BALLISTIC PERFORMANCE OF THIN TITANIUM PLATES

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In the United States, titanium armor is procured to the requirements of the MIL-DTL-46077F armor specification. However, this specification does not cover thicknesses below 6.35mm. The Army Research Laboratory (ARL) conducted an initial assessment to determine if the specification can be modified to include thicknesses as low as 3mm. Plates in thicknesses from 3mm to 6.35mm were obtained for testing. In some cases, thicker plates were machined down in order to reduce potential performance variations due to variations in chemistry. Testing was conducted with fragment simulating projectiles (FSPs) and with bullets in order to look at target failure modes and to assess the best ballistic test projectile to use for the modified specification. Some additional testing was performed with commercially pure titanium (CP Ti) and with a high-strength beta alloy (Ti-10V-2Fe-3Al) for comparison.

INTRODUCTION

In the United States, armor grade titanium is procured to the requirements of the MIL-DTL-46077F specification [1]. Since this specification does not allow thicknesses below 6.35mm, ballistic data for these plate thicknesses are very limited. In order to gain a better understanding of the ballistic performance of thin titanium, the U.S. Army Research Laboratory (ARL) conducted an initial assessment of three commercial titanium alloys: a low strength commercially pure titanium alloy (CP Ti), an intermediate strength alpha-beta alloy (Ti-6Al-4V), and a high-strength beta alloy (Ti-10V-2Fe-3Al). These alloys, in thicknesses from 3mm to 8.4mm and manufactured to various commercial specifications, were obtained for testing with fragment simulating projectiles (FSPs) and with bullets in order to look at target failure modes and to assess the ballistic performance.

BACKGROUND

Titanium can exist in a hexagonal close-packed crystal structure (the alpha phase) and a body-centered cubic structure (the beta phase). In unalloyed titanium, the alpha phase is stable at all temperatures up to 882^{o} C, where it transforms to the beta phase. This transformation temperature is known as the beta transus temperature. As alloying elements are added to pure titanium, the beta transus temperature and the proportion of each phase change. Alloying additions to titanium, except tin and zirconium, tend to stabilize either the alpha or the 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 aluminium is an alpha stabilizer, stabilizing the alpha phase to higher temperatures, and the vanadium is a beta stabilizer, stabilizing the beta phase to lower temperatures. The addition of these alloying elements raises the beta transus temperature to approximately 996^{o} C. Alpha-beta alloys, such as Ti-6Al-4V, are of interest for armor applications because they are generally weldable, can be heat treated, and offer moderate to high strengths. [2]

Two additional alloys were included in this investigation: CP Ti, grade 2 and Ti-10V-2Fe-3Al. CP Ti, grade 2, is an alpha titanium alloy where the strength level is controlled by the oxygen content. Alpha alloys tend to have low strength, high ductility, and exceptional weldability and corrosion resistance. The CP Ti, grade 2, was purchased from a metal supplier to commercial specification ASTM B265-03 [3]. Ti-10V-2Fe-3Al, with its high content of Fe and V beta stabilizers, is a heat treatable, high strength beta alloy. The Ti-10V-2Fe-3Al plates were produced by the U.S. Department of Energy Albany Research Center (ARC) in Albany, OR [4,5]. CP Ti, Ti-6Al-4V, and Ti-10V-2Fe-3Al represent a wide spectrum of potential commercially-available titanium alloys. Mechanical properties and basic chemistries for all three alloys are provided in Table 1.

Table 1. Typical Properties of Various Titanium Alloys [3,4,5]

Material	Tensile strength (MPa)	0.2% yield strength (MPa)	Elon-gation (%)	Chemical Composition[1] (%)					
				Al	V	N	C	Fe	O
Ti-6Al-4V	895 min	828 min	10 min	5.50-6.75	3.5-4.0	0.05 max	0.08 max	0.40 max	0.20 max
CP Ti, Grade 2	345 min	275-450	20 min	---	---	0.03 max	0.08 max	0.30 max	0.25 max
Ti-10V-2Fe-3Al	943-1159	914-1090	8.5-16.7	2.6-3.4	9.0-11.0	0.05	0.05	1.6-2.2	0.13

[1] maximum 0.150% H for all alloys listed. Remainder/Balance is titanium.

