



**Status Report on SPS  $\text{TiB}_2/\text{TiB}/\text{Ti}$  Functionally Graded  
Materials (FGMs) for Armor**

**by James W. McCauley, G. D'Andrea, Kyu Cho, Matthew S. Burkins,  
Robert J. Dowding, and William A. Gooch, Jr.**

**ARL-SR-143**

**September 2006**

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**September 2006**

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## **Status Report on SPS TiB<sub>2</sub>/TiB/Ti Functionally Graded Materials (FGMs) for Armor**

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14. ABSTRACT The pioneering research by Wilkins and colleagues in the 1960s led many investigators to conclude that ceramic armor performance could be significantly enhanced with materials macrostructurally designed to grade from a pure ceramic to a stiff, more ductile material at the back surface. Several configurations of TiB <sub>2</sub> /TiB/Ti functionally graded materials were fabricated using a spark plasma sintering process. Detailed microstructural characterization of the as-processed material is presented as well as x-ray flash radiographs of penetrating projectiles in a reverse ballistic configuration using a 1-MeV x-ray system in a 100-mm gas gun apparatus. This report is a collection of the charts used for an oral presentation at the 28th International Cocoa Beach Conference and Exposition on Advanced Ceramics and Composites.					
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## 1. Introduction

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Ceramics were first used extensively in body armor and helicopter seats during the Vietnam era, when work on armor ceramics reached its first peak on both opaque and transparent glass and ceramic materials. Much of the early work starting in the mid 1960s was guided by the pioneering modeling research of Mark Wilkins and colleagues from the Lawrence Radiation Laboratory, mostly focusing on thin ceramic armor plates. This pioneering research led many investigators to conclude that ceramic armor performance could be significantly enhanced with materials macrostructurally designed to grade from a pure ceramic to a stiff, more ductile material at the back surface. In recent years, these types of materials have been referred to as functionally graded materials (FGMs).

Seven samples of TiB<sub>2</sub>/TiB/Ti FGMs were fabricated by Masao Tokita and Masakazu Kawahara, Sumitomo Coal Mining Co. Ltd., Tokyo, Japan, using a spark plasma sintering (SPS) process. Materials with four, five, and six layers with varying grading schemes of Ti, TiB, and TiB<sub>2</sub> were produced. Characterization of the material was carried out, including x-ray radiographic CT scans by Mr. William Green and detailed x-ray diffraction and field emission scanning electron microscopic microstructural analysis by Mr. Kyu Cho, both of the U.S. Army Research Laboratory (ARL), Aberdeen Proving Ground, MD.

A series of the samples were then tested in low and high velocity impact tests. Professor Kasano of the Takushoku University, Tokyo, Japan, carried out low-velocity impact tests and high-speed photography on one FGM sample (FGM 1–4). Matthew Burkins and William Gooch then used the ARL 100-mm reverse ballistics gas gun facility with a 1-MeV x-ray system to get real time radiographs of the FGM material with comparison to monolithic TiB<sub>2</sub> material. No dramatic improvements over the monolithic material were observed in these tests.

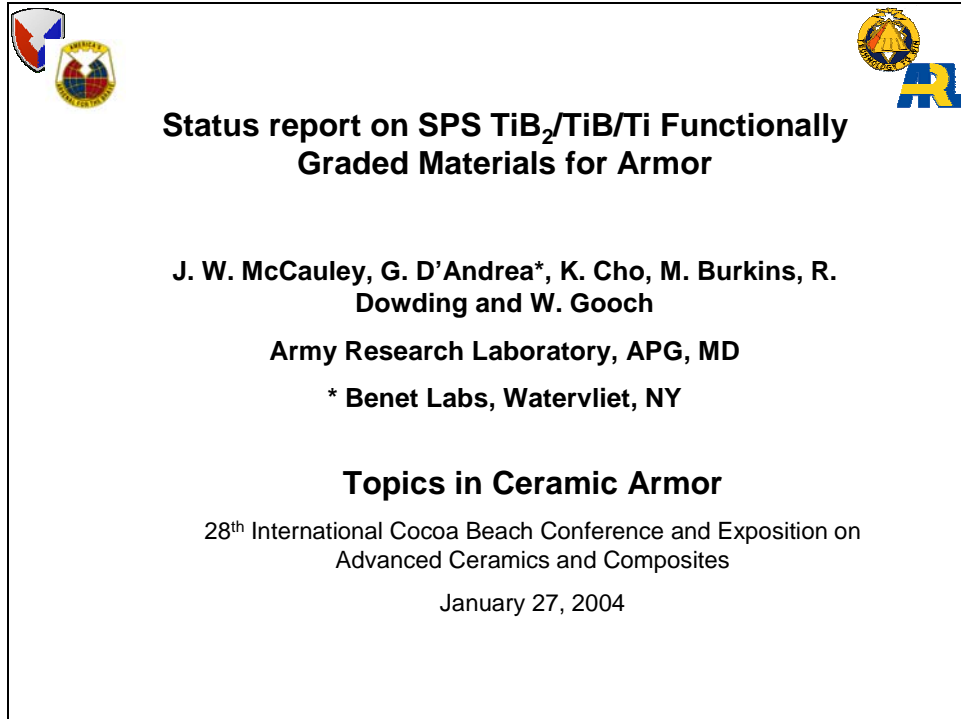


Figure 1. Status report on spark plasma sintering (SPS) TiB<sub>2</sub>/TiB/Ti functionally graded materials (FGMs) for armor.

