ARMY RESEARCH LABORATORY

Ballistic Performance of Titanium Alloys: Ti-6Al-4V Versus Russian Titanium

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14. ABSTRACT

A Ti-6Al-4V baseline plate and a Russian titanium alloy plates were ballistically tested against .30-cal armor-piercing (AP) M2 rounds. The V_{50} ballistic limit of each plate was determined and compared to the MIL-DTL-46077F V_{50} ballistic acceptance chart for Ti-6Al-4V alloy. Based on these results, no clear ballistic performance advantage would be achieved by using the Russian titanium alloy against 0.30-cal AP M2 threats.

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1. Introduction

Titanium alloys are of interest for ballistic armor systems because of their battlefield benefits. Titanium alloys are highly corrosion resistant, about 60% density of steel, readily machinable, and are joinable (*1*). Over many years, various titanium alloys have been tested for their ballistic performance. The U.S. Army has chosen the titanium alloy Ti-6Al-4V for structural and appliqué armor, and it is the Army's baseline for evaluating the performance of similar armor systems (*2*).

This study evaluated the ballistic performance of a Russian titanium alloy compared to the baseline Ti-6Al-4V alloy. If the performance difference is greatly in favor of the Russian alloys, then possible modifications in the baseline armor may have to be considered.

2. Background

Titanium can exist in a hexagonal closely packed crystal structure (known as the alpha phase) and a body-centered cubic structure (known as the beta phase). In unalloyed titanium, the alpha phase is stable at all temperatures as high as 883° C, where it transforms to the beta phase. This transformation temperature is known as the beta transus temperature. The beta phase is stable from 883° C to the melting point. As alloying elements are added to pure titanium, the phase transformation temperature and the amount of each phase change. Alloy additions to titanium, except tin and zirconium, tend to stabilize either the alpha or beta phase. Ti-6Al-4V, the most common titanium alloy, contains mixtures of alpha and beta phases and is therefore classified as an alpha-beta alloy. The aluminum is an alpha stabilizer, which stabilizes the alpha phase to higher temperatures; vanadium is a beta stabilizer, which stabilizes the beta phase to lower temperatures. The addition of these alloying elements raises the beta transus temperature to approximately 996° C. Alpha-beta alloys, such as Ti-6Al-4V, are of primary interest for armor applications because they are generally weldable, can be heat treated, and offer moderate to high strength. Table 1 shows the titanium alloy specifications for both the Ti-6Al-4V and Russian titanium alloys chemistry composition, while table 2 shows the minimum mechanical properties of the Ti-6Al-4V (*1, 3, 4*).

Table 1. Chemical compositions of Ti-6Al-4V and Russian titanium alloy.

Wt. %	Titanium Alloys	
	Ti-6Al-4V	Russian Titanium
Al	5.5 to 6.5	2.99
Sn	…	0.07
Zr	…	0.341
Mo	…	0.391
V	3.5 to 4.5	5.18
Cr	…	3.63
Ni	…	0.02
B	…	58 ppm
N	0.02	0.01
C	0.04 max	0.013
H	0.0125	…
Fe	0.25	0.44
O	0.14	0.124
Y	…	0

Table 2. Tensile mechanical properties and densities of Ti-6Al-4V and Russian titanium alloy.

Titanium Alloy	Tensile Strength (min) (MPa)	0.2% Yield Strength (min) (MPa)	Elongation (%)	Reduction in Area (%)	Density (g/cc)
Ti-6Al-4V	896	827	14	30	4.43
Russian titanium	*	*	*	*	4.62

*not measured; insufficient quantity of specimen available

3. Results and Discussion

3.1 Ballistic Properties

Ballistic testing was performed on the baseline and Russian titanium alloy with 0.30-caliber armor-piercing (AP) M2 projectiles. The 0.30-caliber projectile is shown in figure 1. The specification data for this projectile are shown in table 3 (*5*). The target plate was positioned normal (0 degree obliquity) to the projectile's path of flight at impact for each test.

