ULTRA-HIGH-STRENGTH STEELS VS TITANIUM ALLOYS

This study compares the strength, ductility, toughness, and fatigue properties of AerMet alloys, maraging steels, and titanium.

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The range of ultra-high-strength steels with good toughness has expanded in recent years to allow more alloy choices. In addition to maraging steels, another family of ultra-high strength steels that possess outstanding toughness has been developed to meet the same demanding service requirements.

This article discusses evolution of the newer AerMet alloy family, then compares those steels with maraging steels and titanium alloys. Relative strength, ductility, toughness, and fatigue properties of the three groups are described in detail, showing that the AerMet alloys have better fatigue life and overall better combinations of strength and toughness than either the maraging steels or titanium alloys.

Family evolution

The AerMet 100 alloy was developed in response to a need from McDonnell Douglas and the U.S. Navy for a stronger and tougher material for the landing gear of the F/A 18 E/F fighter aircraft. The Navy wanted an alloy that could be a drop-in replacement for 300M, but with twice the fracture toughness. The AerMet 100 alloy met the Navy's requirements with its minimum ultimate tensile strength of 280 ksi (1930 MPa) and minimum fracture toughness of 100 ksi$\sqrt{\text{in}}$.

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A cloud builds up around an F/A-18C Hornet as it breaks through the sound barrier above the Pacific Ocean.

AerMet 100 was followed by higher-strength derivatives such as the 875°F-Aged AerMet 100 alloy and the AerMet 310 alloy, which has minimum ultimate tensile strength of 310 ksi (2137 MPa). Another AerMet alloy development program was undertaken because it appeared that even higher strength alloys could be designed. That effort led to the development of AerMet 340 alloy, which has a 340 ksi (2344 MPa) minimum UTS.

Table 1 — Nominal compositions (wt%) of the ultra-high-strength/high-toughness maraging steels and AerMet alloys

	18 Ni maraging family			AerMet family		
Element	**Marage 250**	**Marage 300**	**Marage 350**	**AerMet 100**	**AerMet 310**	**AerMet 340**
C	0.03 max.	0.03 max.	0.05 max.	0.23	0.25	0.33
Cr	0.50 max.	—	0.25	3.1	2.4	2.25
Ni	18	18.5	18	11.5	11	12
Mo	5	5	4.2	1.2	1.4	1.85
Cu	0.50 max.	—	0.15	—	—	—
Co	7.5	9	12.25	13.5	15	15.6
V	—	—	0.04	—	—	—
Ti	0.4	0.6	1.7	0.015 max.	0.015 max.	0.015 max.
Al	—	—	—	0.015 max.	0.015 max.	0.015 max.
B	—	0.003 Add	0.003	—	—	—
Zr	—	0.02 Add	0.01	—	—	—
Ca	—	0.05 Add	0.05	—	—	—

Table 2 — Structure and heat treatment of ultra-high-strength/high-toughness alloys

	18Ni maraging family	AerMet family
Structure		
Type of structure	Precipitation hardened	Precipitation hardened
Matrix	Low C, Fe-Ni lath martensite	Low C, Fe-Ni lath martensite
Strengthening mechanism	Ni_3Mo, Ni_3Ti, $Ni_3(Mo,Ti)$; FeMo, FeTi, Fe(Mo,Ti) precipitates	$(Mo, Cr)_2C$ carbides
Heat Treatment		
Hardening or solution temperature	1500°F (816°C)	1625 to 1775°F (885 to 968°C)
Quench	Air	Air or Oil
Refrigeration	No	–100°F (–73°C), 1 h
Age	900°F (482°C), 3 to 8 h	825 to 925°F (441 to 496°C), 3 to 8 h

Physical metallurgy

Nominal compositions listed in Table 1 show that the AerMet alloy family and the 18Ni maraging steels are closely related chemically.

Table 2 compares the physical metallurgy of both alloy families, which both have a structure that consists of a low-carbon, Fe-Ni-Co lath martensite matrix that is age-hardened. However, the precipitates that age-harden the alloys are different.

The 18Ni maraging steels are hardened through the precipitation of intermetallic compounds, primarily Ni_3Mo, Ni_3Ti, and $Ni_3(Ti, Mo)$. On the other hand, the AerMet alloys are strengthened through the precipitation of $(Mo, Cr)_2C$ carbides. Fig. 1 shows the typical microstructure of AerMet 100.

Design criteria

Designers often have other criteria for evaluating alloys before they make a choice based on mechanical properties. Some of these criteria are space limitations, corrosion resistance, service temperature, magnetic properties, and cost.

