Advanced Materials & Manufacturing (AMM)

SUPERIOR BALLISTIC AND BLAST RESISTANCE IN ATI TITAN 27™ ALLOY WITH A NOVEL DEFORMATION MECHANISM

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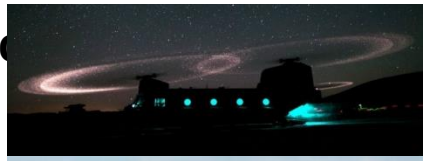
Ti-64 the Legacy in Armor and Aerospace

Advanced Materials & Manufacturing (AMM)

Legacy Alloy Ti 6Al-4V is the most common aerospac

- Used as ballistic applique armor in ground vehicles,
- Extensively in aerospace and defense air systems as a
- Typical yield strength of 130 ksi in mill-annealed conditic
- Limited cold formability, which prevents cold rolled or for



ATI 425® Alloy (Ti-425) is a comparable strength titanium alloy used in plate and sheet due to its cold workability and similar ballistic performance to Ti-6Al-4V

ATI has developed a new alloy, ATI Titan 27™ Alloy (Ti-27):

- Assessed two formulations to date, shown within:
  - One performing better than Ti-6Al-4V at FSP
  - One performing better than Ti-6Al-4V at APS
- Processability, cost and density similar to Ti 6Al-4V
- Typical yield strength of 140-160 ksi in mill-annealed condition

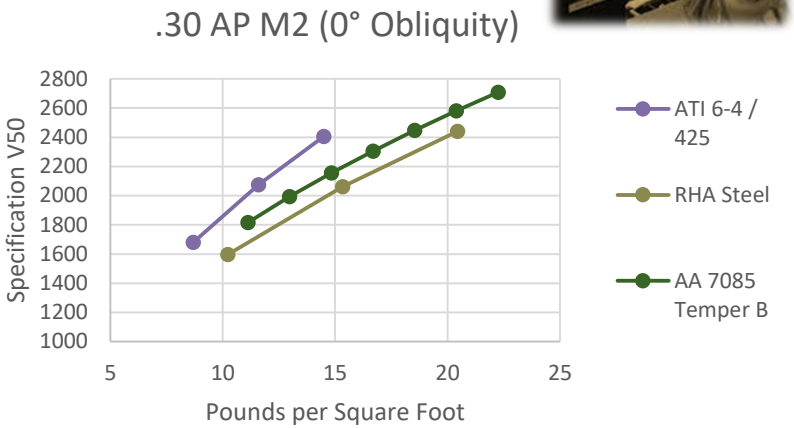
In this presentation we will explore the mechanisms of the cold workability relating to the ballistic performance

Titanium Armor in Use Today

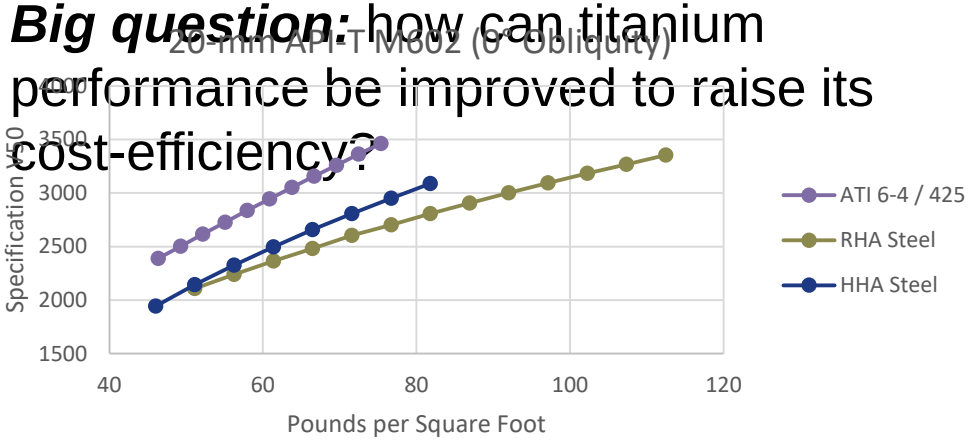
- Commercially used for armor, forgings, hatch covers, and rings
  - Lower cost flow path compared to Aerospace grade titanium
  - Able to be exported from US
- 20-40% weight savings over steel depending on threat and applic
- Thick p to

