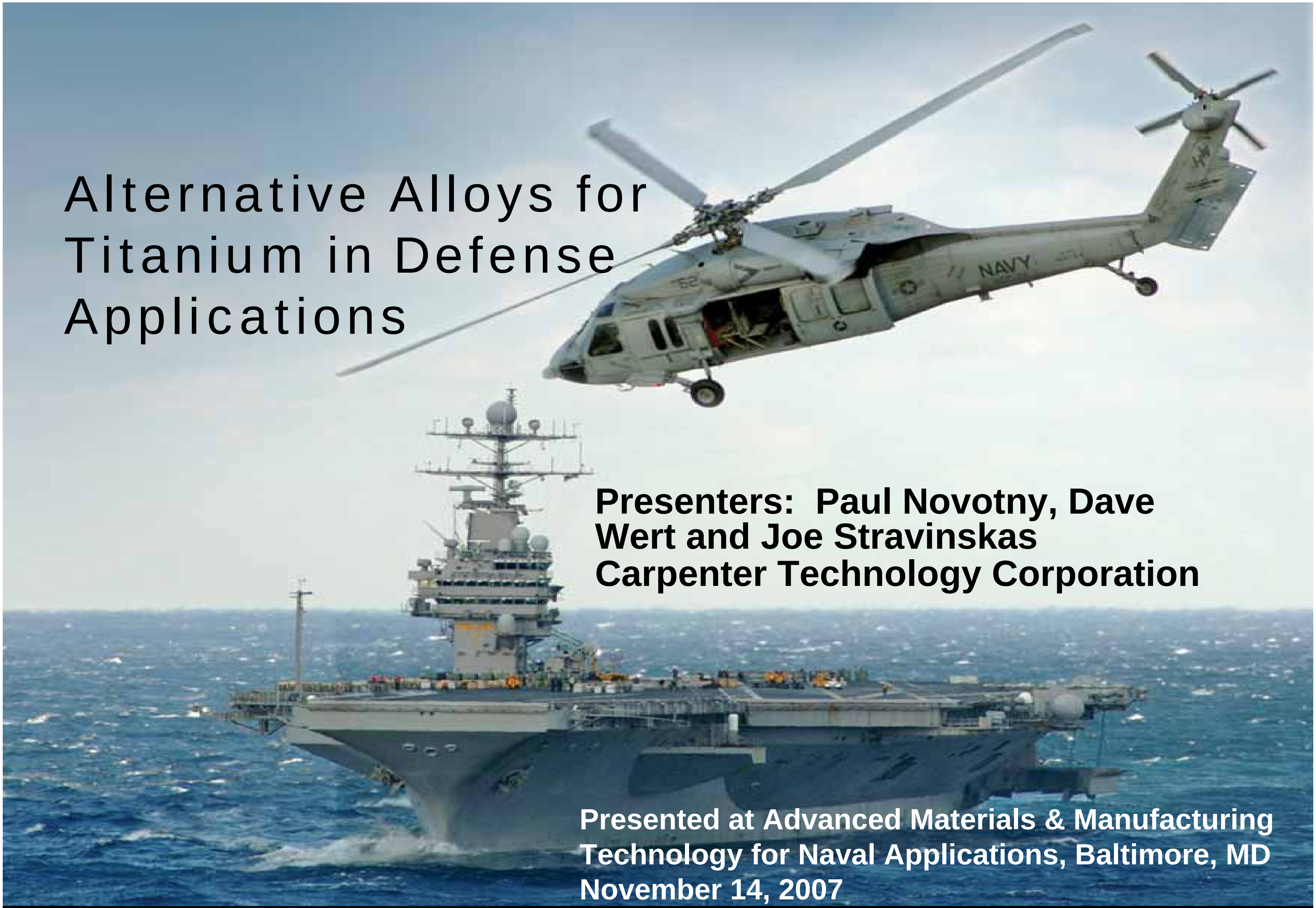


Alternative Alloys for Titanium in Defense Applications

Presenters: Paul Novotny, Dave Wert and Joe Stravinskas
Carpenter Technology Corporation

Presented at Advanced Materials & Manufacturing Technology for Naval Applications, Baltimore, MD
November 14, 2007

Scope of Presentation

- Overview of titanium properties
- Overview of high-performance alloys
- Engineering measures of properties
    - Specific strength
    - Toughness index
- Comparison of properties of alloys
    - Advantages/disadvantages
    - Options on materials

Selection of Materials

- All materials have advantages and disadvantages.
  - Engineering involves trade-offs of properties.
  - Material options exist in almost all situations.
  - Design considerations vary widely by end use criteria.
- Driving forces for selections involve commercial as well as engineering considerations.
  - No single correct solution exists.
- Ultimately, properties are compared and contrasted, and decisions are made to meet end user requirements.

Titanium Properties – High Level View

- Inherent corrosion resistance
  - No need for plating
- Weight Savings
  - Density is approximately 60% of steels
- Lower Stiffness
  - Modulus of 16M psi vs. 28M psi for steels
- Non-magnetic
- Moderate operating temperatures, 800 - 1000°F
- Commercial considerations
  - Reliability of supply chain is in question
  - High cost
  - Long lead times
- Ti alloys selected for comparison in this study
  - Ti-6Al-4V
  - Ti-10V-2Fe-3Al

Traditional Alloys

- **4340 Family**
  - **4340 circa WWII**
    - **“Granddaddy” of alloy steels**
  - **300M – landing gear upgrade to 4340**
    - **Circa 1960’s**
    - **UTS $\geq$ 280 ksi**
  - **Both 4340 and 300M are excellent alloys but in many cases the design criteria now exceed capabilities.**
- **Maraging Family**
  - **18% Ni and Ti & Mo additions for strength and toughness**
  - **Hardened by precipitation of intermetallic compounds**
  - **Improved strength, toughness and fatigue properties**

Custom 465® Stainless – Overview

- Premium melted, martensitic, age hardenable alloy
- Full fledged stainless steel (12% Cr, 11% Ni)
- General corrosion resistance comparable to type 304, 17-4, and Carpenter 13-8
- Strength comparable to high performance structural alloys
- A <u>stainless</u> alternative to high strength alloys
  - Eliminates the need for plating
  - High strength allows for smaller design envelope
  - Good Stress Corrosion Cracking (SCC) resistance
- Meets Navy KIc/Y.S. > 1.0 in overaged condition

AerMet® Family – Overview

- AerMet 100 alloy
    - Developed to fill a void identified by U.S. Navy for a strong, tough alloy for F/A-18 landing gear
    - Drop-in replacement for 300M with 2X fracture toughness
    - Benchmark material
    - Best combination of U.T.S. and Fracture Toughness
- AerMet 310 – minimum U.T.S. of 310 ksi
- AerMet 340 – minimum U.T.S. of 340 ksi
- AerMet family characteristics
    - Premium melted
    - Ductile lath martensite
    - Very high toughness at a given strength level
    - High strength allows for a smaller design envelope
    - Not a stainless steel

