Evaluation of Advanced Aerospace Aluminum Alloys For Armor and Structural Applications

Reference: ARL-TR-3185

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Introduction

Solutions to High Fuel and Material Costs

Materials, Processing, and Performance Improvements

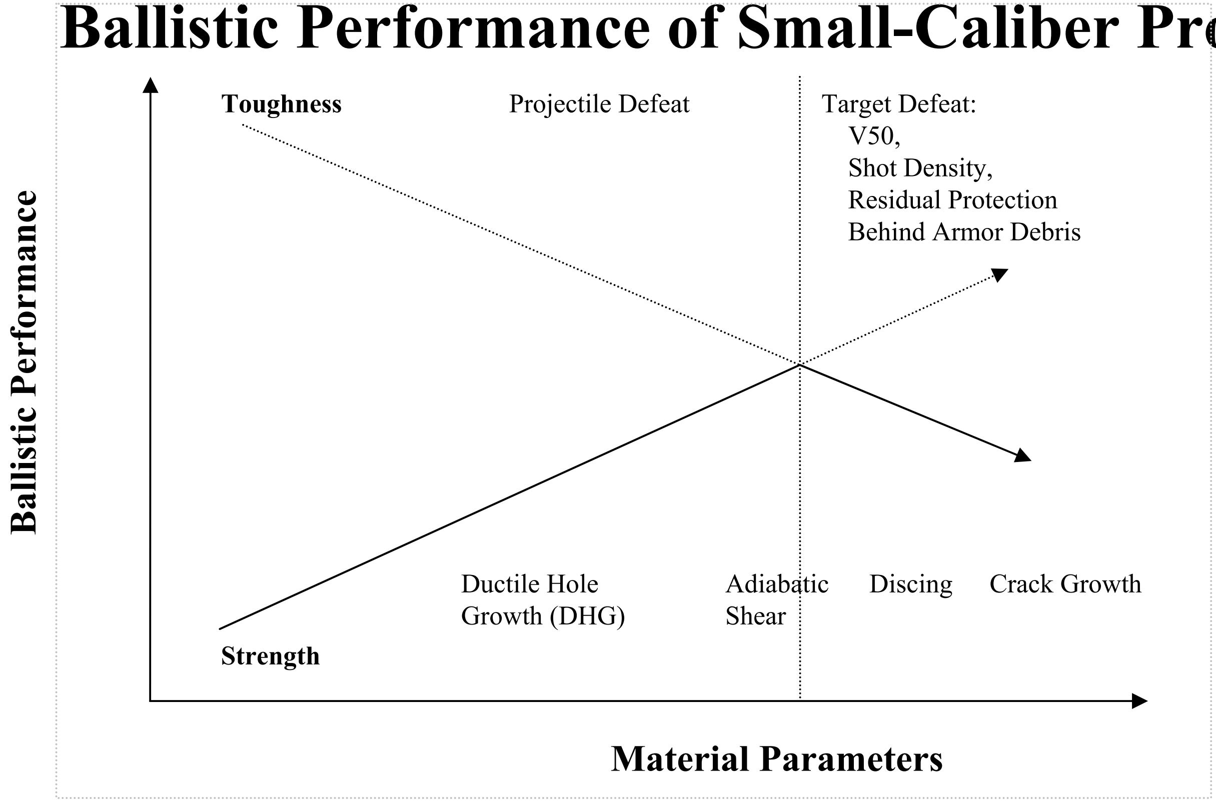
- **Durability**
- **Specific-Strength and Toughness**
- **Low Material and Operating Costs**
- **Isotropic Mechanical Properties**
- **Weldable Al-Cu-Li Alloys**

Lithium as Alloy-Element

- **Non-Toxic**
- **3% Density-<u>Reduction</u> / Weight-%**
- **6% Elastic Modulus <u>Increase</u> / Weight-%**

Introduction

Aluminum Armor:
Material Parameters and
Ballistic Performance of Small-Caliber Projectiles



- Plastic Flow, and Failure Modes Determine Performance
- At High-Strength Levels, Localization of Plastic Flow and Fracture Decrease Ballistic Performance

Introduction

- Al-Li Alloys versus Al-Armor 7039
  - Literature: Investigations Controversial-
    - a. 2090-T8: No significant improvement, either at 0° or 30°;
    - b. 2090-T8: Improvement claimed with 0° impact obliquity, but not oblique; Al-Li material parameters claimed significant
    - c. 2090-T8 & 2049 Improvement claimed at 30° obliquity, effect improves with strength.
- Quantitatively,

  What are the V50 mean and variance of 7039 Al-armor performance?

  Do the experimental materials provide significant V50 improvements?

  What are the improvements?

- Do the material parameters or failure modes enhance ballistic protection?

Experimental Aluminum Alloy Target Materials

- **C47A, C458 Al-Cu-Li-Zn (C458 → 2099)**
- **7055 Al-Zn-Cu-Mg**
- **2195 Al-Cu-Li-Mg-Ag**

Experimental Mechanical Properties In Tension with Range Variation - Comparison to Reference Alloys

Property	Experimental Alloys and Tempers				Reference Data:Al Armor and Al-Li		
	C47A -T8	C458 -T861	2195 -T8	7055 -T7751	7039 -T64	2519 -T87	2090 -T8
Young's Modulus (GPa)	76.8 (0.6)	77.7 (0.4)	75.9 (0.6)	70.6 (0.6)	70	72	79
0.2% Yield Strength (MPa)	437 (4.2)	525 (5.2)	592 (1.8)	602 (1.9)	400	423	490
Ultimate Strength (MPa)	469 (1.5)	558 (2.7)	627 (0.9)	632 (2.1)	458	465	550
Elongation (%)	13.2 (1.7)	9.3 (1.4)	9.6 (2.7)	14.5 (0.7)			
Reduction of Area (%)	44.3 (0)	23.5 (7.1)	22.2 (9.1)	40.7 (1.1)			

Experimental Results: average of 3 specimens strained to failure, except C458 = 6 specimens

Experimental Results

Physical Properties And Specific Strength

Property	Experimental Alloy				Al Armor			Ti Armor
	C47A -T8	C458 -T861	2195 -T8	7055 -T7751	5083	7039	2519	6Al-4V
Density (ρ), (g/cm^3)	2.642	2.633	2.709	2.866	2.66	2.73	2.82	4.43
Hardness (HRB)	75.0	80.4	88.3	92.1	—	—	—	—
Young's Modulus (GPa)	76.8	77.7	75.9	70.6	70.3	69.6	72.4	110
Specific Modulus $(E/\rho)/10^{-8}$ (cm)	2.96	3.01	2.86	2.51	2.69	2.60	2.62	2.53
Specific Strength $(YS/\rho)/10^{-6}$ (cm)	1.69	2.03	2.23	2.14	1.20	1.45	1.53	1.75–2.10

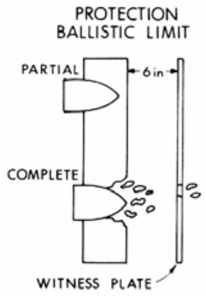
- **Al-Cu-Li Alloys Have the Highest Specific Modulus and Strength**

Experimental Results

Ballistic V50 Test: Procedure, Results, Criteria

Projectile		Target Characteristics			Penetration Result Intervals		V50 Prot. Limit Averaged	
Type	Impact Obliquity (°)	Alloy	Thickness (t) (mm)	AD (kg/m^2)	Target Impacts (No.)	Distribution of All P, C, Penetrations	Shots (No.)	(S) Spread (m/s)
0.50-cal. FSP	0	C47A	19.10	50.46	8 UM	3P ≤ S ≤ 5C	2	1.2
	0	2195	19.13	51.83	5 UM	3P≤ S ≤ 2C	2	2.4
	0	C458	19.91	52.43	8 M	3P≤ S ≤ 3C	4	15.8
20-mm FSP	0	7055	31.72	90.95	5 UM	3P≤ S ≤ 2C	2	5.8
	0	2195	40.16	108.8	6 UM	4P≤ S ≤ 2C	2	17.7
0.30-cal. APM2	0	C47A	19.02	50.26	10 UM	7P≤ S ≤ 3C	2	2.7
	0	2195	19.11	51.76	4 M	1P≤ S ≤ 1C	4	15.5
	0	C458	19.91	52.43	6 UM	3P≤ S ≤ 3C	2	11.0
	0	7055	18.95	54.34	4 UM	2P≤ S ≤ 2C	2	4.9
	0	2195	31.76	86.02	9 UM	4P≤ S ≤ 5C	2	4.3
	0	7055	31.75	91.03	11 UM	8P≤ S ≤ 3C	2	3.7
	0	2195	40.18	108.9	11 UM	7P≤ S ≤ 4C	2	13.4
	30	C47A	19.08	50.40	10 M	3P≤ S ≤ 3C	6	23.2
	30	2195	19.11	51.76	12 M	4P≤ S ≤ 3C	4	20.4
	30	C458	19.94	52.50	9 M	4P≤ S ≤ 3C	4	17.4
	45	C458	19.90	52.40	12 UM	9P ≤ S ≤3C	2	7.9
0.50-cal. APM2	0	2195	39.65	107.4	9 UM	5P ≤ S ≤ 4C	4	7.9