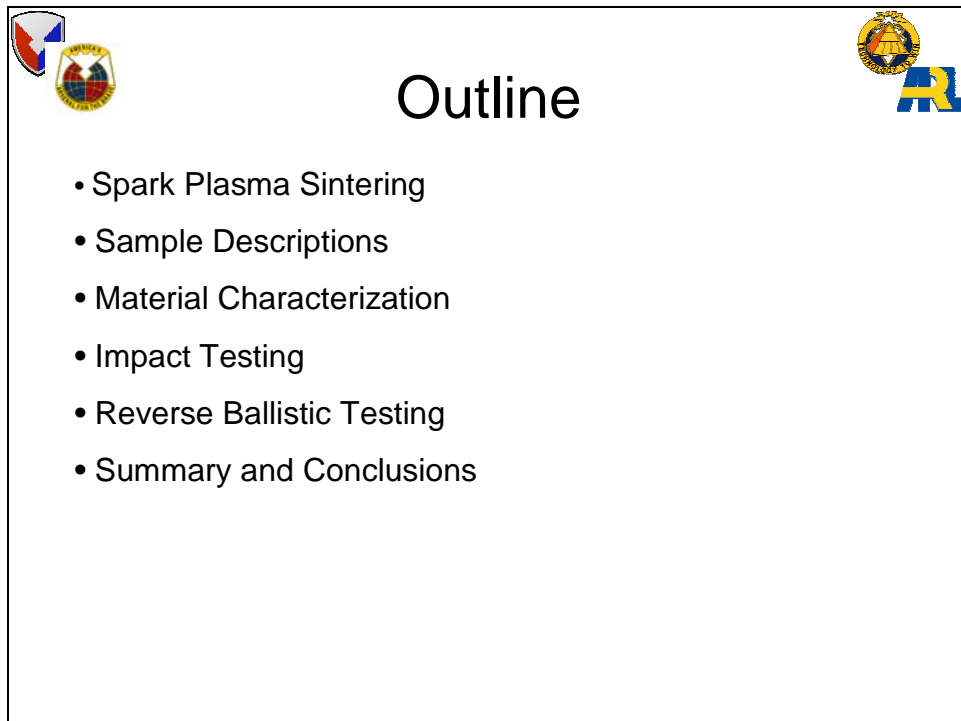


Figure 2. Outline.



Figure 3. SPS.

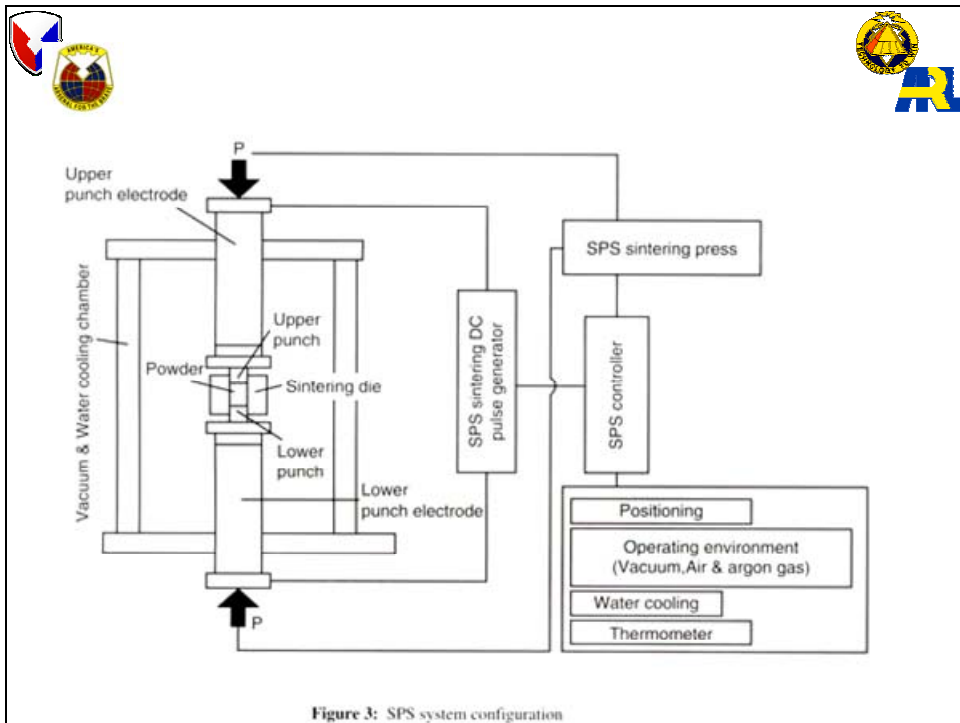


Figure 4. SPS system configuration.

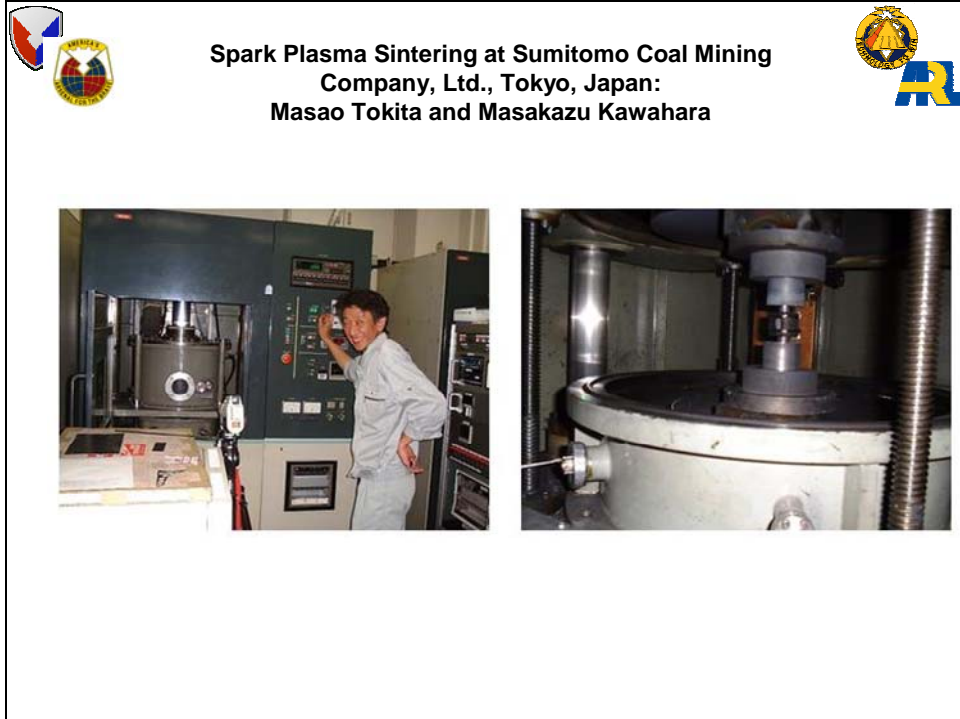


Figure 5. SPS at Sumitomo Coal Mining Company, Ltd., Tokyo, Japan: Masao Tokita and Masakazu Kawahara.