Because of density differences, parts made from the AerMet alloys and maraging steels have an advantage over titanium alloys in that they occupy a smaller envelope than parts made from a titanium alloy. However, with their inherent corrosion resistance, titanium alloys have an advantage over ultra-high strength steels that do not contain significant chromium or other elements that impart stainless behavior. These steels are frequently plated or coated to prevent rusting in aerospace applications.

Titanium alloys also can operate at higher temperatures than the AerMet alloys and maraging steels. In addition, titanium alloys are not magnetic, while the ultra-high strength steels are magnetic. Finally, price can be a consideration. Raw material prices have been fluctuating a great deal in recent years and, in general, titanium alloys can be more expensive than either the AerMet alloys or maraging steels.

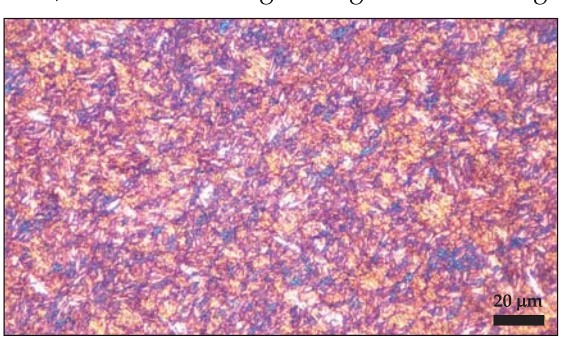

Fig. 1 — Microstructure of AerMet 100 Alloy. Courtesy George Vander Voort, Buehler Ltd.

Mechanical properties

The two most preferred titanium alloys, Ti-6Al-4V and Ti-10V-2Fe-3Al, were chosen for comparison with the AerMet alloys and maraging steels in this study. Many sources were consulted for

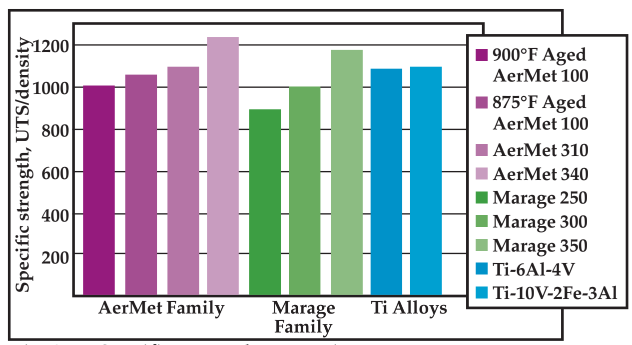

Fig. 2 — Specific strength comparison.

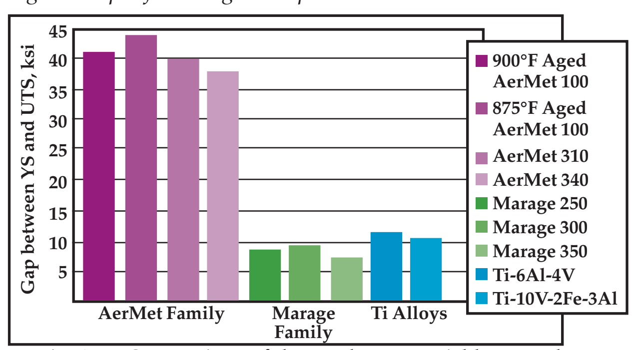

Fig. 3 — Comparison of the gap between yield strength (YS) and ultimate tensile strengths (UTS).

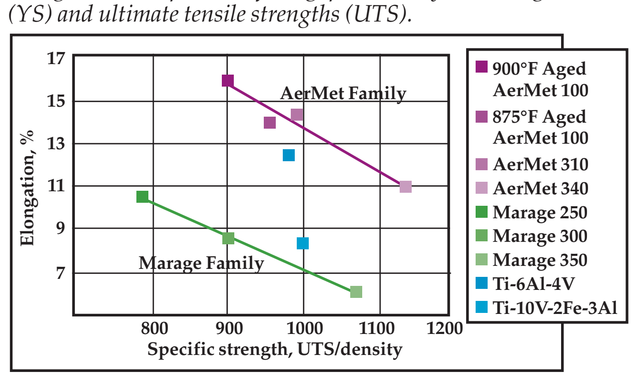

Fig. 4 — Elongation vs. specific strength.

