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Wiebull Analysis of Variability in Dynamic HEL and Spall Properties of Tantalum

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Objective: Measure variability of Ta response

Confirmation of continuum properties:
- Loading and unloading curves
- HEL
- Hugoniot
- Hysteresis

Variability in strength properties:
- Spall strength
- HEL

The present discussion

Attenuation measurements

Effects of edge releases

• Ta samples supplied by AFRL were thermomechanically processed from rods supplied by H. C. Starck Inc.

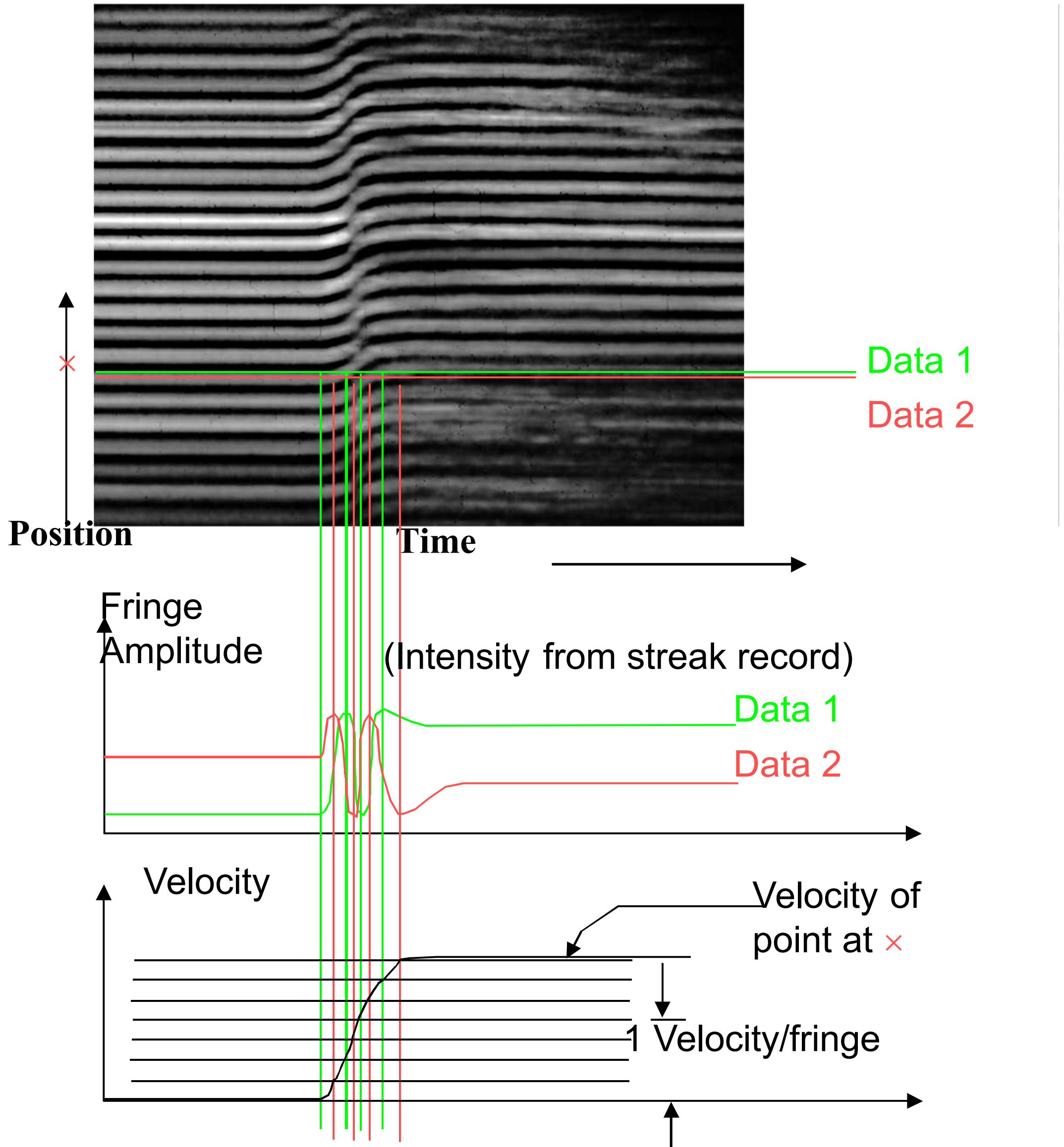
  ➔ Uniform refined grain structure

  ➔ Grain size ~20 microns

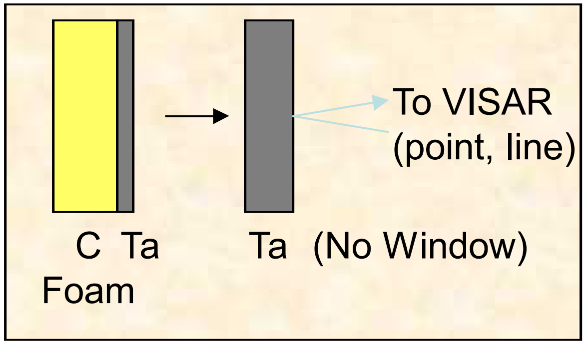
  ➔ Strong axisymmetric [111] crystallographic texture

- Ta samples supplied by LANL were equiaxed; grain size ~ 20 μm
- COTS Ta samples were not analyzed for microstructure.

The line-imaging VISAR provides spatially-resolved velocity histories

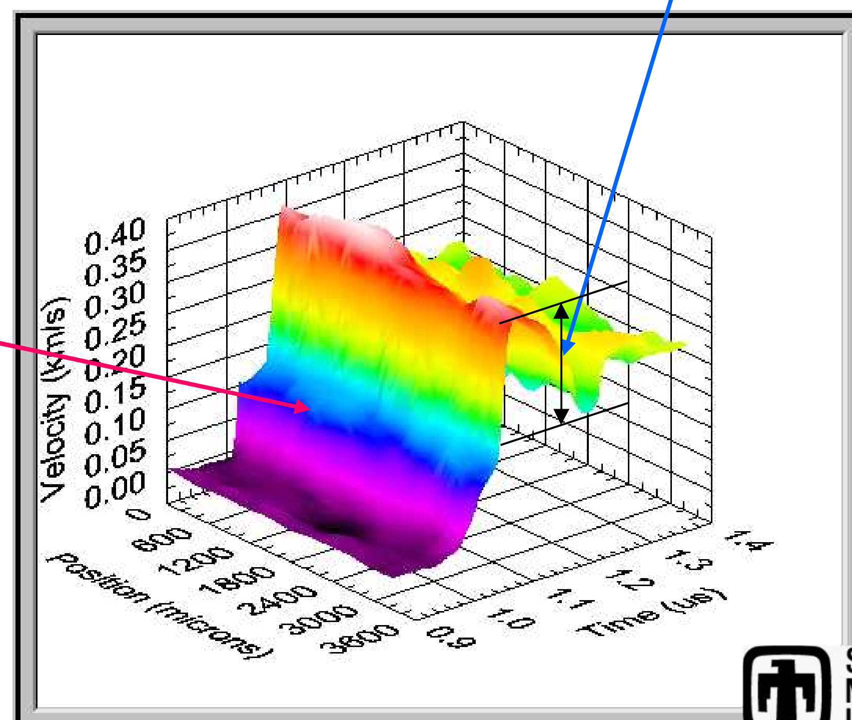


Tantalum is a mesoscopically heterogeneous material, with heterogeneous yield behavior

