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THE PENETRATION RESISTANCE OF A TITANIUM ALLOY AGAINST JETS FROM TANTALUM SHAPED CHARGE LINERS

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Abstract - Titanium alloys, notably Ti-6AL-4V, are known to provide high mass effectiveness against kinetic energy penetrators. However, the penetration effectiveness of titanium against shaped charge jets has not been investigated in detail. An experimental study was conducted with Ti-6Al-4V billets impacted by shaped charge jets formed from 100-mm, 42-degree conical shaped charge liners fabricated from tantalum. This work represents the first study of hypervelocity, high-density jet penetration into titanium alloys. © 2001 Elsevier Science Ltd. All rights reserved.

INTRODUCTION

The use of titanium alloys for aerospace applications is well-established for lightweight airframe and jet engine components. The high cost of titanium, however, has historically prevented its use in military ground vehicles. In recent years, the cost of titanium has fallen and is very competitive with composite and ceramic armors, and titanium is now a valid option for armor applications, particularly in thicker cross-sections.

As early as 1950, Pitler and Hurlich [1] noted that titanium alloys showed promise as armors against small arms projectiles. By the early 1960s, Sliney [2] presented ballistic performance data for Ti-6Al-4V alloy that demonstrated significant weight reductions over rolled homogeneous armor (RHA) steel armors for small arms threats. Little work with larger threats was conducted due to the then prohibitive cost of the titanium. Until 1993, a major impediment to the consideration of titanium for armor applications had been the lack of baseline titanium ballistic performance data against modern penetrators. Since 1993, the U.S. Army Research Laboratory has published a series of papers in the literature that baseline the performance of titanium against modern kinetic energy penetrators, with the most complete ballistic data derived from joint tests with the French-German Research Institute Saint Louis in France [3,4,5]. Additionally, significant research efforts and ballistic testing continue on efforts to develop low cost titanum alloys [6,7]. However, during this period, only limited ballistic testing data was available for shaped charges. The few tests conducted indicated that titanium provided a mass effectiveness about 1.6 times that of RHA, roughly equivalent to the ballistic performance of tungsten alloy kinetic energy penetrators fired at semi-infinite titanium.

This paper provides the first systematic experimental study conducted with Ti-6Al-4V based armors impacted by jets from 100-mm, 42-degree conical shaped charge liners fabricated from tantalum. The first tests were for calibration purposes and the tantalum liner shaped charges were fired into semi-infinite RHA and semi-infinite Ti-6Al-4V billets at a fixed 3 charge diameter (CD) standoff. Next, at the same standoff, tests were conducted against three Ti-6Al-4V billets of 100-, 200-, and 300-mm lengths, each preceded by a 50.8-mm RHA plate and backed by semi-infinite RHA. Then, the same three thicknesses of Ti-6Al-4V alloy billets were tested without the 50.8-mm

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RHA cover plate against the same charge at the same standoff. The limited number of shaped charges prevented multiple shots against the targets, but the jet from the shaped charge liner was of high quality and showed minimal round-to-round variability based on earlier tests. The space and mass effectiveness of the titanium alloy armor were calculated based on the shots conducted and are presented along with the total penetration depths and hole profiles. Conclusions that illustrate the effectiveness of Ti-6Al-4V as an armor are drawn. Potential advantages of thick titanium alloy armors and the optimal location of the titanium alloy in an RHA sandwich are discussed.

BACKGROUND

Titanium can exist as two crystalline structures, hexagonal close-packed (alpha phase) and body-centered cubic (beta phase). Ti-6Al-4V, the most common titanium alloy, contains mixtures of alpha and beta phases. The aluminum stabilizes the alpha phase to higher temperatures, and the vanadium stabilizes the beta phase to lower temperatures. Alpha-beta alloys, such as Ti-6Al-4V, are of interest for armor applications because they are generally weldable, heat treatable, and moderate to high in strength [8]. Ti-6Al-4V can be ordered to various worldwide commercial and military specifications. The titanium billets used in these tests were manufactured to specification MIL-T-9046J, which defines alloy chemistry ranges, processing, minimum mechanical properties, and handling and inspection procedures, but does not define ballistic requirements. Mechanical property data are found in Table 1. The hardness values are as measured on the billets tested; hardness is not specified in MIL-T-9046J.

