic x-ray emission would create a more difficult shielding issue than the original beta radiation, which could otherwise easily be shielded with lower cost, lower Z number materials such as plastics or Al alloys.

WHA excels in the shielding of high energy photonic radiation that occurs from radioisotope sources (such as ^{60}Co), reactor operation, and from high voltage x-ray generators. The principal mechanisms for the attenuation of energetic photonic radiation create a sensitivity to both the Z number and density of given shielding material. WHA offers many benefits over widely used Pb that include higher strength, superior thermal stability, greatly reduced toxicity, and better shielding efficiency (up to ~36% reduction in thickness for ^{60}Co radiation). These and other advantages of WHA shielding over other candidate materials is apparent in Table 7, which provides a comparison of various metallic gamma shielding materials. WHA offers linear attenuation close to that of pure W, which in turn is only slightly less than that of depleted uranium (DU). WHA offers distinct advantages over both DU and Pb in that it is not subject to special OSHA, EPA, NRC, or other regulations governing its sale, handling, and/or use. For shielding that must operate at elevated temperature or undergo thermal transport of decay heat from very high activity sources, the relatively high thermal conductivity and solidus temperature of WHA allow it to be used in instances where Pb-based shielding would deform or melt. WHAs containing Co should never be used for radiation shielding in the presence of particle radiation or photonic radiation >10 MeV due to potential activation.

TABLE 7

Comparison of metallic gamma shielding materials in order of attenuation efficiency.

Element/Alloy	μ (cm⁻¹) for 1.25 MeV*	Z	Density (g/cc)	Melting Point or Solidus (C)	Therm. Cond. (W/m-K)	CTE (ppm/K)	UTS (MPa)
304 SS (Fe-19Cr-9Ni)	0.428	mixed	8.0	1400	16	17	515
Cu	0.471	29	8.96	1083	390	17	<365
Pb	0.667	82	11.35	328	33	29	~21
WHA (W-Ni-Fe)	0.953 – 1.04	mixed	17.1 – 18.5	~1450	~70 – 100	~5.8 – 4.8	870
W	1.076	74	19.3	3420	160	4.2	980
U	1.217	92	19.1	1132	27	19	400

Calculated using the NIST XCOM photon scattering program.

The linear attenuation coefficient (μ) is the most fundamental parameter for comparing the gamma shielding capability of various materials, calculated for the given photon energy of interest. The radiation transmissivity (T) through a slab type shield is given by:

$$T = \exp -(\mu \cdot x)$$

where μ is given in cm⁻¹ and x is the shield thickness in cm. (While this so-called "narrow beam" analysis is the most basic calculation of the shielding ability of a given material, it may underestimate the actual thickness of shielding required for a given protection level once specific source/shield/sensor geometry aspects are considered.) To calculate the "tenth value layer" (TVL) thickness (or 10% transmissivity)

for a typical Class 1 WHA (having a μ = 0.953 cm⁻¹) for shielding the 1.25 MeV average gamma energy of ⁶⁰Co, this equation would become:

$$\ln (0.1) = -0.953 \cdot x$$

$$x = 2.42 \text{ cm}$$

For convenience in quickly estimating the approximate thickness of shielding required for a given application, Table 8 provides a listing of TVLs of the various Kennametal Densalloy™ grades for a range of photon energies. The addition of TVLs amounts to multiplication of attenuation. Thus, a shield to provide 10⁴:1 attenuation of incident radiation would require 4 TVLs thickness.

Calculated TVLs for Kennametal Densalloy™ at various photon energies (cm).

| Energy (MeV)	SD170	SD175	SD180	SD185	Dens21	Dens23	Dens25	W ref.	Pb ref.	U ref.
0.12	.053	.051	.048	.046	.053	.050	.048	.043	.058	.028
0.14 ^{99m}Tc	.078	.074	.071	.068	.079	.074	.071	.064	.085	.040
0.20	.186	.178	.169	.163	.186	.178	.169	.153	.204	.094
0.36 ^{131}I	.619	.591	.566	.549	.618	.589	.565	.519	.722	.340
0.47 ^{192}Ir	.933	.893	.863	.838	.933	.893	.861	.795	1.14	.509
0.51 from β+	1.05	1.01	.960	.933	1.04	.993	.960	.890	1.30	.637
0.66 ^{137}Cs	1.41	1.36	1.31	1.28	1.40	1.35	1.31	1.22	1.83	1.54
1.00	2.10	1.99	1.92	1.88	2.04	1.98	1.92	1.80	2.86	1.54
1.25 ^{60}Co	2.42	2.35	2.28	2.22	2.41	2.34	2.28	2.14	3.46	1.91
2.22 H(n,γ)	3.13	3.05	2.95	2.88	3.12	3.04	2.95	2.78	4.54	2.58
6.00	3.27	3.16	3.05	2.96	3.27	3.15	3.05	2.84	4.63	2.66
10.0	2.93	2.82	2.72	2.64	2.92	2.82	2.71	2.52	4.09	2.34
20.0	2.39	2.28	2.20	2.14	2.38	2.28	2.20	2.02	3.27	1.88

The above values are estimates calculated using the NIST XCOM routine and do not include any buildup factor.
Actual required thickness should be empirically verified before final shielding design and/or use.