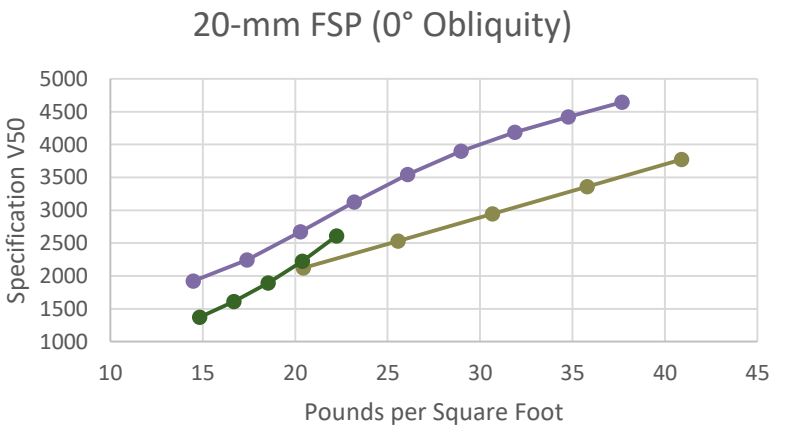
Titanium Cuts Weight vs Steel or Aluminum

- Titanium offers weight efficiency vs steel and aluminum
- Aluminum solutions require 3-5x thickness of titanium for the same protection



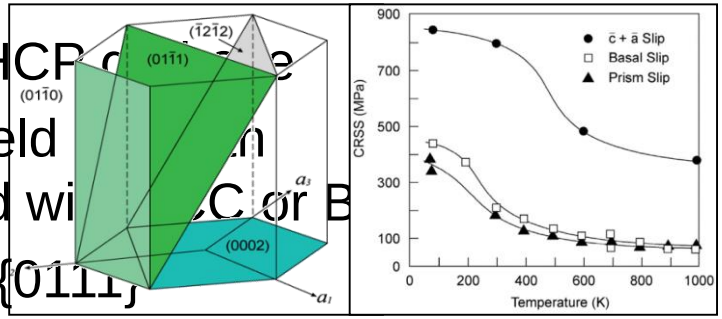
- ***Big question:*** how can titanium performance be improved to raise its cost-efficiency?





Crystallographic Differences Ti vs Steel

- Ti-6Al-4V, Ti-425 and Ti-27 contain ~80-95% HCP α-phase
- HCP metals like titanium exhibit anisotropic yield behavior and have relatively few slip systems compared with FCC or BCC
  - <a> type dislocations on {0001}, {0110}, & {0111}
  - <c+a> type on {01$\bar{1}$0}, {01$\bar{1}$1} and {12$\bar{1}$2}
  - 3 twinning systems: {10$\bar{1}$2}, {1121}, {1122}
- Oxygen is known to reduce cross-slip within α-phase, and therefore typically reduces ductility