Table 1. Titanium and RHA Mechanical Properties

Material	*Density (g/cm^3)*	*Tensile Strength (MPa)*	*Hardness (HB)*	*Elongation (%)*
Ti-6Al-4V	4.43	>896	302-364	>10
RHA	7.85	794-951	241-331	11-21

U.S. RHA MIL-A-12560 steel was used as the baseline for ballistic comparisons and the mechanical properties are provided in Table 1 for plate thicknesses ranging from 38 mm to 152 mm. The mechanical properties of RHA vary as a function of plate thickness due to differences in thermomechanical processing, e.g., a 38-mm RHA plate has higher strength and hardness than a 152-mm plate. While titanium has poor hardenability in thick sections and cannot be rapidly quenched, excellent mechanical properties can be developed through thermomechanical working (rolling). Titanium mechanical properties are very uniform through the plate thickness, which increases the relative ballistic performance when compared to equivalent thicknesses of RHA. In thick sections, titanium has significantly better mechanical properties for ballistic application than equal thicknesses of RHA.

TANTALUM SHAPED CHARGE WARHEADS

Previous tests of shaped charges against titanium alloys consist only of a few semi-infinite penetration shots from small (about 60-mm diameter) shaped charges with conical copper liners. For this work, shaped charges with tantalum liners were used. These liners consisted of a 42-degree cone with an outside diameter of 100 mm. The explosive fill was 75/25 Octol. This charge represents a homologous scaling of a 152.4-mm liner outer diameter charge. This charge proved to be an effective penetrator, and performance data are given in both Walters and Summers [9]and Walters et al. [10]. The measured jet characteristics were obtained from ARLs Experimental Facility 16 test number 4042. A total of 60 jet particles were observed on the free flight flash radiograph. A representative x-ray is shown in Figure 1. The jet tip velocity was 8.2 km/s, and the velocity of the last measured jet particle was 2.14 km/s. The jet particles had an average length of 18.77 mm, an average radius of 1.85 mm, and an average particle L/D (length to diameter) ratio of 5.04. The average velocity difference between particles was 0.108 km/s, and the average jet breakup time was 168.7 μs. The virtual origin was located 53.6 mm inside the base of the liner. The jet from this charge was well aligned and demonstrated excellent repeatability. Since ten of these rounds were still available from the program described in Walters et al. [10], testing against the titanium alloy armor was conducted. This program represented the first tests of high density jets from shaped charge liners against titanium based armors.

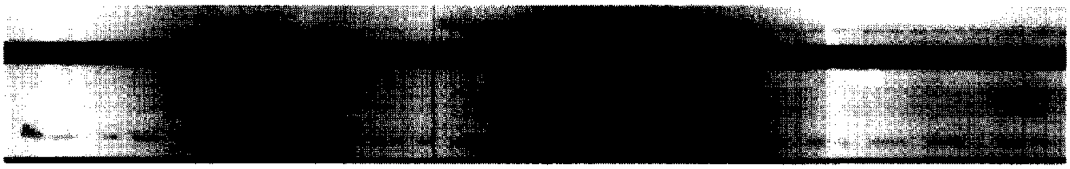

Fig.1. X-ray images of tantalum metal liner jet.

