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TITANIUM ROAD WHEELS: A COST-EFFECTIVE LOW-RISK ALTERNATIVE FOR LEGACY AND NEXT GENERATION COMBAT VEHICLES

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ABSTRACT

The U.S. Army identified the use of advanced materials in next generation combat vehicles design as a focal technology area of interest and urged industry to develop replacements that realize weight, sustainment, and cost savings. An initial life cycle analysis suggests that using Titanium road wheels as an alternative to legacy road wheels could cut 555.6 lbs. and reduce cost by $39,760.00 per each M-1 tank over a life cycle of 8,000 mi, resulting with $71.72 savings per each pound reduced. Secondary side-effects of the weight reduction achieved by the Titanium road wheels include improvements such as fuel economy, mobility, transportability, and risk-reduction in the inclusion of emerging metal matrix composite technologies in next generation combat vehicles. The paper recommends conducting field evaluation and considering the application of Titanium road wheels in the M-1/M-88, M-109, AMPV, MPF, OMFV, DLP/FDL, and RCV (H) platforms

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1. INTRODUCTION

The M-1 Abrams Main Battle Tank (MBT) and the M-2/M-3 Bradley Fighting Vehicle constitute the crux of the current Army's Armored Brigade Combat Teams (ABCTs). Both platforms have been in service since the early 1980s with current Army modernization plans projecting continued service with Active and National Guard forces beyond FY2028 where they would be gradually replaced by manned and optionally-manned Next Generation Combat Vehicles (NGCV), Optionally-Manned Fighting Vehicles (OMFV), and Optionally-Manned Tanks (OMT) [1-3]. History tells that certain aspects of combat vehicle performance, such as overall weight and actual operational tempo (OPTEMPO), usually exceed their nominal rates over their lifecycle, resulting with elevated rates of wear, reduced operational availability, and higher than planned maintenance and repair costs [5-10].

This paper addresses the potential of Titanium road wheels as alternatives for legacy Aluminum and Steel solutions in legacy and future tracked combat platforms, in general, and the M-1 Abrams MBT fleet, in particular. The paper commences with framing the problem and defining quantitative measures. Next, the paper reviews analytic, simulation-based, and economical aspects of the Titanium core road wheel alternative compared to the legacy M-1 wear-reinforced aluminum core road wheel alternative. Last, the paper outlines a notional roadmap for further evaluation and formation of an acquisition strategy for the near future.

2. PROBLEM

Comparing the M-1 Abrams Reliability, Availability, Maintainability, and Durability (RAM-D) requirements at nominal OPTEMPO with actual values - as a result of weight increase and accelerated wear due to higher-than-nominal OPTEMPO - lead to discrepancy between the required and the actual performances [4-6]. Focusing on track performance, the M-1 RAM-D requirement for track life is 2000 mi, whereas actual track life for the M1A1 is lower than 840 mi [4-6]. The M-1 RAM-D requirement for road/idler wheel durability is 20% in 3000 mi, whereas M1A1 road wheels may require being re-elastomerized after less than 850 mi and for only one cycle [4, 6].

Given that the main limiting factor in a road wheel life cycle is the elastomeric layer performance [8, 9] and that the road wheel core could be reused, the problem could be framed in cost-effectiveness terms, which for the purposes of this paper determined as Life Cycle Cost (LCC) and Life Cycle Cost per Pound Saved (LCCPS). The LCC of each alternative will be estimated as the overall cost associated with procuring, and reusing the road wheels. Although a complete LCC should include revenues of scraped road wheel cores, this aspect will not be addressed in this paper, given the volatility of market prices. The LCCPS is defined in (1) below.

$$LCCPS_{Ti} = \frac{LCC_{Al} - LCC_{Ti}}{Weight_{Al} - Weight_{Ti}} \qquad (1)$$

3. ANALYSIS

In lieu of elastomeric materials significantly outperforming the existing ones and given that the cost and weight of elastomerization are approximately 15% and 21%, respectively, of the legacy M1 road wheel (see section 3.4.), a reasonable approach would be seeking an alternative that extends core life cycle, reduces overall weight, and eases wear even at higher-than-nominal OPTEMPO. Consequently, this section would address the analytic, numerical, and economical aspects of the problem.

