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Amorphous Matrix Composites (AMC) were developed and fabricated using Tungsten and Carbon reinforcements. Emphasis was placed on achieving high loading fractions of the reinforcing materials. A process to commercially manufacture AMC's was studied and mapped. The feasibility of the process was also determined. Rods of AMC were fabricated using this process. The samples were fully dense and the amorphous nature of the binding matrix was confirmed. The results from this study will provide valuable process data for the future development of AMC products such as Kinetic Energy Penetrators and sporting goods

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DEVELOPMENT OF HIGHLY REINFORCED AMORPHOUS METAL MATRIX COMPOSITES

Final Report For Phase I Developed Under SBIR Contract Contract Number: DAAG55-98-C-0008

Technical Objectives of Phase I

1) Develop and demonstrate the fabrication of highly reinforced AMC rods with Tungsten and Carbon fibers/wires (Objective successfully achieved.)

We demonstrated the fabrication of highly loaded AMC rods with Tungsten wires. Samples of AMC rods with 70-85 % volume Tungsten wires were prepared. The AMC rods are typically 3" to 5" long and 0.35"- 0.40" diameter whereas the Tungsten wires are 0.020" diameter. The samples were fully dense and the amorphous nature of the binding matrix was confirmed. We have also demonstrated the fabrication of 3" long and 0.3" diameter rods of AMC with 20-30 % volume Carbon reinforcements.

2) Establish the maximum fiber/wire reinforcement loading levels for Tungsten and Carbon (Objective successfully achieved.)

AMC rods of 70-85 % volume Tungsten wires were readily prepared. The samples were fully dense. Higher reinforcement loading levels were hindered by our ability to prepare suitable Tungsten preforms at higher volume fractions. There were no issues regarding the wetting and flow characteristics of the amorphous metal within the process parameters we established. We expect that AMC rods of 90 % volume Tungsten wires could be prepared within the process parameters we established provided a suitable preform can be prepared. Similarly, higher Carbon reinforcement loading levels of more than 30% were hindered by the difficulty to prepare suitable preforms due to very small diameter of high strength and high modulus Carbon fibers. Accordingly we focused our efforts on Tungsten reinforced AMC's.

3) Develop a Process Map for the fabrication of AMC's (Objective successfully achieved.)

We developed a practical process for making AMC's and established the key process parameters. The process allowed us to attain high loading levels while successfully retaining the amorphous structure of the binding matrix. We believe this is a rugged and robust enough process to lead to a production process. The process uses relatively simple equipment and employs lower temperatures and shorter process times compared to the process of WHA alloys. The process itself does not impose any significant limitation on the size of the AMC that can be produced.

Results of Phase I

1) We chose VITRELOY^{TM}-001 ($Zr_{63}Ti_{11}Cu_{13}Ni_{10}Be_3$ in weight %) composition from existing bulk amorphous alloys as the best candidate for the study of AMC's due to two critical reasons. **First**, the lower melting temperature of VITRELOY-001 allows us to process composites at lower temperatures which then reduces the reaction of amorphous alloy matrix with reinforcements. **Second**, the better processability of VITRELOY-001 allows us to make large bulk objects of amorphous metals even in the presence of impurities. The thickness of the amorphous metals is limited due to the high cooling rate requirements during their process. The chemistry of the amorphous alloys determines the critical cooling rate, which in turn determines the maximum processable thickness of the amorphous alloys. When, deviations occur from the ideal chemistry due to impurities and other factors (such as reactions with reinforcements and/or container), the cooling rate requirement drastically increases which in turn limits the processable dimensions to millimeters. In this respect, VITRELOY-001 is the most friendly amorphous alloy in processing large bulk objects as it has a very forgiving and robust chemistry to form amorphous phase. This is shown in Figure 1. This issue becomes especially critical for the production of AMC's, as reaction of amorphous matrix with reinforcements and/or container can easily produce deviations from ideal chemistry as much as few atomic percent from the ideal chemistry of amorphous metals.