90° Bend Radius Testing

AerMet 100 - Fully Aged

Diam. (inch)	Bend Radius (inch)	Bend	Result
0.183	1/2	2.7t	Pass
0.256	1/2	2.0t	Pass
0.350	1/2	1.4t	Pass

AerMet 340 - Fully Aged

Diam. (inch)	Bend Radius (inch)	Bend	Result
0.186	1/2	2.7t	Pass
0.271	1/2	1.8t	Fail
0.271	3/4	2.8t	Pass
0.351	3/4	2.1t	Pass

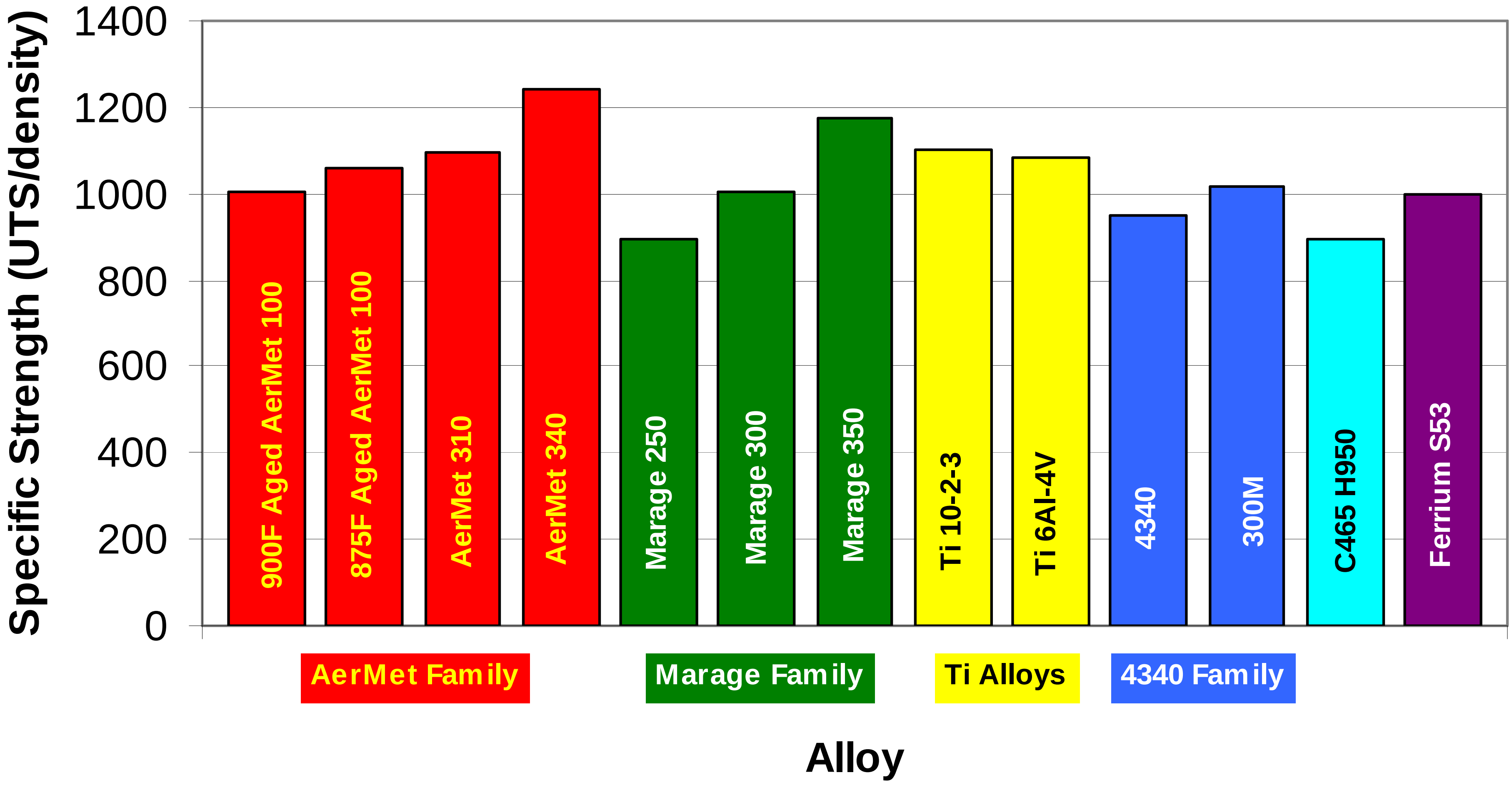
Ferrium S53 – Overview

- Developed by QuesTek Innovations, LLC
  - Designed as a landing gear alloy
  - Designed to be a drop-in replacement for 300M
  - U.T.S. ≥ 280 ksi
  - Corrosion resistance superior to 300M
- Qualification
  - AMS 5922 specification to be issued January ‘08
  - MMPDS
    - 10th heat melted Fall ’07
    - Qualification anticipated in 2008
  - Carpenter licensed to melt and distribute the alloy