TEST METHODOLOGY

Prior testing with thicker plates of Ti-6Al-4V alloy [6,7] used both FSPs and bullets in order to study plate failure modes. Although this prior work showed that the V_{50} ballistic limit velocity for the FSPs was more sensitive to changes in titanium processing than the V_{50} ballistic limit for bullets, testing on the thin titanium plates was conducted with both types of projectiles in order to more thoroughly characterize performance. The most logical choice of FSP for the thin plates appeared to be the 5.56mm FSP [8], shown in Figure 1. These FSPs were manufactured locally from 4340H steel and had an average hardness of R_C 29.8.

Testing was conducted with two full-metal jacketed bullets, the 7.62mm APM2 and the 5.56mm M193, both shown in Figure 1, also. The APM2 has a hard steel core and is used for the ballistic acceptance of Ti-6Al-4V armor plate to the MIL-DTL-46077F specification for thicknesses of 6.35mm to 15.6mm. Since the minimum V_{50} ballistic limit velocity for the APM2 for a plate thickness of 6.35 mm is 356 m/s, testing with thicknesses below 6.35mm is not practical or reasonable. Consequently, the 5.56mm M193, lead core ball bullet was selected to evaluate the titanium alloys from 3-8.4mm. However, whenever possible, testing was conducted with both bullets, where the APM2 provides a performance baseline back to the MIL-DTL-46077F requirements.

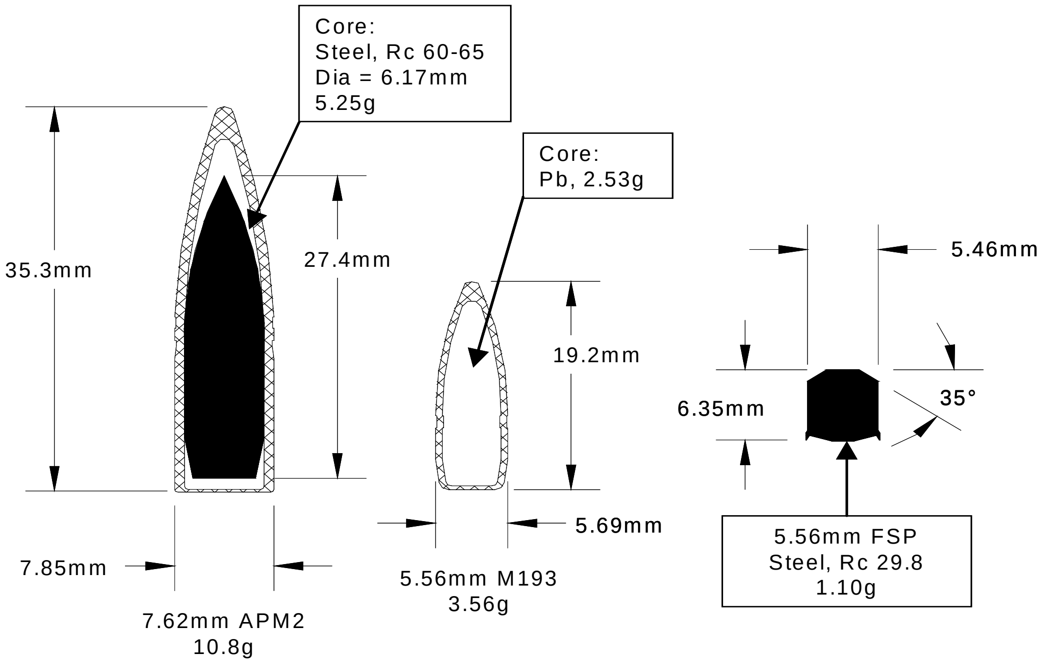

Figure 1. Test Projectiles

Regardless of the projectile used, all V_{50} limit velocity testing was conducted per MIL-STD-662F [9]. A 0.5mm 2024-T3 aluminum alloy witness plate was placed behind and parallel to the target. If penetrator or target debris perforated the witness plate, then the shot was classified a complete perforation (CP). Any other fair impact result that was not a CP was classified as a partial penetration (PP). Equal numbers of CPs and PPs were averaged in order to determine the V_{50} limit velocity with the assumption of a Gaussian distribution. Based on the MIL-DTL-46077F requirements, V_{50} limit velocities were calculated using 2 CPs and 2PPs for a velocity spread of 18 m/s or less, 3 CPs and 3 PPs for a velocity spread between 18 m/s and 27 m/s, or 5 CPs and 5 PPs when the velocity spread exceeded 27 m/s.