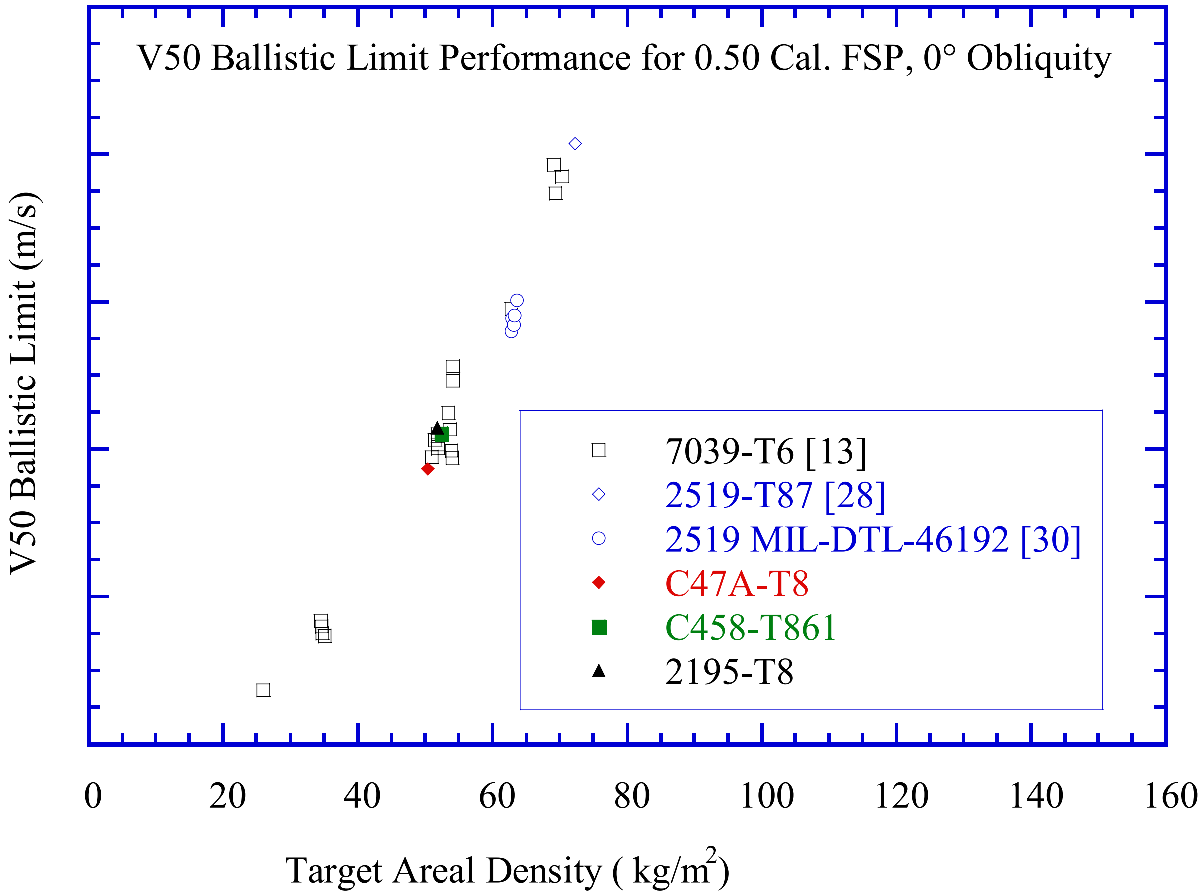
Test Criteria



UM = UnMixed, all P or all C results
M = Mixed, includes P & C results
P = Partial Penetration
C = Complete Penetration
S = spread, range of velocities of P and C results used in V50 estimate

Results - Discussion

0.50 cal. FSP, 0° Obliquity

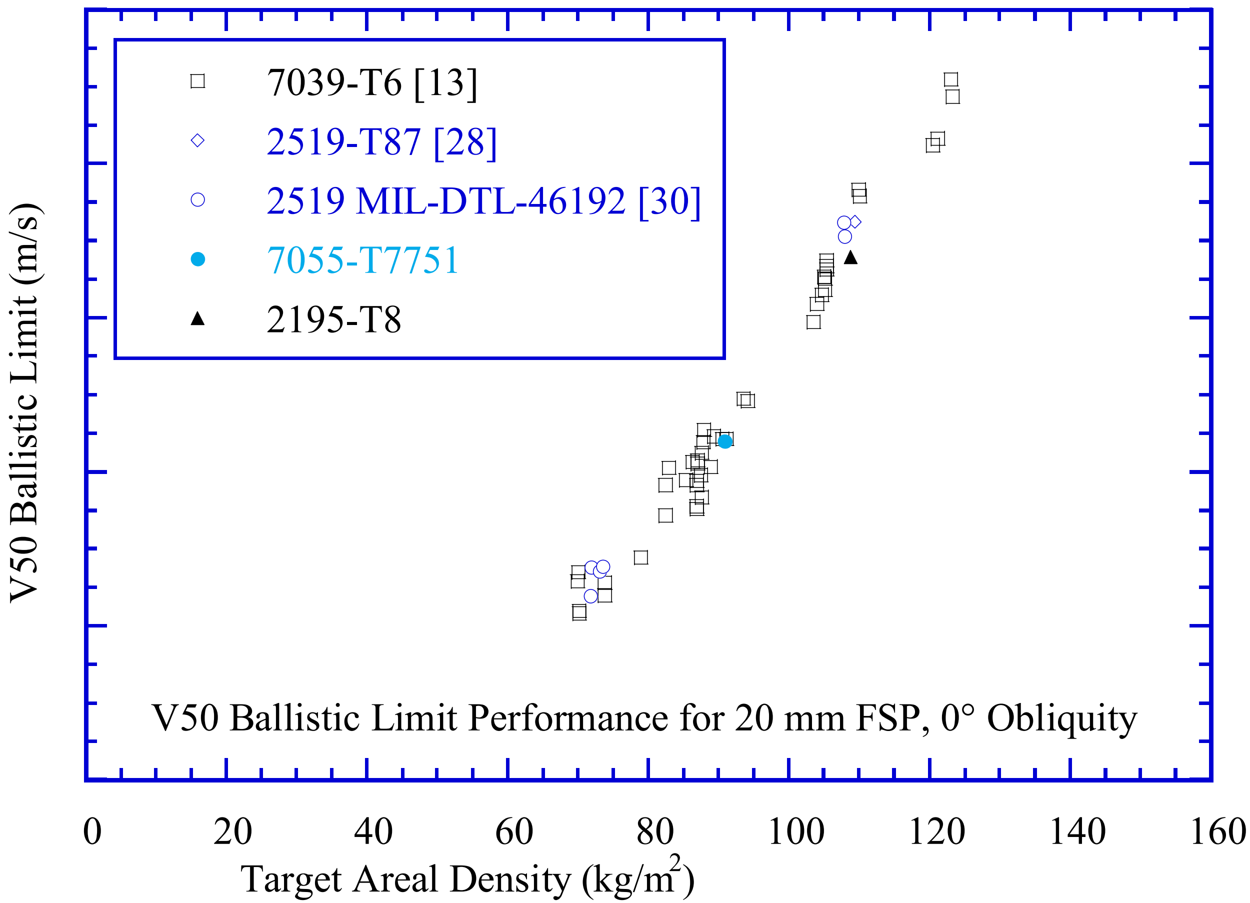


Scales of V50 and AD axes:
FSP = 0.30 cal. APM2
= 0.50 cal. APM2(V50)