WHA expands only minimally in response to temperature rise, thus offering attractive shape stability. In shielding designs that undergo a significant temperature change during a use cycle, the W component will expand less than any surrounding stainless steel structures over the same temperature range whereas a Pb shield would present greater thermal expansion. In the latter case, a Pb shield would be expected to undergo permanent distortion due to creep. WHA conducts heat 4-6 times more efficiently than parts constructed from an austenitic stainless steel such as alloy 304 — valuable in spreading the heat from the interior to larger area heat dissipation surfaces for improved thermal management.

Large cylindrical shields can be constructed of stacked WHA rings — each possessing turned axial offsets (male/female steps) for nesting. The steps serve both for mechanical alignment as well as creating "radiation joints" which preclude any straight line radiation shine from the interior. Offset radiation joints can also the laterially offset, as shown in Figure 12.

FIGURE 12

End-on views of split cylindrical radiation shields illustrating sequential opportunities for improvement in straight line leakage prevention.

POOR   GOOD   BETTER
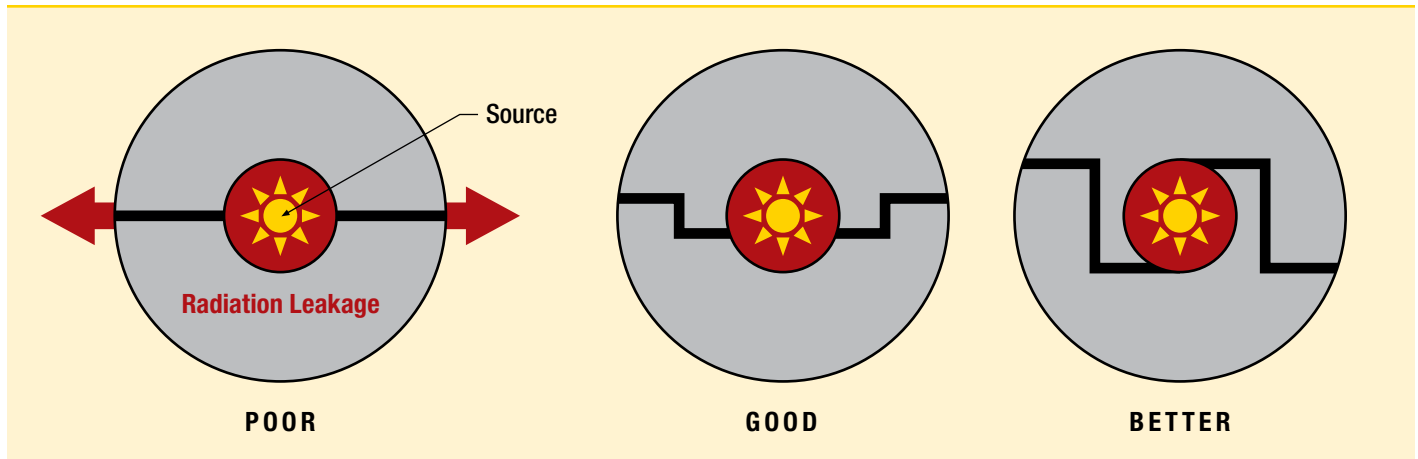
Neutron shielding is typically performed with water, H-rich polymers such as PE, or materials such as borated concrete. WHA is never selected for the purpose of neutron shielding alone. Nevertheless, its high W content provides a greater level of neutron absorption than does many other common metals, as can be seen in Table 9. W is seen to possess a neutron capture cross section over 100 times greater than Pb and nearly 7 times that of pure Fe. While never selected for use in a primary neutron shield due to its weight and cost, WHA may still play an important secondary shielding role in mixed radiation environments. A typical secondary shielding role would be the attenuation of 2.2 MeV gamma emissions from H capture of neutrons in PE or similar H-rich primary shielding layer in addition to any other gamma flux present.

The term "radiation shielding" may also arise in the context of RFI/EMI shielding. WHA is a poor choice for the shielding of radiofrequency radiation due to its cost, density, and low magnetic permeability. Alloys such as mumetal, permalloy, and similar would provide superior shielding in such applications.