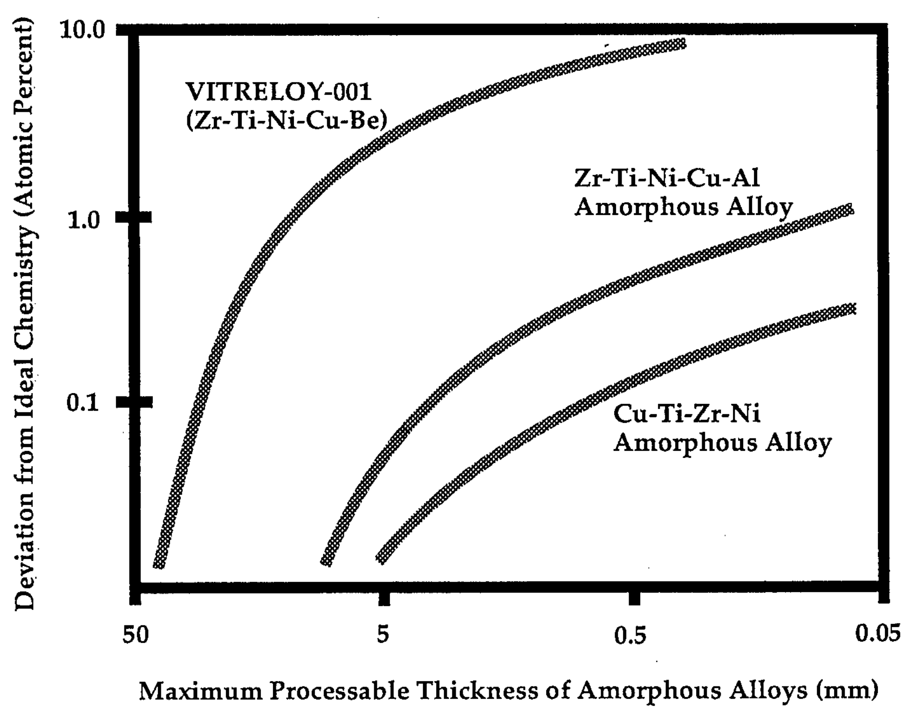


Figure 1: Processability of various bulk amorphous alloys

2) We demonstrated the fabrication of highly loaded AMC rods with Tungsten wires. Ten samples of AMC rods with 70-85 % volume Tungsten wires of 0.020" diameter were prepared. AMC rods were typically 3" to 5" long and 0.35"-0.40" diameter as shown in Figure 2. The samples of Tungsten reinforced AMC have density as high as 17.2 g/cc. All samples were cross-sectioned at both ends and no porosity was observed. The amorphous nature of the binding matrix was also confirmed. Four of those samples were machined further and cross-sectioned at various lengths and still no porosity was observed. The Tungsten reinforcements were also uniformly distributed. Further, we could not see any Tungsten to Tungsten contact throughout our examinations of the cross-section of the AMC. This demonstrates the extremely good wetting and infiltration characteristics of the process. Figure 3 shows the cross-section of AMC at various magnifications.