BALLISTIC CHARACTERIZATION

Ballistic performance of armors or elements of armors are characterized by dimensionless factors which compare the areal density (mass/area) and thickness of the material to baseline RHA. Many variations and terminologies exist, but Frank [11] developed and described a concise set of mass and space effectiveness factors whose conventions are in use at ARL. The shaped charge tests in this paper are similar to standard depth of penetration tests, and the equivalent RHA performance of the titanium relative the semi-infinite penetration of the rod can be determined. The ballistic characterization can be defined by the mass effectiveness (e_m), the space effectiveness (e_s) and the armor quality factor (q^2) as described by equations below; the small e indicates that the performance indices are elemental rather than system effectiveness values. The term (P_{RHA}-P_R) relates the baseline RHA penetration of the rod to the residual RHA penetration depth and represents how much baseline RHA penetration was removed by the titanium thickness T_{TI} at the same impact velocity. The titanium mass effectiveness can then be related to e_S by the titanium density (ρ_{TI}) and the RHA density (ρ_{RHA}). RHA has an e_M and e_S of 1.0 and higher indices indicate better ballistic performance. The quality factor has significance for armor designers as this factor relates both the mass and space factors; values over 1.0 indicate armors or materials which are thinner and/or lighter than the baseline RHA performance and high values indicate superior armors or materials.

$$e_s = \frac{P_{RHA} - P_R}{T_{TI}} \qquad e_m = \frac{(P_{RHA} - P_R) \times \rho_{RHA}}{T_{TI} \times \rho_{TI}} = e_s \times \frac{\rho_{RHA}}{\rho_{TI}} \qquad q^2 = e_m \times e_s$$

EXPERIMENTAL TEST PROGRAM

The first tests consisted of penetrations into a stack of 152.4-mm x 152.4-mm x 76.2-mm thick blocks of RHA at a fixed standoff of 3 CD or 300 mm. Two shots were fired into each target. The total penetration was 640 mm and 659 mm for the two tests. The hole profiles are provided in Tables 2 and 3, where the entrance and exit hole diameters were measured for each perforated RHA block. These two shots, designated as 148 and 149, were very similar. Slug material from the jet was evident at the top and bottom of the RHA stack.

The next two rounds were fired into a 203.2-mm diameter cylindrical billet of Ti-6Al-4V at a fixed standoff of 3 CD or 300 mm. The final penetration into this billet was 655 mm for shot 150 and 697 mm for shot 151. The entrance hole diameters for the billets were 60.06 mm x 57.63 mm and 57.19 mm x 57.75 mm for shots 150 and 151, respectively. Later, the RHA blocks and the titanium alloy billets were cross-sectioned, and exact hole profile tracings were obtained for shots 149 and 151. Figure 2 depicts the penetration channel for shot 149 into RHA and Figure 3 depicts the penetration channel for shot 151 into Ti-6Al-4V. Comparing shot 149, the minimum penetration obtained for RHA with shot 151, the maximum penetration obtained for Ti-6Al-4V, yields a mass effectiveness of 1.6 and space effectiveness of 0.9 for the Ti-6Al-4V billets. Shots 148 and 150 had nearly equal penetration depths for both the Ti-6Al-4V and the RHA, which implies a mass effectiveness of 1.7 and a space effectiveness of 1.0.

Table 2. Hole Profile Diameters for RHA Shot 148

RHA Block	*Entrance Hole (mm)*	*Exit Hole (mm)*	*Comments*
1	55.75 x 55.75	26.80 x 20.84	Liner material present
2	20.13 x 18.25	14.94 x 13.55	Liner material present
3	14.61 x 17.00	13.92 x 13.90	Liner material present
4	14.70 x 15.67	10.43 x 9.94	
5	9.42 x 10.40	8.93 x 9.58	
6	11.7 x 11.43	10.52 x 11.97	Liner material present
7	12.36 x 12.18	10.05 x 10.52	Liner material present
8	17.74 x 16.99	9.14 x 9.53	
9	15.60 x 14.45	---------	
Total Penetration = 659 mm			

Table 3. Hole Profile Diameters for RHA Shot 149

RHA Block	*Entrance Hole (mm)*	*Exit Hole (mm)*	*Comments*
1	60.20 x 53.56	23.47 x 21.20	
2	20.85 x 17.88	14.46 x 13.28	Liner material present
3	15.14 x 15.00	13.52 x 13.13	Liner material present
4	14.32 x 14.32	11.23 x 10.97	
5	12.59 x 12.46	10.01 x 10.01	
6	11.18 x 10.97	10.55 x 10.17	
7	11.43 x 11.08	10.49 x 11.08	Liner material present
8	11.06 x 11.17	18.15 x 17.06	Liner material present
9	18.08 x 16.80	---------	Liner material present
Total Penetration = 640 mm			