3.1. Theoretical Analysis

Given that the metal fatigue characteristics of Titanium (reference alloy Ti-6AI-4V) are approximately 200% and 300% higher than Steel (reference alloyA656 GR HSLAS) and Aluminum (reference alloy T6 2014), respectively (see Table 1). Given that these estimated results are congruent with empirical testing results [15, 16], Titanium road wheel cores demonstrate a valid potential for improved lifecycle.

Alloy (Density) [Reference]	**Ultimate Tensile Strength** S_U	**Estimated Endurance Limit** S'_n	**Estimator (Condition) [Reference]**
Aluminum T6 2014 (2.8 g/cc) [12]	483 MPa	193 MPa	$S'_n = 0.4\ S_U$ (for $S_U < 331$ MPa; $n \approx 10^8$) [10, 11]
Steel ASTM A656 GR80 HSLAS (7.8 g/cc) [13]	620 MPa	310 MPa	$S'_n = 0.5\ S_U$ (for $S_U <$ 1,400 MPa; $n \approx 10^6$) [10, 11]
Titanium Ti-6Al-4V STA (4.43 g/cc) [14]	1,170 MPa	585 MPa	$S'_n = 0.5\ S_U$ ($n \approx 10^6$) [10, 11]

Table 1: Estimated endurance limits of pertinent Aluminum, Steel, and Titanium alloys.

3.2. Numeric Analysis and Simulation

In order to validate its design, Tamor conducted a computerized static load strength analysis and simulation on a Merkava Mk4 road wheel use case (see Figure 1) using a static load of 40,000 N (4,078 kgf).

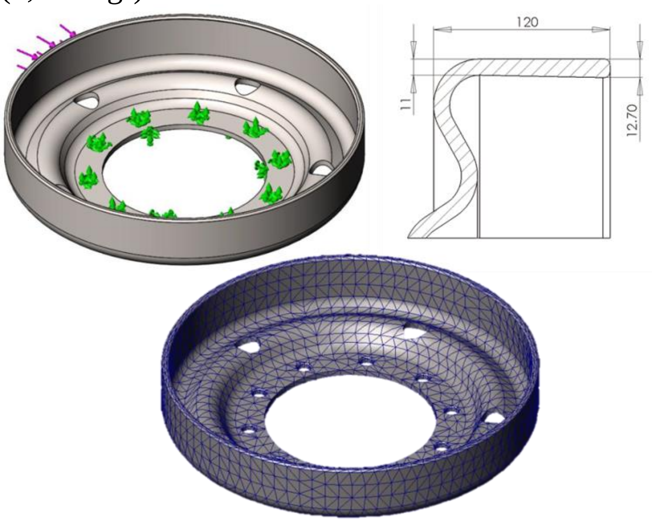

Figure 1: Model Information (Mass: 26.7118 kg, Volume: 0.00603141 m^3, Density: 4428.78 kg/m^3, Weight: 261.776 N, Name: Ti-6Al-4VSolution treated and aged (SS), Model type: Linear Elastic Isotropic, Yield strength: $8.27x10^8$ N/m^2, Tensile strength: $1.05x10^9$ N/m^2); source: Tamor SMR Ltd. (Solidworks Simulation software).

Given that the nominal static load on each M1A2 is approximately 2,454 kgf and that reported road wheel load tests [8] did not surpass 3,756 kgf, this measure seems plausible.

The analysis was performed using Solidworks Simulation software; all bodies were treated as solid bodies and modeled using the linear elastic isotropic model type with the appropriate volumetric (mass 26.71 kg, volume $6.03 \cdot 10^3$ m^3, density 4,428.78 kg/m^3, weight 261.78 N) and material (type Ti-6Al-4V SS, yield strength $8.27 \cdot 10^8$ N/m^2, tensile strength $1.05 \cdot 10^9$ N/m^2).

Following the analysis and simulation, the resulting stress (model type: von Mises (VON)) ranged from 121.83 to $2.3 \cdot 10^8$ N/m^2 (see Figure 1), and the resulting deformation (model type: Resultant Displacement (URES)) ranged from 0 to 3.49 mm (see Figure 2).

The results demonstrated a substantially comfortable safety factor (Max von Mises Stress) of 359.6%, which is more than sufficient for the M-1 Abrams application and may lead to reduced weight and cost.