Each plate was shot with .30-caliber AP M2 projectiles, and orthogonal flash radiographs (*6*) were used to measure the striking velocities, pitch, and yaw of the projectiles. Residual x-rays were used in place of the 0.51-mm (.020-inch) 2024-T3 aluminum witness plate to determine when a complete perforation (CP) occurred. If penetrator or target material broke a paper break screen behind the target and an image appeared in the radiographs, then the shot was classified as a CP. In addition, residual x-rays provide the velocity, as well as an estimate of size and mass of the material ejected from the rear surface of the target plate. The V_{50} ballistic limit and sample standard deviation were calculated in accordance with the U.S. Department of Defense MIL-STD-662E (*7*).

The Ti-6Al-4V plate was manufactured by TIMET, a titanium metals corporation in Henderson, Nevada, and was marked test J3858. The Russian titanium alloy plate was marked VST3553+0.6 Zr and was 0.09 mm thicker than the Ti-6Al-4V plate. The Brinell hardness number (BHN) was measured on site. Ballistic test results are summarized in table 4. Detailed ballistic data are provided in appendix A.

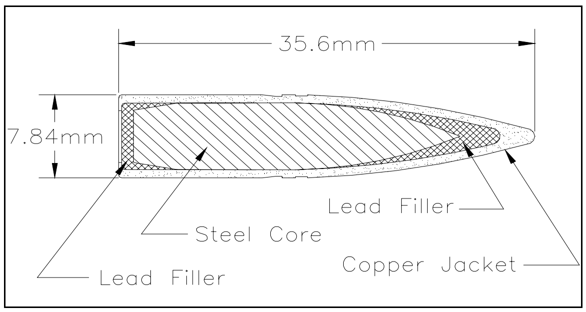


Figure 1. 0.30-cal AP M2 projectile dimensions.

Table 3. 0.30-cal AP M2 projectile specifications.

Projectile Type	Projectile			Jacket		Core/Penetrator			
	Length (mm)	Dia. (mm)	Weight (g)	Material	Weight (g)	Material	Length (mm)	Dia. (mm)	Weight (g)
AP M2	34.75	7.85	10.76	GM*	4.21	Steel PB**	27.43 --	6.17 --	5.25 1.30

*GM = guilded metal
**PB = lead

Table 4. Ballistic results of Ti-6Al-4V and Russian titanium alloy versus 0.30-cal AP M2.

Titanium Alloy	Thickness (mm)	Hardness (BHN)	Test V_{50} (m/s)	Standard Deviation (m/s)	Required V_{50} from MIL-DTL-46077F (*6*) (m/s)
Ti-6Al-4V*	12.83	332	633	7	636
Russian Titanium	13.72	387	622	7	666

*baseline

The thickness of the plates was normalized with the MIL-DTL-46077F V_{50} ballistic acceptance chart for Ti-6Al-4V alloy (*8*). Table 4 and figure 2 list and show the minimum required ballistic limit based on the thickness of each plate. Although both plates were below the minimum required V_{50}, the Russian titanium alloy was 7% lower, while the Ti-6Al-4V was 0.5% lower, based on normalization by the thickness.

Photographs of the front and back surfaces of the Ti-6Al-4V and Russian titanium alloy are shown in figures 3 and 4, respectively. The baseline Ti-6Al-4V alloy had a 2% higher V_{50} with a standard deviation equivalent to the Russian titanium alloy for these tests; therefore, Ti-6Al-4V outperformed the Russian titanium alloy.