TABLE 9

Thermal neutron absorption of various metals.

Element	Capture Cross Section (barns)
B	760
W	18
Ni	4.5
Fe	2.6
Al	0.23
Pb	0.172

SECTION 9
Designing WHA Components

P/M Implications

The design, fabrication, and integration of WHA components are straightforward provided the unique characteristics of the material are taken into account. Most significant are the differences in available shapes (P/M versus traditional melt/cast), its very high density, and its sensitivity to both impact and geometric stress concentration.

P/M is limited in its ability to provide long strips, wide sheets, and extremely massive bodies. While other dense metals with lower melting temperatures such as Pb and U can easily be melted and cast into very large shapes, fundamental considerations in both pressing and sintering make very large shapes impractical. This is seldom a real limitation however in most WHA applications given its density, as larger designs are commonly made as assemblies. Smaller building blocks are much easier to handle and sometimes allows components to be fabricated that would otherwise be impracticle, as suggested in Figure 13 for a larger area plate. As an example, 1 ft^3 of 95W-Ni-Fe weighs ~1124 lbf, demonstrating the rapid buildup in weight with size. The modular approach to larger WHA structures often provides other advantages as well, such as the ability to upgrade key features (beam apertures

in large radiation shields, etc.) while the remaining assembly can remain unmodified. For assemblies that may be subject to mechanical damage, modularity allows only a damaged portion to be replaced. This can lead to significant cost savings given the price of W-containing materials.

Designing for Maximum Mechanical Integrity

The general mechanical design practice of avoiding unnecessary stress concentration becomes even more significant when designing for WHAs given their notch sensitivity. Several general guidelines are:

- Incorporate as generous radii as possible at internal corners, thread roots, and cutouts. Ideally, no concave radius should be smaller than 0.020 in.
- Locate attachment holes or other cutouts no closer than 1.5 hole diameters from a free edge.
- Use machined surface finishes 63 μ-in rns or finer.
- Protect the WHA part from impact during fabrication.

Attention to these design details help preserve maximum mechanical integrity of a WHA part.

The ability to fabricate large panels of WHA is limited by the P/M process.
Approaching such needs in a modular fashion often make large components possible with minimal changes to functionality or support structures.

ORIGINAL REQUIREMENT   OFTEN BEST OPTION
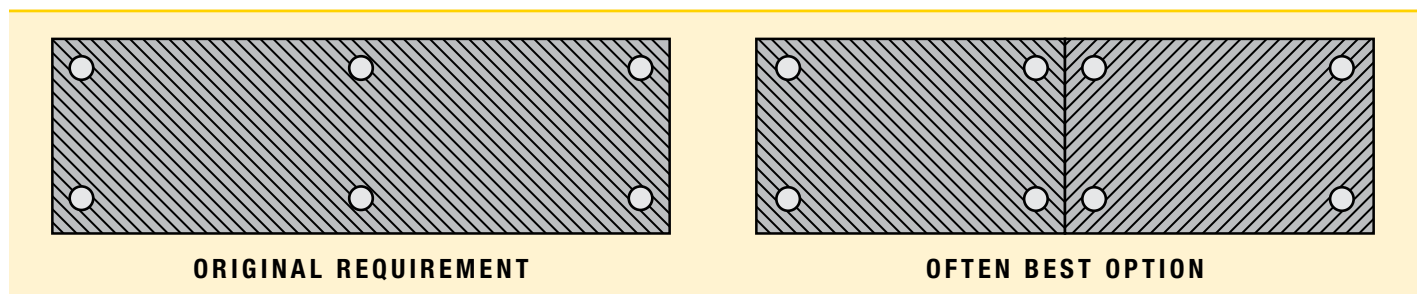
Minimizing WHA Part Cost through Design

Best economy is obtained when a given part can be manufactured as net shape, in which the final configuration of the part is produced directly as a pressed and sintered shape. This eliminates both the material otherwise lost during subsequent machining and the time/energy required to remove the excess material. Net shape parts are typically compacted in a uniaxial hydraulic press using hard tooling for more precise shape definition. Net shape parts must be pressed with a slight relief angle on vertical sides to facilitate damage free ejection from a pressing die. Consistent pressed density is critical in net shape manufacturing so as to provide uniform shrinkage. Dimensional control (avoidance of gravitationally induced slump) during LPS is challenging for the lower W content WHAs.

In reality, most applications for WHA require higher dimensional precision and/or shape complexity than can be produced net shape. For this majority case, near net shape blanks are produced and subsequently machined — still providing greater material economy than would be possible starting from standard mill shapes.