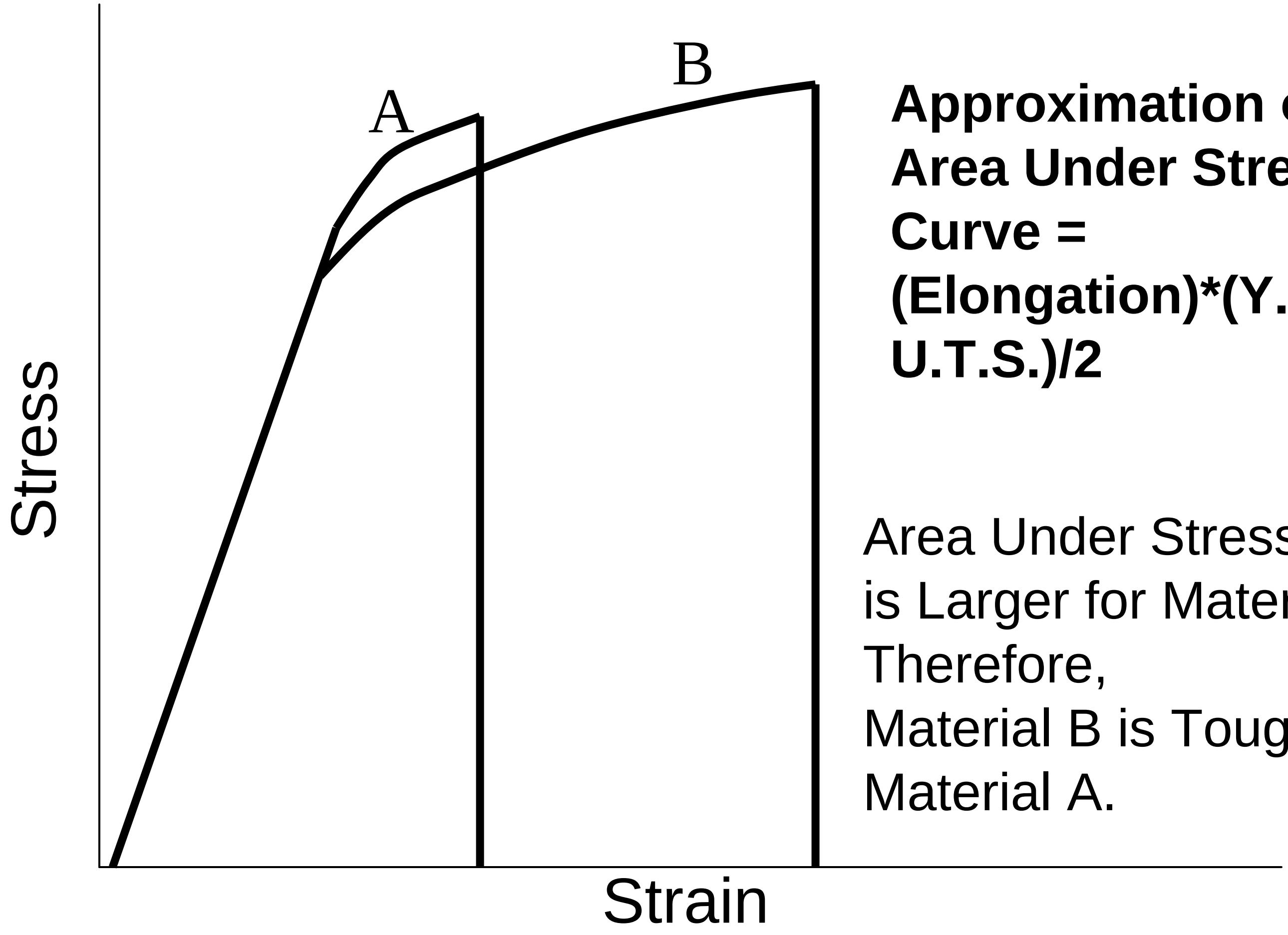
Specific Strength

- Density of titanium is 60% of the density of steels
  - Comparison or properties becomes difficult unless this is taken into consideration
- Specific strength
  - Ultimate Strength (U.T.S.) divided by density
  - Normalizes the U.T.S. by removing the density factor
- Clearly highlights a key benefit of titanium

Specific Strength Comparison



Toughness –
Area under the Stress-Strain Curve



Approximation of Area Under Stress-Strain Curve = (Elongation)*(Y.S. + U.T.S.)/2

Area Under Stress-Strain Curve is Larger for Material B than A. Therefore,
Material B is Tougher Than Material A.

Reference: Dieter, G. E., Mechanical Metallurgy, 3rd. Edition, McGraw-Hill, NY, (1986), p. 283

Toughness considerations expanded…

Maximize Strength AND Toughness - Inverse Relationship

Strength Measure is **U.T.S.**

Use 3 Toughness Measures in **“Toughness Index”**

Classical Mechanics of Materials Toughness Measure:
“Bend-Before-Breaking” or Damage Tolerance
Area Under Stress-Strain Curve

2 Toughness Measures when Stress Concentrations Present:

Notches	**Charpy V-Notch Impact Tests**
Cracks	**Fracture Toughness (KIc) Tests**

Normalize all 3 toughness measures to a 0 - 100 scale

Toughness Index is Geometric Mean of 3 Toughness Measures
(multiply the 3 toughness measures together and take cube root)

Toughness Index* =

$$\sqrt[3]{\underbrace{[((\text{Elong.})*(\text{Y.S.}+\text{U.T.S.})/2)/50]}_{\substack{\text{Area Under Stress-Strain Curve}\\ \text{Divided by 50 to Normalize}}}*[\text{CVN}*3]*[\text{KIc}]}$$

CVN Impact Energy
Multiplied by 3 to Normalize

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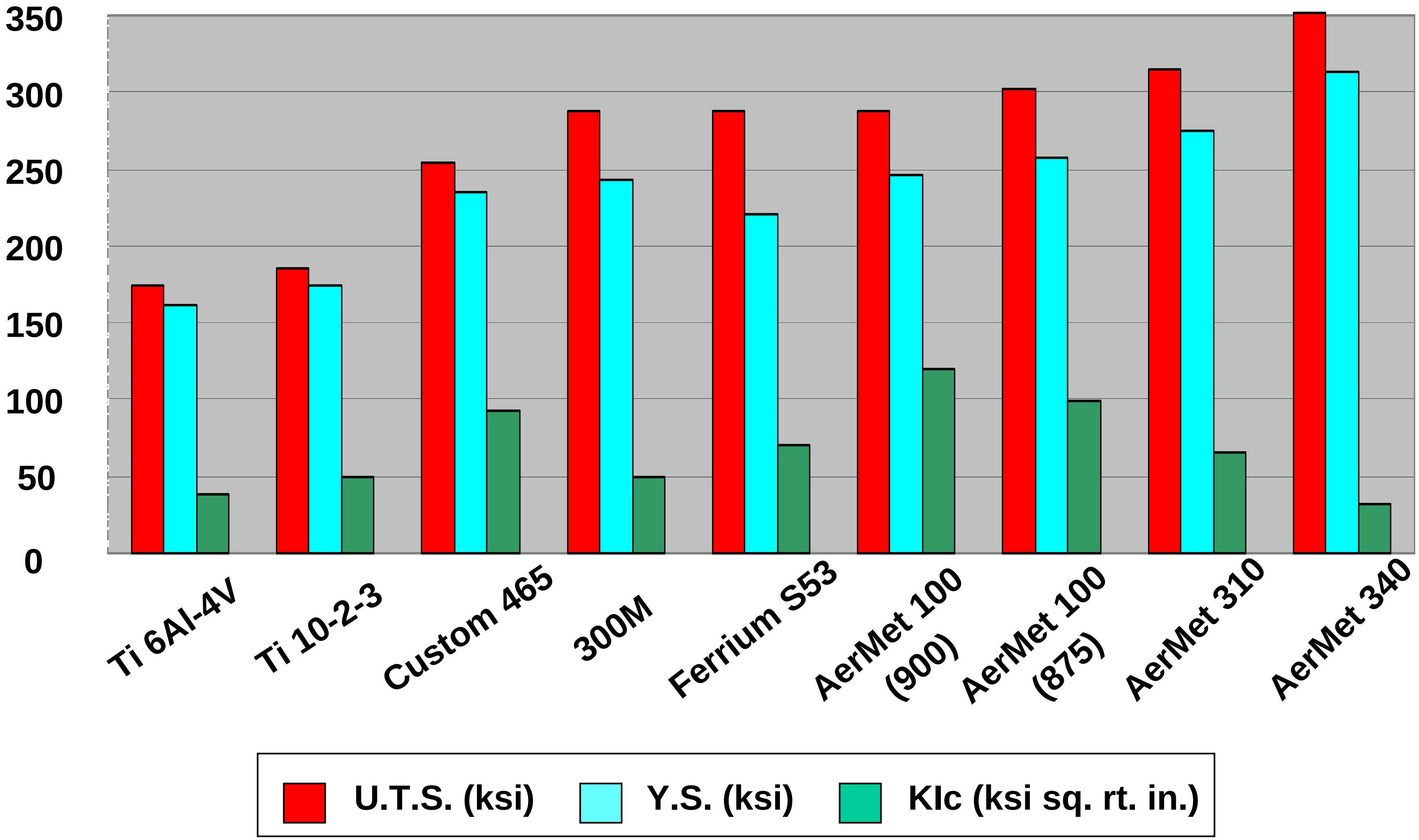
* From P. Novotny, "Toughness Index for Alloy Comparisons," Advanced Materials & Processes, May 2007.