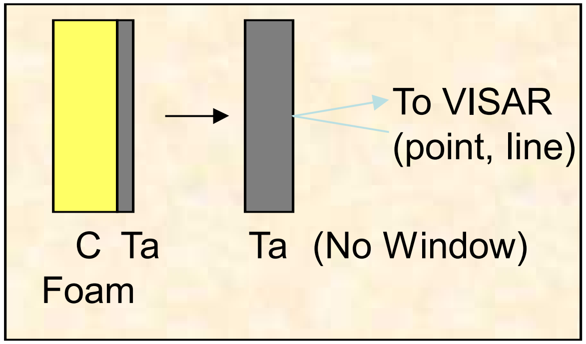


Spall strength calculated from pullback

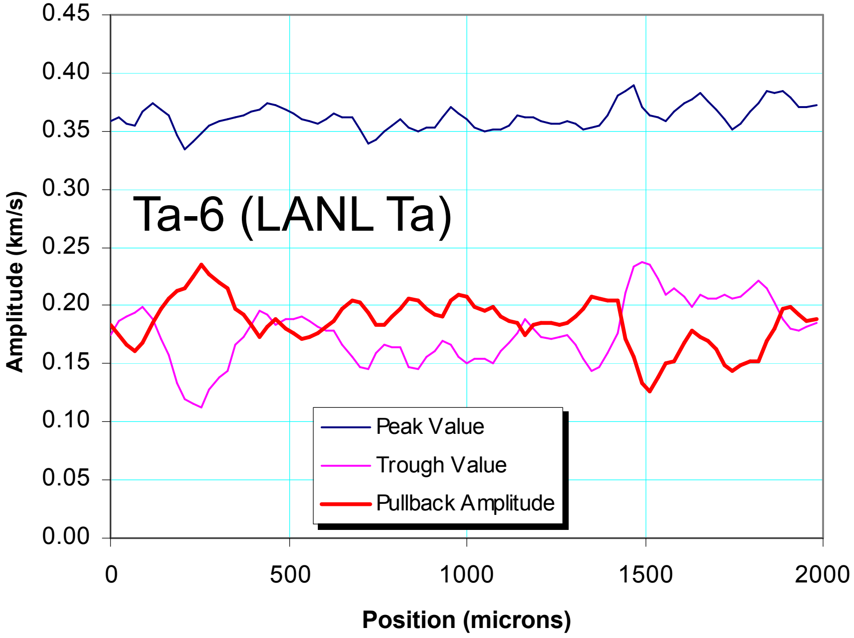
HEL strength calculated from elastic wave amplitude