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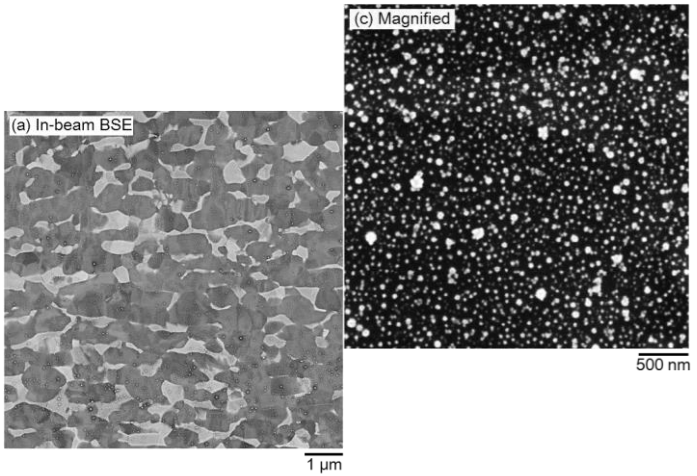
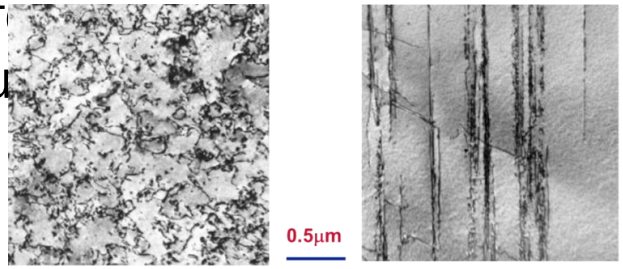
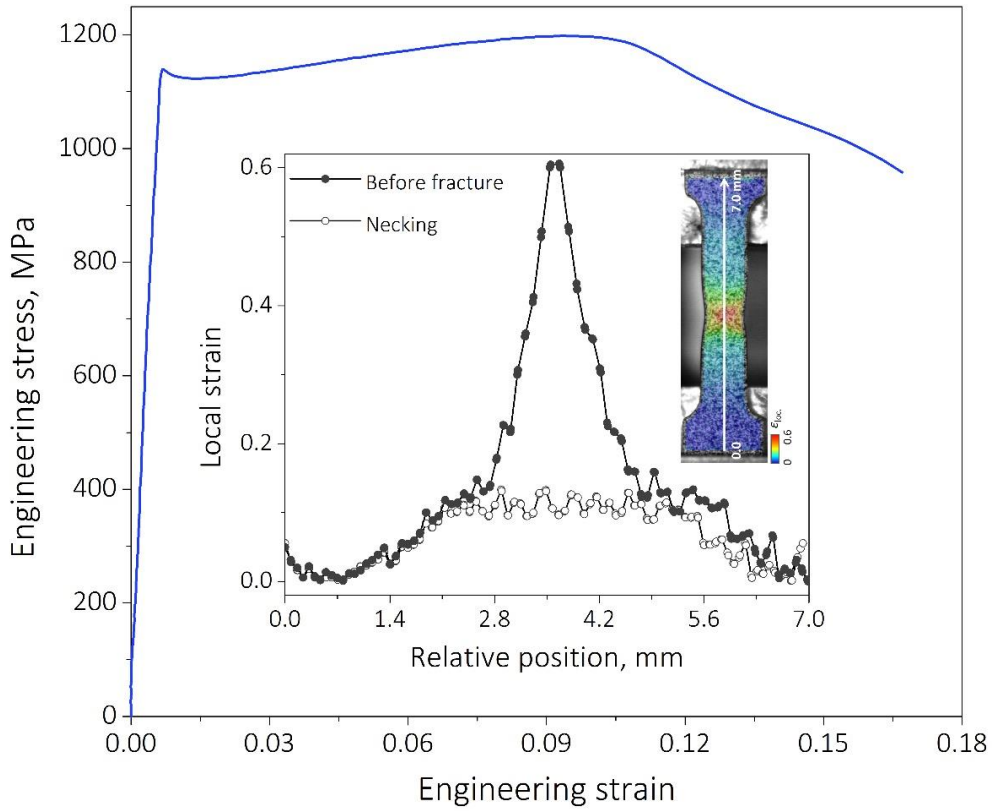
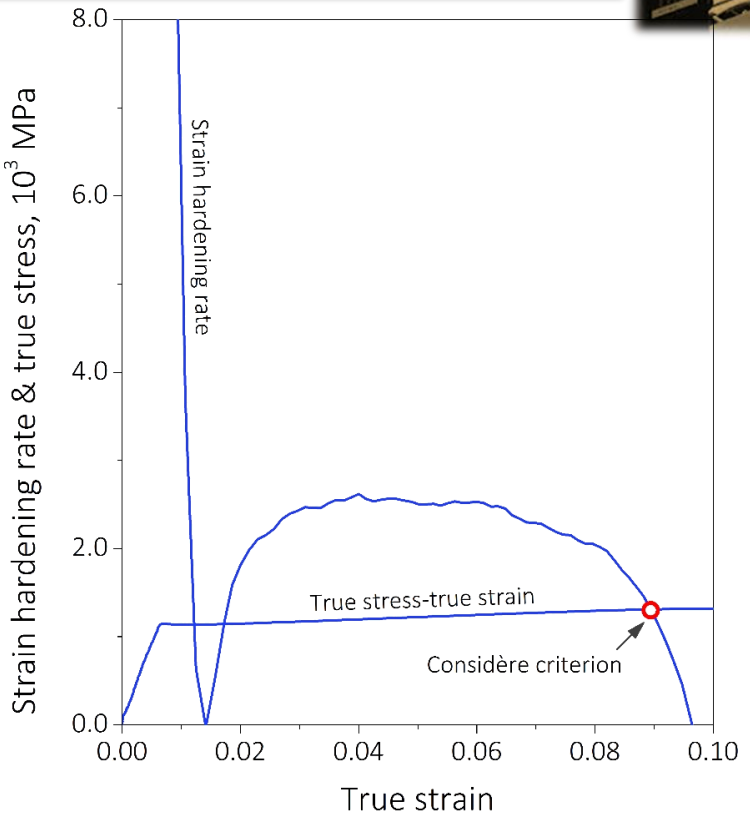