Comparisons of Mechanical Properties

	900 F Aged	875 F Aged			Marage								
Property	AerMet 100	AerMet 100	AerMet 310	AerMet 340	250	300	350	Ti 10-2-3	Ti 6Al-4V	4340	300 M	C465 H950	S53
Y.S. (ksi)	246	258	275	314	250	282	336	175	162	225	243	235	220
U.T.S. (ksi)	287	302	315	352	259	291	344	185	174	269	287	254	288
Elong. (%)	16.1	14.2	14.5	11.3	10.7	8.6	6.1	8.5	12.5	12.0	9.8	14.0	15.0
R.A. (%)	67.3	63.8	63.0	55.2	51.1	40.8	22.2	17.5	52.0	40.0	35.0	63.0	60.0
KIc (ksi in. $^{1/2}$)	120.0	98.7	65.0	31.5	91.5	67.7	38.5	49.6	39.1	70.0	50.0	92.0	74.0
CVN I.E. (ft-lbs.)	35.0	30.0	20.0	10.8	20.5	18.5	10.0	22.0	18.5	18.0	18.0	20.0	18.0
Modulus (psi x 10^6)	28.2	27.9	27.9	27.9	27.0	27.5	27.0	16.0	16.0	30.0	29.0	28.8	28.8
Density (lbs./in.^{3})	0.285	0.285	0.288	0.284	.289	.289	.292	0.168	0.160	.283	.283	0.283	.288
Area Under Curve	4291	3976	4278	3763	2720	2462	2074	1528	2097	2964	2597	3423	3810
Fatigue Stress (ksi)	137	137	150	143	110	128	112	120	102	79	85	105	120
Toughness Index	103	89	69	43	67	57	36	46	45	61	52	72	67
Specific Strength	1007	1060	1094	1239	895	1007	1177	1101	1084	951	1014	898	1000