FSP V_{50} TEST RESULTS

Ballistic test results for the 5.56mm FSP into various titanium plates at 0° obliquity are presented in Table 2. A single 6.35mm Ti-6Al-4V plate was cut into three smaller plates, two of which were machined to a reduced thickness. This removed any issue of variability in chemical or mechanical properties affecting the V_{50} limit velocity. Since surface finish of the rear surface has an effect on the V_{50} limit velocity [7], the plates were machined on the front only, thereby maintaining the standard mill surface finish on the rear of all three plates.

Table 2. Performance of Titanium Alloys versus 5.56mm FSP at 0° Obliquity

Material	Density [10] (g/cm^3)	Thickness (mm)	Areal Density (kg/m^2)	Measured Hardness (BHN)	V_{50} Limit Velocity (m/s)	Standard Deviation (m/s)
Ti-6Al-4V	4.43	4.29[M]	19.0	321	580	9.4
		5.23[M]	23.2	321	662	7.5
		6.35	28.1	340	988	15.1
		2.84[a]	12.6	No Data	526	14.3
		3.77[a]	16.7		598	9.0
		4.61[a]	20.4		695	28.7
		1.19[b]	5.29		271	10.2
		1.52[b]	6.75		375	11.1
		2.01[b]	8.89		488	6.3
		3.63[b]	16.1		613	10.1
CP Ti, Grade 2	4.51	2.24[M]	10.1	201	356	12.8
		4.95	22.3	217	626	5.7
Ti-10V-2Fe-3Al	4.65	2.16	10.0	311	495	9.9
		4.32	20.1	332	627	20.1
		5.26	24.5	293	786	8.3

[a] AR-21326 [11]   [b] AR-21343 [12]   [M] Machined on front side only

Additional prior V_{50} firing data for Ti-6Al-4V was obtained to supplement the three plates tested [11,12]. When all of the Ti-6Al-4V V_{50} data was plotted, Figure 2, the data appeared to have significant scatter on a linear regression fit. This data also appeared to be a better fit against a third order equation. Although it is difficult to fully ascertain which model is correct, there does appear to be a change in penetrator failure mode (i.e. the penetrator undergoes significant deformation "mushrooming") above 15 kg/m^2, which may explain the apparent inflection point. The Ti-10V-2Fe-3Al, although possessing higher strength than the Ti-6Al-4V, had V_{50} limit velocities very similar to an equal areal density of Ti-6Al-4V. All of the Ti-10V-2Fe-3Al plates were received from ARC with a machined surface finish on front and back. The lower strength CP-Ti, especially for the thicker plate, performed similarly to the Ti-6Al-4V. The thicker CP Ti plate was machined on the front only, for the same reasons as the Ti-6Al-4V, to obtain the thinner plate that was tested. Consequently, chemical and mechanical property variations cannot be fully responsible for the apparent departure from the baseline Ti-6Al-4V data. Unlike prior work with thicker plates, the FSP appeared to be a poor discriminator for titanium properties and would, therefore, make a poor ballistic acceptance projectile.