Due to a number of practical considerations, P/M favors "blocky" shapes where dimensions x~y~z. Thin shapes (x<<y~z) and long shapes (x>>y~z) are certainly feasible, but invoke certain limitations due to handling, shrinkage, and/or sintering gradient considerations. These all have cost and property implications. Similarly, in that the LPS condition is required for high mechanical properties in WHA, self supportive tall forms or thin walled cylinders are very difficult to produce as near net shapes due the likelihood of distortion in sintering. Parts requiring deep holes as would be produced by gun drilling are challenging and costly due to the combined considerations of hardness and high stiffness of WHA on the drilling operation.

Minimizing WHA part cost is a key consideration given the currently high global price of W. There are several steps in the part design phase that can facilitate lower cost manufacturing.

- Design mass conservative parts, using WHA only where its unique set of properties is needed, as this minimizes basic material cost without functional compromise. Extremely large WHA parts present special handling issues and extended processing times. Individual part size should ideally be under ~700 kgf. When WHA is used in combination with other materials in designs subject to temperature variation, attention must be directed to CTE differences, as mismatch becomes more pronounced with part size.

- Minimize the use of cavities or other reentrant features that represent material that must be machined away in most cases.

- Avoid the use of curved surfaces that require time intensive contour milling. Use faceted features instead when possible that can be rapidly created by high stock removal rate milling techniques.

- Make dimensional tolerances and surface finishes as loose as feasible. Consider the use of as-sintered surfaces on non-critical regions of a part.

- Though often impossible, avoid the incorporation of features requiring EDM, grinding, or other very slow stock removal operations.

- Ensure 3-D model construction and detail facilitate seamless translation into CNC tool paths and QA inspection routines.

Following these and similar guidelines from the design phase forward facilitates easier to manufacture, lower cost WHA parts.

SECTION 10

Fabrication Considerations for WHA

A prime advantage of WHAs over pure W is their ability to be machined to complex geometries using common metalworking tools and techniques.

Lower ductility WHAs will in general machine somewhat similar to gray cast iron, forming short chips. In contrast, highly ductile, lower W content alloys may tend to form continuous chips and require more attention to chip breaking, such as is common in machining of stainless steel. As all WHAs possess high elastic stiffness (50% greater than a steel toolholder), cutting forces will be higher than for common metal cutting operations, thus requiring carbide tooling, rigid fixturing, and adequate spindle torque. The use of metal cutting coolants/lubricants is optional except for thread tapping. If a cutting fluid is to be used in milling, boring, or turning, it should be a water based, non-alkaline formulation.

Sectioning

As the hardness of WHA in most conditions is only 30 HRC or less, it may be readily cut using a heavy duty shop bandsaw equipped with either a bi-metal blade with hook profile teeth or a segmented edge carbide blade at low speed (0.5 – 1.3 m/s) or alternately by water cooled abrasive cutoff saw. Complex profiles are readily cut in WHA using abrasive (garnet) waterjet. EDM, both wire and sinker type, is routinely used to shape WHA — but as a last resort given the low spark erosion rate of W. Despite this limitation, EDM remains the only practical shaping option for cutting such features as divergent rectilinear windows in radiation collimators. Other common metal cutting techniques such as oxyfuel, plasma jet, and laser cutting should never be used with WHAs. Such methods typically produce unacceptable levels of oxidation and can result in localized thermally induced microcracking.

Milling

Milling of WHAs is best performed using multi-insert cutter heads fitted with ISO grade K10 cemented carbide inserts. Some modern cutter/insert combinations will permit depths of cut on roughing to exceed 6 mm on machines of sufficient power. Best final surface finish is promoted by the use of large nose radius inserts, high spindle speeds, light feed rates, and positive rake inserts. While coated inserts offer improved life when machining most metals, this advantage is sometimes offset when machining WHAs due to the higher cutting forces created by the rounded (honed) edges necessary for coating of the insert. This should be evaluated on a case by case basis. Diamond shaped inserts from 35 – 80° all function well, with larger angles providing more durable cutting edges. Hexagonal inserts provide further economy for roughing with 6 usable cutting edges, but are restricted from machining narrow features. Typical milling parameters are provided in Table 10.

Turning

Turning operations are also best performed using K10 inserts. Sharp insert edges are vital for minimizing cutting force. Initial stock removal should be made using negative rake angle inserts, though tooling forces will be high. Tightest tolerance finishing passes are made with positive rake inserts. WHAs can easily be turned dry. Typical turning conditions are presented in Table 11.

TABLE 10

Suggested milling parameters for as-sintered WHA.