Strength/Toughness Comparison



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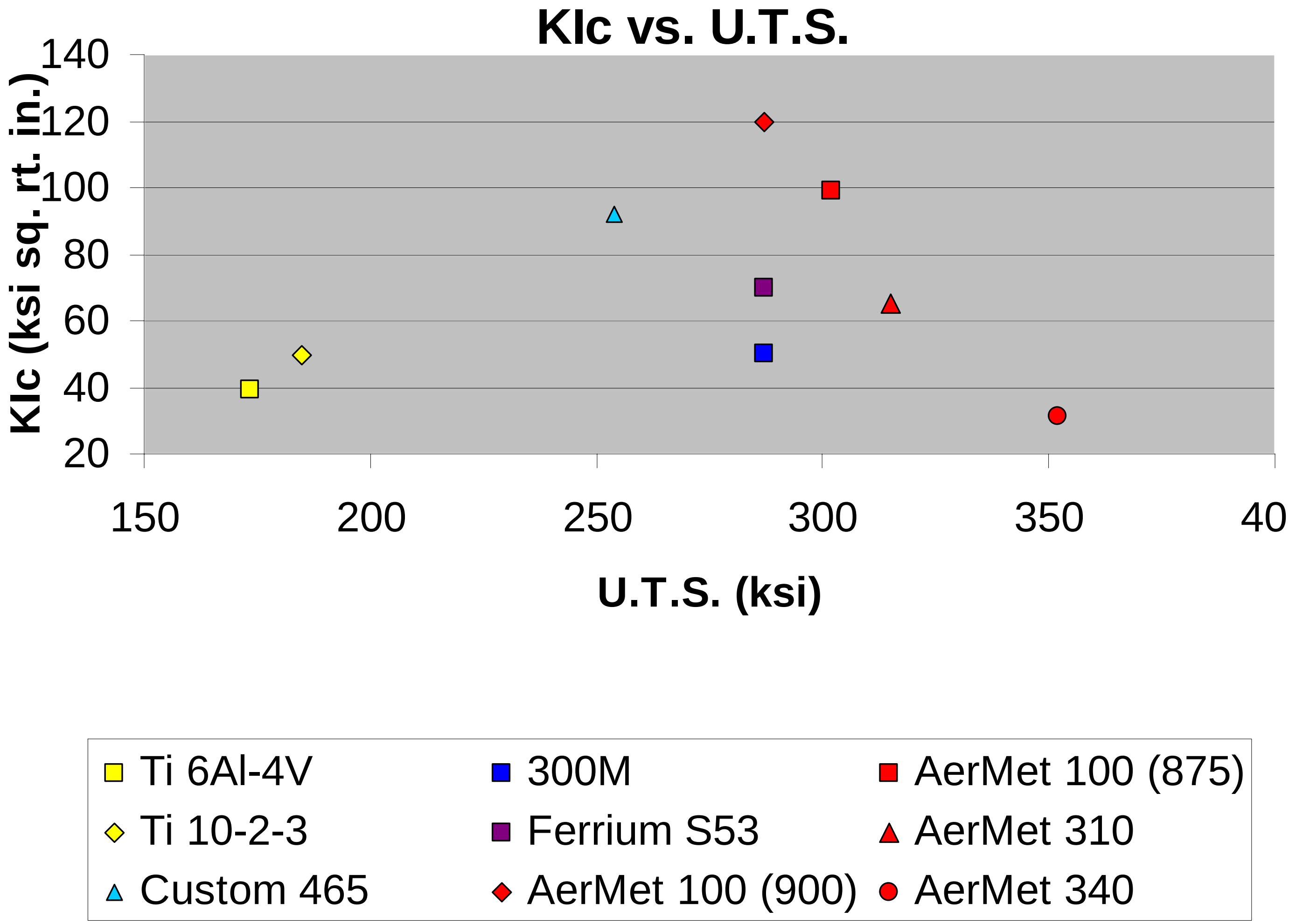
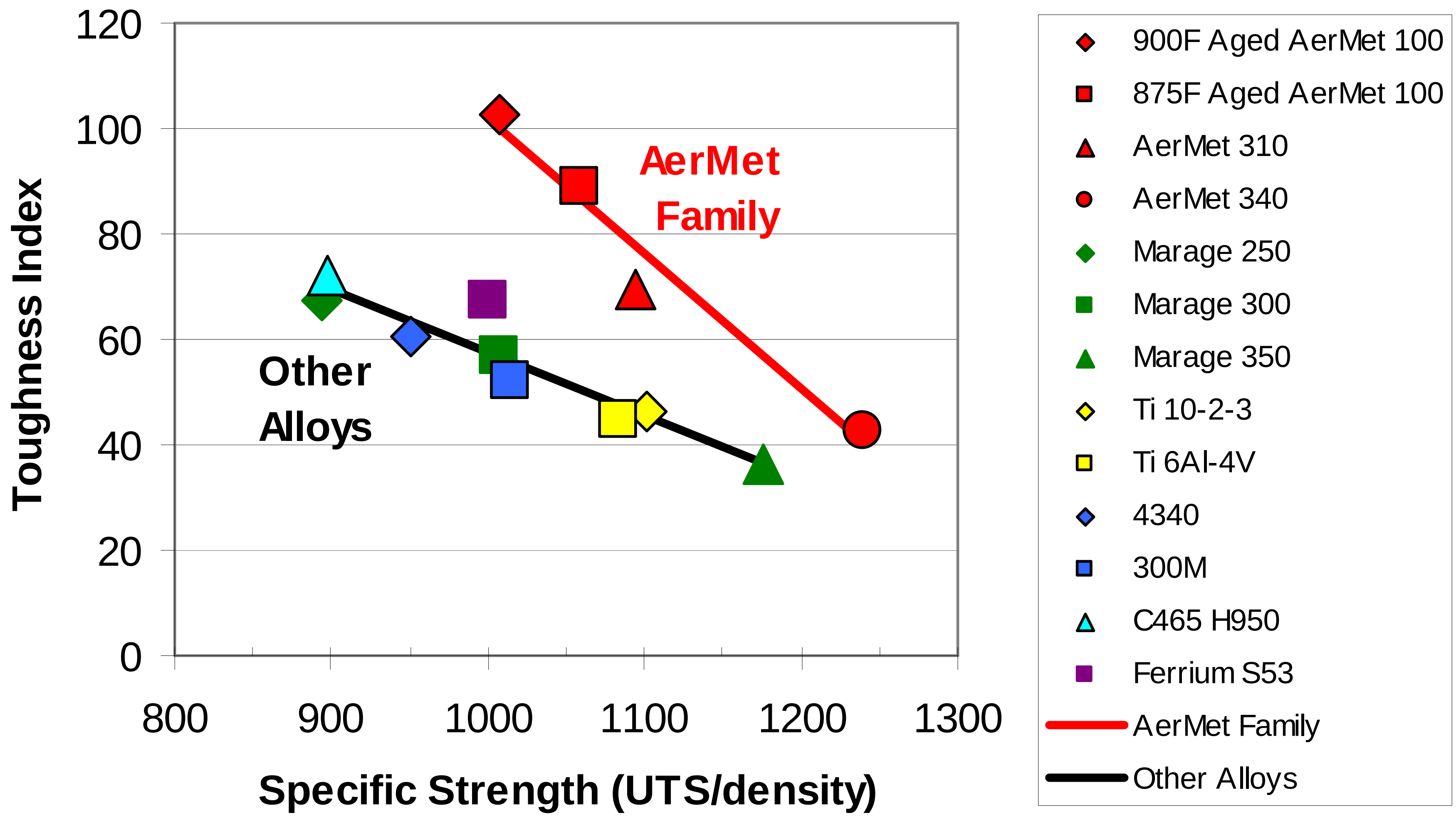
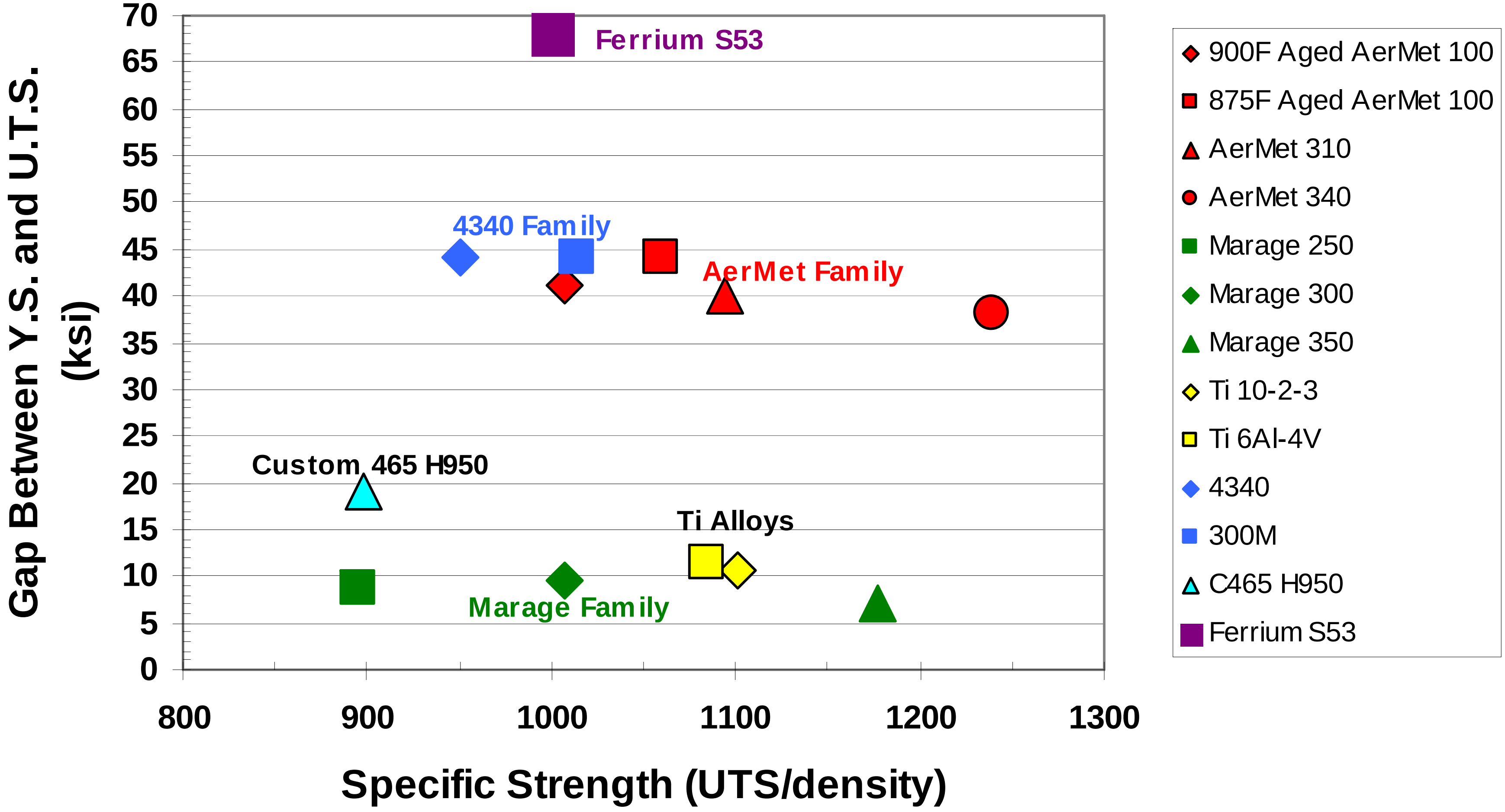
Toughness vs. Strength Comparison