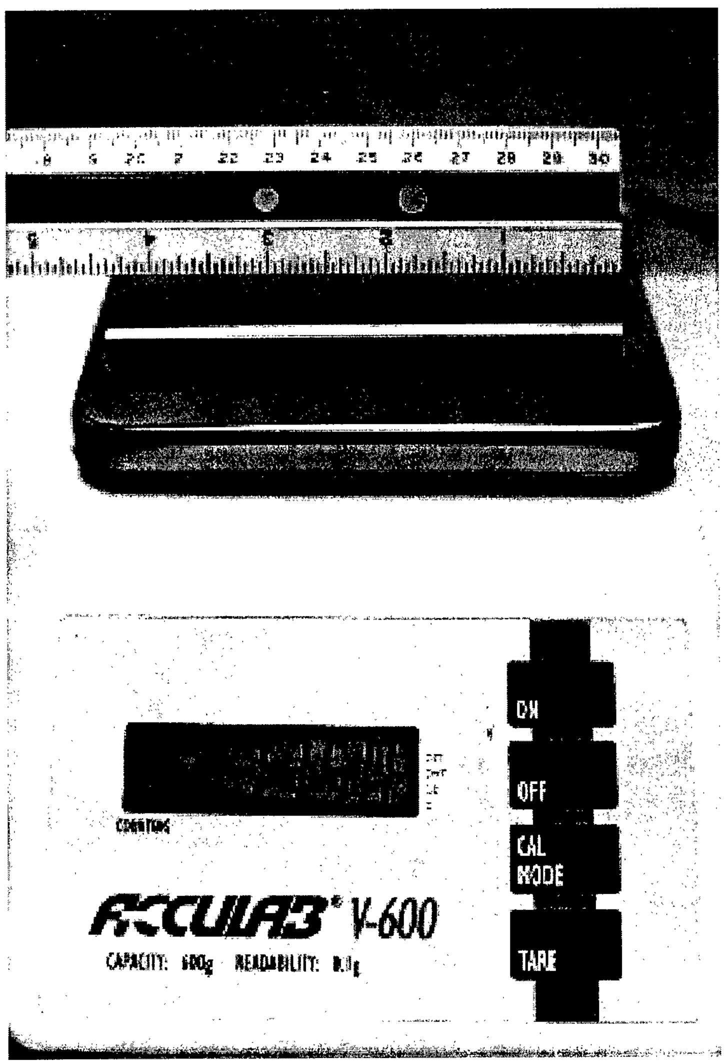


Figure 2: Tungsten reinforced AMC rod of 4.36" long and 0.374" diameter. The rod weighs 135 grams and has a density of 17.2 g/cc.