Experimental Alloys with 7039 and 2519 Al armor V50 Performance

Results - Discussion

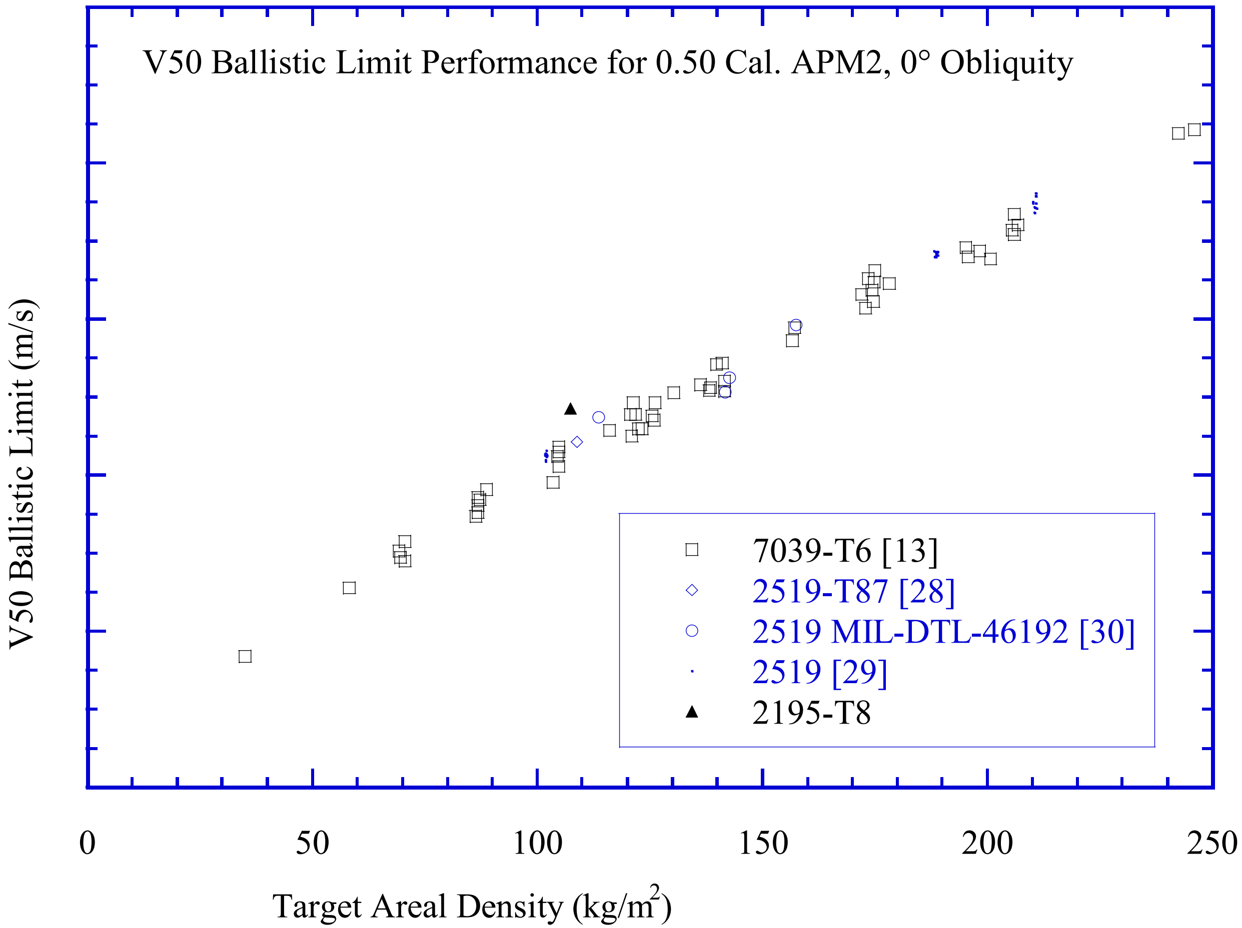
20 mm FSP, 0° Obliquity



Experimental Alloys with 7039 and 2519 Al armor V50 Performance

Results - Discussion

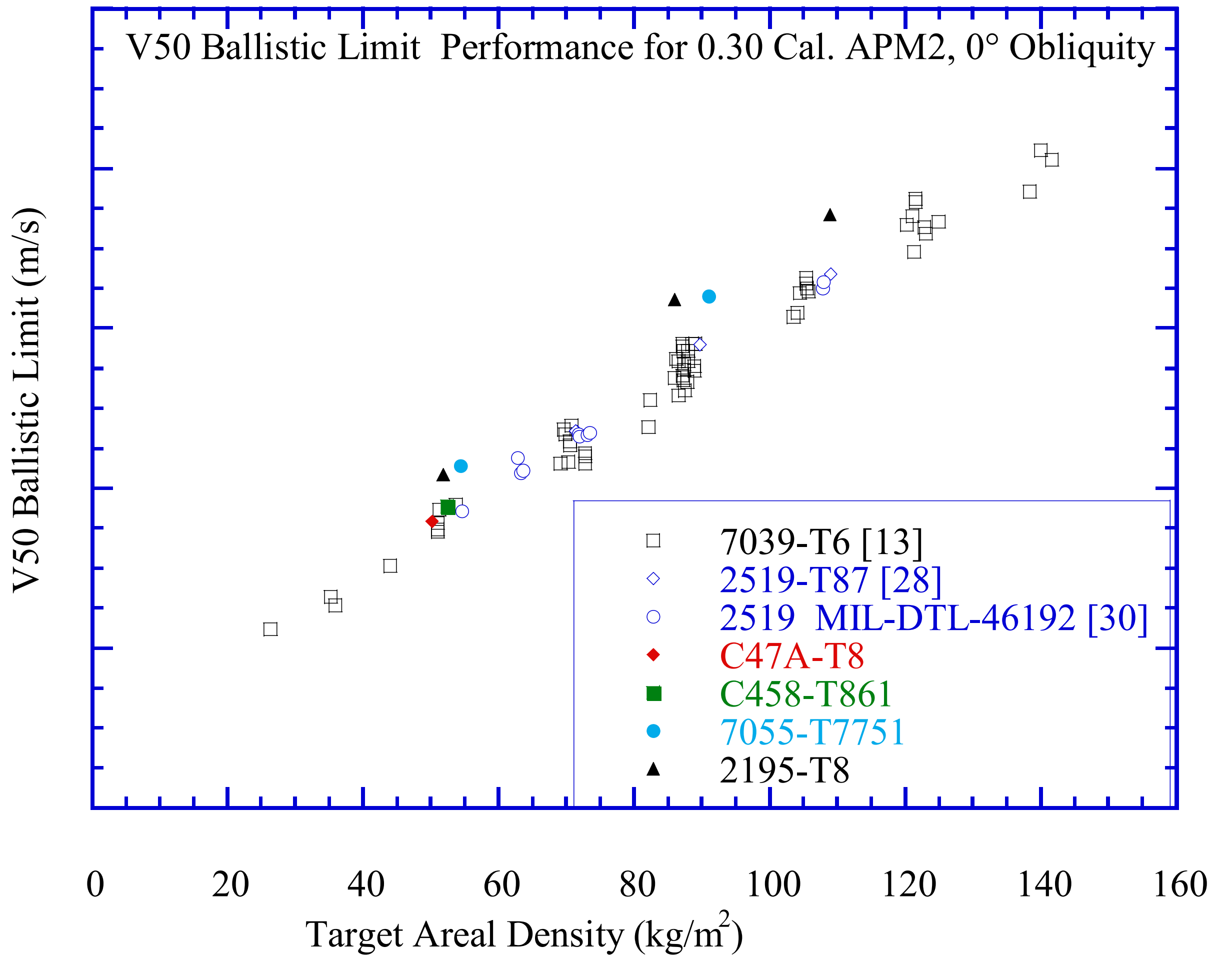
0.50 cal. APM2, 0° Obliquity



Experimental Alloys with 7039 and 2519 Al armor V50 Performance

Results - Discussion

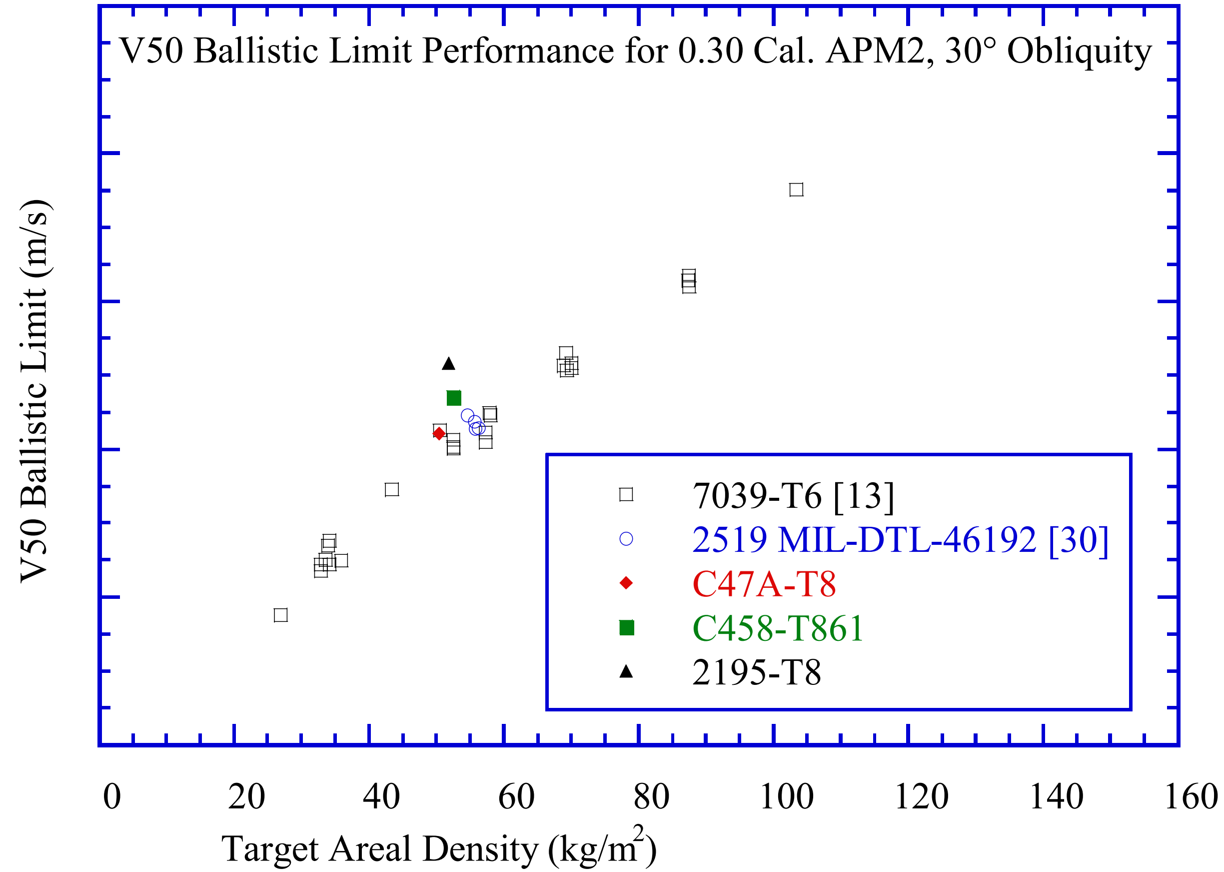
0.30 cal. APM2, 0° Obliquity



Experimental Alloys with 7039 and 2519 Al armor V50 Performance

Results - Discussion

0.30 cal. APM2, 30° Obliquity



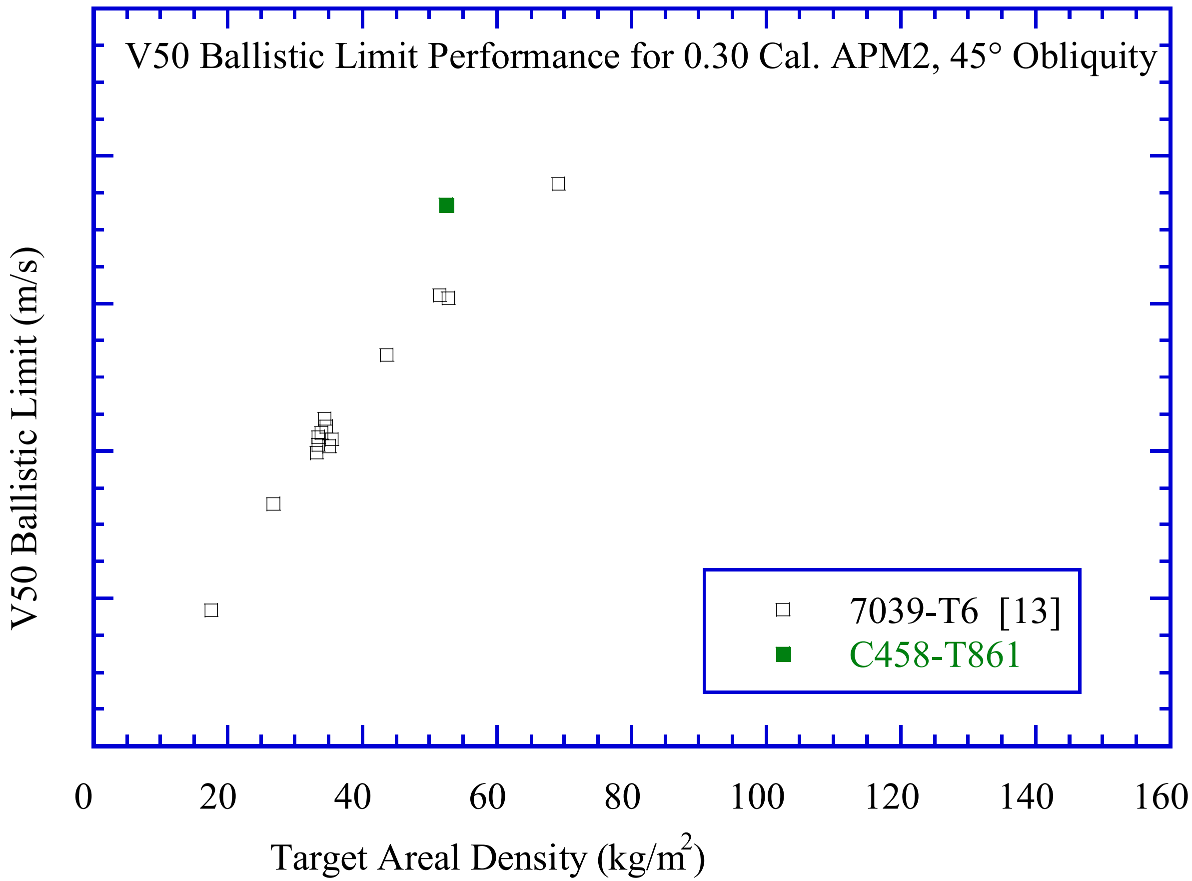
Experimental Alloys with 7039 and 2519 Al armor V50 Performance