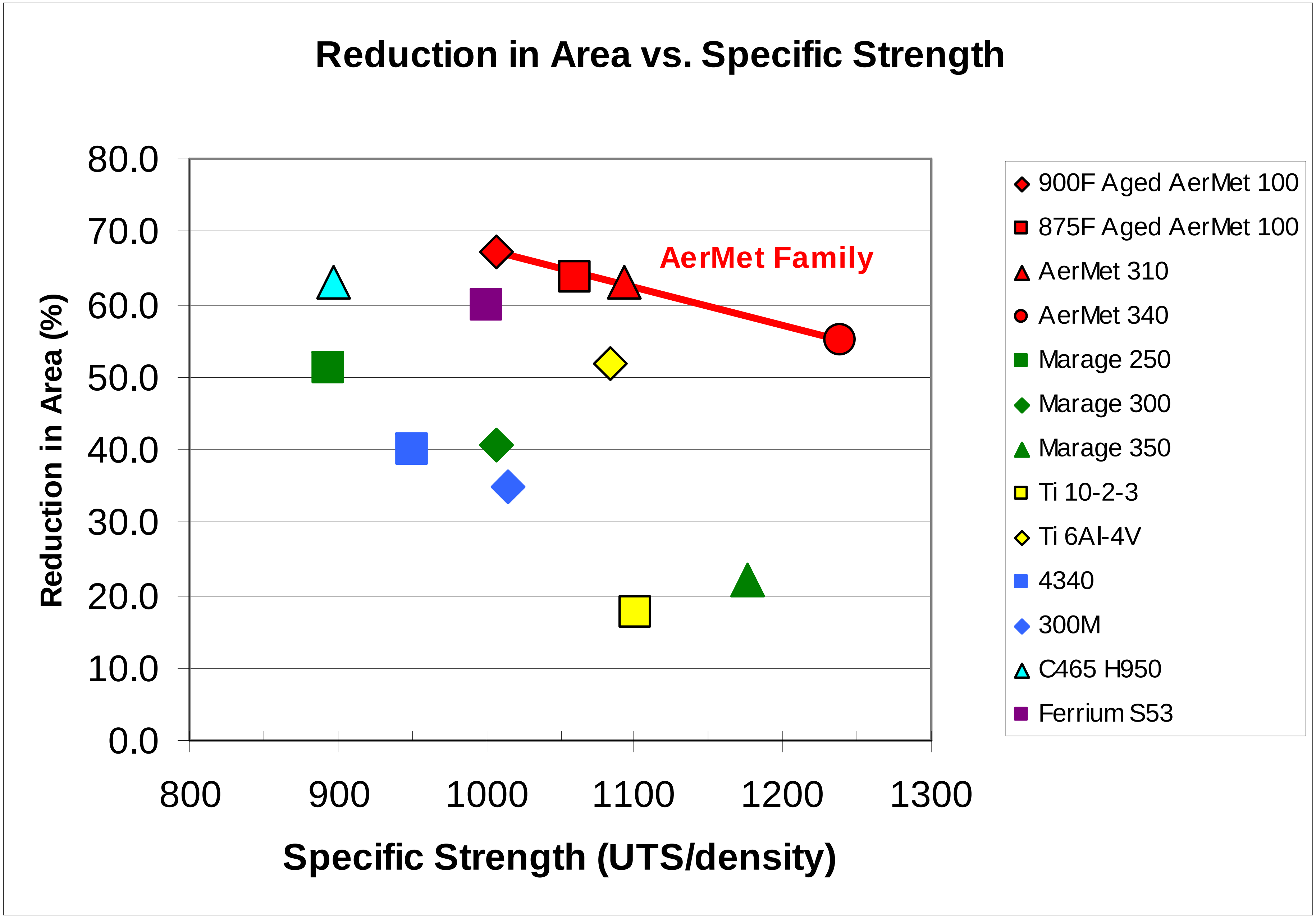


Toughness Index vs. Specific Strength

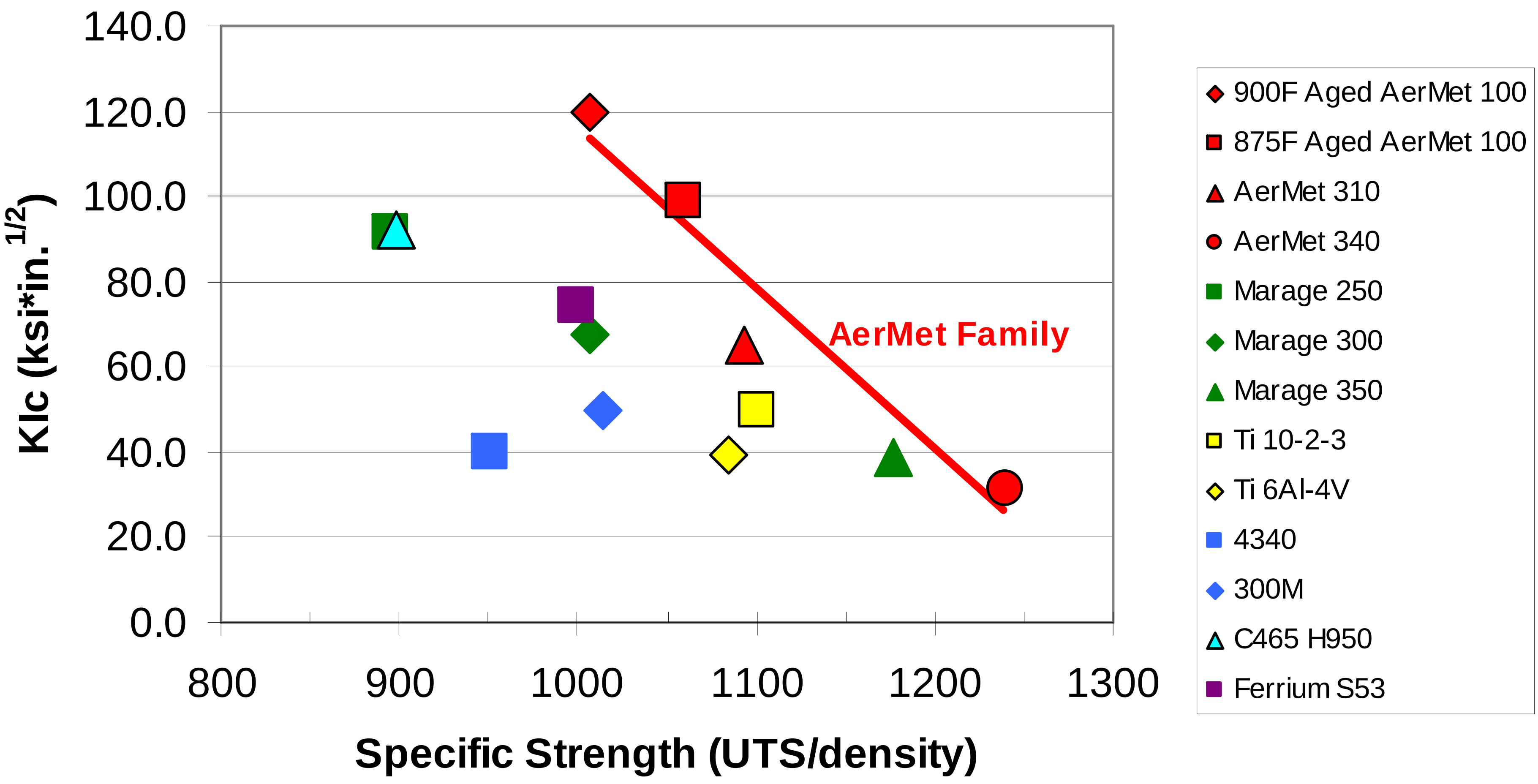


Gap Between Yields and Ultimate Tensile Strengths vs. Specific Strength

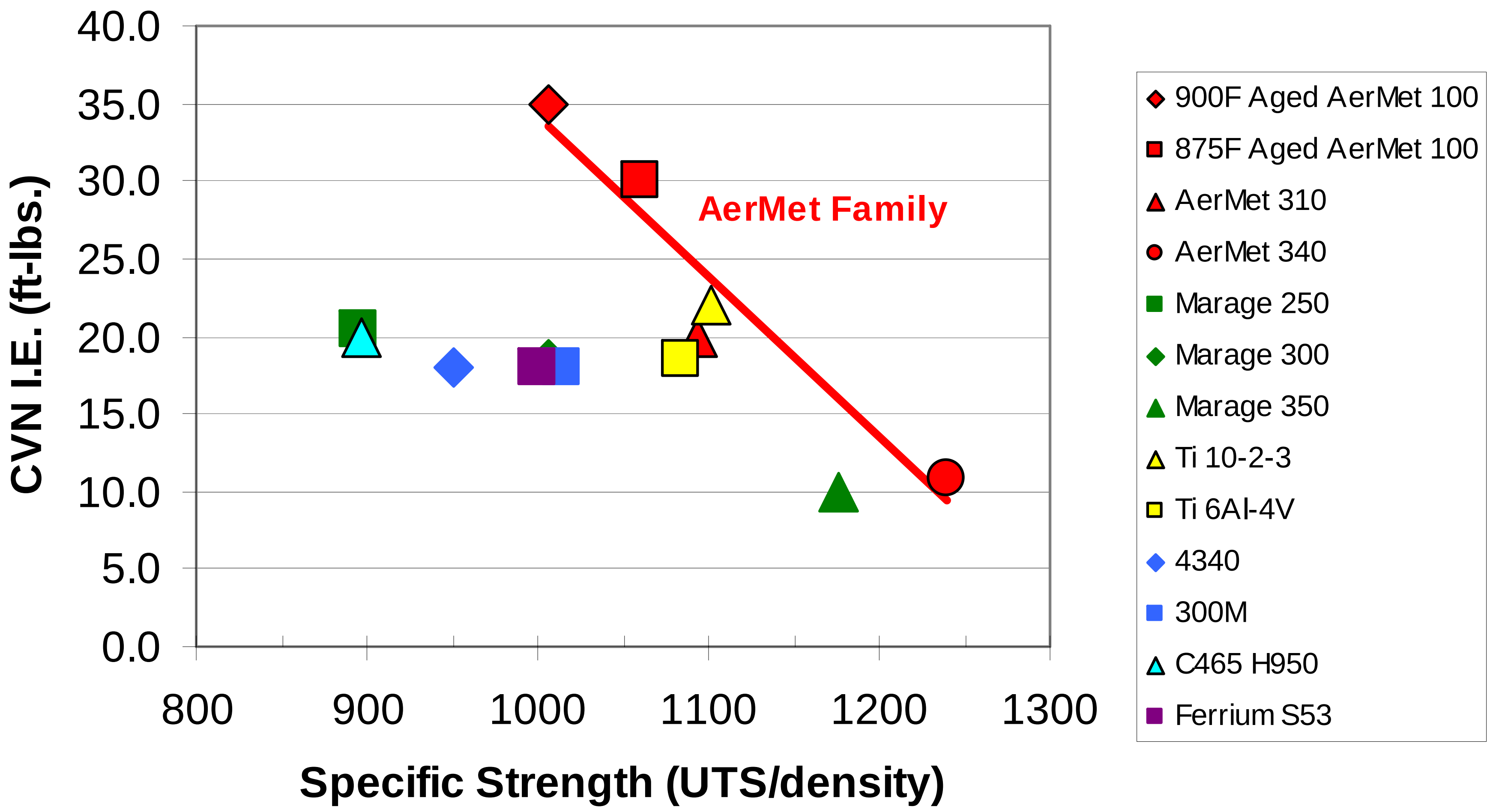



Reduction in Area vs. Specific Strength
Reduction in Area (%)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
800
900
1000
1100
1200
1300
Specific Strength (UTS/density)
AerMet Family
◆ 900F Aged AerMet 100
■ 875F Aged AerMet 100
▲ AerMet 310
● AerMet 340
■ Marage 250
◆ Marage 300
▲ Marage 350
□ Ti 10-2-3
◇ Ti 6Al-4V
■ 4340
◆ 300M
△ C465 H950
■ Ferrium S53