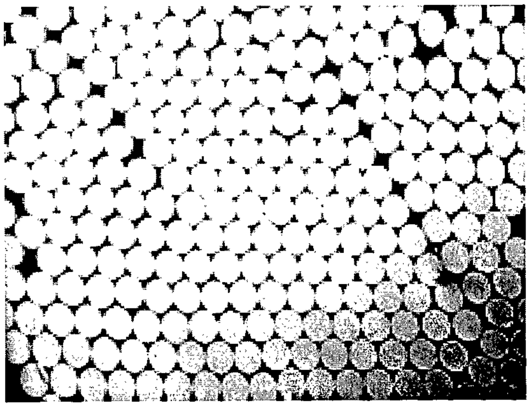


Figure 3.a: 10X

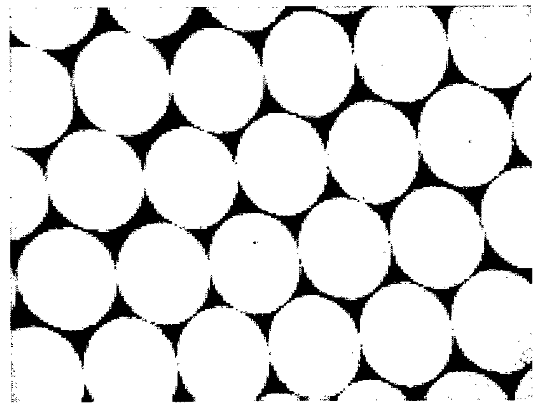


Figure 3.b: 28X

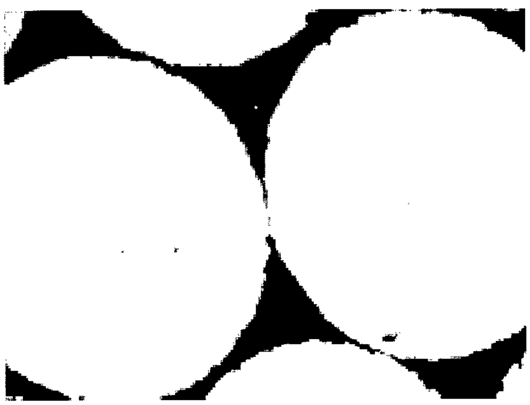


Figure 3.c: 100X

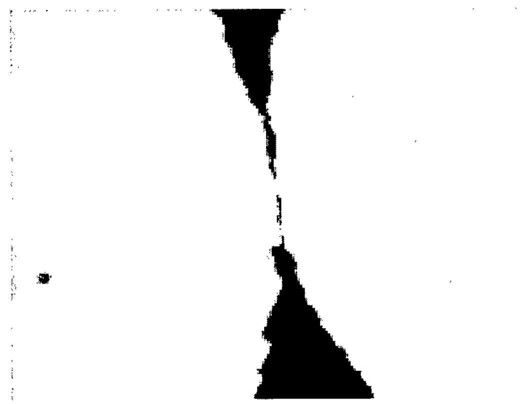


Figure 3.d: 250X

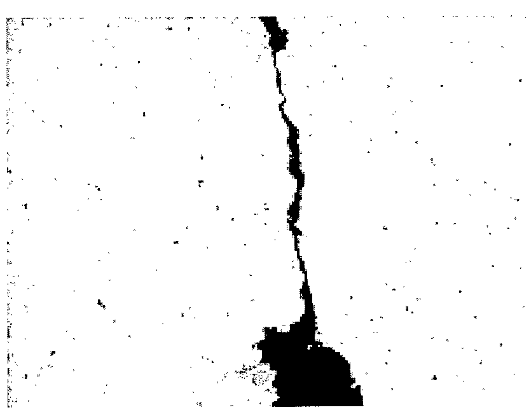
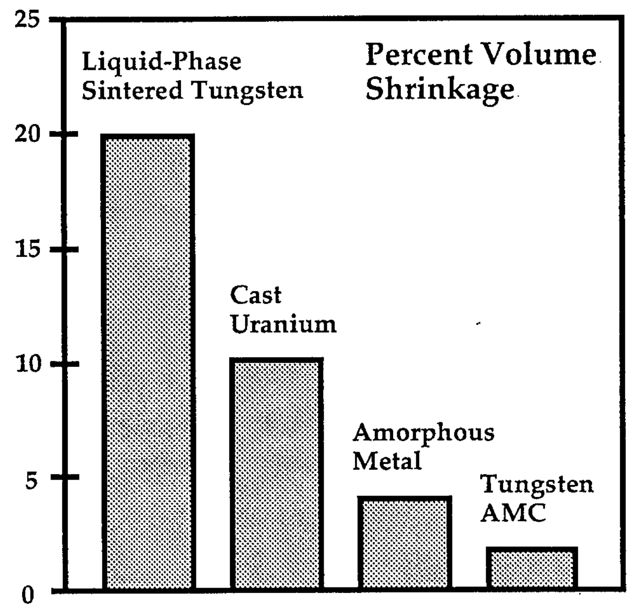


Figure 3.e: 1,000X

Figure 3: Cross-sectional views of Tungsten reinforced AMC at various magnifications. Lighter area is circular Tungsten wire of 0.020 diameter whereas the darker area is amorphous metal matrix. Note the lack of Tungsten to Tungsten contact.

3) We developed a practical process for making AMC's and established the key process parameters. We prepared 10 samples of Tungsten reinforced AMC with varying time and temperature during the infiltration process. The process allowed us to attain high loading levels while successfully retaining the amorphous structure of the binding matrix. We believe this is a rugged and robust enough process to lead to a production process. The process itself does not impose any significant limitation on the size of the AMC that can be produced. Further, we also showed that the process has good fabrication characteristics such that the volume shrinkage of AMC parts are quite small compared to other materials and processes. The Tungsten preform is not allowed to change its shape significantly during the process, which limits the volume shrinkage of the AMC parts. The following chart compares the volume shrinkage of AMC with Tungsten reinforcements with other materials, used in Kinetic Energy Penetrators (KEP).



4) Compression tests were performed on four of the Tungsten reinforced AMC samples. We observed the formation of localized adiabatic shear bands (ASB) in Tungsten reinforced AMC's. This is a critical feature when considering the use of these materials as KEP. The ASB promotes self-sharpening at impact which enhances the penetration ability of the projectile. Furthermore, the interface between the Tungsten reinforcements and Amorphous Metal Matrix was strong enough to hold throughout the extensive deformation of the composite in our compression tests. The AMC samples deformed as much as 30% before the Tungsten wire reinforcements failed by buckling and splitting as shown in Figure 4. The deformation mechanism in the amorphous metal was the formation of localized adiabatic shear bands which were spaced evenly.