- Oblique-Impact V50 Performance of Al-Li Alloys > 7039

ACAS, 20-22 October, 2004

Results - Discussion

0.30 cal. APM2, 45° Obliquity

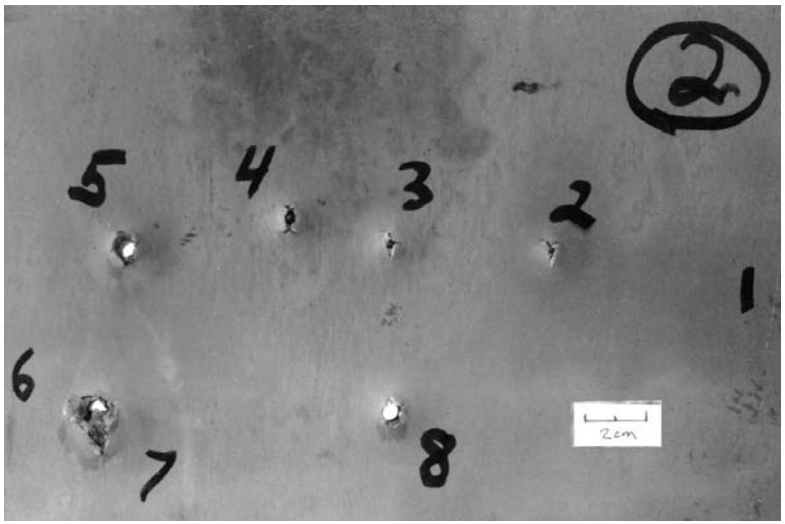


Experimental Alloys with 7039 and 2519 Al armor V50 Performance

- Oblique-Impact V50 Performance of Al-Li Alloys > 7039

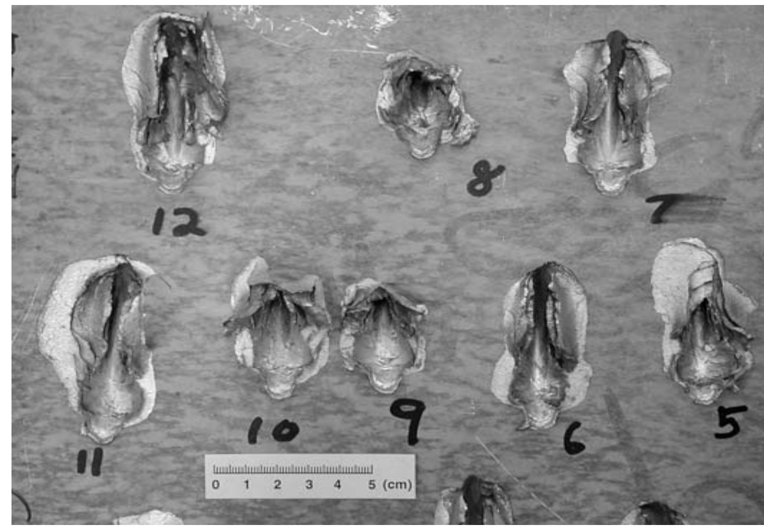
Results and Discussion

0.30 cal. APM2 Penetration Modes



C458-T861: 0° Obliquity

- Damage-tolerant
- High shot-density
- Multiple impacts

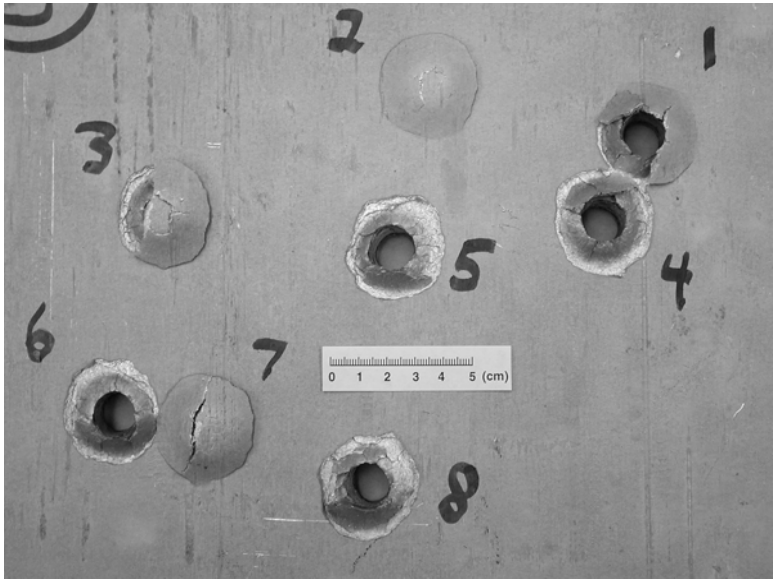


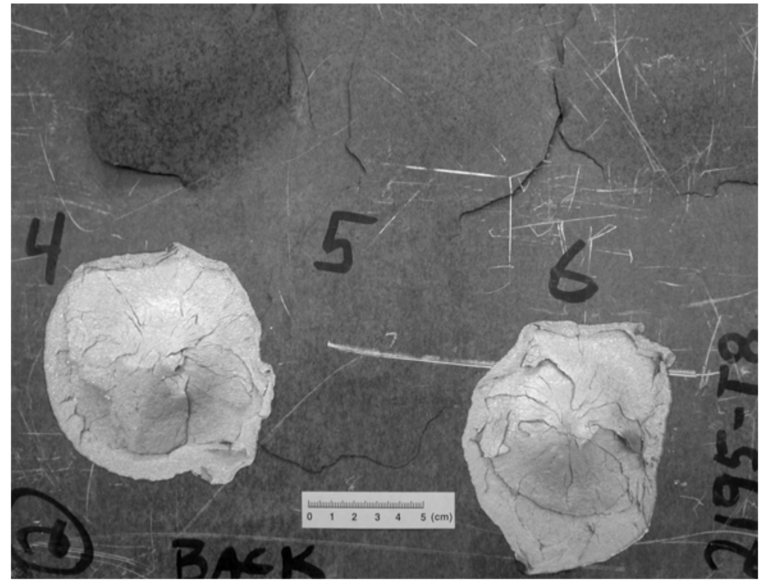
C458-T861: 45° Obliquity

V50 45° = 1.62 x V50 0°

Results and Discussion

FSP Penetration Mode





C47A-T8 versus 0.50 cal. FSP

- Damage-tolerant
- High shot-density
- Multiple impacts

2195-T8 versus 20 mm FSP

- Ductile Hole Growth
  + Discing Failure

Results and Discussion

Linear Regression in Matrix Notation

$\mathbf{Y} = \mathbf{X}\beta + \varepsilon$ Model with k order or regression variables, p = k + 1 regression coefficients (parameters)

βj, = 0, 1,2,...k, **Y** = n x 1 vector of observed values, **X** = n x p matrix of levels of regressor variable(s), β = p x 1 vector of regression coefficients, ε = n x 1 vector of random errors

$(\mathbf{X}'\mathbf{X})\hat{\beta} = \mathbf{X}'\mathbf{Y}$ Normal equations

$\hat{\beta} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y}$ Parameter estimates

$\hat{\mathbf{Y}} = \mathbf{X}\hat{\beta}$ Fitted values (mean-estimates) corresponding to observed values, **Y**

$= \mathbf{X}(\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{Y}$ "Hat matrix" maps vector of observed values into vector of fitted values

$= \mathbf{HY}$

$\mathbf{e} = \mathbf{Y} - \hat{\mathbf{Y}} = (\mathbf{I}-\mathbf{H})\mathbf{Y}$ Residuals, vector of residual errors **e**

$\mathbf{Var}(\hat{\beta}) = (\mathbf{X}'\mathbf{X})^{-1}\,\sigma^2$ Variance of $\hat{\beta}$

$\mathbf{Var}(\hat{\mathbf{Y}}) = \mathbf{X}[\mathbf{Var}\,\hat{\beta}\,]\mathbf{X}'$ Variance of all mean estimates, $\hat{\mathbf{Y}}$

$= \mathbf{X}(\mathbf{X}'\mathbf{X})^{-1}\,\mathbf{X}'\,\sigma^2 = \mathbf{H}\,\sigma^2$

$\mathbf{Var}(\hat{\mathbf{Y}}_{\text{pred}}) = (\mathbf{I} + \mathbf{H})\,\sigma^2$ Variance of prediction, single point future

$\mathbf{Var}(\mathbf{e}) = (\mathbf{I} - \mathbf{H})\,\sigma^2$ Variance of the residual errors

$\mathbf{Y}'\,\mathbf{Y} - n\,\overline{\mathbf{Y}}^2 = (\hat{\beta}'\,\mathbf{X}'\,\mathbf{Y} - n\,\overline{\mathbf{Y}}^2) + (\mathbf{Y}'\,\mathbf{Y} - \hat{\beta}'\,\mathbf{X}'\mathbf{Y})$

Total sum of squares (corrected) partitioned into errors due to regression + residual, $S_{yy} = SS_R + SS_E$

Results and Discussion

Regression in Matrix Notation

$$R_a^2 = 1 - \frac{SS_E / n-p}{S_{yy} / n-1}$$ Coefficient of determination

$$= 1 - \frac{n-1}{n-p}(1-R^2)$$ Adjusted coefficient of determination

$$\frac{S_{yy}}{n-1} = \frac{SS_R}{k} + \frac{SS_E}{n-p}$$ Mean sums of squares partitioned, corrected,
$k = p - 1$, k = variables n = observations, p = coefficients

$$MS_E = \frac{SS_E}{n-(k+1)} = \frac{SS_E}{n-p}$$ the residual mean square s^2, a model-dependent estimate of variance σ^2, where $SSE = \sum_{i=1}^{n} e_i^2 = \mathbf{Y'Y} - \hat{\boldsymbol{\beta}}'\mathbf{X'Y}$

$$T = \frac{\hat{Y}_o - \mu_{Y|1, x_{01}, x_{02}, \ldots, x_{0k}}}{s\sqrt{\mathbf{x}_0'(\mathbf{X'X})^{-1}\mathbf{x}_o}}$$ statistic for construction of $100(1-\alpha)\%$ confidence intervals on the mean (predicted) response $\mu_Y = | \, 1, x_{01}, x_{o2}, \ldots x_{ok}$ where s^2 is an estimate of the variance σ^2, $\mathbf{x}_o$ or $\mathbf{x}'_0 =$

$[1, x_{01}, x_{02}, \ldots x_{0k}]$ is the condition vector, and where the statistic is T distribution probability determined by degrees of freedom $\upsilon = n - p = n - k - 1$

$$s(\hat{Y}_0) = \sqrt{\mathbf{x}_0'(\mathbf{X'X})^{-1}\mathbf{x}_0 s^2}$$ Conditional standard error on the mean estimate (response)

$$s(\hat{Y}_0 - Y_0) = \sqrt{(\mathbf{1} + \mathbf{x}_0'(\mathbf{X'X})^{-1}\mathbf{x}_0)\, s^2}$$ Conditional standard error for a single point future prediction on an observed response

[1] Walpole, R. E.; Myers, R. H.; Meyers, 1972.
[2] Montgomery, D. C.; Peck, 1992.
[3] Rawlings, J. O. 1988.
[4] Gerald, C. F. 1980.