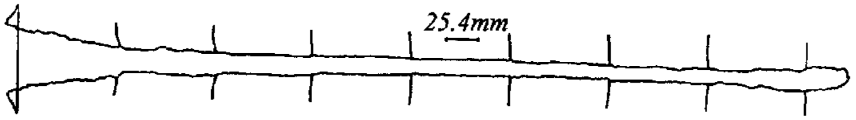

Fig.2. Penetration channel in RHA for shot 149.

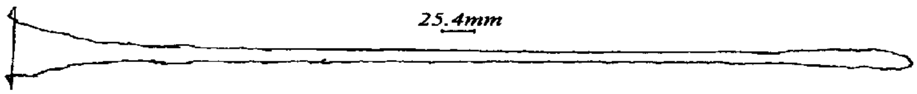

Fig.3. Penetration channel in Ti-6Al-4V for shot 151.

Following these "calibration" shots, steel/titanium alloy laminate targets were constructed and Figure 4 is a schematic of the targets. Two targets were considered. The first consisted of a 50.8-mm RHA plate followed by a 203.2-mm diameter cylinder of Ti-6Al-4V of three different lengths, followed by a semi-infinite stack of RHA. The three titanium billet lengths were 100, 200, and 300 mm. The second target series was identical to the first, except that the 50.8-mm RHA front plate was omitted, i.e., the three targets used in the second test series consisted of 100-mm, 200-mm, and 300-mm thick titanium billets followed by semi-infinite RHA. In all six tests, the standoff distance was held constant at 3 CD or 300 mm. The ballistic test results and hole profiles are shown in Tables 4 and 5. The RHA penetrations are the sum of the 50.8-mm and residual plates. The mass effectiveness of the titanium, e_m, is also shown and represents the increase in performance relative to RHA for the titanium billet.

The penetrated titanium plates were taken to the large industrial x-ray facility at the Army Test Center at Aberdeen Proving Ground, MD, and exposed to a long time period x-ray exposure. The cavities could then be observed on the x-ray film. Two representative cross-sections are shown in Figures 5 and 6 for shots 4811 and 4808, respectively. The jet slug can be seen in each of the x-rays, as well as additional jet residue. The main difference in these two tests is the large diameter entrance hole in the titanium when directly impacted and compared to the smaller diameter entrance hole while using the 50.8-mm RHA cover plate. When the titanium was placed between RHA plates, the entrance and exit holes had similar diameters.

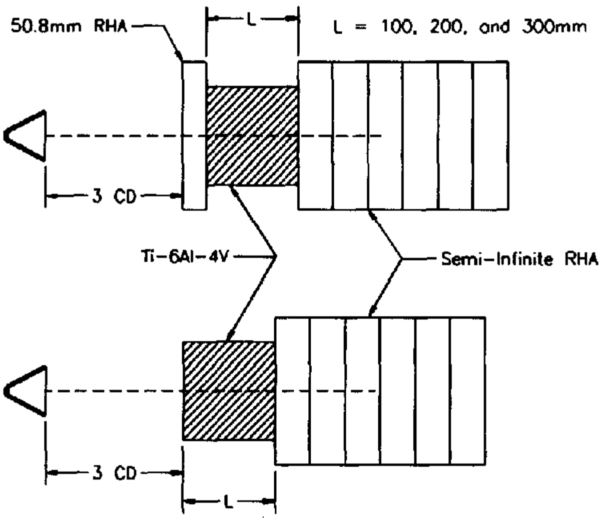

Fig.4. Schematic cross-sections of the steel/titanium targets.

Fig.5. X-ray of cross-section of 300-mm titanium billet without cover plate (shot 4811).