Milling Operation	Carbide Grade	Rake	Clearance	Edge Condition	Tooth Load (in)	Depth of Cut (in)	Speed (sfpm)
Roughing	K10	-7° – 0°	0°	honed	0.005 – 0.015	0.030 – 0.125	200 – 400
Finishing	K10	0° – +7°	0° – -11°	sharp	0.003 – 0.010	0.005 – 0.030	300 – 500

TABLE 11

Typical turning parameters for as-sintered WHA.

Milling Operation	Carbide Grade	Rake	Clearance	Edge Condition	Feed Rate (in/rev)	Depth of Cut (in)	Speed (sfpm)
Roughing	K10	-7° – 0°	0°	honed	0.005 – 0.020	0.030 – 0.125	200 – 350
Finishing	K10	0° – +7°	0° – -11°	sharp	0.005 – 0.010	0.005 – 0.015	250 – 400

Grinding

WHAs are capable of excellent surface finishes when centerless or surface ground. Grinding is best performed with vitrified bond alumina or silicon carbide wheels of medium hardness, as the ductility of WHA tends to load diamond wheels rather quickly. A water soluble coolant should be used.

Drilling

For drilling, standard surface treated HSS twist drill bits generally perform satisfactorily. Very high %W alloys or special high hardness WHAs may require the use of carbide bits. As hole size decreases, attention to clearance and the continuous removal of work hardened cutting debris become more critical to avoid seizing or bit breakage. The use of high shear strength lubricant is recommended. A through-spindle coolant provision is useful in larger bit sizes.

Tapping

Tapping is typically the most challenging metal shop operation for WHA due to the high resultant torque on the tap shank caused by the high stiffness of WHA in combination with the high contact area between tap flutes and workpiece. This is especially true for swaged WHAs containing Co, which may prove virtually impossible to tap. For this reason, 2 or 3 flute, positive rake, spiral point, high clearance taps should be used. Surface treated premium cobalt steel taps typically perform best for this application. The use of a high shear strength tapping lubricant is essential. Sulfonated oils are effective lubricants as well as many proprietary tapping fluids.

The coarsest possible thread should be chosen for a given diameter and application. With care, threads as fine as 2-56 can be successfully tapped. Approaches to minimizing tap/work contact area include the use of larger pilot hole sizes, and a 60% thread area engagement should be considered. Holes ¼ – 20 and finer may require dropping to 50% engagement. Holes should be tapped to completion without back threading to avoid binding work hardened chips. For larger holes, single point threading may prove the best option.

Forming

Mechanical forming operations are rarely used for WHA but are a viable option in some cases to create specific shapes. WHA sheet rolling is one such example. Forming is limited to cases involving relatively thin stock and high ductility WHA. Press brake orming should be performed at low speed and with generous tool radii. Slight heating of the stock immediately prior to working helps ensure dependable, fracture-free forming of the alloy above its DBTT. For the former shape production approach, operations such as press forming, rolling, or swaging are performed at elevated temperature ranging from only slight heating of stock to ~300F (so as to ensure the operation is being performed above the DBTT for the alloy) to temperatures on the order of ~1300F at which yield strength has significantly decreased.

Rudder Weight

Joining

Mechanical fastening techniques should be employed where possible in joining WHA either to itself or other metals so as to minimize the uncertainties associated with thermal bonding techniques, most of which relate to the formation of incomplete joint bonding, annealing of induced strain hardening, differential CTE effects over large surfaces, and/or detrimental thermochemical alteration of the parent metal(s).

Joining is most commonly performed using standard fasteners such as bolts and pins. Mechanical fasteners are of known strength, and such joints can be readily inspected. WHA parts can be likewise be machined with threads or interlocking features to function as fasteners. Standard sized threaded fasteners can be machined from WHA for use in attachment of WHA radiation shielding so as to avoid the creation of "hot spots" that would result from the use of steel fasteners. While ideal for this use, WHA screws or bolt should not be used for lifting or in dynamic stress applications due to the inherent notch sensitivity of all WHAs.