Discussion

Summarize & Predict V50 Performance of 7039-T6 Armor,

Mean Estimates and Confidence Intervals,

Independent Variable = Areal Density(AD) the Target Weight / Unit Area

$$V50_{i\ 7039\text{-}T6} = \beta_0 + \beta_1\ AD_i + \beta_2 AD_i^2 + [\beta_3\ AD_i^3]_, \quad \text{(Mathematica v2.2)}$$

Polynomial Least Square (LS) Regression, Coefficients and Statistics

Projectile		Polynomial Regression, 7039-T6 V50 Ballistic Performance f(AD)								
Type	Obl. (°)	Obs. (n)	R^2_a	s (m/s)	Coefficient Estimates B_0	B_1	B_2	B_3	t Dist. t (1-0.025, ν)	d.f. (ν)
0.50-cal. FSP	0	23	0.99170	32.36	XXX.xxx	-XX.xxxx	0.xxxxxx	–0.00xxxxxx	2.093	19
20-mm FSP	0	44	0.98110	25.76	XXX.xx	-XX.xxx	0.xxxxxx	–0.00xxxxxx	2.021	40
0.30-cal. APM2	0	58	0.98090	19.69	XXX.xxx	X.xxxx	0.0xxxxx	–0.000xxxxx	2.005	54
	30	26	0.99100	14.09	–XX.xxxx	XX.xxxx	–0.xxxxx	0.00xxxxxx	2.074	22
	45	14	0.99087	13.22	XXX.xxx	XX.xxxx	–0.0xxxx	—	2.201	11
0.50-cal. APM2	0	55	0.99180	13.53	XXX.xxx	X.xxxxx	–0.00xx	0.0000xxxx	2.008	51

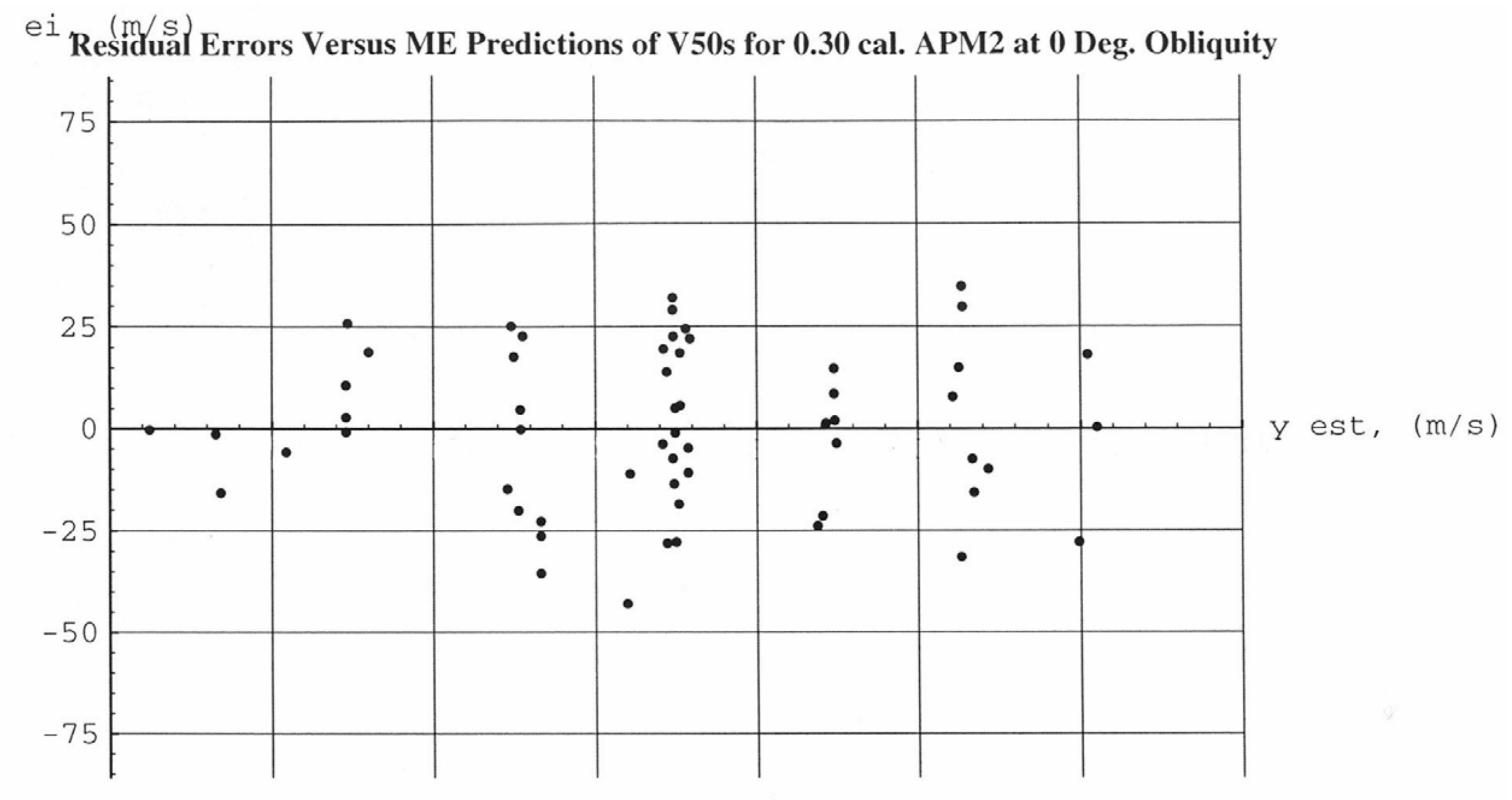
Notes: s = standard error

t = critical values of t-distribution for determination of a two-tailed 95% confidence interval

ν = degrees of freedom

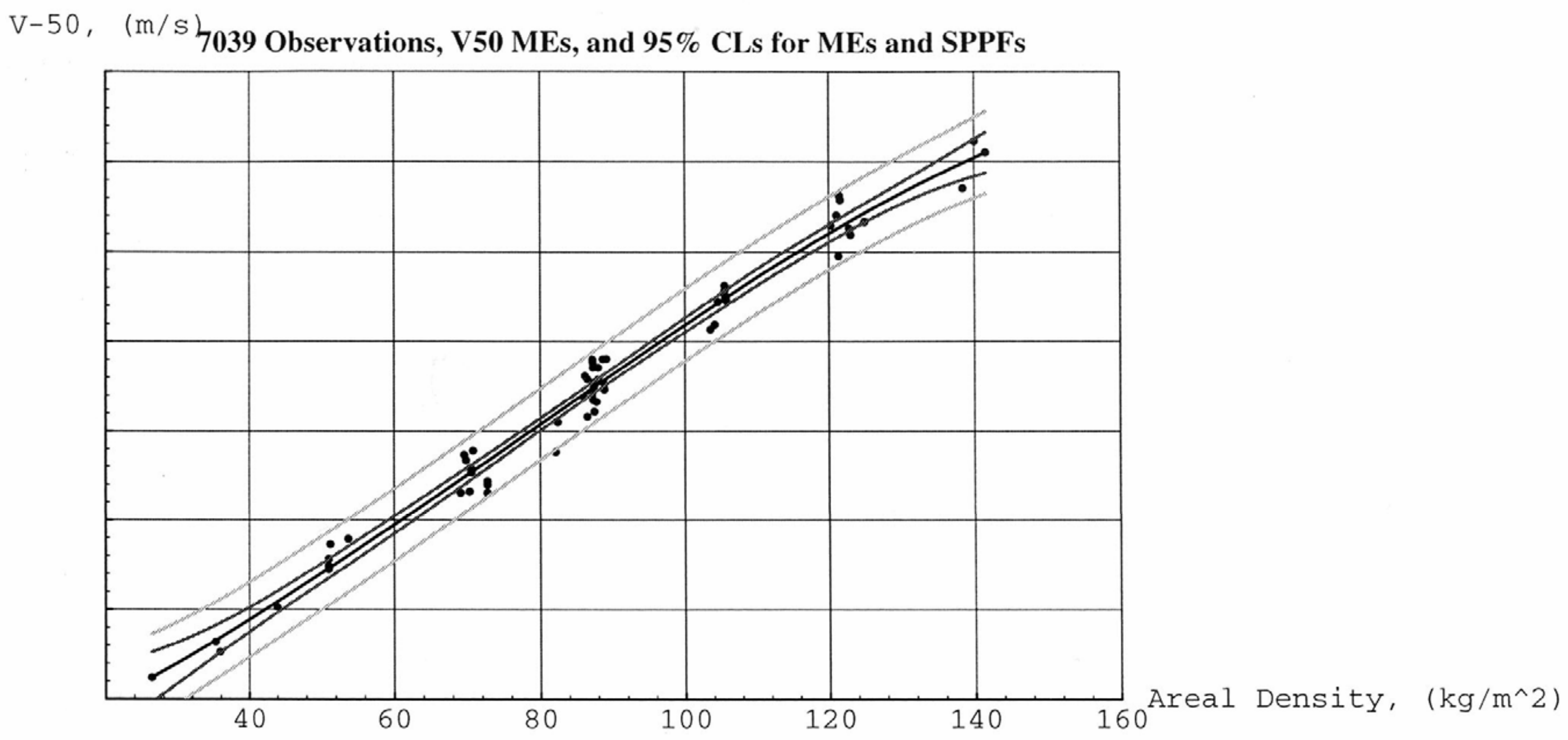
R^2_a = adjusted coefficient of determination