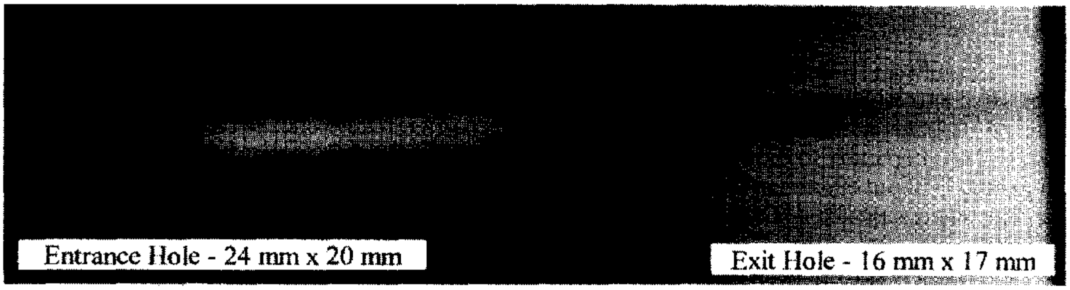

Fig.6. X-ray of cross-section of 300-mm titanium billet with cover plate (shot 4808).

Table 4. Tantalum Shaped Charge Jet Penetration Performance

SHOT 4806	RHA	50.8 mm	*SHOT 4809*	TITANIUM	100 mm
	TITANIUM	100 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	62.0 mm		RHA	36.0 mm
TOTAL RHA PENETRATION = 570 mm TITANIUM e_m = 1.24			TOTAL RHA PENETRATION = 569 mm TITANIUM e_m = 1.25		
SHOT 4807	RHA	50.8 mm	*SHOT 4810*	TITANIUM	200 mm
	TITANIUM	200 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	38.0 mm		RHA	76.2 mm
TOTAL RHA PENETRATION = 470 mm TITANIUM e_m = 1.51			TOTAL RHA PENETRATION = 526 mm TITANIUM e_m = 1.01		
SHOT 4808	RHA	50.8 mm	*SHOT 4811*	TITANIUM	300 mm
	TITANIUM	300 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	76.2 mm		RHA	76.2 mm
	RHA	3 mm		RHA	25 mm
TOTAL RHA PENETRATION = 435 mm TITANIUM e_m = 1.21			TOTAL RHA PENETRATION = 406 mm TITANIUM e_m = 1.38		

DISCUSSION

The results and possible conclusions from these tests were limited by the fact that only one round was fired into each titanium/RHA configuration. The largest variation occurred between shots 4807 and 4810, utilizing the 200-mm billets. The 56-mm penetration difference between shots 4807 and 4810 was comparable to the 42-mm variation between the semi-infinite penetrations into monolithic titanium. Without additional testing, it is not possible to determine if round-to-round variations are completely responsible for the difference in penetration for shots 4807 and 4810. Overall, the mass effectiveness average for all six titanium/RHA laminate targets was 1.27. Significantly, the mass effectiveness values obtained for the titanium/RHA laminate targets were substantially lower than the 1.6 -1.7 mass effectiveness values obtained for monolithic titanium penetration.

Table 5. Hole Profiles for Penetrated Titanium and RHA Plates

SHOT 4806				***SHOT 4809***			
TARGET MATERIAL	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***	***TARGET MATERIAL***	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***
50.8 mm RHA	52 x 56	27 x 28		–	--	--	–
100 mm Ti Alloy	25 x 35	26 x 27		100 mm Ti Alloy	59 x 59	18 x 20	
76.2 mm RHA	15 x 18	14 x 16		76.2 mm RHA	16 x 17	16 x 16	
76.2 mm RHA	14 x 15	13 x14		76.2 mm RHA	16 x 15	13 x 13	
76.2 mm RHA	13 x 13	12 x 12		76.2 mm RHA	15 x 15	13 x 13	
76.2 mm RHA	13 x 13	10 x 10		76.2 mm RHA	14 x 13	11 x 11	
76.2 mm RHA	10 x 10	12 x 11		76.2 mm RHA	12 x 12	10 x 11	
76.2 mm RHA	12 x 10	15 x 12		76.2 mm RHA	11 x 11	11 x 11	
76.2 mm RHA	18 x 16		Plugged, 16	76.2 mm RHA	11 x 10	15 x 15	
–	--	–	--	76.2 mm RHA	13 x 13		Plugged, 34