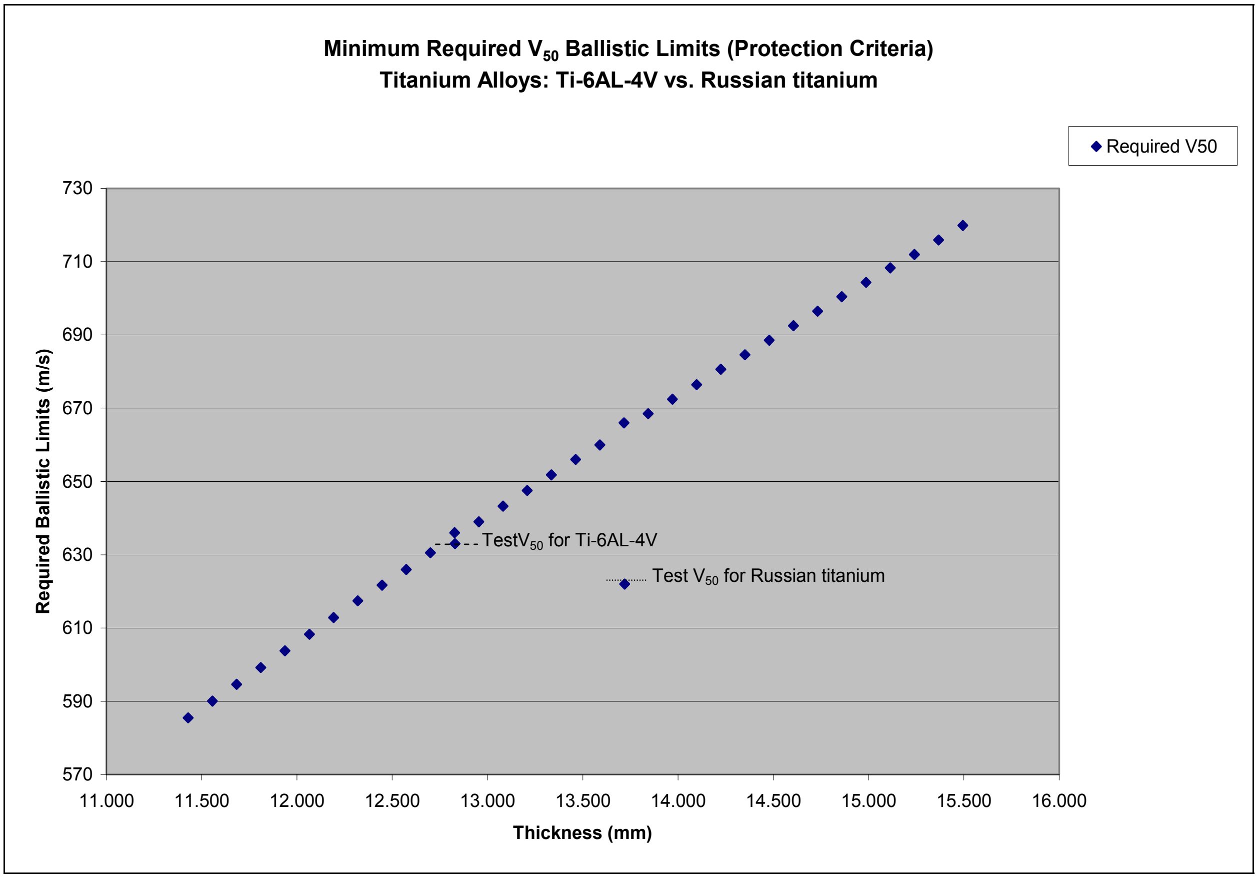


Figure 2. 0.30-cal AP M2 projectile dimensions.

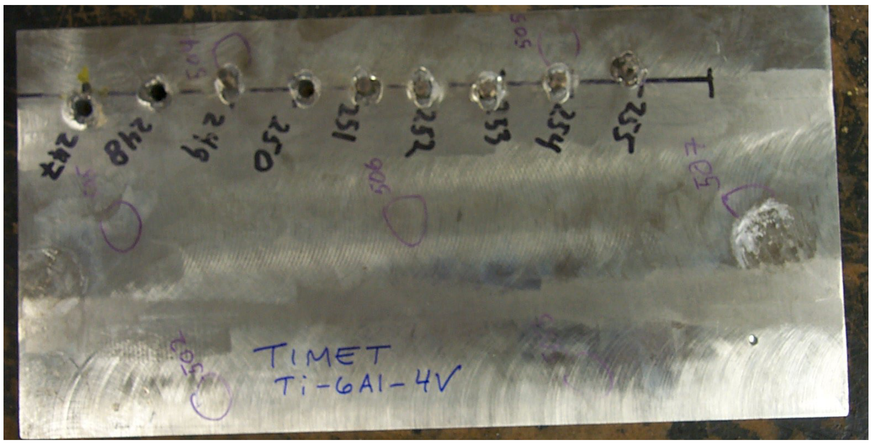
4. Summary and Conclusions

Ballistic testing was performed on a Russian titanium alloy and the results were compared to the performance for baseline Ti-6Al-4V. The results of the ballistic results may be summarized as follows:

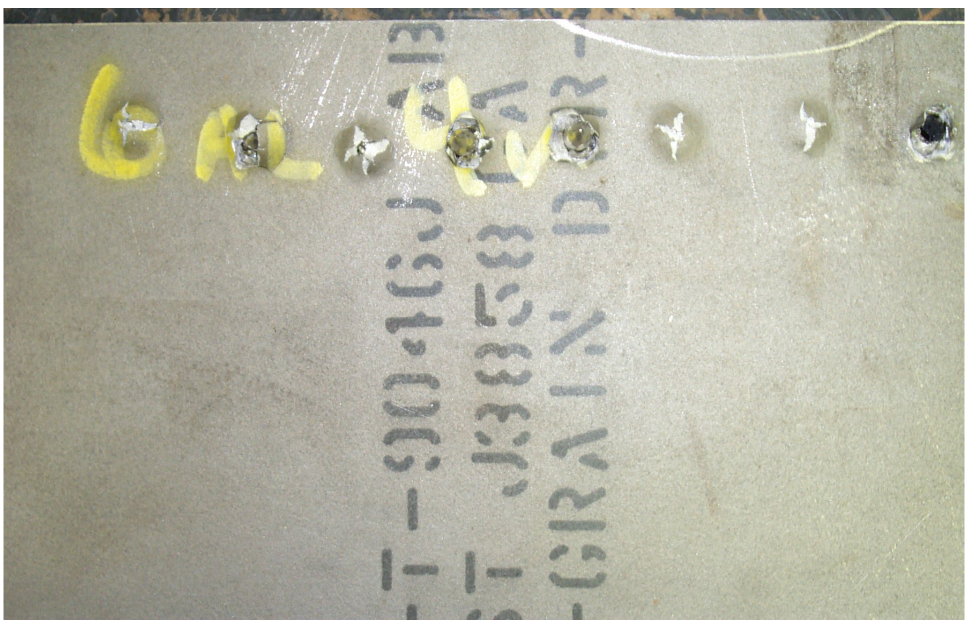
- The Russian titanium alloy was slightly harder, based on the measured BHN.
- The V_{50} ballistic limit of the Russian titanium alloy was significantly lower (7% lower) than the expected performance of Ti-6Al-4V alloy when the results were normalized for the different thickness.

- The Russian titanium was 4% heavier than Ti-6Al-4V based on measured density.
- The Ti-6Al-4V outperformed the Russian titanium alloy based on ballistic test results.
- Both materials appeared to have multiple hit capabilities.

Based on these results for monolithic armor, no clear ballistic performance advantage would be achieved if the Russian titanium alloy were used against 0.30-cal AP M2 threats. Available data were insufficient to determine how the Russian alloy would have performed as part of a system or at obliquity.

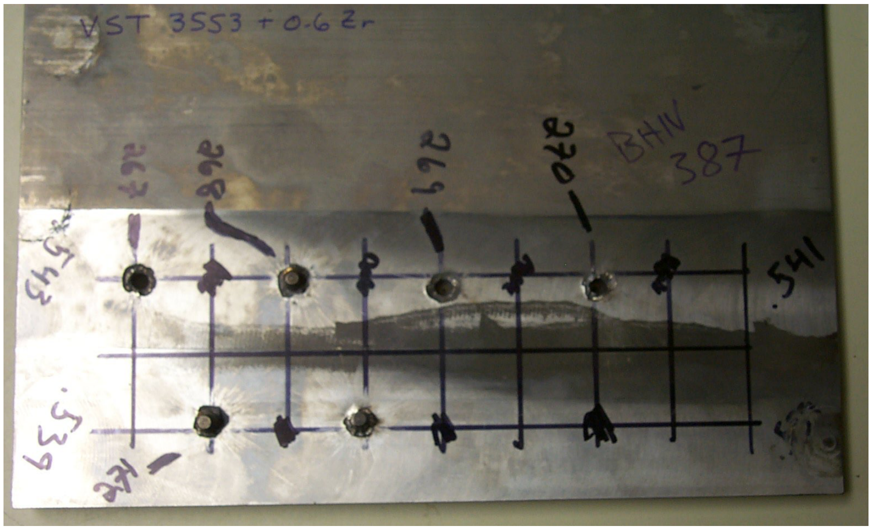


a. front



b. rear

Figure 3. Photographs of 12.83-mm (0.51-in.) Ti-6Al-4V plate after ballistic testing.



a. front

b. rear

Figure 4. Photographs of 13.72-mm (0.54-in.) Russian titanium alloy plate after ballistic testing.