In addition to notch sensitivity, the low CTE (only ~33% of that for 304 stainless) of WHAs must also be considered to avoid fasteners that loosen with repeated (thermal) use cycles. Impact fastening techniques such as impact wrenches and riveting should never be used. Shrink fitting is also a joining option for small assemblies, provided the WHA part is the inner member.
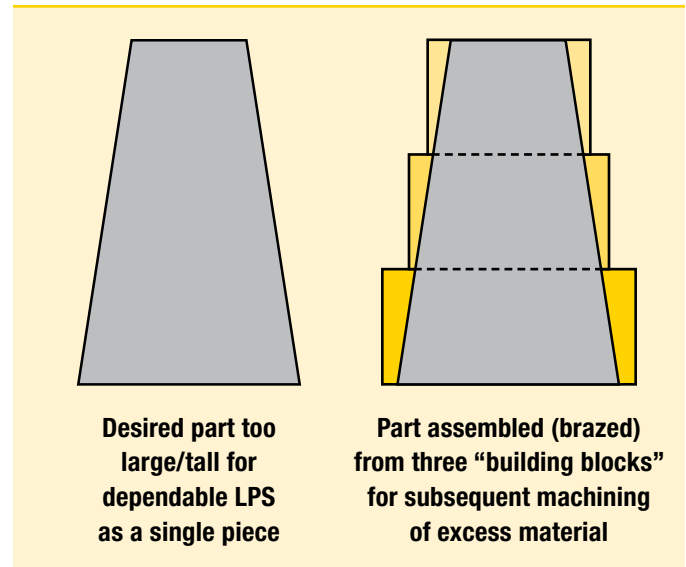
Brazing

Due to differences in CTE, chemistry, and melting point of the W phase and the binder, WHAs are not readily weldable as microcracking and selective binder element volatilization can occur in the vicinity of a weld. When a thermal joining technique is required, brazing provides a means of joining WHA to itself or other metals. Brazing is best performed in a hydrogen atmosphere furnace to protect the WHA parts from oxidation and also permit fluxless joining. Compatible filler metals include pure Cu, monel 400, and standard AWS defined Ag-Cu brazing alloys such as BAg-13a. Filler alloys containing S, P, Zn, Cd, or Al should be avoided due to possible interfacial embrittlement. Brazing temperature constraints and the end application generally determine optimum filler metal choice. As with any brazing operation, good joint preparation is essential for producing fully bonded interfaces. Brazing can minimally alter the chemistry within the immediate vicinity of the joint, such that points of attachment should not be located near such zones.

While furnace brazing is preferred, manual oxyfuel torch brazing using a flux is also possible for smaller parts but will result in oxidation. Another useful and cleaner approach to manual brazing of small assemblies is the use of a TIG (GTAW) torch as a very intense heat source to flow the filler alloy. Leading and trailing inert gas shields promote better protection of the hot WHA against oxidation. Low temperature solders will not wet WHA.

FIGURE 14

Brazing and sinter bonding allow the generation of shapes not possible by direct press and sinter.

Desired part too large/tall for dependable LPS as a single piece

Part assembled (brazed) from three "building blocks" for subsequent machining of excess material

A special extension of furnace brazing can be employed when it becomes necessary to join massive sintered WHA bodies together to form a shape impossible to sinter as a self-supporting, monolithic form (Figure 14). In this technique termed sinter bonding, previously sintered and machined pieces are placed in contact and heated slightly above the solidus temperature of the WHA. At this temperature, the previously sintered WHA holds its shape. A thin braze filler foil may optionally be used at the interface to promote surface melting and flow. If done properly, this technique yields an imperceptible joint with no significant local degradation in tensile properties. This technique differs from furnace brazing in that brazing does not involve melt formation in the parent metal. The building block approach also makes possible the creation of functionally gradient assemblies.

SECTION 11

Alloy Selection Criteria by Example

WHA grade selection is often made on the basis of maximum density, but that may lead to an unsatisfactory outcome in the end use.

A better strategy for many applications is to first define what minimum set of mechanical properties are needed. Over the W content range for WHAs, ductility can vary widely due to the microstructural influences of the weaker W-W interfaces (a contiguity consideration) and the amount of ductile binder phase present (which decreases with increasing alloy density). Thus, as the W content of a WHA is increased:

• There are gradual increases in alloy density, elastic stiffness, hardness, yield strength, and thermal conductivity.

• There are gradual decreases in CTE and magnetic permeability.

• Attainable UTS decreases slightly due to the earlier onset of fracture.

• "Magnetic" commercial grades typically provide higher tensile properties than "nonmagnetic" grades.

In stark contrast to these more subtle changes, ductility can vary a factor of 4 or more in some cases over the 90 – 97% W compositional range — making it a far more sensitive parameter to be considered up front in the alloy selection process. With only a slight sacrifice in density, an appreciable gain in alloy ductility can be realized, as seen in Table 12. This reality recommends ductility as being the prime consideration in selection of the optimum WHA for a given application, with other factors such as density and magnetic permeability being secondary considerations. While stationary components such as balance weights or stationary radiation

shielding may require only minimal mechanical properties, it is recommended that any end use involving either stress service (static or dynamic) or application of a critical nature utilize WHA with as much ductility as possible — thus promoting "bend before break" behavior. Class 4 WHAs should be avoided for dynamic applications. The consideration of ductility takes on added importance as practical aspects of structural attachment method, impact resistance, temperature response, and inertial effects of massive parts are considered.