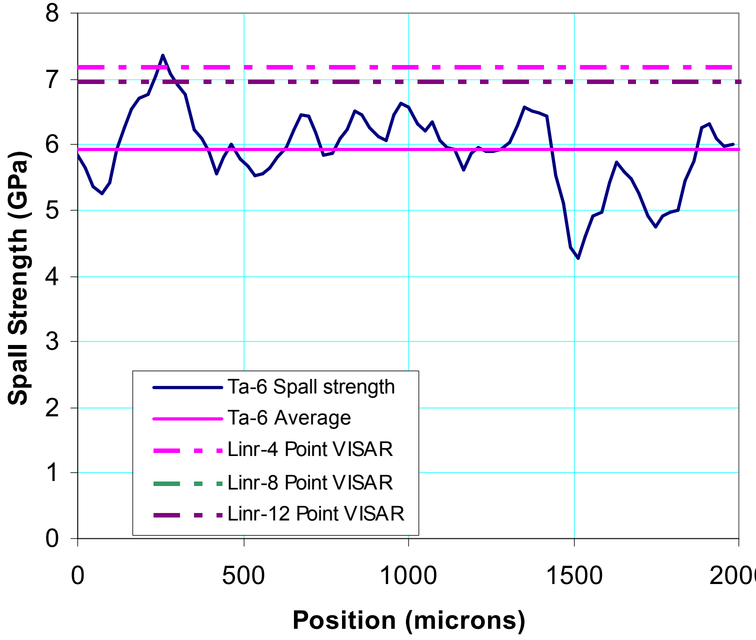


Spall strengths vary from shot to shot and from point to point



Spall strength = $0.5*\text{Pullback}*\rho_0*C_0 + h/2*(dp/dt)*(1/C_b-1/C_l)$





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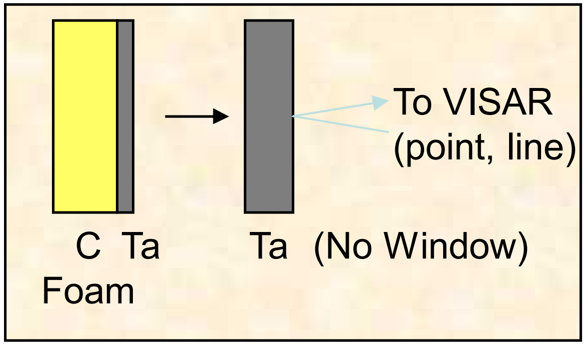
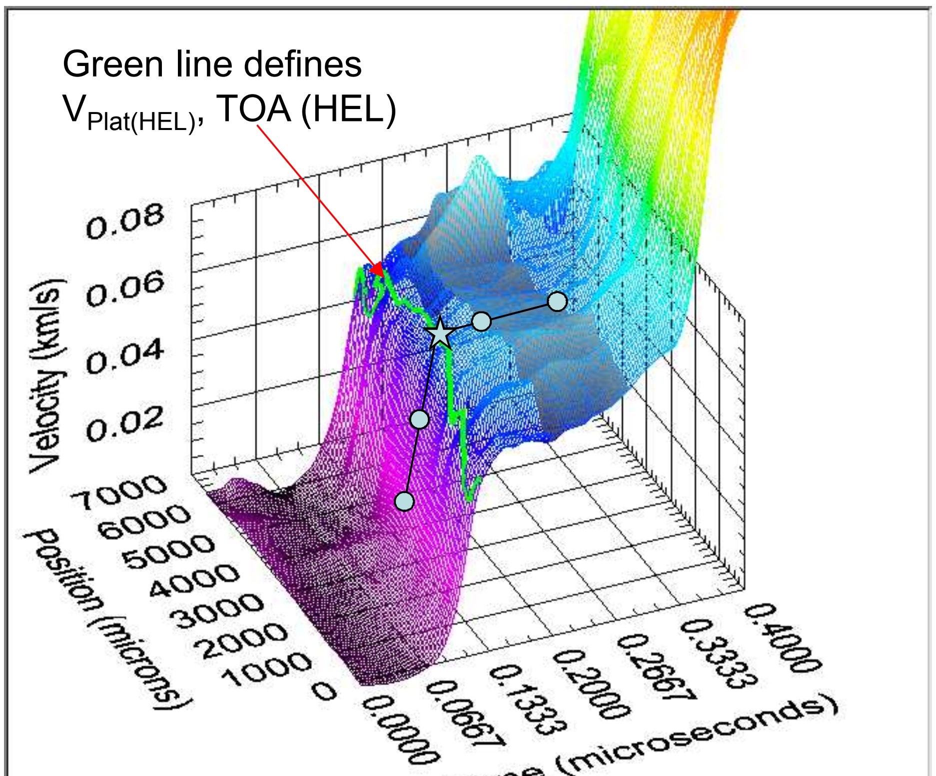
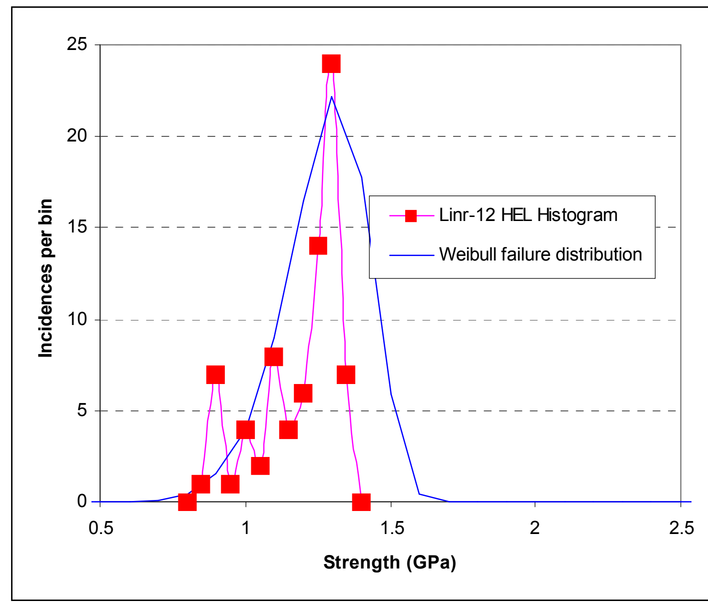
HEL levels vary from shot to shot and from point to point as well



Strength at HEL $= \sigma_{HEL} * (1-2\nu)/(1-\nu)$
$= (1/2) * V_{Plat(HEL)} * U_{S(HEL)} * (1-2\nu)/(1-\nu)$





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A useful way to express failure properties is via Weibull statistics

The probability of failure at or below a given stress $P(\sigma)$ is:

$$P(\sigma) = 1 - \exp[-(\sigma/\alpha)^{\beta}]$$

Here, α is a scale parameter (dimensions of stress) and β is the Weibull modulus. <u>Larger β means a narrower range of σ over which yield occurs.</u>

Convention:

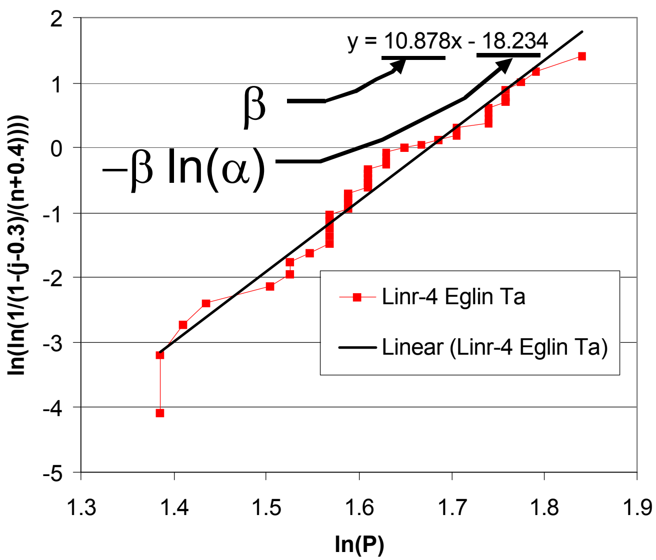
α is often referred to as σ_0; β as m

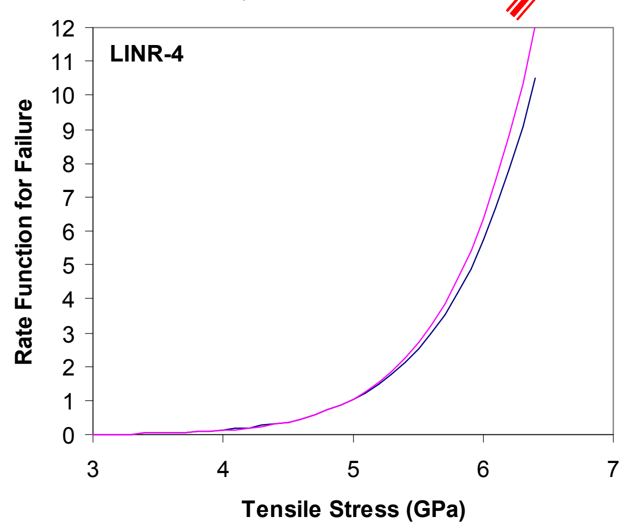
For a set of *n* samples (ordered from first-to-fail to last), the *j*th result is assigned a cumulative probability of failure P_j. A common estimator is:

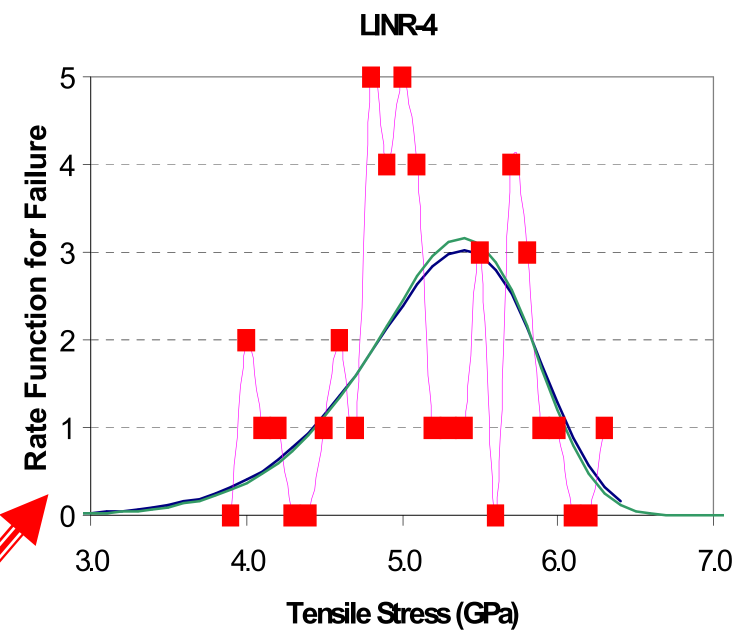
$$P_j = j / (n + 1)$$

(although there are others)

Weibull statistics parameterize the failure histogram of a sample







(spall strength here appears low)

The rate function is what fraction of the unfailed points will be expected to fail over the next 1 GPa stress increment.

α = 5.35 (~ centroid)

β= 10.88 ($\propto$ 1/spread)

$P(\sigma) = 1 - \exp[-(\sigma/\alpha)^{\beta}]$

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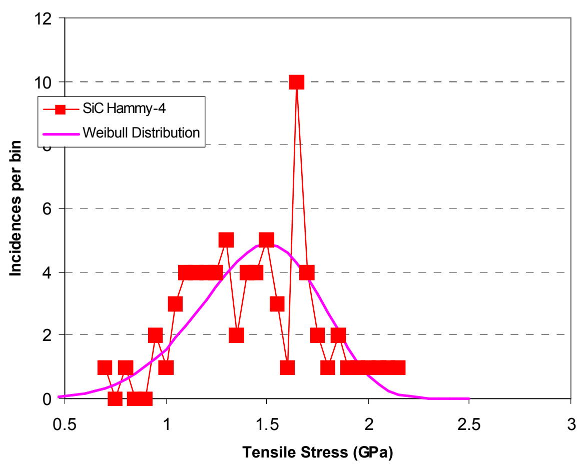
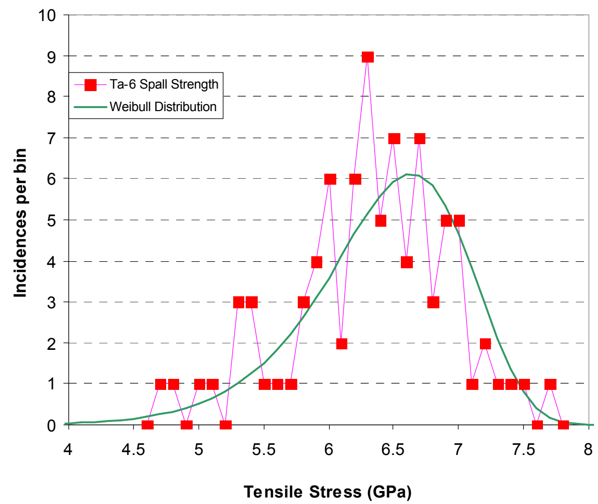
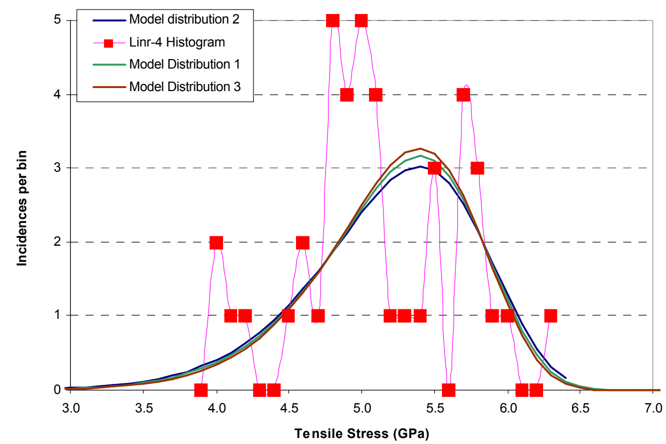
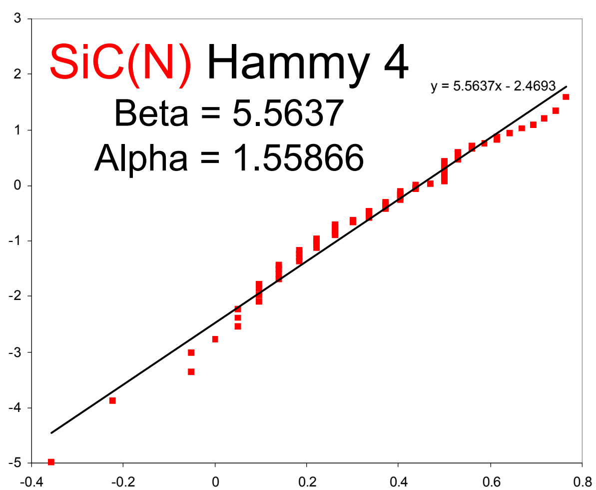
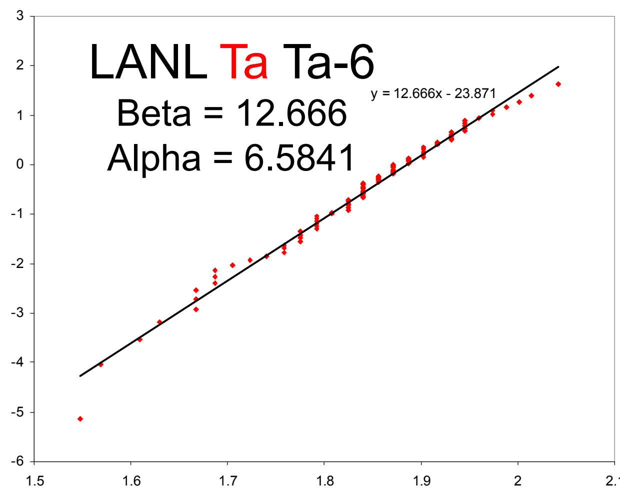
Spall strength distributions vary according to material, stress level, waveform, and possibly other factors