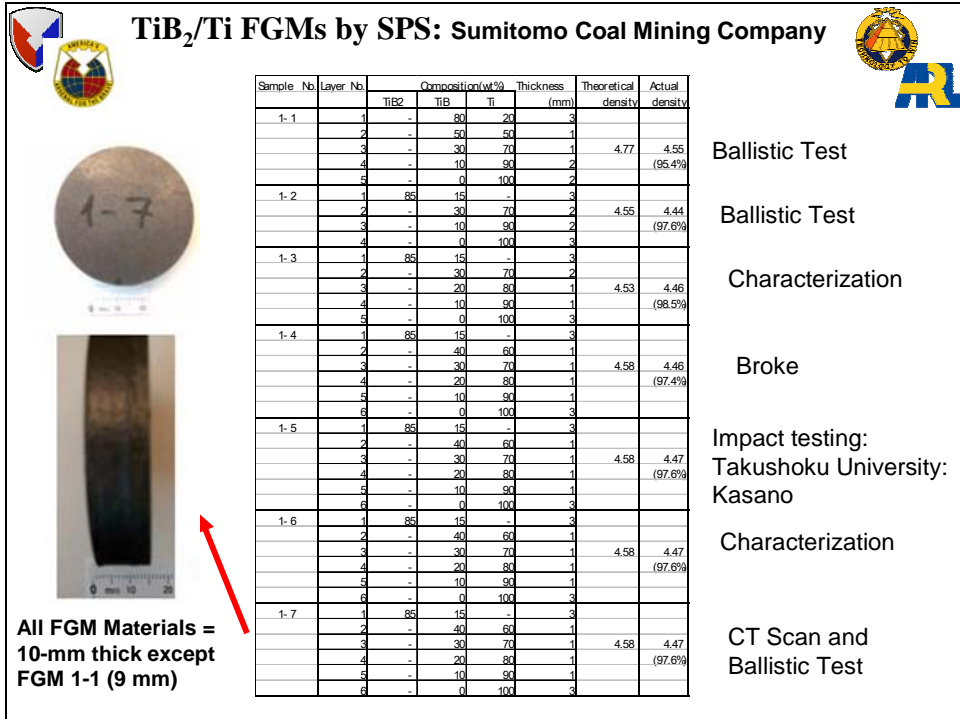
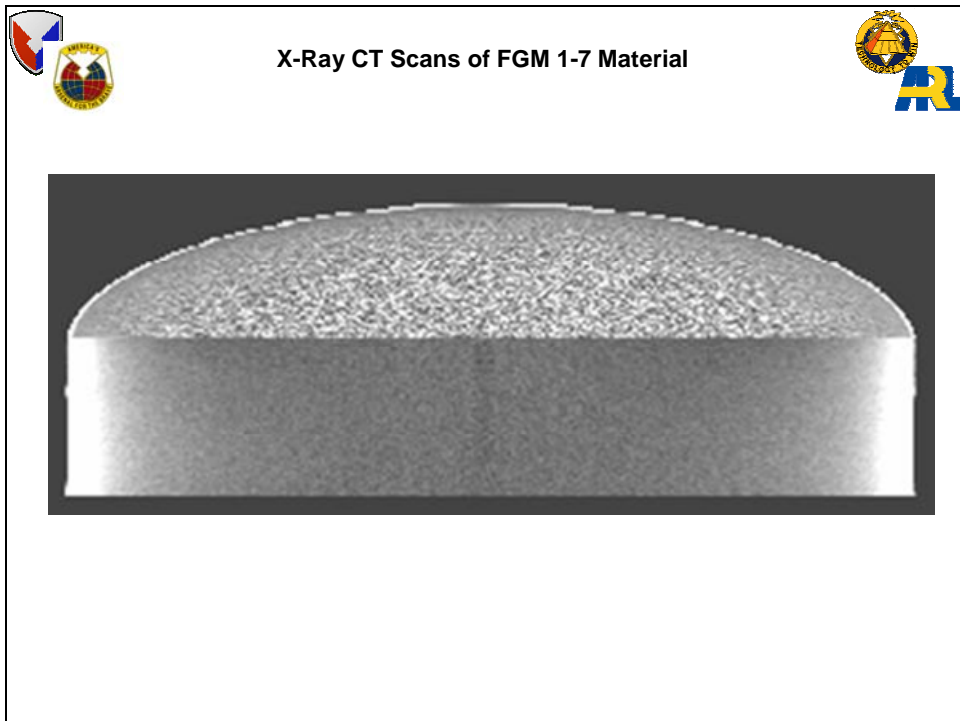


Figure 6. TiB<sub>2</sub>/Ti FGMs by SPS: Sumitomo Coal Mining Company.



Source: William Green, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

Figure 7. X-ray CT scans of FGM 1–7 material.



Source: William Green, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD.

Figure 8. X-ray CT scans of FGM 1–7 material.