SHOT 4807				***SHOT 4810***			
TARGET MATERIAL	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***	***TARGET MATERIAL***	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***
50.8 mm RHA	55 x 54	28 x 29		--	–	--	–
200 mm Ti Alloy	28 x 28	12 x 13		200 mm Ti Alloy	57 x 58	19 x 15	
76.2 mm RHA	14 x 13	12 x 12		76.2 mm RHA	15 x 15	13 x 14	
76.2 mm RHA	13 x 13	11 x11		76.2 mm RHA	15 x 14	12 x 13	
76.2 mm RHA	14 x 14	12 x 11		76.2 mm RHA	13 x 13	11 x 11	
76.2 mm RHA	13 x 12	13 x 13		76.2 mm RHA	12 x 11	11 x 10	
76.2 mm RHA	13 x 13	17 x 15		76.2 mm RHA	13 x 15	12 x 12	
76.2 mm RHA	15 x 15		Plugged, 23	76.2 mm RHA	15 x 15	15 x 17	
				76.2 mm RHA	21 x 16		38

SHOT 4808				***SHOT 4811***			
TARGET MATERIAL	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***	***TARGET MATERIAL***	***ENTRANCE HOLE (mm)***	***EXIT HOLE (mm)***	***PENETRATION DEPTH (mm)***
50.8 mm RHA	53 x 60	26 x 25		–	--	--	–
300 mm Ti Alloy	24 x 20	16 x 17		300 mm Ti Alloy	57 x 60	16 x 16	
76.2 mm RHA	12 x 12	12 x 12		76.2 mm RHA	12 x 12	11 x 12	
76.2 mm RHA	12 x 12	11 x11		76.2 mm RHA	12 x 12	12 x 11	
76.2 mm RHA	11 x 12	11 x 12		76.2 mm RHA	13 x 13	12 x 11	
76.2 mm RHA	12 x 13	24 x 22		76.2 mm RHA	12 x 12	15 x 17	
76.2 mm RHA	14 x 13	10 x 9		76.2 mm RHA	11 x 18	18 x 18	Entrance Key Hole
76.2 mm RHA	14 x 14		3	76.2 mm RHA	15 x 16		Plugged, 25

CONCLUSIONS

This study represents the first analysis of a high-speed, high-density jet penetrating titanium Ti-6Al-4V subjected to hypervelocity impact (8.2 km/s) and high density (16.6 cm^3) jet impact. This alloy has approximately the same strength as RHA steel, but has a density about 40% less than steel. A comparison of penetrations (at 3 CD standoff) into semi-infinite RHA and titanium yielded a mass effectiveness of 1.6 to 1.7 for the Ti-6Al-4V. This performance level is comparable to the limited prior semi-infinite penetration data with small copper shaped charges and tungsten kinetic energy penetrators. The mass effectiveness based on density considerations was expected to be only 1.32.

When tantalum charges were fired into titanium/RHA laminate targets at 3 CD standoff, the mass effectiveness values ranged from 1.0 to 1.5, both extremes obtained with the 200-mm billet targets. This level of performance was much lower than achieved with monolithic titanium targets, which seemed to indicate that the optimal titanium thickness should be greater than 300 mm for titanium/RHA laminate targets. Overall, the mass effectiveness average for all six titanium/RHA laminate targets was 1.27. Without additional testing, it is not possible to determine if round-to-round variations are completely responsible for the difference in penetration for the 200-mm billets.

The limited number of tests conducted have not permitted the determination of the optimal thickness of titanium or optimal location in a laminated titanium/RHA target. Future work will attempt to address these issues. Also, the titanium alloy billets will be sectioned in order to further investigate the failure mechanisms of the titanium.

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