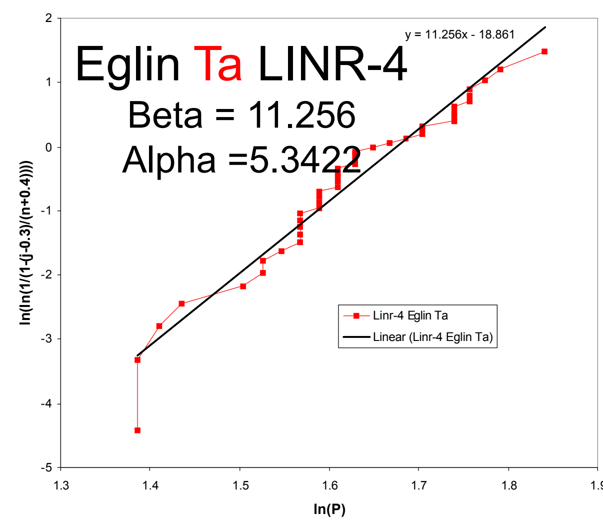












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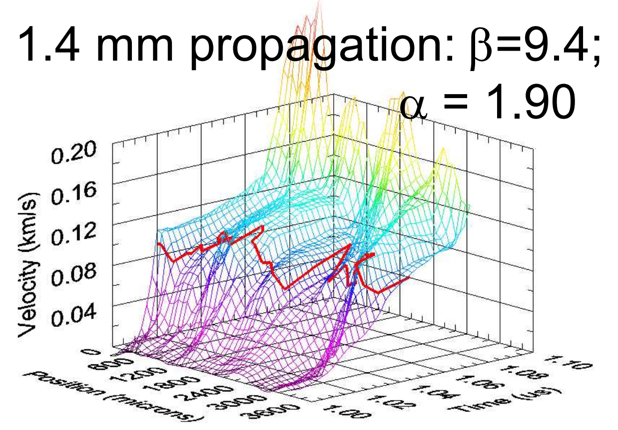
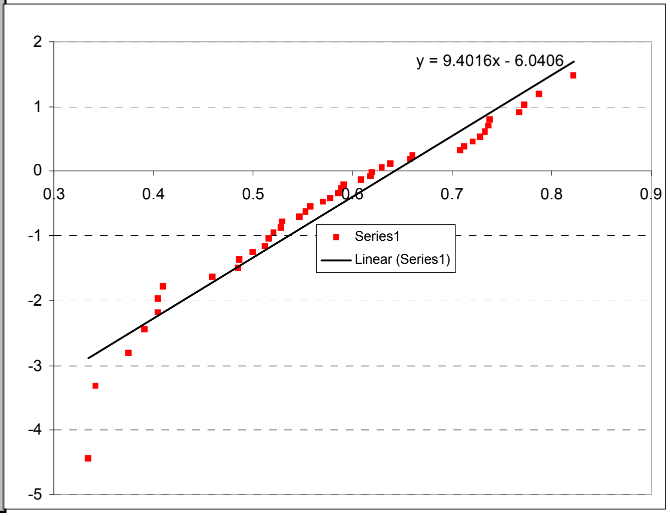
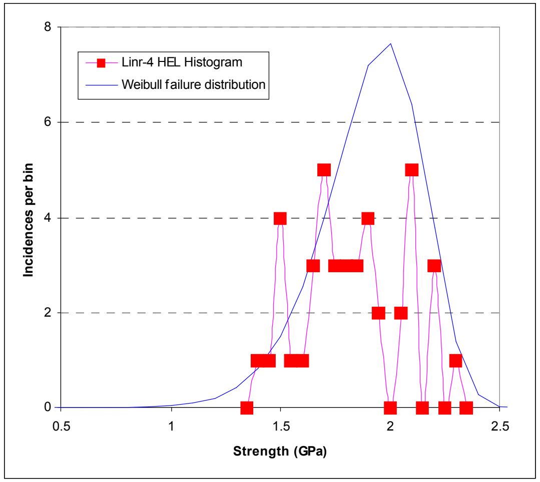
HEL strength distributions vary according to material, travel distance, and possibly other factors