TABLE 12

Effects of W content for commercial WHA compositions.

Variation in wt.% W from Class 1 to 4	+7%
Resultant change in nominal alloy density	+1.5 g/cc
Typical change in attainable ductility (%EL)	typ. -75%

For a wide range of commercial applications, a Class 2 WHA will often be the best general choice, balancing considerations of density, uniformity, ease of manufacture (leading often to lower part cost), and durability in end use. Similarly, a number of previous ordnance-related studies have identified the 93% W content for WHA as the optimum for long rod kinetic energy penetrator use.

Aerospace Counterweight

WHA has been widely used for various aerospace counterweights for many decades, such that the use of more corrosion prone DU has been effectively eliminated. Such weights are employed for vibration damping of control surfaces or balancing of structures. The overall set of advantages provided by WHA are seen in Table 13, which explain its widespread use for such components. The combination of density, strength, machinability, and freedom from toxicity and radioactivity concerns make it the clear material of choice. WHA provides the serospace designer the means to place considerable mass exactly where it is needed. This mass property use is typically addressed by the selection of a Class 1 WHA. Best economy can be further promoted by utilizing as many as-sintered surfaces on the part as possible. Closer shape tolerances may require selection of a Class 2 WHA, which would present better shape preservation during LPS. Regardless of the WHA selected, a corrosion prevention coating should be applied.

Radioisotope Transport/ Storage Container

Due to its unique set of properties, WHA is ideal for the construction of containers — commonly called "pigs" — for the transport and/or storage of high activity gamma sources. Such containers must provide space efficient attenuation of highly penetrating radiation, accommodate secure locking and fixturing hardware, and offer durability for handing damage resistance — especially important considering its mass and consequence of failure. While Pb shielding bodies must be contained in a higher strength encasement material such as stainless steel, WHA offers a yield strength comparable to some medium carbon steels and can be machined directly into the needed shape without the need for containment, though encasement may be desirable for other reasons. A Class 3 WHA provides a balance in high attenuation and attainable ductility (for handling damage resistance) for transportable pigs whereas a Class 4 WHA would be ideal for stationary storage units.

TABLE 13

Comparison of various metallic candidates for counterweights.

Material	Density (g/cc)	Tensile Strength	Stiffness	Machinability	Toxicity	Radioactivity	Material Cost
Steel	~7.9	moderate	medium	excellent	high	none	low
Lead	~11.3	very low	very low	very low	high	none	low
WHA	17.0 – 18.5	moderate	high	excellent	low	none	moderate
DU	18.7 – 19.1	moderate	medium	special	high	present	moderate

CT Scanner Collimator

CT scanners utilize parallel plate collimators to precisely define the x-ray beam angle for each tomographic image slice. The high radiopacity of WHA compared to Cu makes for sharper beam cut-on/off, thus yielding higher definition images. This application requires WHA to be rolled into sheets on the order of 0.030 in thick. A ductile Class 1 WHA would provide maximum yield out of rolling — thus enabling a lower part cost option while offering an order of magnitude higher radiopacity than Cu sheet for 120 keV x-rays. Rolled WHA sheets are easily profiled to shape using abrasive waterjet trimming.

Kinetic Energy (Long Rod) Penetrator

WHA is an ideal low toxicity material for the manufacture of long rod penetrators designed for the defeat of armor based on kinetic energy of flight alone. While shorter, spin stabilized rod penetrators are typically made of higher W content alloys for minimum velocity falloff during flight, fin stabilized long rods (L/D typically 20 – 30) are generally made from WHAs with 91 – 93%W. Such alloys enable the resolutionized and quenched rod blank to be swaged to ~20%RA or greater, which serves to double the yield strength while preserving sufficient ductility to survive bending stresses induced on impact with multiple spaced armors.

Table 14 presents the property evolution of a Class 2 WHA blank during sequential processing to develop ordnance grade properties. W-Ni-Fe alloys are currently in the greatest use, although the highest terminal ballistic performance provided by W-Ni-Co alloys — approaching that available from DU-0.75Ti alloys in this application.

Collimator for Radiation Therapy

Modern electron linac based radiation therapy machines for the treatment of cancer can generate x-ray energies up to 25 MeV, such that primary shielding and beam collimation become formidable tasks to ensure patient safety. WHA is an ideal material for this application — superior to Pb both in its ability to attenuate high energy x-rays and in durability, resisting handling damage and creep. It is not susceptible to photofission as is DU. Class 3 and Class 4 WHAs are ideal for this application given their higher attenuation. W-Ni-Fe is favored over W-Ni-Cu at x-ray energies ~15 MeV and above based on lower activation result-ing from photonuclear reactions. When shielding must be placed in close proximity to electron optics such as bending magnets, a low permeability W-Ni-Fe should be selected so as to provide minimum perturbation of magnetic flux lines.