Discussion



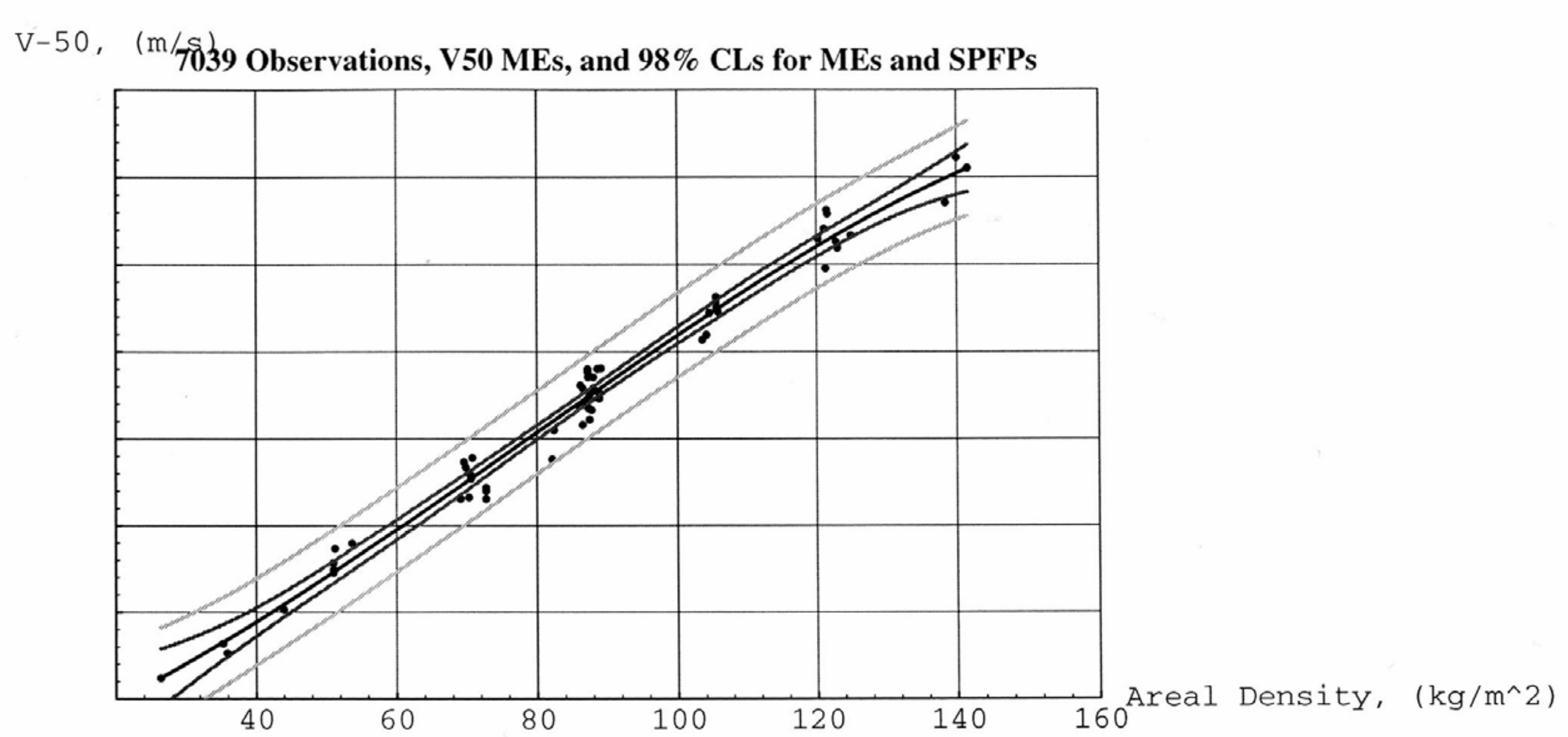
Plot of residuals versus fitted regression values of 7039-T6 V50s

Discussion



7039-T6 V50 observations, n = 58, and 95% CLs for mean estimates (MEs), and single point future predictions (SPFPs)

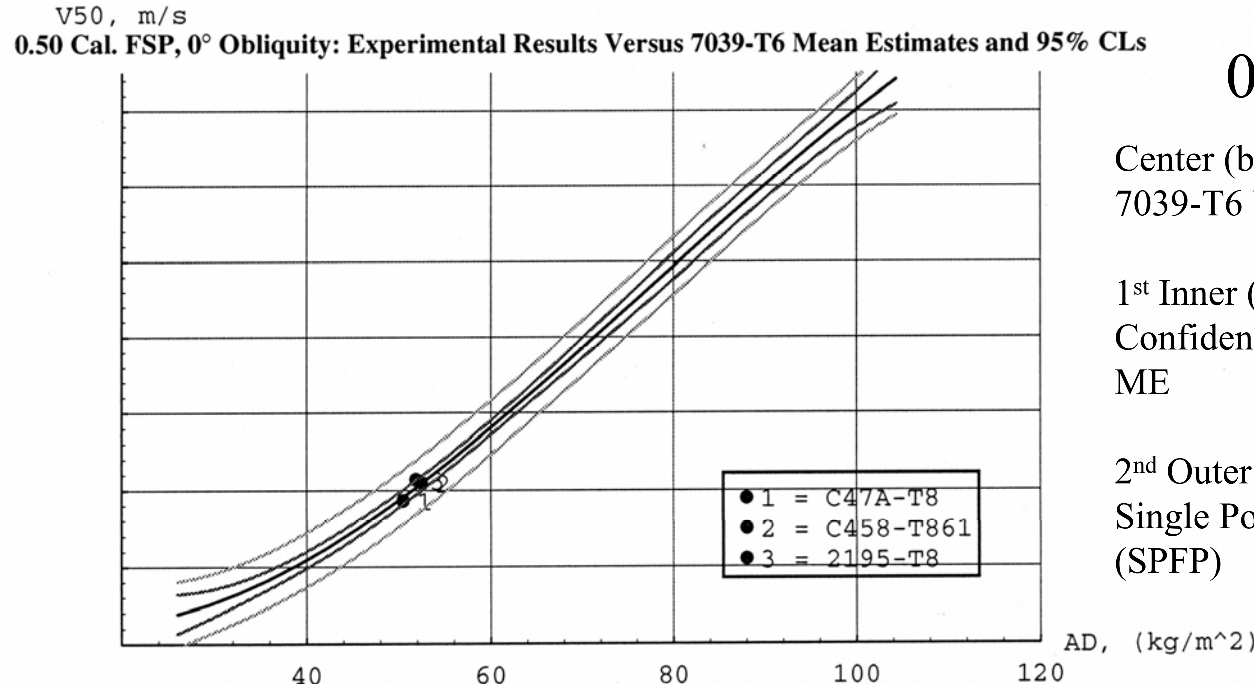
Discussion



7039-T6 V50 observations, n = 58, and 98% CLs for mean estimates (MEs), and single point future predictions (SPFPs)

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression



0.50 cal. FSP, 0°

Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

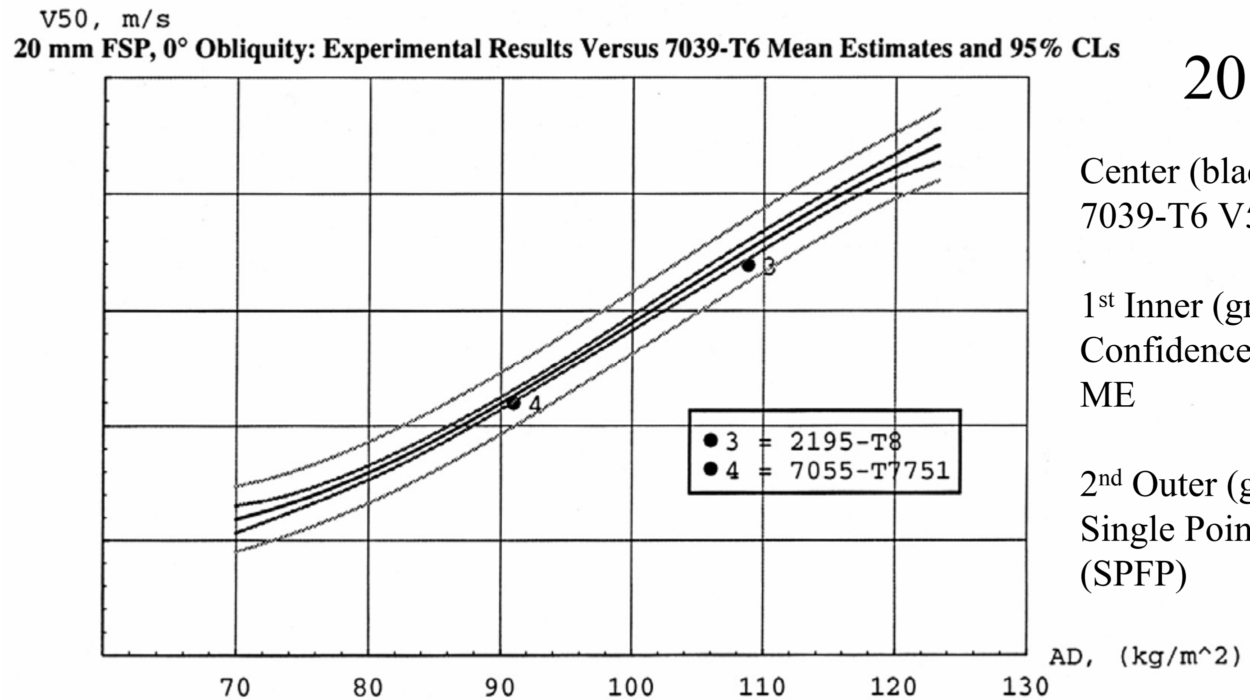
2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

0.50 cal. FSP
Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy (i)	AD (kg/m2)	V50-VME7039 (m/s)	Conditional s, mean m/s)	Conditional s, pred (m/s)	t	ME 95% CL (± m/s)	SPFP 95% CL (± m/s)
1	50.46	-8.489	9.238	33.65	-0.2523	19.33	70.44
3	51.83	21.83	9.032	33.6	0.6499	18.9	70.32
2	52.43	3.622	8.947	33.57	0.1079	18.73	70.27