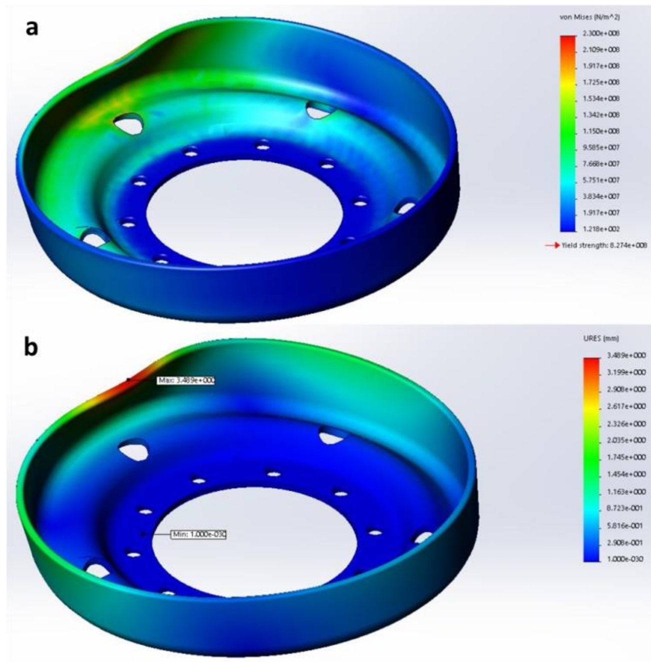

Figure 2: Stress (a) and Displacement (b) Simulations; source: Tamor SMR Ltd. (Solidworks Simulation software).

3.3. Empirical Test and Evaluation

In order to substantiate its analyses and recommendations, Tamor conducted an empirical friction wear field test evaluation of one pair of 6mm-thick Titanium support rollers, which replaced two regular support rollers on a Merkava Mk4 tank (see Figure 3). The base material used in this evaluation was Grade 38 Titanium alloy, which performs similarly to Ti-6Al-4V and demonstrates better drawing characteristics.

The evaluation spanned 3000 mi on Golan Heights (mostly tuffic clay soil and basalt rocks) and Mediterranean coast (mostly quartz sand with some sandstones and bioclasts) tracks and resulted with 0.2-0.3 mm wear (see Figure 3). Consequent to the tests, Tamor has established for Titanium wheels an expected life cycle of at least 8,000 mi.

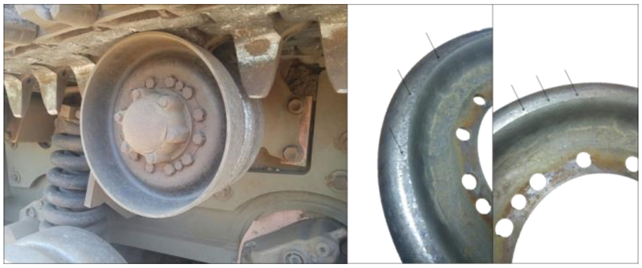

Figure 3: Merkava Mk4 Titanium track support wheel without wear ring showing less than 0.3 mm wear following a 3,000 mi field evaluation; source: Tamor SMR Ltd.

3.4. Economic Analysis

To complete the comparative cost-effectiveness review of the legacy and Titanium M-1 road wheel alternatives, this section provides an estimate of the following parameters for each alternative: Estimated life cycle in miles, estimated procurement cost, estimated life cycle cost normalized to 8,000 mi, and estimated weight (see Table 2).

Item	Est. Life Cycle (mi)	Est. Proc. Cost	Est. LCC (a)	Est. Weight (lbs.)
Legacy M-1 Road wheel				
Aluminum Core	2,000	$730.00	$2,920.00	61.7
Steel wear plate	1,000	$150.00	$1,200.00	19.8
Rubber	1,000	$150.00	$1,200.00	22.0
Total		**$1,030.00**	**$5,320.00**	**103.6**
Titanium M-1 Road wheel				
Titanium Core	8,000	$2,700.00	$2,700.00	61.7
Rubber	1,000	$150.00	$1,200.00	22.0
Total		**2,850.00**	**$3,900.00**	**83.8**

Table 2: Economical factors associated with the procurement and life cycle costs of legacy and Titanium M-1 road wheels. Note: (a) Per 8000 mi; incl. shipping; excl. scrap core revenue.