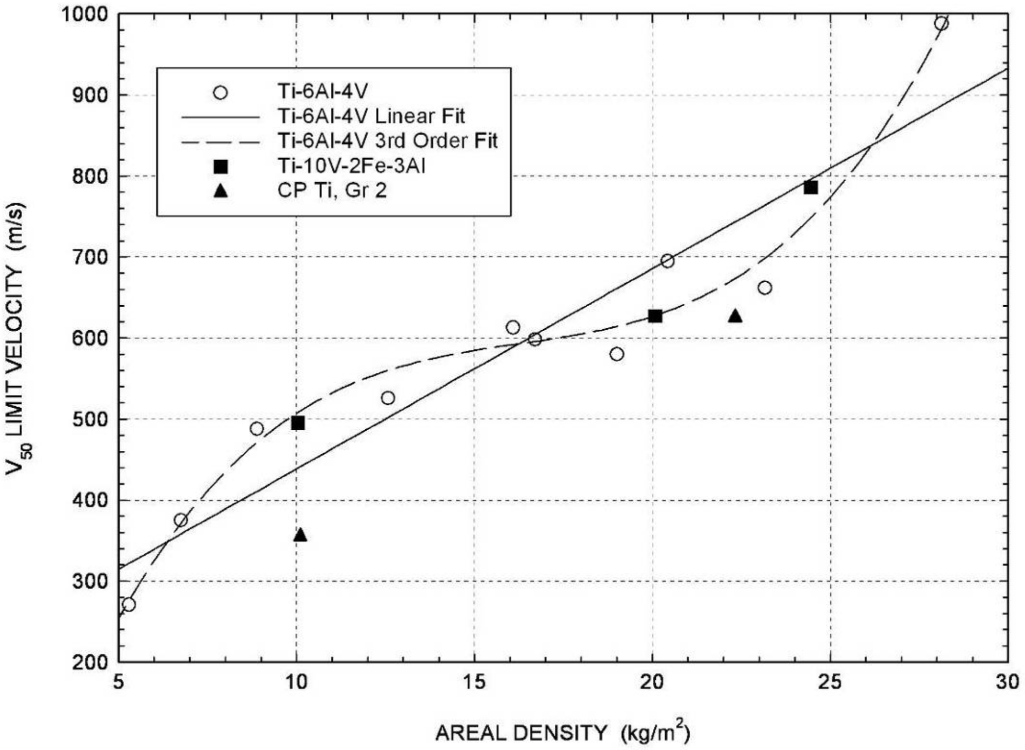

Figure 2. 5.56mm FSP V_{50} Limit Velocity Test Data

BULLET V_{50} TEST RESULTS

The results for the ballistic V_{50} testing at 0° obliquity for both the AMP2 and the M193 bullets is presented in Table 3. The 7.62mm APM2 was used to determine if the plates met the requirements of MIL-DTL-46077F, of which only the TIMET and VSMPO plates did. The 6.50mm thick TIMET plate was produced by milling the front surface of the 9.50mm plate. ARC produced a number of 3.2mm to 8.4mm thick Ti-6Al-4V plates by a high temperature “A” process and a low temperature “B” process. The “B” process was inferior to the “A” process on the basis of the APM2 V_{50} results; however, the two processes appeared to deliver comparable V_{50} limit velocities for the M193. No beta alloy plates were available for testing; however the single plate of CP Ti tested performed substantially worse than the Ti-6Al-4V.

Table 3. Performance of Titanium Alloys 0° Obliquity versus Two Bullets

Plate	Thick-ness (mm)	Hard-ness (BHN)	7.62mm AP M2			5.56mm M193	
			V_{50} Limit (m/s)	Std Dev (m/s)	MIL-DTL-46077F Requirement (m/s)	V_{50} Limit (m/s)	Std Dev (m/s)
TIMET Ht #CN3003	**9.50**	**332**	**536**	**10.7**	**511**	**842**	**8.2**
TIMET Ht #CN3003 (machined)	**6.50**	**332**	**385**	**11.9**	**365**	**740**	**18.9**
ATI Wah Chang	7.24	332	336	7.9	405	775	7.3
ARC Process “A”	8.38	332	460	11.0	462	792	10.1
	6.12	321	301	9.8	342	■	■
	6.27	321	■	■	■	732	11.6
	4.85	332	■	■	■	710	8.5
	3.20	321	■	■	■	572	11.9
ARC Process “B”	8.36	321	370	3.0	461	787	10.1
	6.30	321	277	17.7	353	■	■
	6.25	351	■	■	■	725	6.4
	3.25	332	■	■	■	580	5.5
VSMPO Heat 8-11-2084-1, Lot 4081S635	**6.68**	**340**	**426**	**6.7**	**379**	**786**	**7.3**
MIL-T-9046J, AB-1 [13]	4.83	351	■	■	■	712	6.7
	5.89	311	■	■	■	740	6.7
CP Ti, Gr 2	5.26	212	■	■	■	608	16.8

Figure 3 provides a graphical representation of the bullet V_{50} data. The performance of the M193 appeared to be a well behaved second order fit for the V_{50} data. As noted above, plates that failed the APM2 requirements did not necessarily deliver low V_{50} limit velocities for the M193. Plates below 6.35mm thickness could not be tested with the APM2 due to the very low velocities required to perform V_{50} testing.