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression



20 mm FSP, 0°

Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

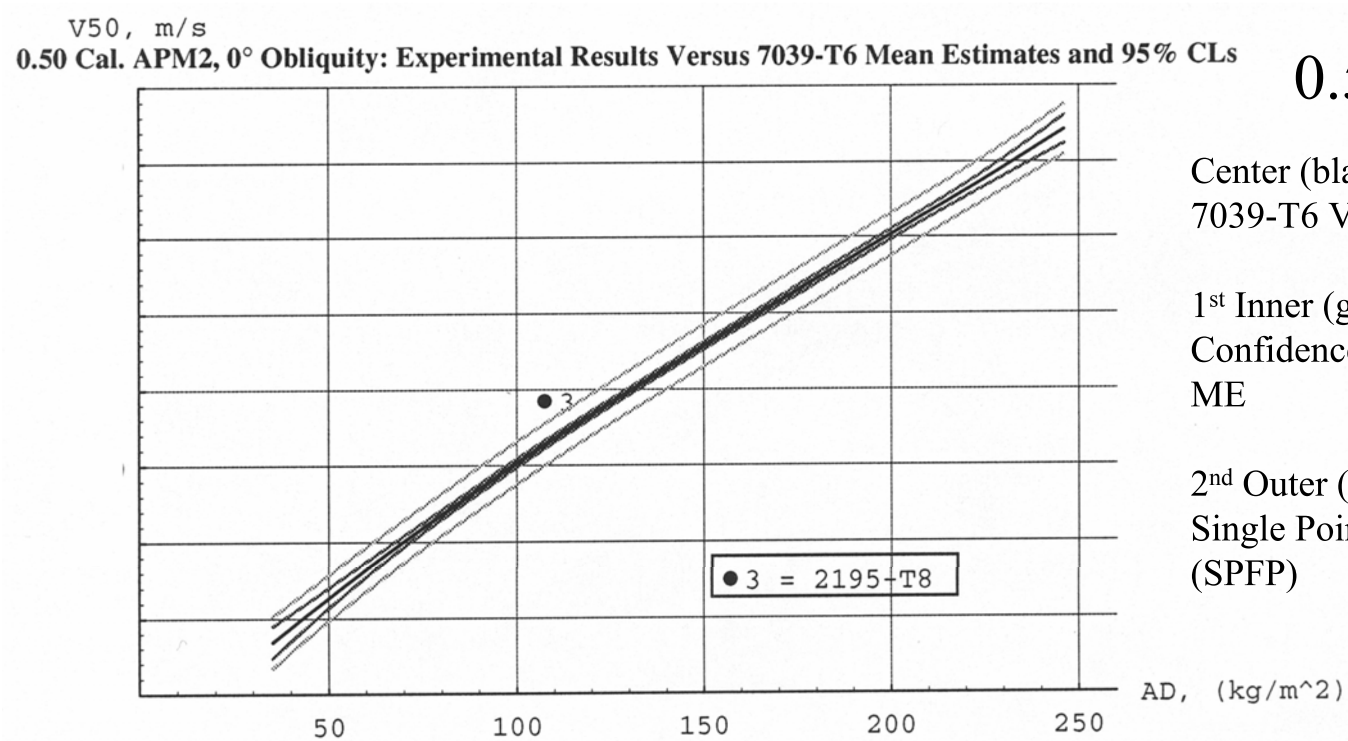
20 mm FSP

Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy (i)	AD (kg/m2)	V50-VME7039 (m/s)	Conditional s, mean (m/s)	Conditional s, pred (m/s)	t	ME 95% CL (± m/s)	SPFP 95% CL (± m/s)
4.	90.95	-12.39	5.186	26.28	-0.4715	10.48	53.11
3.	108.8	-26.13	7.944	26.96	-0.9691	16.06	54.49

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression



0.50 cal. APM2, 0°

Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

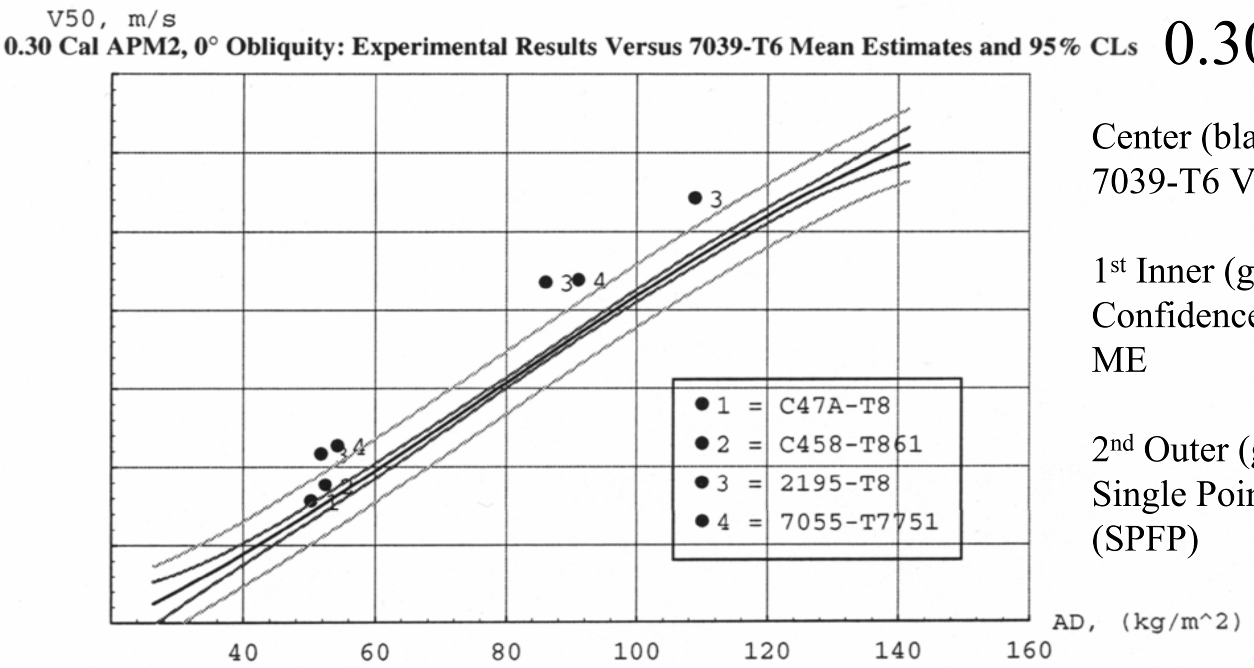
2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

50 cal. APM2
Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy (i)	AD (kg/m2)	V50-VME7039 (m/s)	Conditional s, mean (m/s)	Conditional s, pred (m/s)	t	ME 95% CL (± m/s)	SPFP 95% CL ± m/s)
3.	107.4	57.76	2.7	13.8	4.186	5.42	27.7

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression



0.30 cal. APM2, 0°

Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

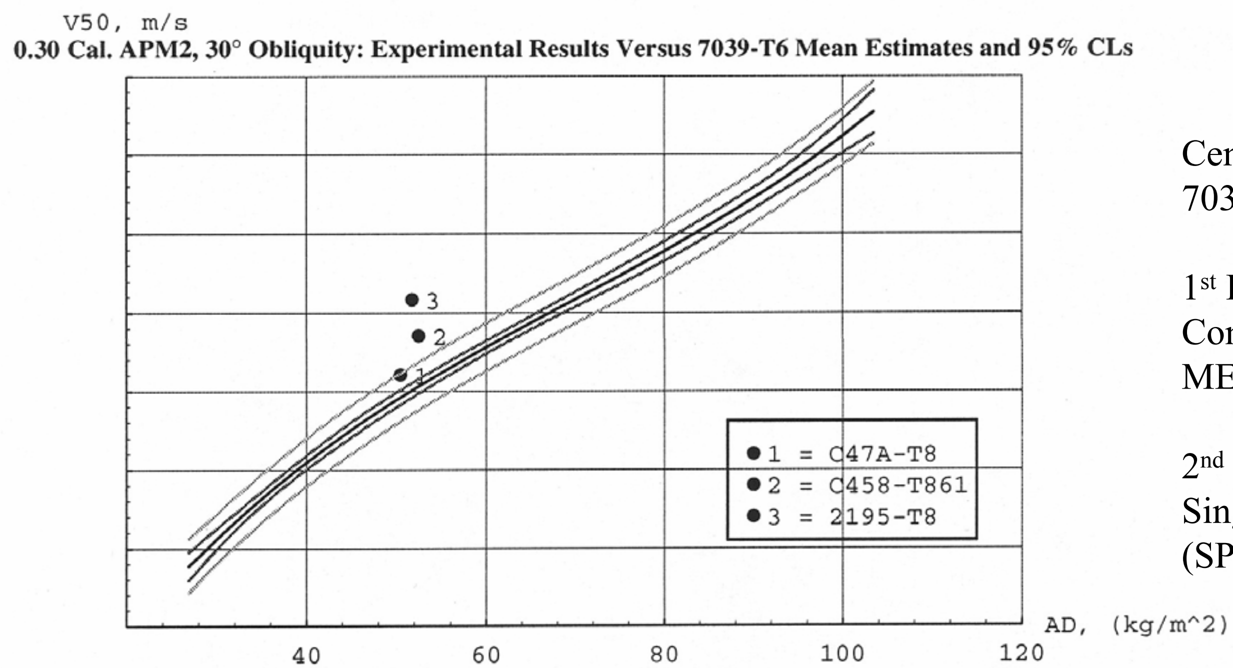
2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

0.30 cal. APM2, 0° Obliquity
Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy (i)	AD (kg/m2)	V50-VME7039 (m/s)	Conditional s, mean (m/s)	Conditional s, pred (m/s)	t	ME 95% CL (± m/s)	SPFP 95% CL (± m/s)
1	50.26	14.63	5.346	20.4	0.7173	10.72	40.9
3	51.76	67.41	5.264	20.38	3.308	10.55	40.86
2	52.43	23.61	5.231	20.37	1.159	10.49	40.84
4	54.34	63.88	5.146	20.35	3.139	10.32	40.8
3	86.02	94.82	3.253	19.95	4.752	6.522	40.01
4	91.03	70.06	3.385	19.98	3.507	6.787	40.05
3	108.90	77.14	4.556	20.21	3.818	9.134	40.51

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression



0.30 cal. APM2, 30°

Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

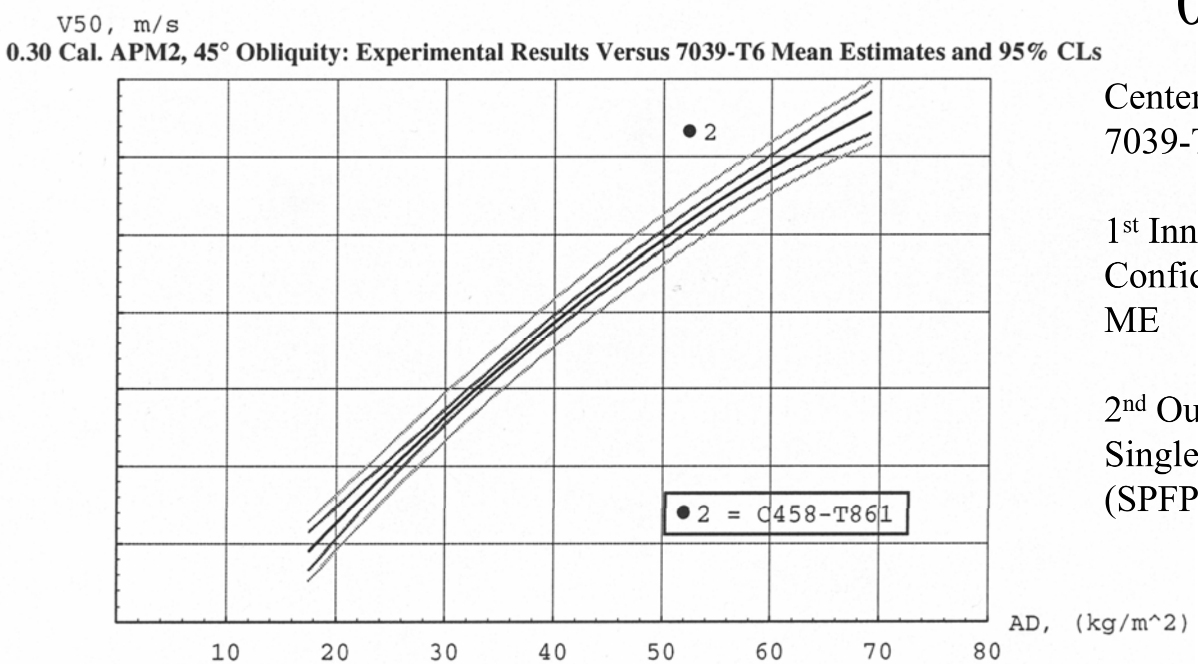
0.30 cal APM2, 30 deg
Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy (i)	AD (kg/m2)	V50-VME7039 (m/s)	Conditional s, mean (m/s)	Conditional s, pred (m/s)	t	ME95% CL (± m/s)	SPFP 95% CL (± m/s)
1	50.4	29.01	4.582	14.82	1.958	9.502	30.73
3	51.76	115.3	4.506	14.79	7.792	9.345	30.68
2	52.5	64.12	4.457	14.78	4.339	9.244	30.65