Based on the estimates in Table 2, the Titanium M-1 Road wheel LCC ($3,900.00) is 73% of the Legacy M-1 Road wheel LCC ($5,320.00) and the LCCPS of the Titanium Road wheel, per each replaced Legacy Road wheel, is $71.72. At the M-1 platform level, the overall replacement translates into $39,760.00 ownership savings over 8,000 mi and reduction of 555.6 lbs. from the overall platform weight.

While this weight reduction amounts to approximately 0.38-0.41% of the overall platform weight, its side effect on the platform's fuel consumption, using prorated values from [18], would amount to 0.31-0.33%. See table 3. This effect would only increase in next generation vehicles that are envisioned to be lighter than their legacy counterparts.

Platform	Weight Saving	Fuel Saving
M1A2 SEPv1	0.40%	0.32%
M1A2 SEPv2	0.39%	0.31%
M1A2 SEPv3	0.38%	0.31%

Table 3: Impact of weight saving on fuel economy; based on proration of the results obtained by Hart and Gerth [18].

In addition to the fuel savings, there are other economic secondary side-effects associated with the reduction in the platform's weight, such as improved mobility, operational range, reduced logistic support, and better transportability. While not addressed in this paper, more detailed analysis is warranted.

Another perspective of this economic analysis is the availability of other emerging alternatives to the legacy road wheels. These alternatives, such as the meso-phase pitch carbon fiber technology [19], seem promising, but the commercial experience thus far shows that their application in the automobile industry is limited due to their high relative cost (x10 higher than traditional rims) compared to their benefits in platform weight savings (0.31-0.36% of the platform weight), and performance improvement (reduced rotational inertia, better damping of high-frequency vibrations, better stiffness and overall strength) [20-21]. See also Table 4.

Platform	Wheel set Relative Cost	Wheel set relative weight	Weight Saving
Fiber-Carbon Wheel Set			
Koenigsegg Agera R	2.00%	1.45%	0.36%
Porsche 911 Turbo S	5.79%	1.04%	0.26%
Ferrari 488 Pista	4.29%	1.63%	0.41%
Ford Shelby GT350R	21.43%	1.22%	0.31%
M1A2 SEPv3	Unknown	Unknown	Unknown
Titanium Road Wheel Set			
M1A2 SEPv3	0.89%	1.61%	0.40%

Table 4: Economical factors associated with the commercial use of Carbon-Fiber wheels in automobiles [21] and Titanium road wheels in the M-1.

Due to the fact that combat vehicles are required to operate in more extreme environments, but at lower speeds, the potential Fiber-Carbon technology's benefits in the military domain may have a diminished return on the investment, compared to the commercial domain, hence require improved cost-effectiveness and assured operational suitability. This situation may pose a risk in the potential application of Matrix Composite road wheels in next generation vehicles, which could be mitigated by developing the Titanium road wheel alternative.

4. RECOMMENDATIONS

The analysis in the previous section suggested cost-effectiveness improvement and risk-reduction incentives to consider replacing the legacy Aluminum core road wheels with a Titanium alternative, specifically as this point in time that features a substantial hectic Research and Development activity in future combat platforms. Consequently, we recommend taking the following actions:

- Conduct a 2100 mi, or longer, comparative evaluation study of standard against Titanium M1 Abrams road wheels to establish an agreeable performance baseline Include Titanium road wheels in the MPF, MPF, OMFV, DLP/FDL, and RCV (H) EMD tests
- Conduct a detailed independent life cycle cost estimate [17] and acquisition strategy covering the production, operations and support, and recycling phases of a potential acquisition program for Titanium road wheels and support rollers for the M-1/M-88, M-109, AMPV, MPF, OMFV, DLP/FDL, and RCV (H) platforms
- Conduct operational analysis to assess the derivative improvement of operational effectiveness as a result of improved mobility, availability, transportability, range, and fuel economy on the M-1/M-88, M-109, AMPV, MPF, OMFV, DLP/FDL, and RCV (H) platforms
- Consider the Titanium road wheels as a complementary risk mitigation option for emerging Matrix Composite technologies in next generation platforms

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