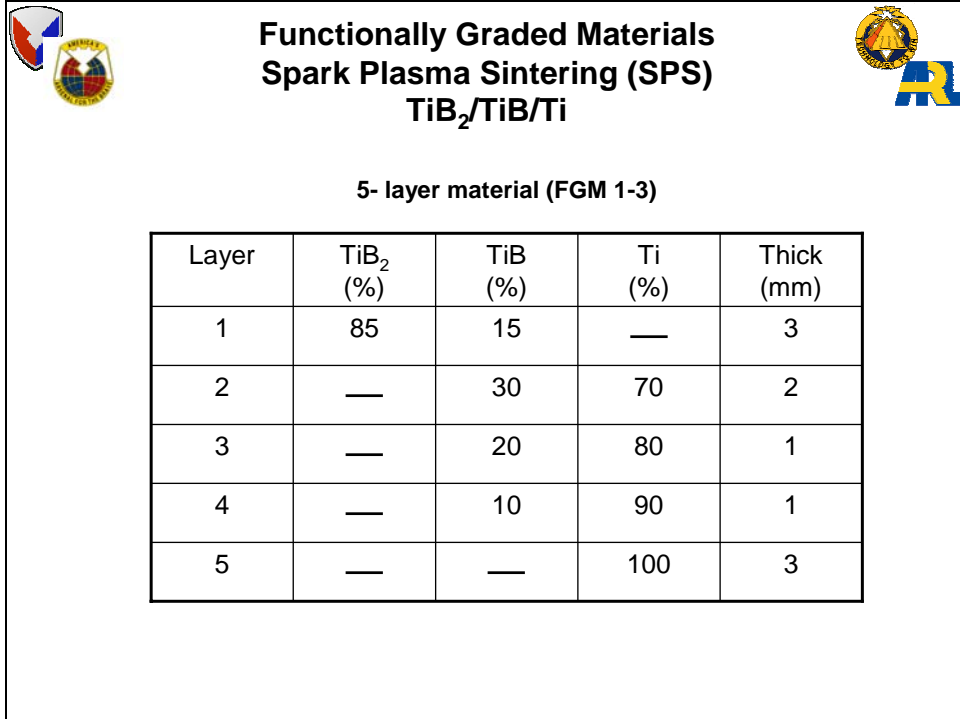
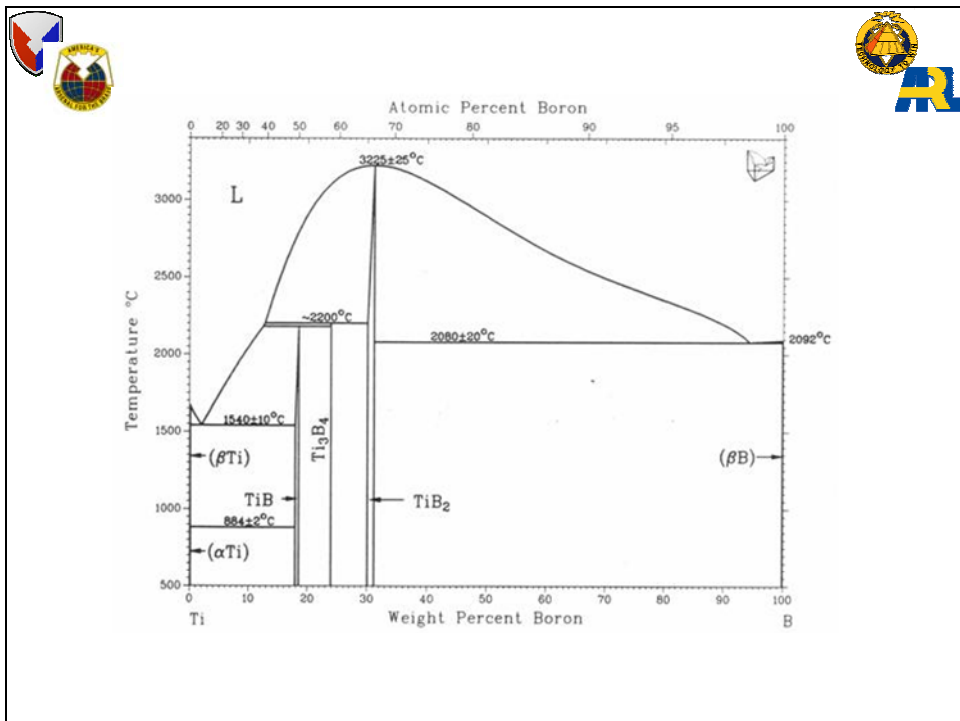


Figure 9. Functionally graded materials SPS TiB<sub>2</sub>/TiB/Ti: five-layer material (FGM 1–3).



Source: J. L. Murray, P. K. Liao, and K. E. Spear, *Bull. Alloy Phase Diagram* **1986**, 7 (6), 550–555 and 587–588.

Figure 10. Ti-B phase diagram.

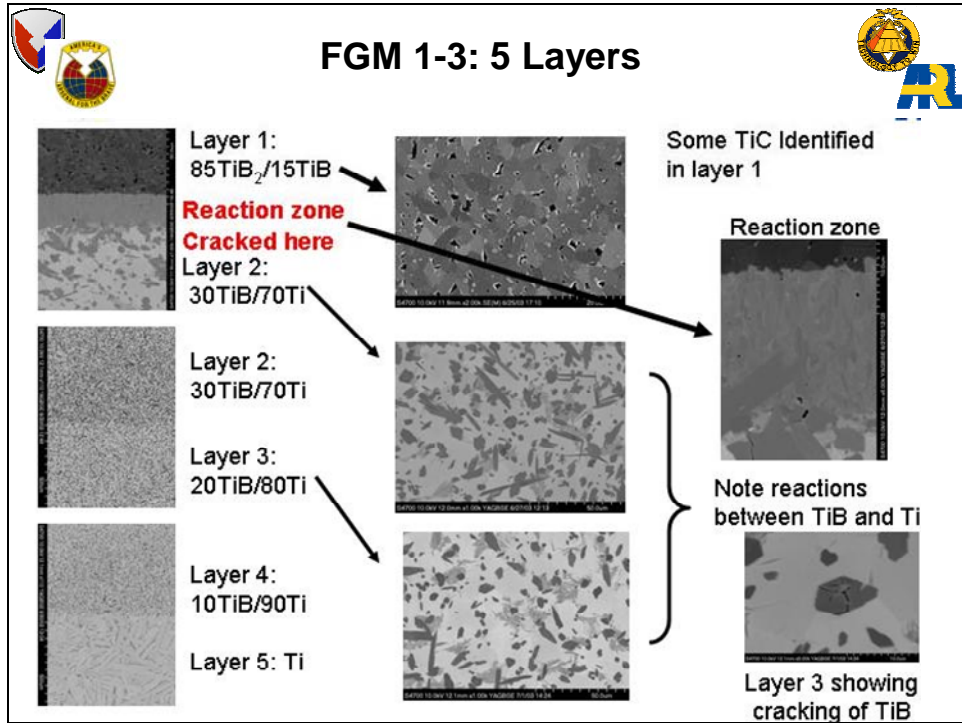


Figure 11. FGM 1–3: five layers.

**Functionally Graded Materials**  
**Spark Plasma Sintering (SPS)**  
**TiB<sub>2</sub>/TiB/Ti**

**6-layer material (FGM 1-6)**

Layer	TiB <sub>2</sub> (%)	TiB (%)	Ti (%)	Thick (mm)
1	85	15	—	3
2*	—	40	60	1
3	—	30	70	1
4	—	20	80	1
5	—	10	90	1
6	—	0	100	3

\* 5-layer material eliminates layer-2

Figure 12. Functionally graded materials SPS TiB<sub>2</sub>/TiB/Ti: six-layer material (FGM 1–6).