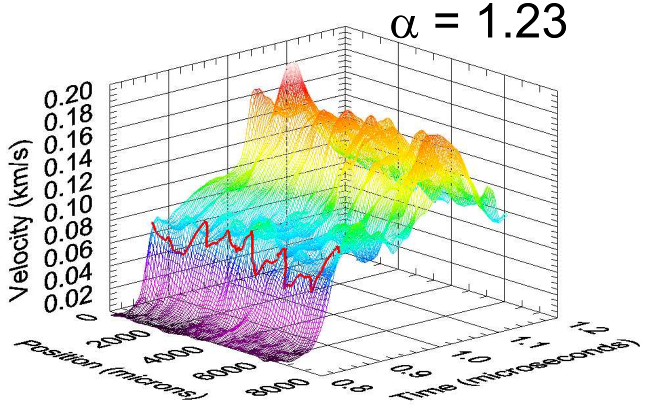
1.4 mm propagation: β=9.4; α = 1.90

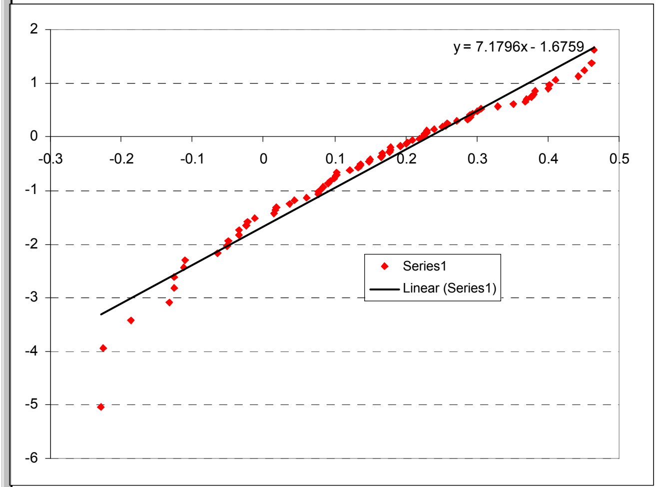


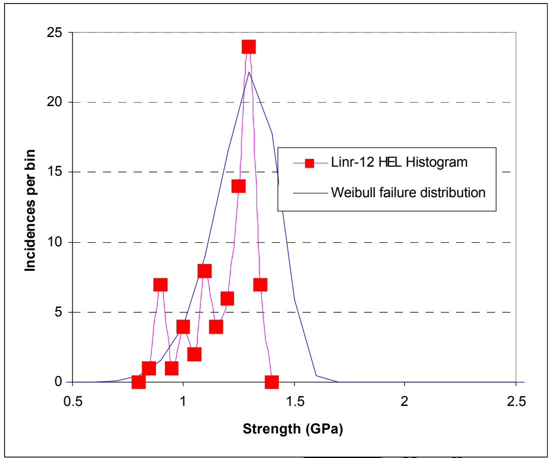




4.5 mm propagation: β=9.54; α = 1.23







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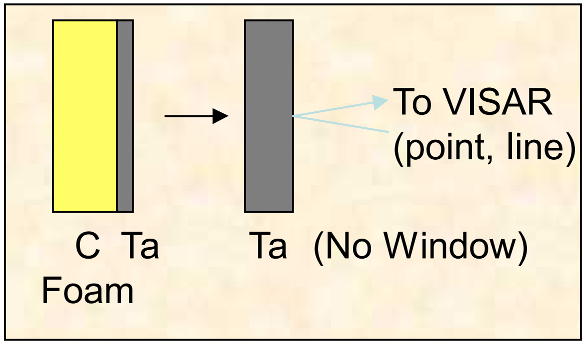
Three types of experiments were conducted with line VISAR to elucidate spatially variability in Ta response

1. Spall (3 shots)

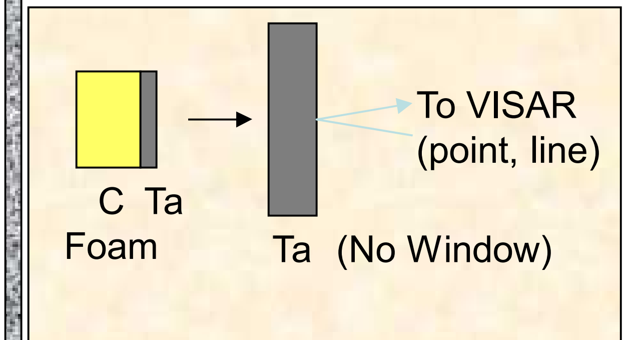


Objectives: Spall strength, spatial variations in properties, HEL, attenuation measurements

Peak pressure: 12 GPa
Impact velocity: 400 m/s
Projectile: 0.20 – 0.25 mm Ta
42 mm dia.
Target: 1.15, 2.25, 4.5 mm Ta
42 mm dia.

Conducted with AFRL Ta; similar experiments conducted with LANL and COTS Ta

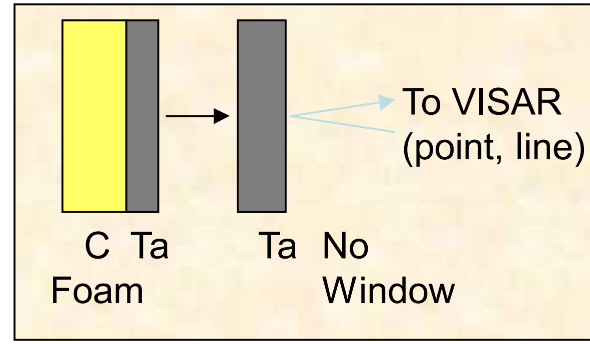
2. Spall, edge effects (4 shots)



Objectives: Assess effects of edge releases plus objectives of (1)

Peak pressure: 12 GPa
Impact velocity: 400 m/s
Projectile: 0.16 – 0.25 mm Ta
21 mm dia.
Target: 1.13, 2.2, 4.5 (x2) mm Ta
42 mm dia.

3. Thick Target Spall (1 shot)



Objective: Measure loading properties and spall where spall plane is deeper in the sample.

Peak pressure: 6 GPa

Impact velocity: 205 m/s

Projectile: 3.4 mm Ta 42 mm dia.

Target: 4.5 mm Ta 42 mm dia.

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The full matrix gives more details

Shot	FP Backer		Flyer Plate				Target Plate				Window		Impact	Compressional	Tensile	VISAR	Date
	Material	Thickness mm	Material	Thickness mm	Density gm/cc	Diameter mm	Material	Thickness mm	Density gm/cc	Diameter mm	Material	Thickness mm	Velocity mm/µs	Stress GPa	Stress GPa		
Eglin Tantalum																	
Linr-1	Al	> 10	Ta	1.2827	16.493	42?	Ta	3.998	16.636	42?	Sapphire	25.4	0.243	7.1	---	Point	
Linr-2	Al	> 10	Ta	1.2802	16.501	42?	Ta	3.97	16.613	42?	Sapphire	25.3	0.392	11.8	---	Point	
Linr-3	Al	> 10	Ta	~1.25	~16.5	42?	Ta	~4	~16.5	42?	Sapphire	~25	~0.65	20	---	Point	
Linr-4 / SP-3	C-foam	8.14	Ta	0.246	15.5268	42	Ta	1.148	16.514	42?	None		0.402	12.2	~6	Point+Line	395; 9/3/03
Linr-5	C-foam	8.143	Ta	0.221	15.336	42	Ta	2.228	16.537	42?	None		0.400	12.2		Point	396; 9/4/03
Linr-6/SP-08	C -foam	8.136	Ta	0.203	14.887	42	Ta	4.488	16.621	42	None		0.396	12		Point+Line	397; 9/8/03
Linr-7	C-foam?	~8?	Ta	0.1125	~16.5	42?	Ta	4.5	~16.5	42?	None		0.4	12.2		Point	
Linr-8	C -foam	8.06	Ta	0.208	15.886	21	Ta	1.135	16.505	42	None		0.394	12		Point	398; 9/9/03
Linr-9	C-foam?	~8?	Ta	0.224	~16.5	21	Ta	2.197	~16.5	42	None		0.326	9.8		Point+Line	399; 2/16/04
Linr-10	C-foam?	~8?	Ta	0.216	~16.5	21	Ta	4.491	~16.5	42	None		0.393	12		Point+Line	400; 2/17/04
Linr-11	C-foam?	~8?	Ta	0.157	~16.5	21	Ta	4.514	~16.5	42	None		0.392	12		Point+Line	401; 2/18/04
Linr-12	C foam	~8?	Ta	3.393	16.616	41.93	Ta	4.5009	16.6155	41.928	None		0.2048	6		Point	405; 2/25/04
ρ_0 = 0.30 - 0.32 gm/cc for C-foam																	
COTS Tantalum	**VPFs are 0.2026 and 0.2823 (except Ta 2: 0.2026, 0.2715)**																
Ta-1			Ta	0.4518		27.0006	Ta	1.94818		31.8186	None		0.363	11			262; 5/11/00
Ta-2	C -foam	5.2	Ta	0.5104	16.4704	27.0256	Ta	1.9634	16.5389	31.801	None		0.255	7.5			314; 10/27/00
Ta-3			Ta	0.9169	16.4022	60.973	Ta	3.9878	16.6424	37.716	None		0.2576	7.5		Point+Line	328; 5/9/01
LANL Tantalum	**VPFs are 0.2026 and 0.2823**																
Ta-4	C -foam		Ta	0.5055	16.8079	26.8554	Ta	1.7704	16.6091	37.73	None		0.2684	8			359; 10/15/01
Ta-5	C -foam		Ta	0.5207	16.7673	26.9697	Ta	1.7653	16.606	37.73	None		0.3147	9.4			360; 10/16/01
Ta-6	C -foam		Ta	0.5258	16.5866	26.929	Ta	1.7628	16.6215	37.716	None		0.3606	10.9			361; 10/17/01
Ta-7	C -foam		Ta	0.3962	16.6045	27.0764	Ta	1.6408	16.5274	37.732	None		0.2412	7.1			367; 4/1/02