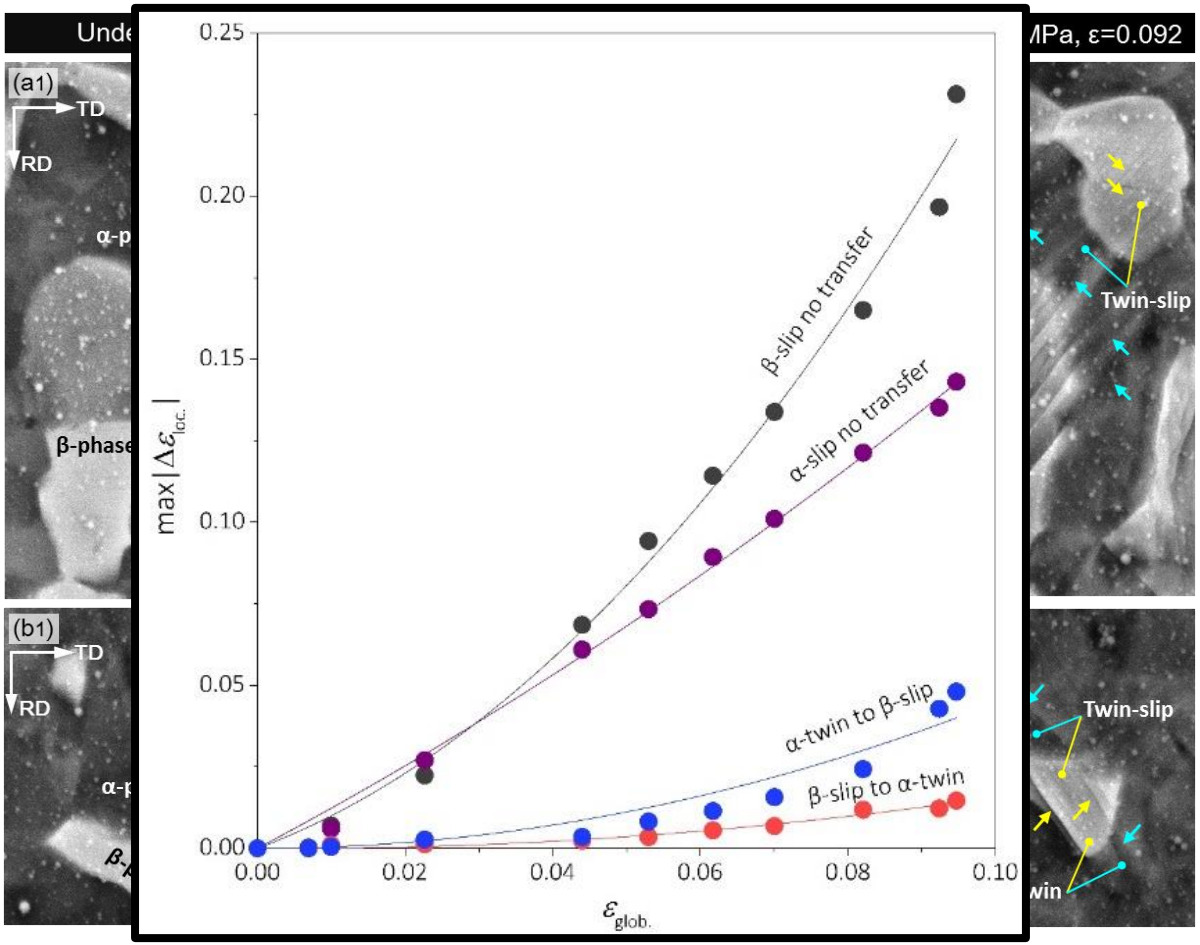
Work Hardening More Like Steel





- What are the operative deformation modules during stable plastic flow?
- What mechanisms contribute to the promising transverse mechanical elongation?