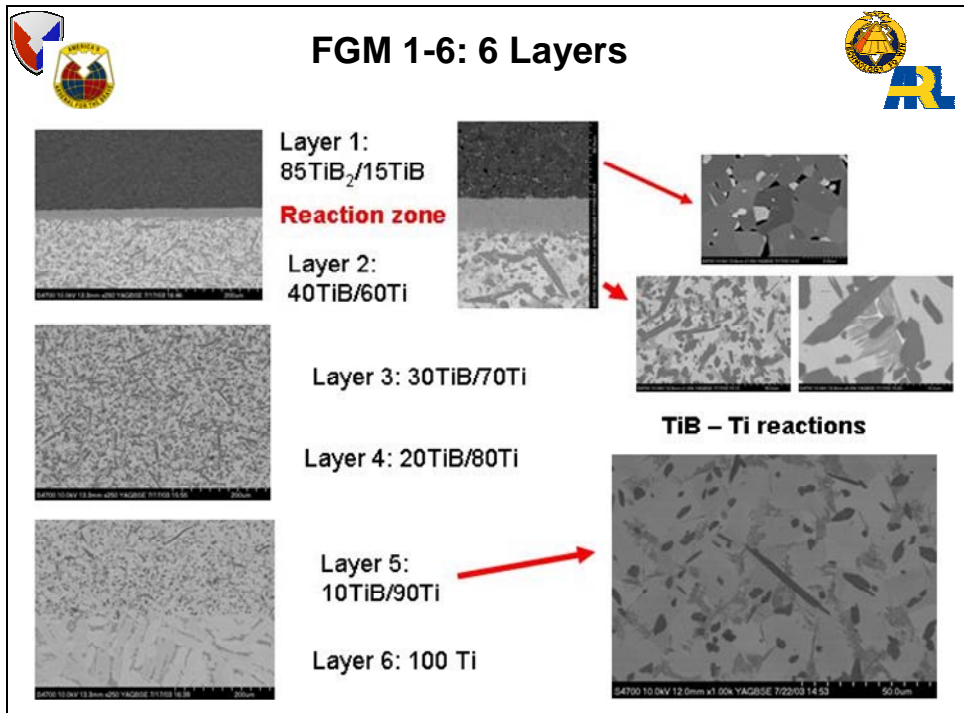


Figure 13. FGM 1–6: six layers.

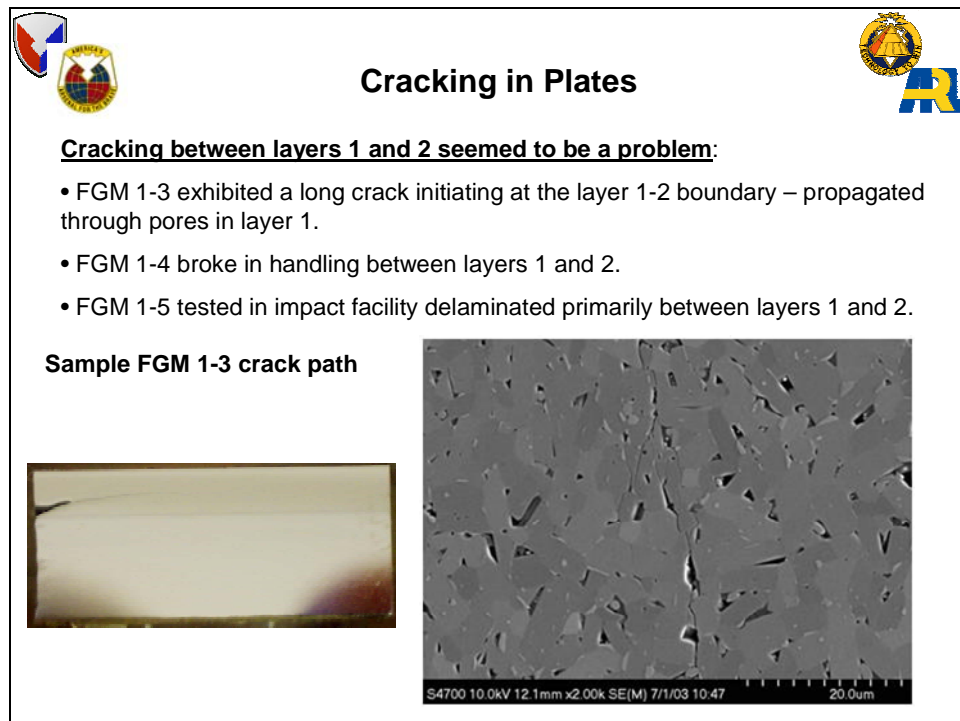


Figure 14. Cracking in plates.

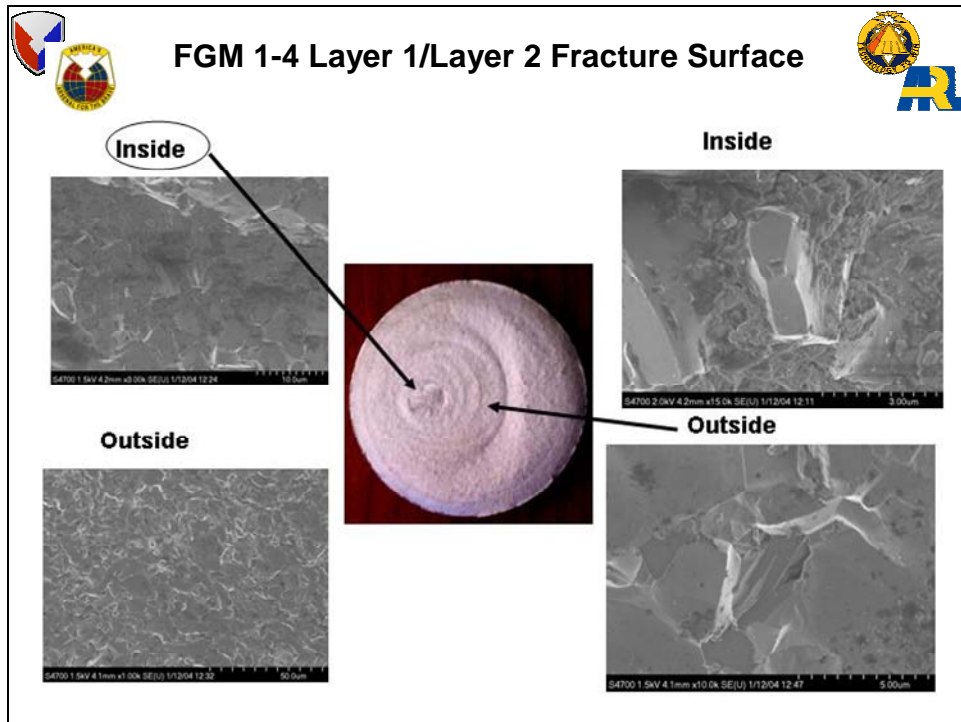
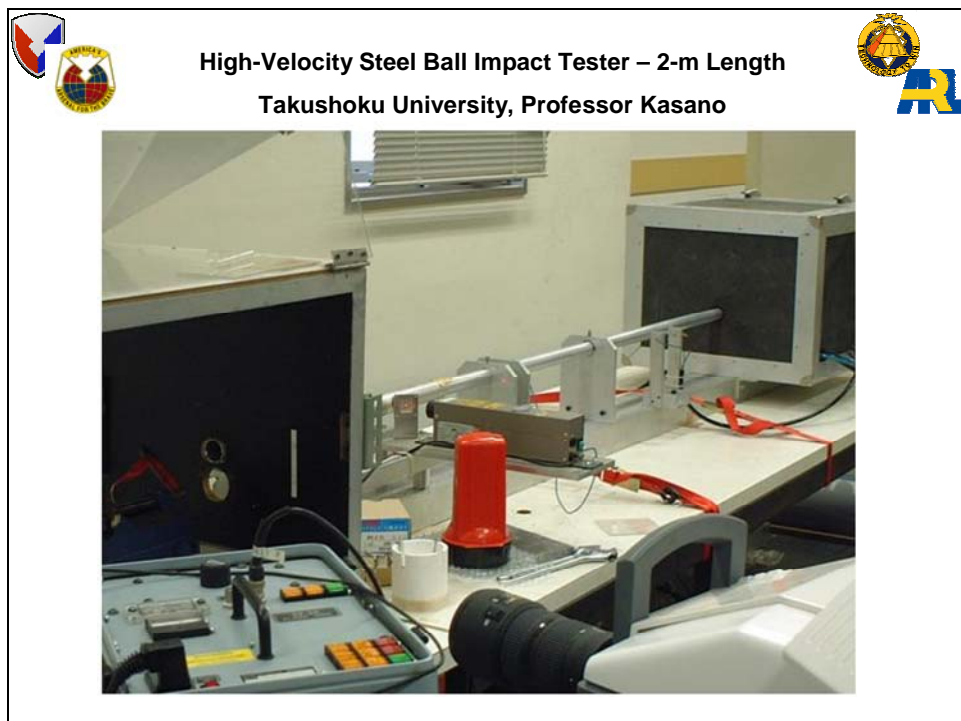