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Appendix A. Ballistic Test Data

Table A-1. Ti-6Al-4V baseline.

Target:	**Titanium (Ti-6-4)**						Date:	**11-Sep-03**	
Plate #:	**J 3858**						Location:	**EF106**	
Thickness:	**12.83mm (.505")**								
Hardness:	**332 BHN**								
Obliquity:	**0 degrees**								
Projectile:	**.30 cal AP M2**								
V_{50}:	**633**	**m/s**	**# shots:**	**9**					
Std Dev:	**7**	**m/s**	**Spread:**	**14**	**m/s**				
Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V_{50}	LOS Pen (mm)	Bulge (mm)	Residual Velocity (m/s)	Comments	Shot #
582	0.25	-3.00	PP	No	12	2	--	Slight crack	247
655	-1.25	0.50	CP	No	--	--	--	Spall hinged open 11mm	248
613	1.50	-0.75	PP	No	PIP	3	--	Cracked	249
615	-1.50	0.50	PP	No	14	3	--	Star-shaped crack	250
642	-0.75	-1.00	PP	No	PIP	--	--	Film disposed	251
629	**0.00**	**-1.50**	**CP**	**Yes**	**PIP**	**--**	**--**	**SV=120m/s; 5.08mm thick**	**252**
638	**-1.25**	**-1.25**	**PP**	**Yes**	**PIP**	**4**	**--**	**Cracked**	**253**
640	**-1.00**	**-0.50**	**CP**	**Yes**	**PIP**	**--**	**--**	**SV=72m/s; 7x5x2mm thick**	**254**
626	**0.50**	**-0.75**	**PP**	**Yes**	**PIP**	**4**	**--**	**Star-shaped crack**	**255**

Table A-2. Russian titanium alloy.

Target:	**Russian Titanium Alloy**						Date:	**11-Sep-03**	
Plate #:	**4145**						Location:	**EF106**	
	(VST 3553+.6Zr)								
Thickness:	**13.72mm (0.54")**								
Hardness:	**387 BHN**								
Obliquity:	**0 degrees**								
Projectile:	**.30 cal AP M2**								
V_{50}:	**622**	**m/s**	**# shots:**	**4**					
Std Dev:	**7**		**Spread:**	**16**	**m/s**				
Striking Velocity (m/s)	Pitch (deg)	Yaw (deg)	Result (PP/CP)	Used for V_{50}	LOS Pen (mm)	Bulge (mm)	Residual Velocity (m/s)	Comments	Shot #
658	0	-0.2	PP	No	--	0.6	73	Spall	267
633	**-0.25**	**0.00**	**CP**	**Yes**	**PIP**	**4**	**--**	**Star-shaped crack**	**268**
611	-0.50	-0.75	PP	No	15	2	--	Cracked	269
619	**0.25**	**-0.50**	**PP**	**Yes**	**14**	**0.2**	**--**	**Cracked**	**270**
620	**0.00**	**-1.00**	**CP**	**Yes**	**PIP**	**3**	**--**	**3/5 diam. plug off plate**	**271**
617	**0.00**	**-0.50**	**PP**	**Yes**	**PIP**	**2**	**--**	**Cracked**	**272**

List of Definitions and Abbreviations

Bulge	Plastic movement of back of plate without cracking
CP	Complete penetration; penetrator/target material exits rear surface of target.
LOS Pen	Line-of-sight penetration depth.
PIP	Penetrator in plate; penetrator lodged in impact crater.
Pitch	Attitude of projectile in the vertical direction.
PP	Partial penetration; the penetrator is defeated by the target.
Plug	Target material ejected off rear of the plate.
Residual velocity	Velocity out of back of plate.
Result	Result of shot; CP or PP.
Spall	Solid phase shear deformation.
SV	Spall velocity.
Striking velocity	Velocity of the projectile just before it impacts the target.
Yaw	Attitude of projectile in the horizontal direction.

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