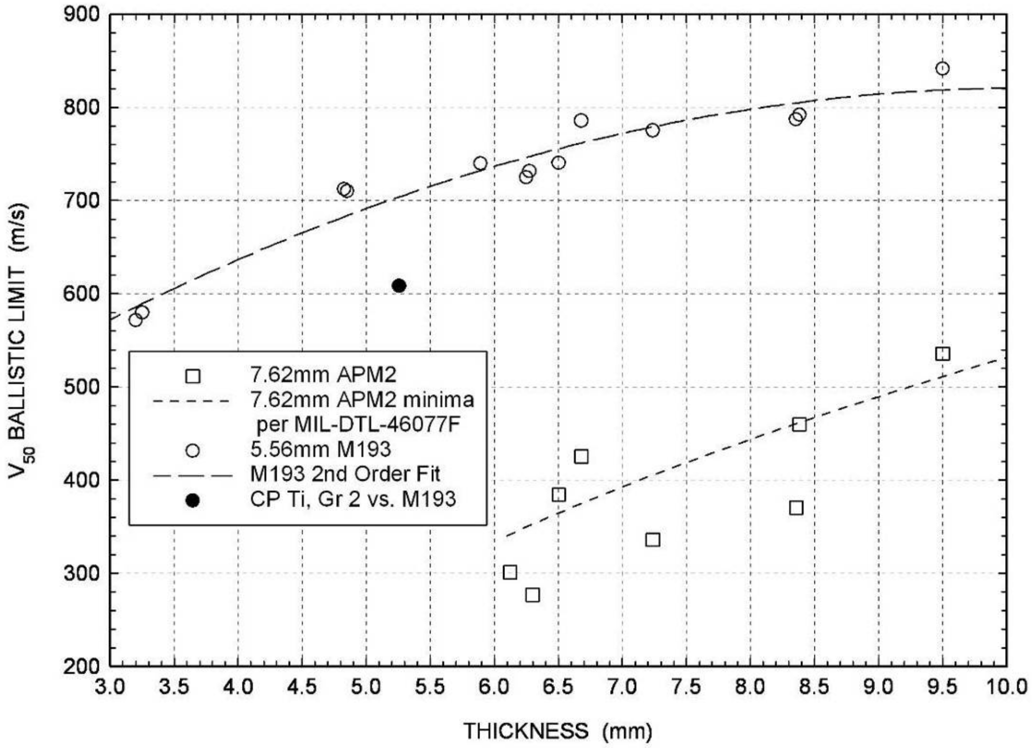

Figure 3. Bullet V_{50} Test Data at 0° obliquity

CONCLUSIONS

Although previous work [6,7] with thicker plates indicated FSPs would be the best projectiles to determine processing variables, this was not the case for plates less than 6.35mm. For Ti-6Al-4V, the relationship between V_{50} limit velocity and areal density appeared to be either a linear response with significant scatter or a 3rd order curve with an inflection point around 15 kg/m^2, possibly due to the inception of deformation mushrooming of the FSP. When corrected for density, the V_{50} performance of all three titanium alloys appeared to be similar over the range from 275-1090 MPa yield strength.

The inability of the FSP to discriminate between different alloys makes the FSP a poor candidate for a specification acceptance projectile.

For bullets, the performance of Ti-6Al-4V was compared between the 5.56mm M193 lead core and the 7.62mm APM2 steel core projectile called out in the U.S. military specification MIL-DTL-46077F. Although there were no beta alloy plates available for this testing, a single plate of CP Ti was tested. The M193 V_{50} performance appeared to be a fairly well behaved second order function for Ti-6Al-4V and the lower strength CP Ti provided a significantly lower V_{50} limit velocity. However, plates which showed large V_{50} performance differences in the 7.62mm APM2 testing, such as the ARC “A” and “B” process plates, did not show a large difference in the M193 tests. Based on the current data, it is not clear that the M193 is the best acceptance projectile for Ti-6Al-4V plates below 6.35mm thickness.

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