Figure 15. FGM 1–4: layer 1/layer 2 fracture surface.



Source: Takushoku University, Professor Kasano.

Figure 16. High-velocity steel ball impact tester; 2-m length.

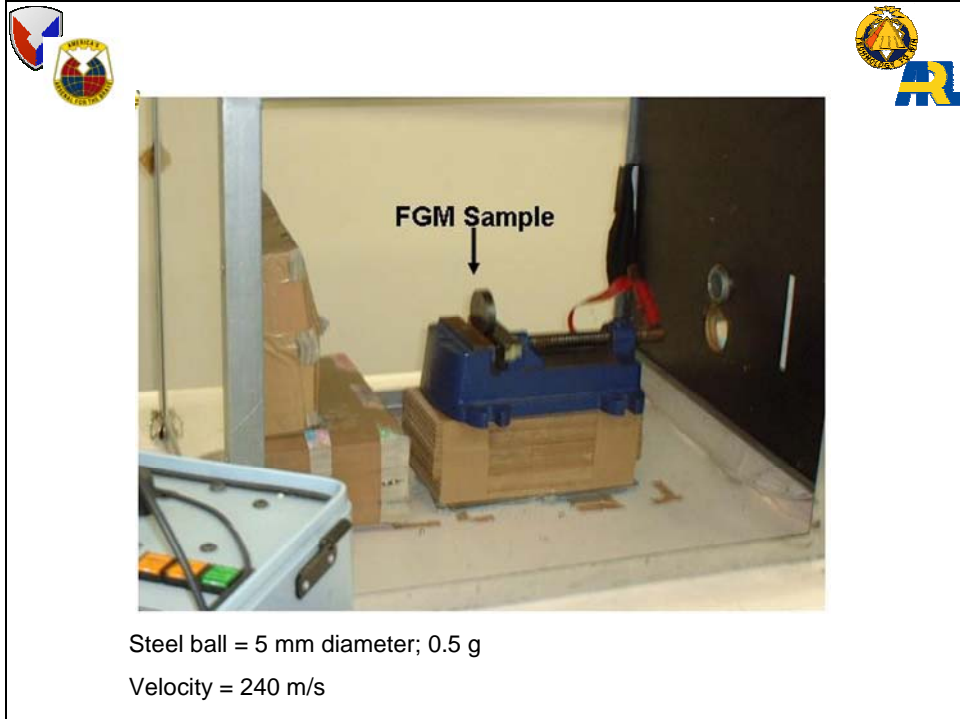


Figure 17. FGM sample.

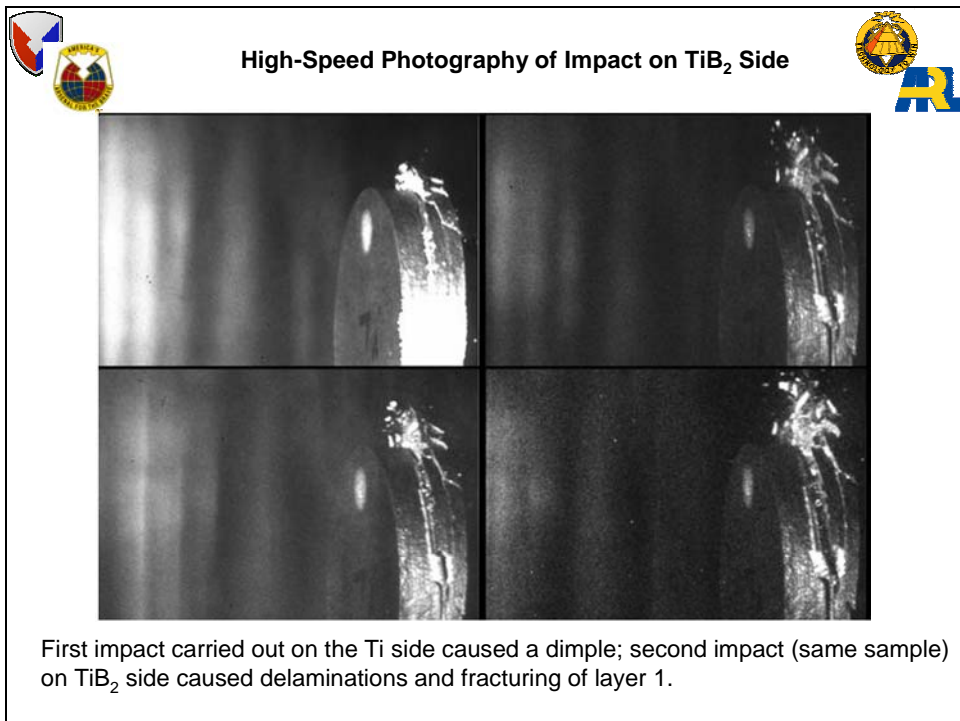


Figure 18. High-speed photography of impact on  $TiB_2$  side.