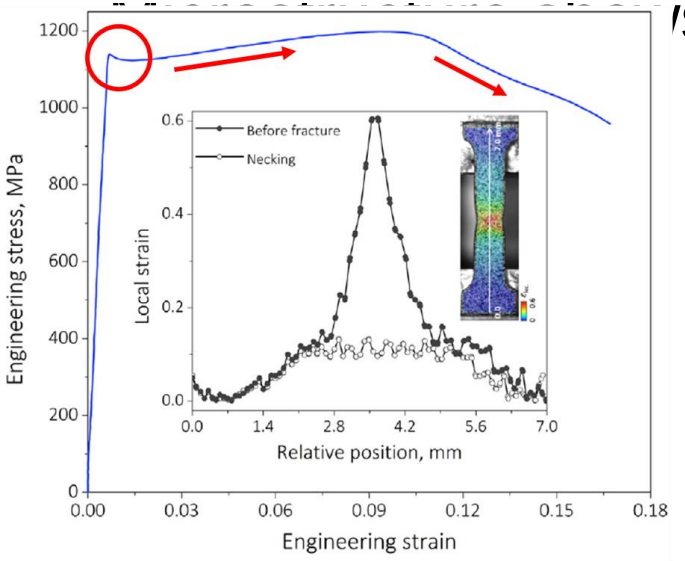
Novel Damage Tolerance Mechanism

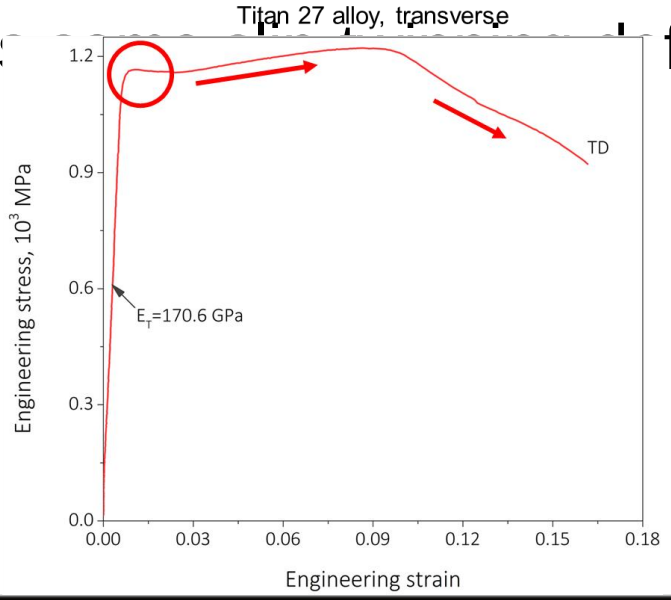


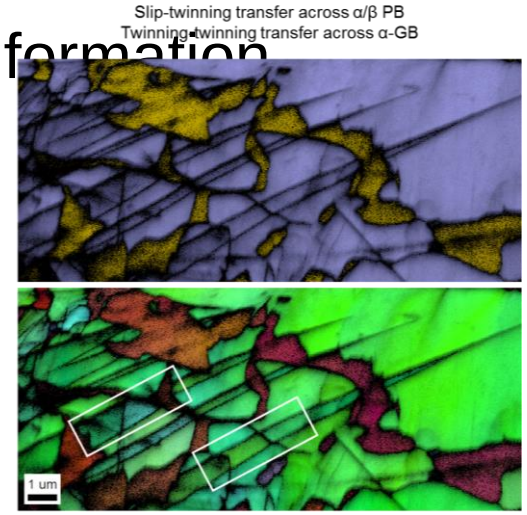
- Upper images: Slip initiated by twinning applying stress to α/β boundaries
- Lower images: Twinning initiated in α grains by slip in β
- Twinning observed in α phase of ATI 425® Alloy with transverse direction in tension
  - Homogenizes the local strain
  - Rotates the twinned material into a soft direction