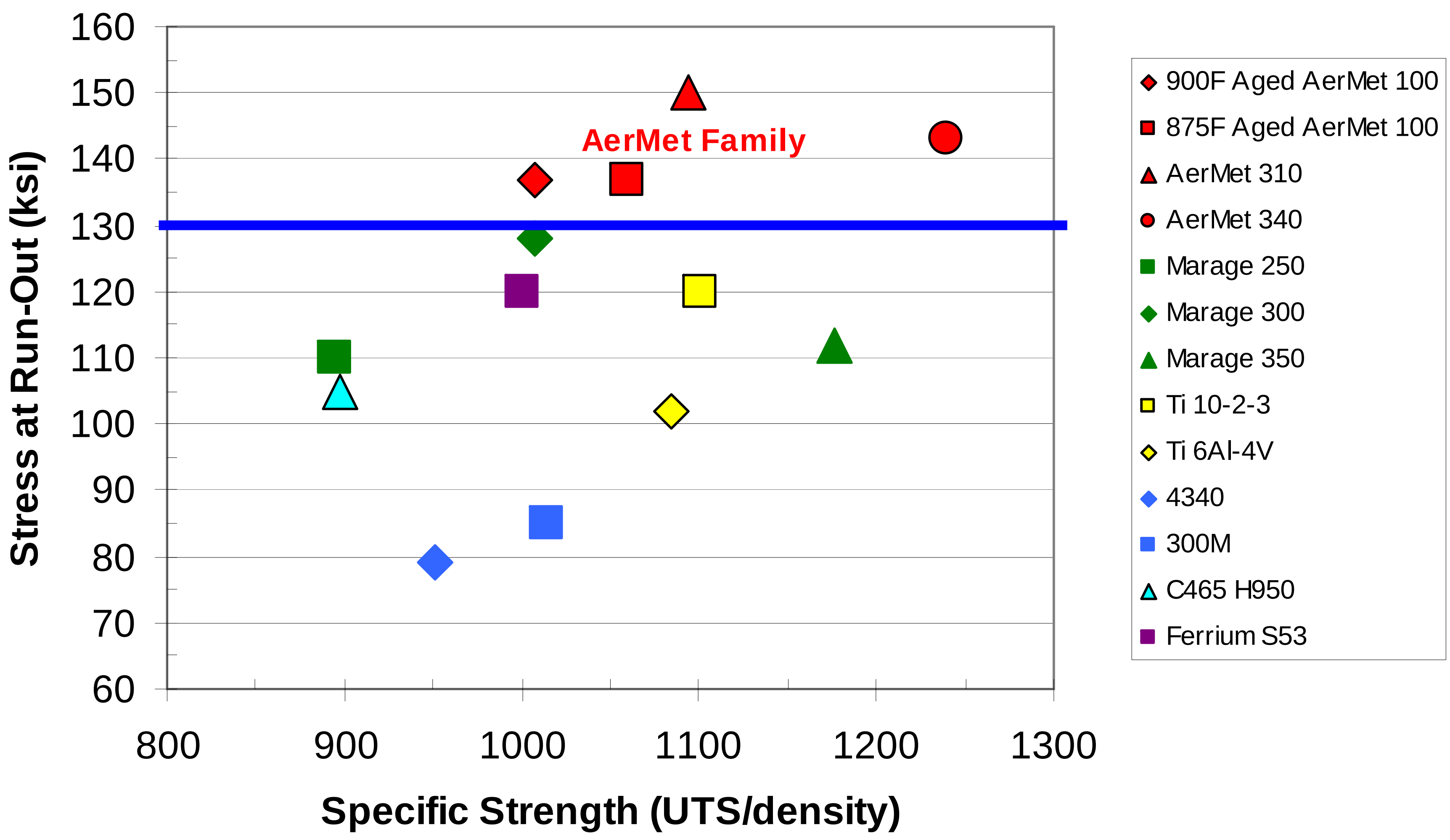
Fracture Toughness vs. Specific Strength



CVN Impact Energy vs. Specific Strength

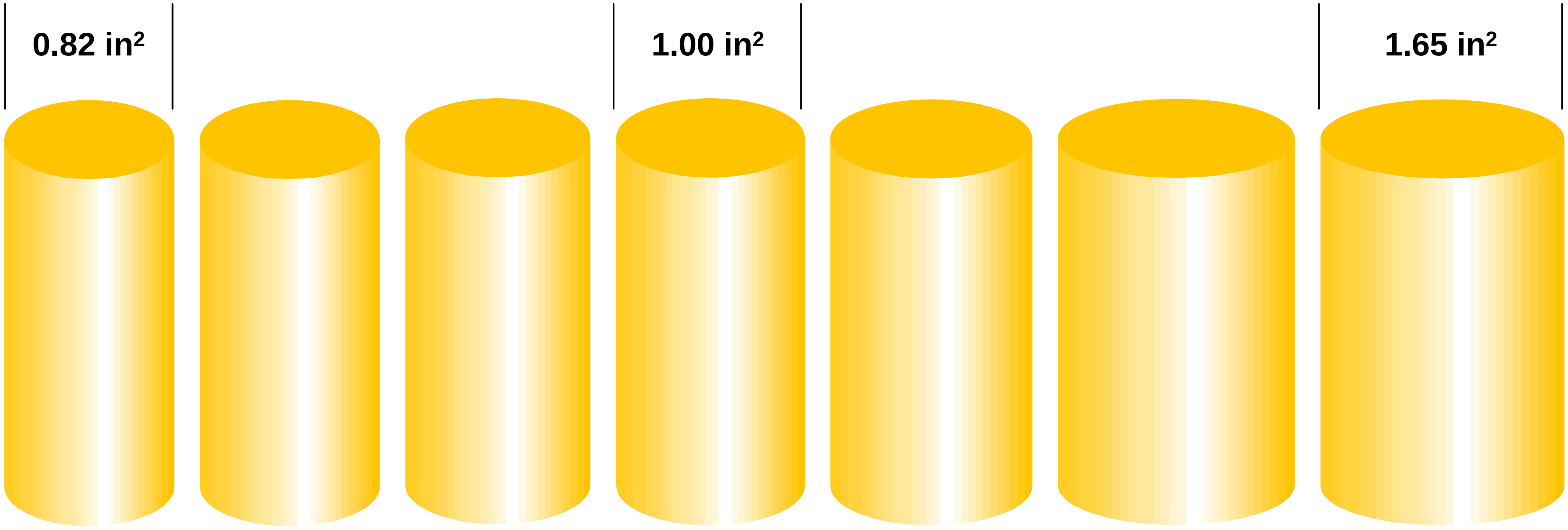


Rotating Bending Fatigue (Kt = 1, R = -1) Run-Out Stress vs. Specific Strength



Volume Envelope Comparison

Footprint of material required to resist fracture at load of 285,000#



AerMet® 340

AerMet 310

AerMet 100 (875F)

300M
AerMet 100 (900F)
Ferrium S53

Custom 465® Stainless

Ti 10-2-3

Ti 6-4

Summary

- Are other alloys direct substitutions for Ti in all instances?
  - Of course not
- There are other alloys that can be alternatives for Ti depending on the design criteria
- AerMet alloys can be an alternative to Ti if corrosion resistance is not a design factor
  - AerMet alloys can be plated or painted
  - AerMet alloys have specific strengths comparable to Ti
  - AerMet alloys should be more damage tolerant than Ti
  - Generally superior toughness index compared to Ti

Summary

- Custom 465 stainless is a full-fledged stainless steel
  - Specific strength lower, but approaches Ti levels
  - Should not be welded or joined to Ti
  - Volume envelope is smaller than Ti for a given load
- Bottom line – consider all design criteria before decision making

Carpenter Technology Corporation

www.cartech.com

Toll-free in the U.S. 800-654-6543

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