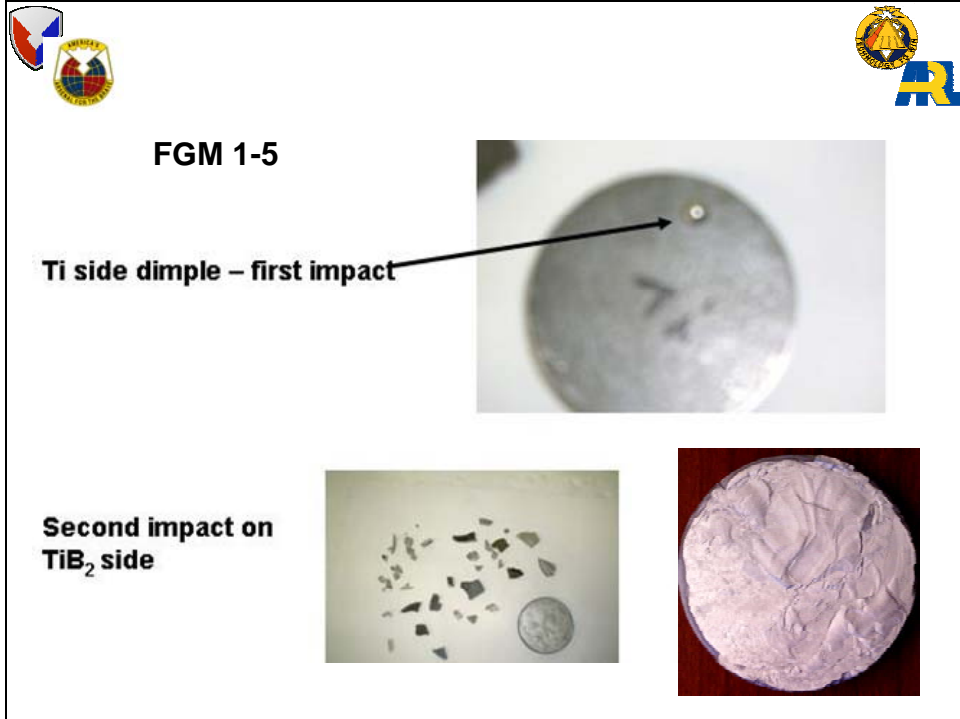


Figure 19. FGM 1-5.



Figure 20. The 100-mm reverse ballistics gas gun facility with 1-MeV x-ray systems.

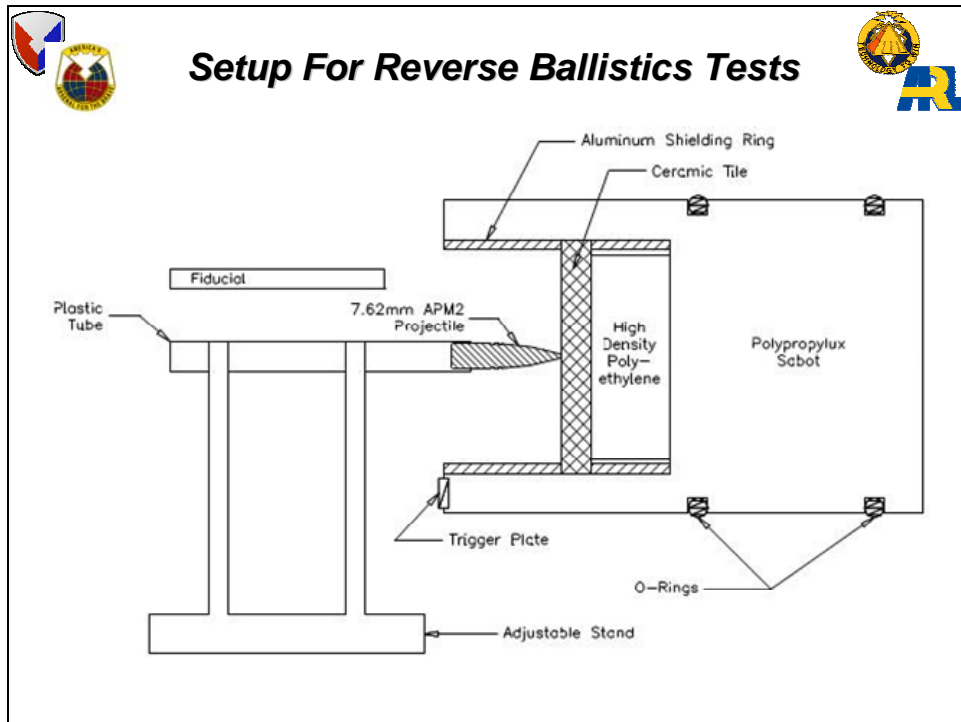


Figure 21. Setup for reverse ballistics tests.

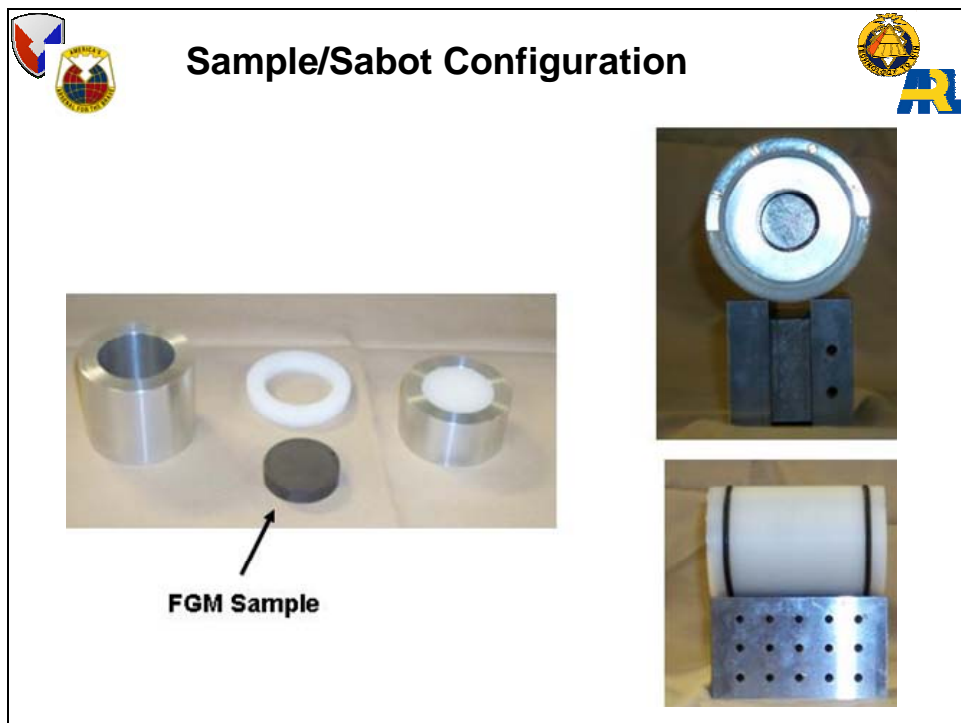


Figure 22. Sample/sabot configuration.