Deformation Mechanism in Ti-27

- Mechanisms and mechanical behavior are similar in Ti-27 as Ti-425
- Transverse (stronger) direction shows yield drop, then extended work hardening



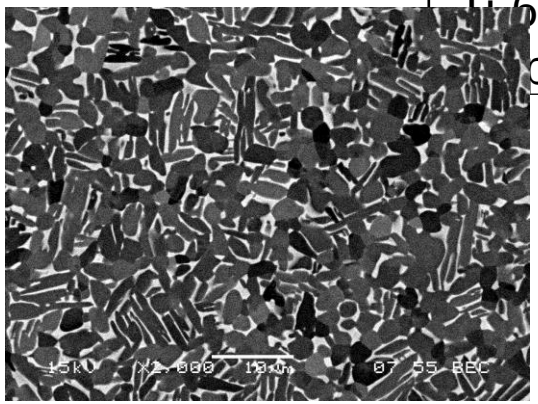




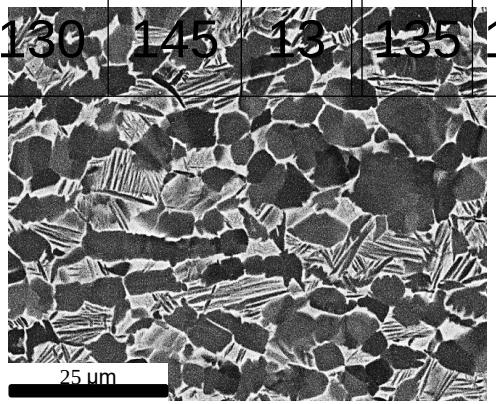
Ti-27 and Ti-425 are Similar Strength

Alloy	YS, L (ksi)	UTS , L (ksi)	Elong., L (%)	YS, T (ksi)	UTS, T (ksi)	Elong., T (%)
Ti-27	144	159	13	154	168	14
Ti-27 DT	128	146	14	138	153	15
Ti-425 Typ	123	142	15	137	152	15
Ti-64 [illegible]o	130	145	13	135	149	