The Weibull analyses show the LANL Ta the most variable point-to-point, except for one spall measurement

HEL

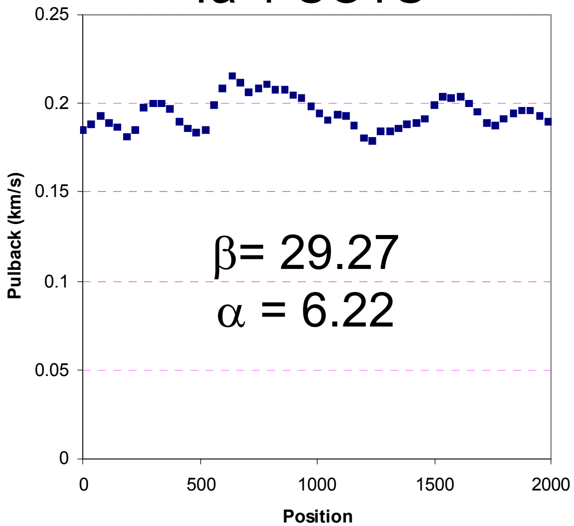
Shot name	Sample Type	β	α	Thickness	Stress
Linr-4	AFRL	**9.402**	**1.902**	1.148	12.2
Linr-6	AFRL	**7.180**	**1.263**	4.488	12
Linr-10	AFRL	**9.001**	**1.214**	4.491	12
Linr-12	AFRL	**9.539**	**1.230**	4.501	6
Ta-1	COTS	**8.135**	**1.011**	1.948	11
Ta-4	LANL	**6.634**	**1.238**	1.770	8
Ta-5	LANL	**8.662**	**1.139**	1.765	9.4
Ta-6	LANL	**5.548**	**1.342**	1.763	10.9
				(mm)	(GPa)

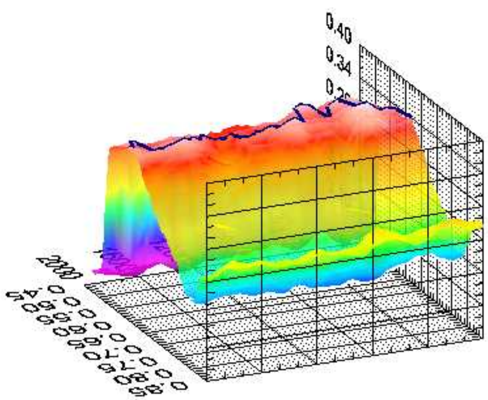
Spall

Shot name	Sample Type	β	α	Spall Depth	Stress
Linr-4	AFRL	**11.283**	**5.293**	0.25	12.2
Ta-1	COTS	**29.270**	**6.222**	0.45	11
Ta-4	LANL	**27.003**	**6.146**	0.50	8
Ta-5	LANL	**13.964**	**4.079**	0.52	9.4
Ta-6	LANL	**12.539**	**6.183**	0.53	10.9
				(mm)	(GPa)

This inconsistency is also apparent in the velocity surface itself (example set; also true for other sets).