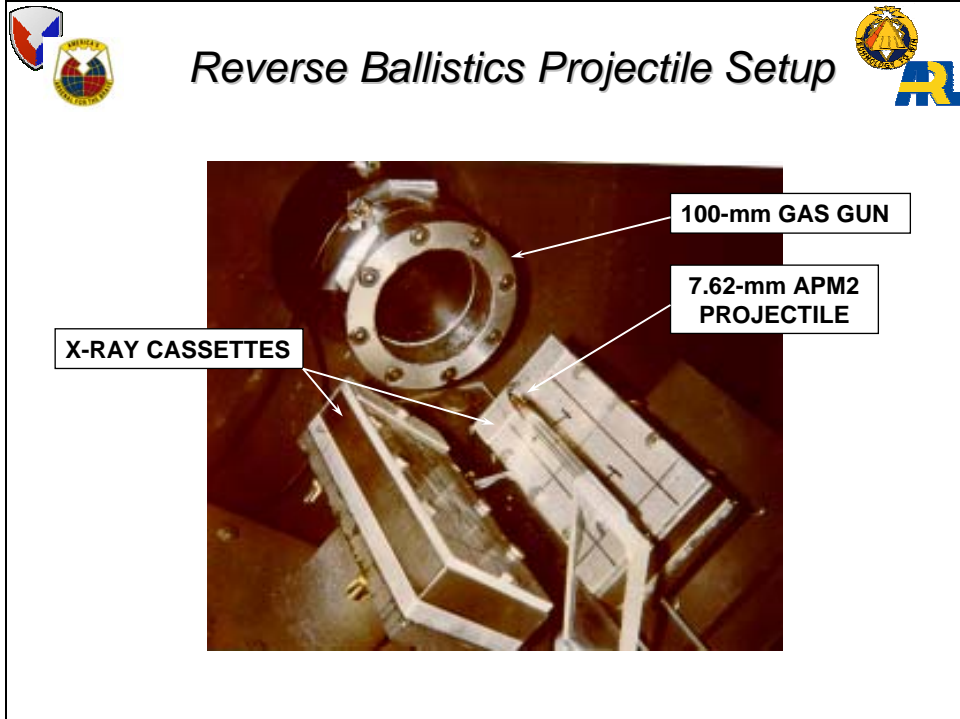


Figure 23. Reverse ballistics projectile setup.

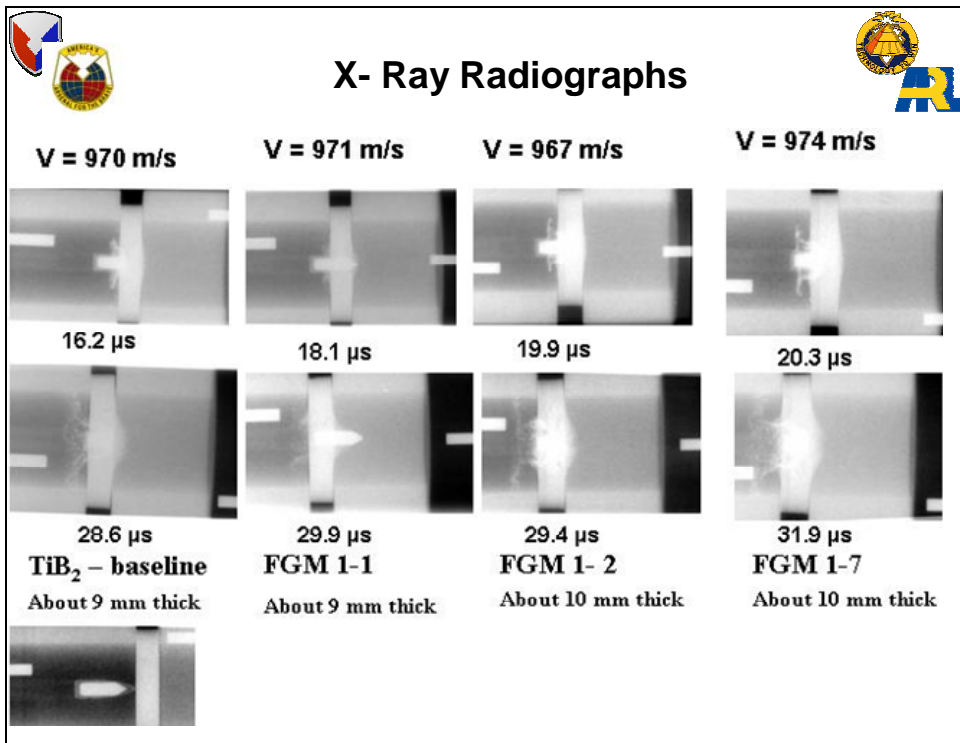


Figure 24. X-ray radiographs.

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## 2. Summary and Conclusions

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- SPS has been successfully used to fabricate  $\text{TiB}_2/\text{TiB}/\text{Ti}$  FGMs with densities approaching 98% of the calculated theoretical density.
- In the configurations fabricated, issues remain concerning the interface between the top  $\text{TiB}_2/\text{TiB}$  layer and the underlying layers.
- Significant reaction and cracking (delamination) occur at this interface.
- Moderate velocity impact tests also exhibit this delamination.
- Reverse ballistic tests indicate that the four- and six-layer  $\text{TiB}_2$  top layer FGM samples exhibited results comparable to the baseline monolithic  $\text{TiB}_2$ .
- These preliminary results, using SPS to fabricate FGM samples, suggest that much more systematic work is warranted, especially between the top  $\text{TiB}_2$  layer and the succeeding layers.
- Future optimization of functionally graded  $\text{TiB}_2/\text{TiB}/\text{Ti}$  materials should be supported by systematic modeling of a variety of configurations.

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S SCHOENFELD  
S SEGLETES  
T WEERASOORIYA

INTENTIONALLY LEFT BLANK.