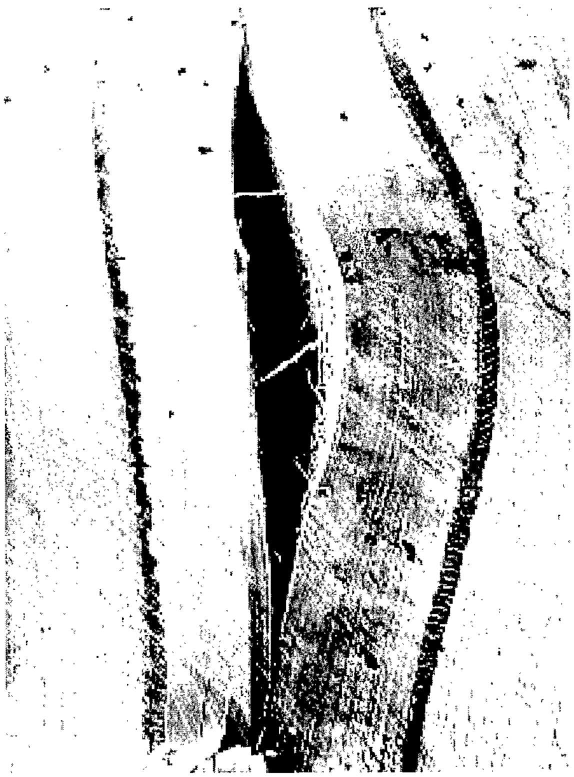


Figure 4.a: 66X

Figure 4.b: 470X

Figure 4.a: Longitudinal cross-section of Tungsten reinforced AMC after 30% deformation in compression. The center lighter area is a single Tungsten wire of 0.020" diameter failed through buckling and splitting. The thinner darker area on both sides of center tungsten wire is binding amorphous metal matrix. The white lines on amorphous matrix are localized shear bands. Magnification is 94X.

Figure 4.b: Higher magnification of Figure 3.a. Center dark area is amorphous metal matrix with Tungsten reinforcements on both sides. White lines are localized shear bands from the deformation of AMC. Note also the intimate interface between the matrix and the reinforcement. Magnification is 666X.

5) We developed a process to fabricate AMC rods, such that a full product development and optimization become feasible. The process allows us to make AMC of Tungsten reinforcements at various loading levels and can be modified to make various shapes such as long rods and plates. The process allowed us to attain high loading levels while successfully retaining the amorphous structure of the binding matrix. We believe this is a rugged and robust enough process to lead to a production process. The process uses relatively simple equipment and employs lower temperatures and shorter process times compared to the process of WHA alloys. The process itself does not impose any significant limitation on the size of the AMC that can be produced. We believe the process is feasible to produce AMC's of three feet long and at least one inch diameter. Further, we also showed that the process has good fabrication characteristics such that the volume shrinkage of AMC parts are quite small compared to other materials and processes.

6) We gathered data concerning the potential costs that may be incurred in scaling up the proposed process. A cost analyses was performed for the production of AMC Kinetic Energy Penetrators and presented below. The analysis included the factors such as material costs, production methods, facilities, as well as comparative analyses of existing WHA products.

The cost analysis was focused on ascertaining the cost associated with the manufacture of Tungsten reinforced AMC. The basic shape assumed was a cylindrical rod, although variations of this shape do not affect the component cost. A comparison of processing parameters of AMC with WHA (Tungsten Heavy Alloy) is given in the table below:

Material	Processing Temperature (°C)	Processing Time	Shrinkage %
AMC	1000	minutes	<2%
WHA	1400-1600	hours	20%

The lower processing temperature and shorter processing time give an advantage in capital and labor requirements for AMC over WHA. The lower shrinkage values for AMC may give an advantage for AMC over WHA in that fewer and perhaps simpler post-consolidation steps may be required. Without a detailed product description and form it is not possible to include this potential advantage of AMC over WHA in the present analysis and this benefit is simply ignored.

Using our standard cost-analysis model we find that W reinforced AMC are relatively inexpensive to manufacture. The most significant component is the cost of the W itself in the analysis for AMC.

<u>Assumptions:</u>

Rod sizes: 5 mm to 50 mm in diameter and from 5mm to 800 mm long
Volume: >40,000 lbs/year
W price: $10 to $30/lb

The expected cost for the W reinforced AMC range from:
15.60/lb to $34.40/lb