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Form Approved  
OMB NO. 0704-0188

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1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE November 19, 2003	3. REPORT TYPE AND DATES COVERED Final Technical Report
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4. TITLE AND SUBTITLE Structure, Properties, and Processing of Two-Phase Crystalline-Glassy W-base Alloys	5. FUNDING NUMBERS DAAD19-00-1-0103
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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER 40450.5-MS
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11. SUPPLEMENTARY NOTES  
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12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)

Amorphous or glassy metals are a unique class of materials that typically exhibit higher strengths than their crystalline counterparts but have limited ductility. Mechanical alloying (MA) of metal powders offers the possibility of forming metallic glasses for a large range of systems. Unfortunately, consolidation of the powder to bulk form usually results in crystallization of the amorphous phase. Previous research has shown that MA can produce a W-Ni-Fe amorphous powder with remnant nanocrystalline W particles in the glassy matrix. The goal of this research was to consolidate mechanically alloyed W-Ni-Fe powders to near or full density without causing crystallization of the W-Ni-Fe glassy phase. A systematic study on the consolidation of the most thermally stable alloy was conducted using different consolidation techniques and binder materials. Experiments were designed to examine the effects of different processing parameters including: temperature, pressure, time, and binder amount. The experimental results showed that it was possible to consolidate the MA W-Ni-Fe to a calculated density of 98 to 99% while retaining the glassy/amorphous structure. The process involved MA elemental Cu powder with the MA W-Ni-Fe powder and consolidating the composite powder by Rapid Sinter Forging (RSF). Pressure was identified as the dominant processing parameter for densification. Temperature's effect on densification was minimal but important for crystallization of the glass.

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### Introduction

Amorphous or glassy metals are a unique class of materials that typically exhibit higher strengths than their crystalline counterparts but have limited ductility. During tensile deformation, metallic glasses fail following propagation of a singular highly localized deformation region called a shear band [1,2]. Research to enhance the ductility of metallic glasses has focused on ways to facilitate multiple shear banding. Plate, fiber, and crystalline particulate composites have all been used to increase ductility and/or toughness of a glassy metal [3-6].

High-density W-Ni-Fe alloys are attractive materials for potential kinetic energy penetrators because of environmental concerns related to the current depleted uranium (DU) penetrators. Unfortunately, high ductility of these W-Ni-Fe alloys results in blunting of the penetrator tip upon impact. This is in contrast to DU, which exhibits 'self-sharpening' behavior attributed to an adiabatic shearing mechanism. According to Dowding *et al* [9], the performance of W-Ni-Fe alloys is slightly worse (8-10% less in depth of penetration tests) than DU. Multiple shear-banding behavior in a metallic glass composite may mimic the adiabatic shearing behavior in DU. Therefore, a glassy W-Ni-Fe alloy with nano-W particles may be an advantageous material for kinetic energy penetrators. Before this connection can be made, it is necessary to determine if it is possible to fabricate a W-Ni-Fe bulk metallic glass composite through the mechanical alloying and subsequent powder consolidation route.

The goal of this research is to consolidate the mechanically alloyed W-Ni-Fe powders to near or full density without causing crystallization of the glassy phases. Previous studies [7,8,11,12] provided an analysis on the crystallization behavior and thermal stability of MA W-Ni-Fe alloys. Using this information, a systematic study of the consolidation on the most thermally stable alloy was conducted. This included different consolidation techniques: liquid phase sintering (LPS), hot isostatic pressing (HIP), and rapid sinter forging (RSF) utilizing different binder materials: Zr-based bulk metallic glass, Cu, MA Cu, and CuO. The end result showed that it was possible to consolidate the MA W-Ni-Fe to >99% density while retaining the glassy/amorphous structure. The process involved mechanically alloying elemental Cu powder with the MA W-Ni-Fe powder and consolidating the composite powder by RSF.

### Conclusions

The goal of this project was to consolidate the mechanically alloyed W-Ni-Fe powders to near full density while retaining the glassy/amorphous structure. A study using different consolidation processes with different binder materials was performed. In the end, samples retaining the glassy structure with densities of 98 to 99% were produced. The process involved mechanically alloying (MA) elemental Cu powder with the mechanically alloyed W-Ni-Fe and consolidating the resultant composite powder by rapid sinter forging (RSF). The mechanical behavior of the consolidated MA W-Ni-Fe was similar to an engineering ceramic, but shear banding was not observed.

Liquid phase sintering (LPS) utilizing a Zr-based bulk metallic glass was unsuccessful. Densification was not enhanced because the Zr-glass did not behave like a typical liquid phase in LPS. Additionally, full crystallization of the glassy W-Ni-Fe phase was observed. Hot isostatic pressing (HIP) using Cu as a binder produced samples with densities as high as 96%, but partial crystallization of the glassy phase was observed.

A fine dispersion of Cu was obtained by MA elemental Cu powder with the MA W-Ni-Fe. This adversely affected the crystallization behavior by lowering the crystallization temperature of the W-Ni-Fe glassy phase, but better densification was possible due to the fine Cu in the resultant composite powders. MA of CuO also produced a fine dispersion of Cu. However, the CuO reduced during milling, and a sample produced with these powders had little mechanical integrity.

Rapid sinter forging (RSF) using MA W-Ni-Fe subsequently MA with Cu produced samples with densities of 98 to 99%. 15 to 20 vol% Cu binder was needed to achieve high densities (10 vol% Cu did not lead to densities greater than 95%). The high densities are attributed, in large part, to the high pressures (as high as 2.0 GPa) possible with RSF. Yielding (plastic flow) of the Cu was identified as the main densification mechanism. Crystallization of the glassy W-Ni-Fe phase was avoided due to the lower temperatures and shorter processing times used in RSF.

Mechanical tests on the RSF samples showed repeatable high hardness values (equivalent to high strength), which is further proof that a glassy W-Ni-Fe phase was maintained after consolidation. In comparing the test results with material design charts, the mechanical properties of the consolidated MA W-Ni-Fe are similar to that of a technical (engineering) ceramic, except for much greater density. Unfortunately, lower fracture toughness estimates coupled with a brittle failure in compression testing lead to the conclusion that the presence of nanocrystalline W and a ductile Cu binder did not substantially increase the toughness of the W-Ni-Fe glass. No shear banding was observed. Cracks, due to the RSF process, most likely caused fracture before a high enough stress level was reached for shear band initiation. The cracks may be minimized or eliminated by proper choice of die/plunger materials and slower cooling rates. However, estimates show that, in the absence of processing flaws, porosity would control fracture before shear banding could be observed.

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