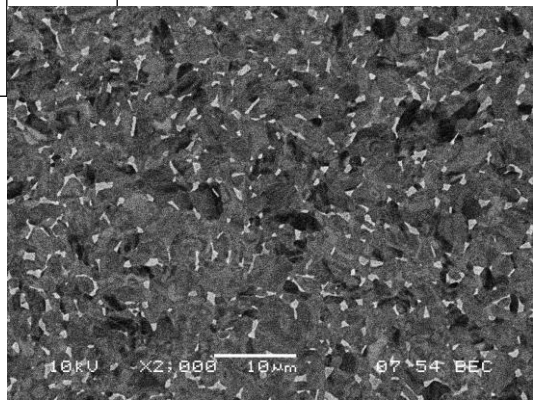
Ti-425 Mill



Ti-27 Mill Anneal



Ti-64 Mill Anneal



Superior Ballistic Results to Legacy Ti-64

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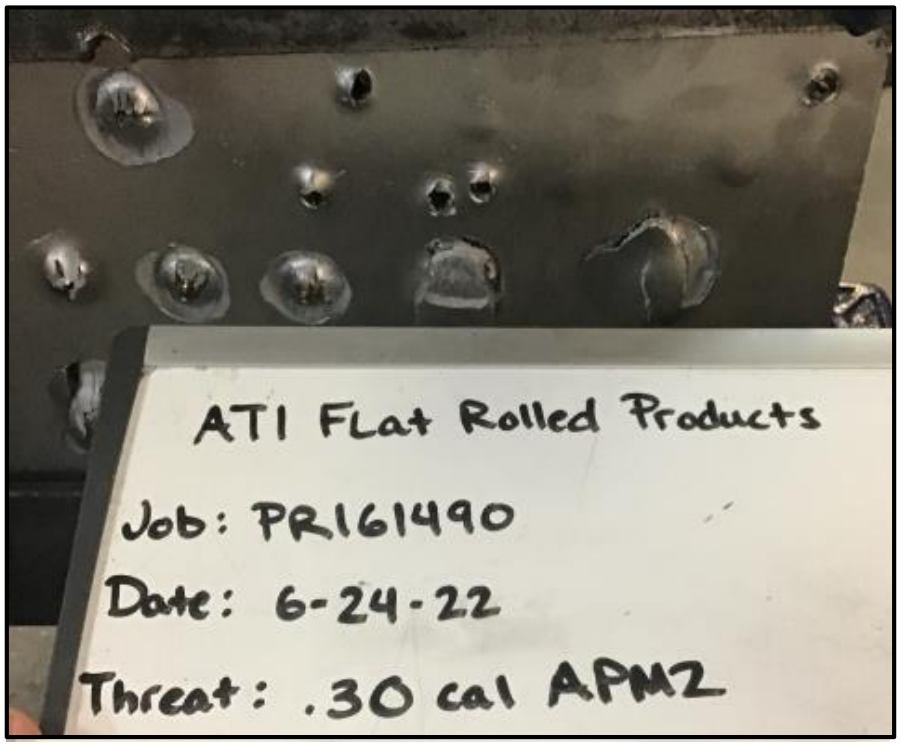
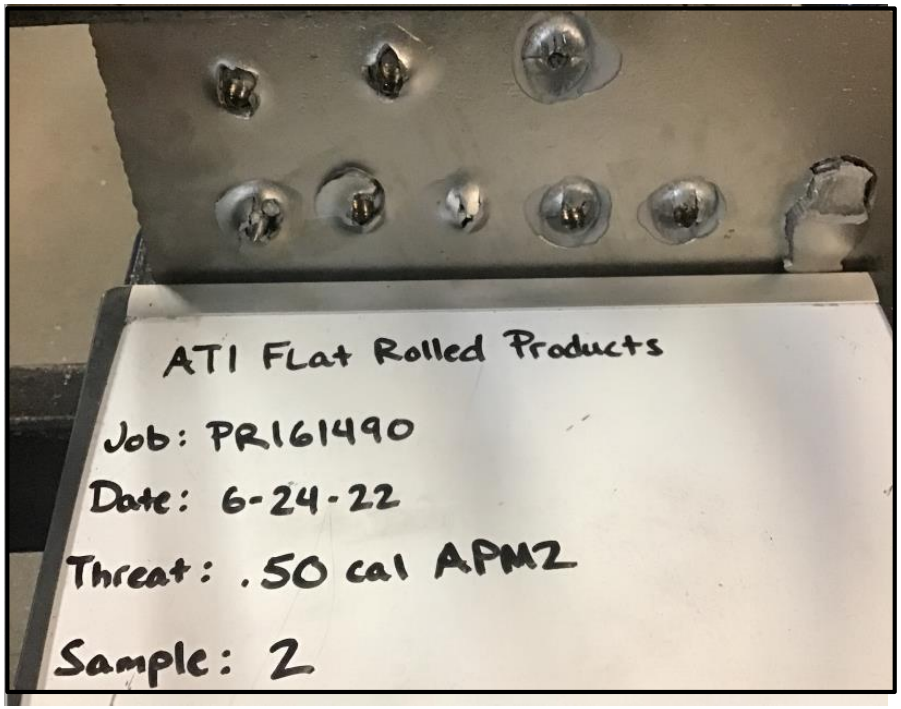
Alloy	20mm FSP V50	20mm FSP Required	20mm FSP Above Req'd V50	0.50 APM2 V50	0.30 APM2 V50	E_m 20mm FSP/ 0.50 APM2
Ti-27	3282	3340	**(58)**	2455	3698	1.26 / 1.37
Ti-27 DT	3351	3138	**213**	2356	3396	1.31 / 1.31
	3447*	3300	**147***	2369	3372	1.34 / 1.30
	3496	3288	**208**	2360	3381	1.36 / 1.30
Ti-425 Typ			**114**			
Ti-64 Typ			**120**			