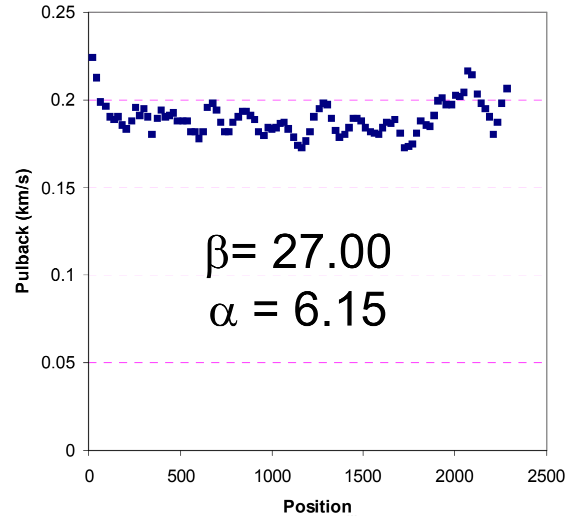
Ta-1 COTS

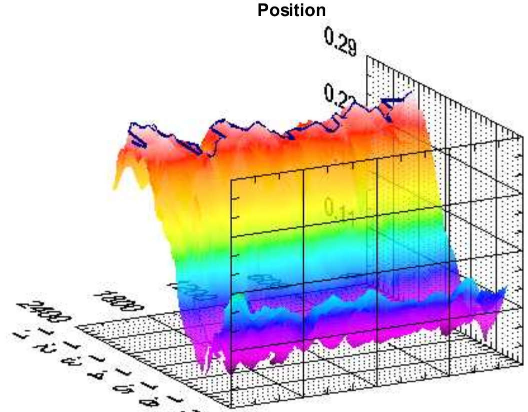




Spall depth: 0.45 mm
Stress level: 11 GPa

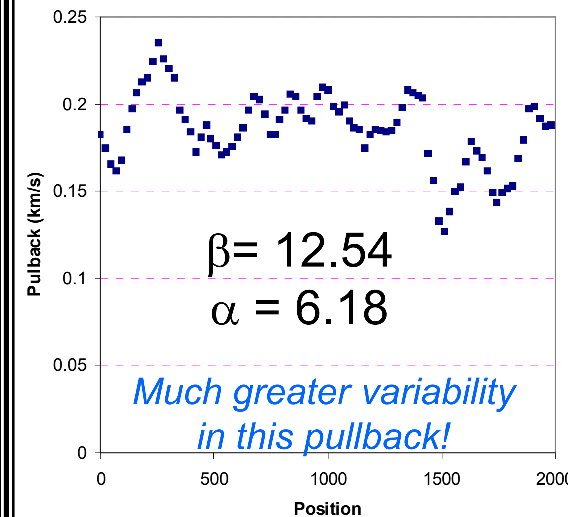
Ta-4 LANL

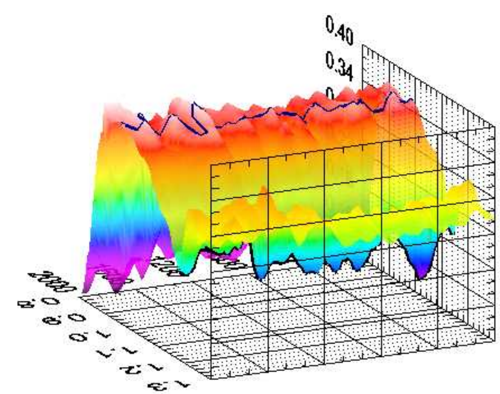




Spall depth: 0.5 mm
Stress level: 8 GPa

Ta-6 LANL





Spall depth: 0.53 mm
Stress level: 11 GPa

Remember – larger β means less variability in failure level

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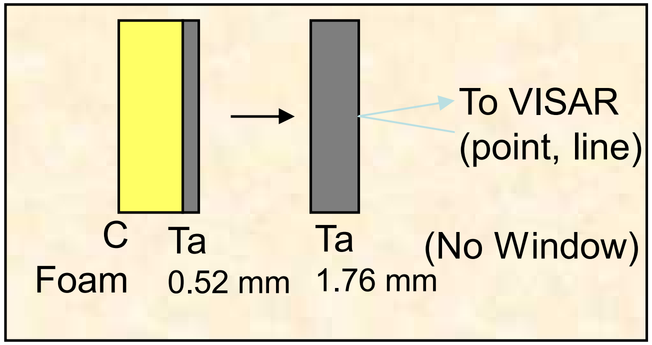
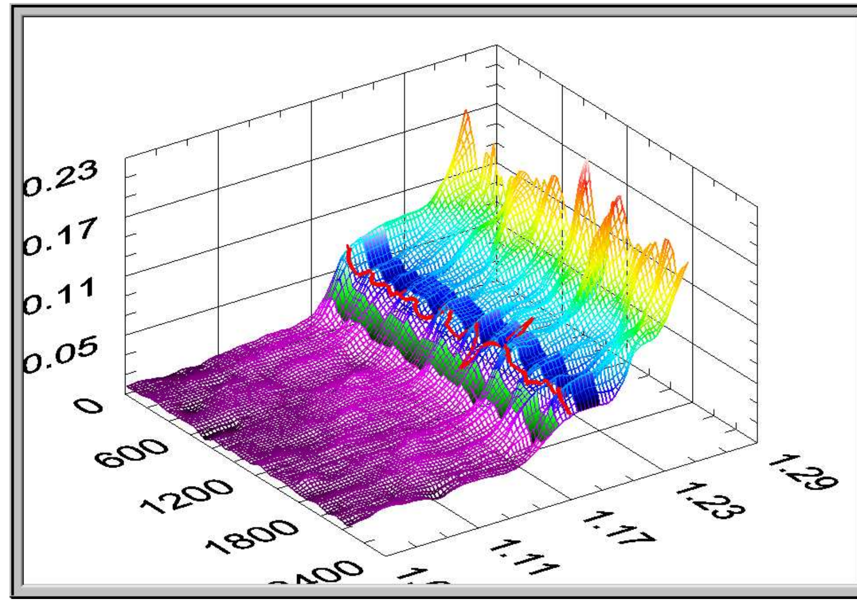
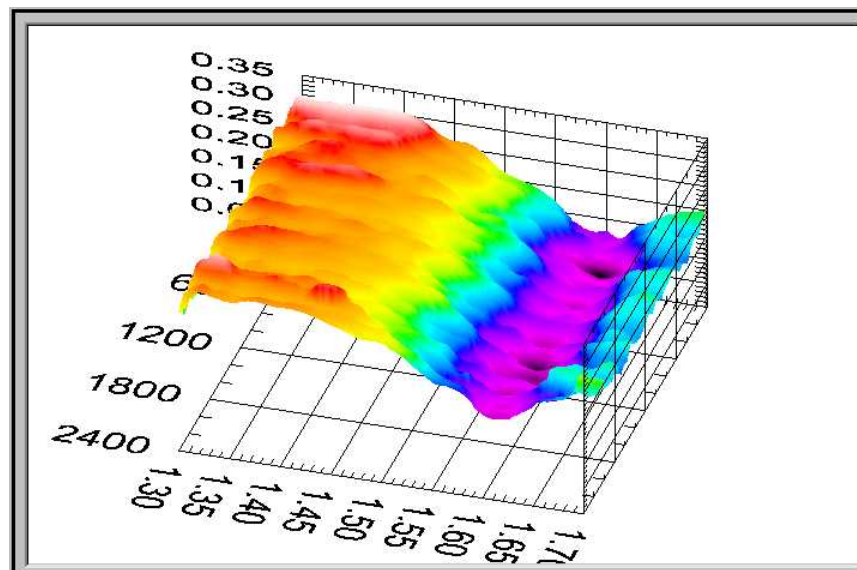
Tantalum appears to be more homogeneous under spall than under initial loading.







Ta-5 (equiaxed Ta)

HEL: Beta = 8.66; Alpha = 1.13
Spall: Beta = 13.94; Alpha = 4.08

Material is more homogeneous under spall than under initial loading.

Shock pressure ~9.5 GPa

Conclusions

- Uniform samples of Ta were tested in gas gun tests with line-imaging VISAR (~6 - 12 GPa peak stresses) to ascertain spatial variability of HEL and spall
- Three materials used:
  - AFRL (Eglin) Ta had refined 20 μm grain structure with strong axisymmetric [111] crystallographic texture
  - LANL Ta had equiaxed 20 μm grain structure
  - COTS (commercial off-the-shelf) Ta had an uncharacterized structure
- A statistical analysis of the variability of the spall strength and the HEL yielding was conducted using the Weibull method to attempt to find systematics
- We found suggestions of greater variability in the equiaxed 20 mm Ta stock than in that with the axisymmetric [111] crystallographic texture, but the statistics were not completely consistent on this point.

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