TABLE 14

Typical property development sequence for 93W-4.9Ni-2.1Fe.

Alloy	UTS (ksi)	EL (%)	Hardness (RC)	Charpy (J)*
As-sintered	125	15	28	–
Vacuum annealed	130	25	28	–
Quenched	135	32	29	200
Swaged 15%RA	160	16	39	150
Swaged 25%RA	175	14	40	95
SW 25%RA + aged 500C/1 hr	200	7	44	60

Standard 1 cm² test bars, unnotched.

Long Extension Toolholder

WHA is widely used for high stiffness boring bars, long extension toolholders, and other "chatter free" tooling. When compared to more standard steel toolholder materials, WHA offers a 70% gain in elastic modulus, as seen in Table 15. While cemented carbide provides superior stiffness, WHA can be directly machined to form cutter pockets and offers better vibration damping. A lower W content WHA is preferable for durability in this end use. Class 1 WHA rods typically exhibit a side-to-side density gradient resulting from gravitational settling of the W phase during LPS in the horizontal position. This out-of-balance condition promotes earlier onset of chatter in long extension tools. A Class 2 WHA is therefore chosen for better axisymmetric density uniformity.

Well Logging Tool

WHA is an excellent material for instrument casings used in down hole logging of oil wells. Well logging tools are used during the completion sequence of a well and among other capabilities, perform formation analysis as a function of depth on the basis of gamma backscatter. The source is typically 1 – 2 Ci of ^{137}Cs. This application is perhaps the best example of an application taking advantage of a number of the uniwue properties of WHA which includes:

- High density – negative bouyancy in drilling muds
- High density – excellent shielding of gamma radiation to isolate crosstalk between onboard radiation source and detector window
- Strength – able to withstand the high hydrostatic pressure
- Low surface reactivity for minimal corrosion in a harsh environment
- Machinable – able to be fabricated with a high level of geometric detail

TABLE 15

Comparison of various toolholder materials.

Material	Modulus (Mpsi)	Damping	Density (g/cc)
4140 steel	30	low	7.9
Class 2 WHA	52	moderate	17.5
WC-10Co	90	low	14.5

Mechanical properties are very significant to the survivability of these rather large components as there are no simple or inexpensive problems downhole. Loss of a source may trigger NRC shutdown of the well. WHA used in this application must have robust mechanical properties for "bend before break" type behavior. A Class 2 alloy such as SD175 in the vacuum annealed condition is ideal for this application. Quenched material would provide an even higher level of durability as logging depths are pushed.

Conformal Weight Strip

A weight strip is to be transitioned from brass to WHA for higher density. The long, narrow weight strip contains a number of deep transverse slots that permit the strip to be bent slightly to conform to a nonplanar surface prior to bonding. There is no ideal WHA choice for this scenario. This is an example of a part that must be redesigned, as no WHA will function well in this application due to its notch sensitivity. Possible solutions would include contour machining of the WHA weight strip mounting surface or, if the strip was sufficiently thin, incremental press forming to create the needed contour. For the latter option, the use of vacuum annealed Class 1 WHA should be considered due to the greater formability it would provide. Well designed WHA parts should never combine deep notches, slits, or thin wall sections with stress service.

SECTION 12
Environmental and Health

As environmental and safety considerations become ever more influential drivers in the design and use of new materials and products, the fact that WHAs have only a slight percentage of their total weight in slightly toxic metals such as Ni and Co provides an incentive for their selection over other common high density materials that are Pb- or U-based. Whereas the latter two materials pose definite toxicity concerns, less than 10% of the total weight of a typical WHA is comprised of less toxic metals such as Ni and Co.

In recent years, there have been a number of studies that have appeared focusing on *in vivo* effects of certain WHA compositions, with metal solubilization being driven by galvanic mechanisms. Such studies address a very unlikely case for exposure that represents a vanishingly small consideration in the overall discussion of metals toxicity. Handling and use of WHAs require no special provisions beyond those considered good general practice for handling other metals such as Cu-based materials or superalloys.

Life cycle considerations are also favorable for WHAs as these materials are readily recyclable by both chemical and oxidation/reduction means. Both WHA machining scrap and spent components serve as valuable raw materials for future alloy production instead of posing a waste disposal problem. WHAs are therefore the ideal green choice for environmentally friendly high density material needs.

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