Discussion

Comparisons to 7039-T6 V50 Performance: LS Regression

0.30 cal. APM2, 45°



Center (black) line = Predicted Mean 7039-T6 V50 Estimate, (ME)

1st Inner (gray) lines = 7039-T6 ME Confidence Interval Limits = 95% (CL) ME

2nd Outer (gray) lines = 7039-T6 CL Single Point Future Prediction = 95% CL (SPFP)

0.30 cal. APM2, 45 deg
Exp. Results Vs 7039-T6 Mean V50 Estimates and Confidence Interval Limits of the Mean and Single Point Future Prediction

Alloy	AD	V50-VME7039	Conditional s, mean	Conditional s, pred	t	ME 95% CL	SPFP 95% CL
(i)	(kg/m2)	(m/s)	(m/s)	(m/s)		(± m/s)	(± m/s)
2	52.4	116.1	5.762	14.42	8.047	12.68	31.74

Discussion

Oblique-V50 Results:

Regression-Estimate Comparisons to V50s of 0°-ADs Up-Scaled by LOS Thickness / Target Thickness (secant θ of Target Obliquity)

Proj. Obl. θ	Experimental Alloys: Oblique Results and Predicted 0° Obliquity V50s					
	Alloy	Thick. (mm)	AD, θ (kg/m^2)	Equiv. LOS at θ = 0° Thick. (mm)	Equiv. LOS at θ = 0° AD (kg/m^2)	Improvement, $V50_\theta$–LOS 0°V50 (m/s)
30	C47A	19.08	50.40	22.03	58.20	21.3
30	2195	19.11	51.76	22.07	59.77	55.8
30	C458	19.94	52.50	23.02	60.62	48.9
45	C458	19.90	52.40	28.14	74.10	235.9
7039-T6: Oblique and 0° Regression Predicted MEs, Reference Data						
	AD, θ (kg/m^2)			Equiv. LOS at θ = 0° AD (kg/m^2)		Improvement, $V50_\theta$–LOS 0°V50 (m/s)
30	50.40			58.20		7.0
30	51.76			59.77		7.9
30	52.50			60.62		8.4
45	52.40			74.10		143.4
	2519: Oblique Point Estimates and Simple Linear 0° Obliquity MEs, Reference Data					
	AD, θ° PE			Equiv. LOS at θ = 0° AD		Improvement, $V50_\theta$–LOS 0°V50
30	55.62			64.24		–31.7

Notes: For 7039, LOS V50s were estimated from LOS ADs by the 0.30-cal. APM2, 0° regression equation

For experimental alloys, LOS V50s were estimated at 0° obliquity with LOS ADs and the 0.30-cal. APM2, 0° regression equation with b_0 = coefficient adjusted upward 14.63 for C47A, 23.61 for C458, and 67.41 for 2195 to fit V50 improvements of the 19- to 20-mm nominal thickness targets.

Discussion

Experimental Oblique-Impact V50 vs. (LOS t / t) Scaled, 0° V50

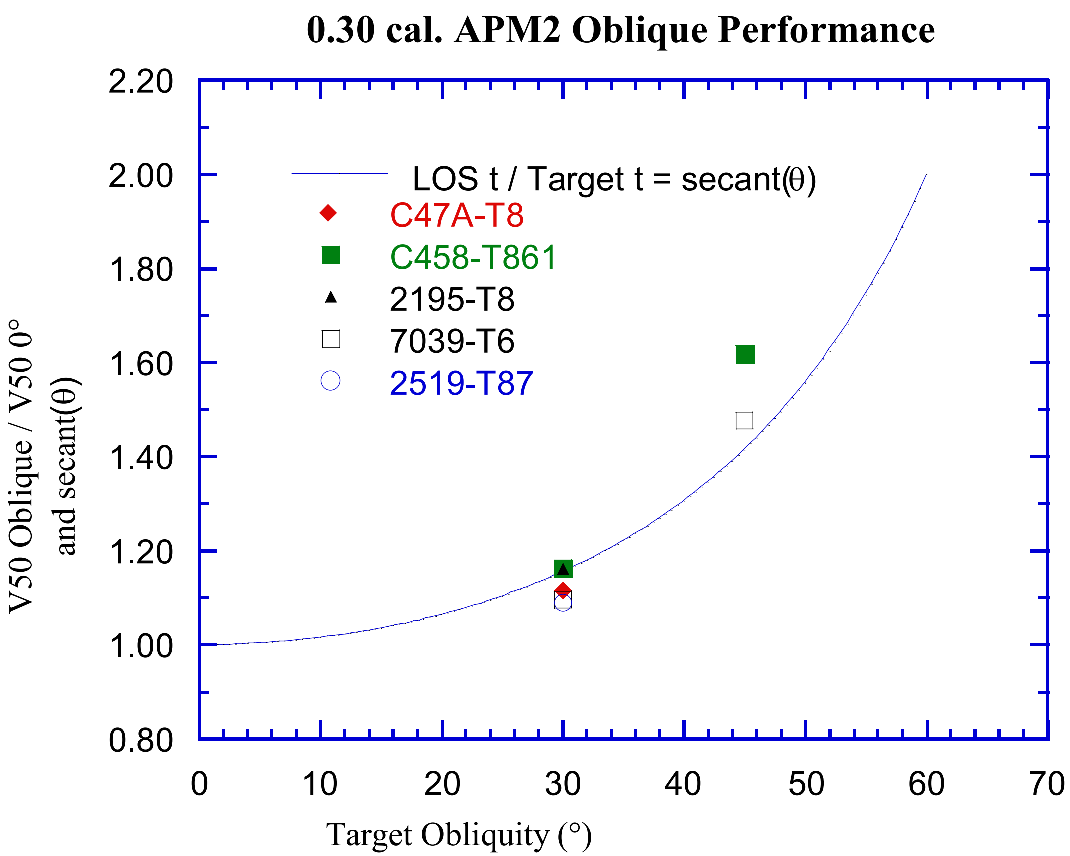
Experimental Results, 0.30-cal. APM2 (Figure 5c–d)						V50, θ Oblique vs. θ = 0° Sec(θ) Scaled Exp.		
Obliquity θ Deg. 0 and θ°	Exper. Alloy	θ = 0° Exp. Data		θ = 30 or 45° Exp. Data		sec θ	sec x 0°	Excess
		Thick. (mm)	AD (kg/m^2)	Thick. (mm)	AD (kg/m^2)	LOSt/ target t	AD (kg/m^2)	V50θ–V500°secθ (m/s)
0 and 30°	C47A	19.02	50.26	19.08	50.40	1.155	58.20	–21.7
0 and 30°	2195	19.11	51.76	19.11	51.76	1.155	59.77	4.0
0 and 30°	C458	19.91	52.43	19.94	52.50	1.155	60.62	4.4
0 and 45°	C458	19.91	52.43	19.90	52.40	1.414	74.10	117.6
Regression of 7039-T6 vs. 0.30-cal.						V50 ME, θ Oblique vs. θ = 0° Sec(θ) Scaled ME.		
Obliquity θ Deg. 0 and θ°	AD Point	θ = 0° Regression		θ = 30, 45° Obl. Regr.		sec θ	sec x 0°	Excess
			AD (kg/m^2)		AD (kg/m^2)	LOSt/ target t	AD (kg/m^2)	V50θ–V500°secθ (m/s)
0 and 30°	C47A		50.26		50.40	1.155	58.20	–33.82
0 and 30°	2195		51.76		51.76	1.155	59.77	–33.45
0 and 30°	C458		52.43		52.40	1.155	60.62	–32.41
0 and 45°	C458		52.43		52.40	1.414	74.10	34.87
Simple Linear and Point Estimates, 2519 vs. 0.30-cal. APM2 Ref. Data						V50 PE, θ Oblique vs. θ = 0° Sec(θ) Scaled SLE		
θ Deg. 0 and θ°	AD Point	θ = 0° SLE Mean		θ = 30° (4 PE Mean)		sec θ	sec x 0°	Excess
			AD (kg/m^2)		AD (kg/m^2)		AD (kg/m^2)	V50θ–V500°secθ (m/s)
0 and 30°	2519		55.62		55.62	1.155	64.23	–37.8
2519 vs. 0.50-cal. APM2, Ref. Data						V50, θ Oblique vs. θ = 0° Sec(θ) Scaled		
θ Deg. 0 and θ°	AD Point	θ = 0° Ref. Data		θ = 45° Ref. Data			sec x 0°	Excess
			AD (kg/m^2)		AD (kg/m^2)	sec θ	AD (kg/m^2)	V50θ–V500°secθ (m/s)
0 and 45°	2519		108.8		109.3	1.414	154.5	24.4

Notes:

ME = LS Regression Mean Estimate, SLE = Straight Line Estimate), PE = (4) Point Estimate

Discussion

Experimental Oblique-Impact V50 vs. V50 0°and (LOS t / Target t)



- 2195-T8 and C458-T861 V50 performance and mass efficiency improve with target obliquity, C4585 V50 Oblique 45°/ V50 0° = 1.62 versus sec(θ) =1.414

Conclusions

- **Al-Li Alloys: Best Specific Strengths**
- **Protection versus FSP, 0°, approximate 7039-T6 Average**
- **Superior Protection Vs AP Projectile:**

  -V50 Performance Improves with Target Strength

  -Al-Li V50 & M_e Performance Improves w Oblique Impact

    *** Exceeds 7039 or 2519 performance**

    *** Material Parameters and Failure Mode of 2195 and C458 Enhance Protection versus AP projectile**

    ***Reduced sensitivity failure mode to increased V**

- **Damage-Tolerant, High Shot Density, Multiple Impact Capabilty**