- E_m describes the normalized weight per ft^2 per threat compared with RHA steel
- Nominally 1" thick plate tested at NTL Chesapeake
  - Average of 6+ shots to determine V50
- Ti-27DT outperforms Ti-425 and Ti-64 in 20mm FSP threats
- Ti-27 outperforms Ti-27DT at 0.50 and 0.30 cal APM2 threats
  - No specific requirement for Ti-425

Ballistic Impacts – High Strength T27

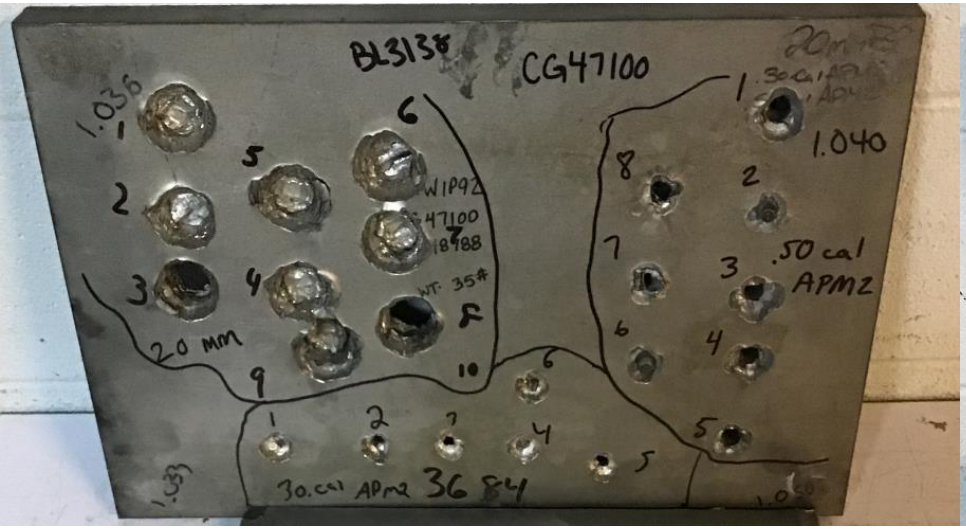




- 0.30 cal 166 grain APM2 V_{50} of 3698 ft/s
- 0.50 cal 695 grain APM2 V_{50} of 2455 ft/s

- 0.50 cal captured rounds and failed by backspallation
- 0.30 cal observed complete and partial penetration

Ballistic Impacts – Damage Tolerant T27



- Top, outer impacts: 20 mm 830-grain FSP
- Top, inner impacts: 0.50 cal 695-grain APM2
- Bottom impacts: 0.30 cal 166-grain APM2

Ballistic Impacts – Ti-425

- 20mm, 830-grain FSP
- Failure occurs by bulging, back spallation, and finally penetration

Conclusions

- Titanium buys its way onto ground vehicles with its similar ballistic protection to steels for a substantial weight savings
  - Millions of pounds produced each year for armor
- The slip-twinning mechanism observed in Ti-425 and Ti-27 enable a better compromise between strength and ductility
  - An *impactful* tradeoff for AP vs FSP threats
- The damage tolerance mechanism may lend itself to other improvements in blast and non-ballistic regimes
  - Cold working and sub-ballistic deformation rates

Questions?

Thank you!

Please see my other talk on another new titanium alloy for structure & AM!

- Ground systems
  - Vehicle armor and structures – titanium
  - Vehicle suspensions – titanium and specialty steels
  - Gun system components – titanium and specialty steels
  - Projectiles and projectile components – refractory alloys and specialty steels
- Maritime
  - Nuclear reactor components – zirconium, hafnium, and nickel
  - Maritime pumps and valves – titanium and nickel alloys
  - Naval decking and superstructures – nickel, titanium, and stainless steels
  - Torpedo and missile launch tubes – specialty steels
- Aero engine, airframe, and vertical lift
  - Aero engine components – nickel and cobalt superalloys and titanium
  - Aero structures – refractory alloys, nickel, titanium, and specialty steels
  - Landing gear and rotorcraft shafts, forgings, and sheet - titanium & specialty steels
- Missiles, UAVs, launch vehicles, and space
  - [illegible] refractory alloys and specialty steels
  - [illegible] hafnium, niobium, and titanium alloys