Table 3 — Mechanical properties of the alloy families

Property	900°F Aged AerMet 100	875°F Aged AerMet 100	AerMet 310	AerMet 340	Marage 250	Marage 300	Marage 350	Ti 6Al-4V	Ti 10V-2Fe-3Al
Ultimate tensile strength, ksi	287.0	302.0	315.0	352.0	258.6	291.0	343.6	173.5	185.0
Yield strength, ksi	246.0	258.0	275.0	314.0	249.9	281.6	336.4	162.0	174.5
Elong., %	16.0	14.0	14.5	11.0	10.7	8.6	6.1	12.5	8.5
Reduction in area, %	67.0	64.0	63.0	55.0	51.1	40.8	22.2	52.0	17.5
Charpy V-notch impact energy, ft-lb	35.0	30.0	20.0	11.0	20.5	18.5	10.0	18.5	22.0
Fracture toughness KIc, ksi-in.$^{1/2}$	120.0	99.0	65.0	32.0	91.5	67.7	38.5	39.1	49.6
Density, lb/in.^{3}	0.285	0.285	0.288	0.284	0.289	0.289	0.292	0.16	0.168
Fatigue strength 10^7 cycles, ksi	137	137	150	143	110	128	112	102	120
Specific strength, UTS/density	1007	1060	1094	1239	895	1007	1177	1084	1101

data to determine average mechanical properties of the AerMet alloys, the maraging steels, and the titanium alloys.

To make a graphical comparison simpler, average values were used rather than value ranges. However, this approach does have disadvantages, mainly because the maraging steels individually exhibit wide ranges for each of the tensile properties, depending on product size and heat treatment. For example, the average yield and tensile strengths for Marage 250 listed in Table 3 are 249.9 and 258.6 ksi, respectively. These averages were calculated based on values ranging from 245.0 to 269.1 ksi for yield strength, and 251.0 to 279.0 ksi for ultimate tensile strength.

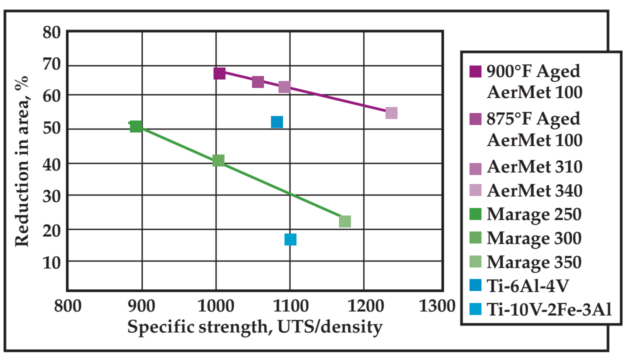

Fig. 5 — Reduction in area vs. specific strength.

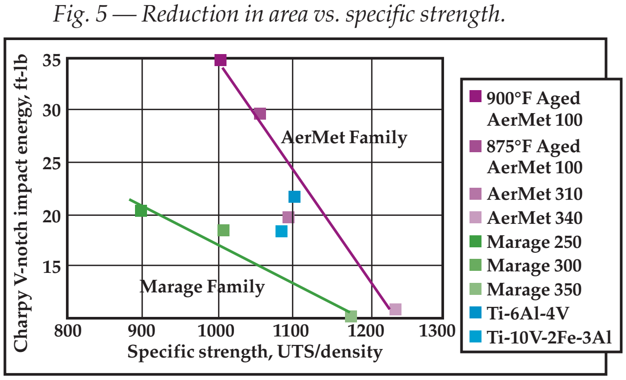

Fig. 6 — Comparison of Charpy V-notch impact energy vs. specific strength.

The average mechanical properties of all the alloys are listed in Table 3 and graphically compared in Fig. 2 through 8. To make valid property comparisons, an effort was made to account for the density differences between the titanium alloys and the two families of ultra-high-strength steels.

Therefore, the specific strength (ultimate tensile strength/density) was used to compare properties of the three groups of alloys (Fig. 2). Note that AerMet 100 is comparable to Marage 250; AerMet 310 is comparable to Marage 300; and AerMet 340 is comparable to Marage 350. In addition, the titanium alloys have specific strengths similar to those of the AerMet 100 and 310 alloys. This gives designers a choice of three alloy types for a given specific strength level.

Ductility properties

Although the AerMet alloys, maraging steels, and titanium alloys have comparable specific strengths, their yield strengths differ considerably, as shown in Table 3. When the gap between yield and ultimate strengths is calculated and plotted as shown in Fig. 3, a major difference between the AerMet alloys and the other two groups emerges.

The titanium alloys and maraging steels generally have only an approximate 8 to 10 ksi difference between yield and ultimate strengths. However, the alloys in the AerMet family have a gap of approximately 35 to 40 ksi between yield and ultimate strengths.

This yield-to-ultimate strength range may explain one of the major differences among the three alloy families: the amount of ductility. Figures 4 and 5 show elongation and reduction in area for the titanium alloys, maraging steels, and AerMet alloys as a function of specific strength.

Observe that linear relationships exist for both the AerMet alloys and the maraging steels. The ductility measurements of the AerMet alloy family are superior to those of the maraging steels at any given strength. The two titanium alloys are intermediate

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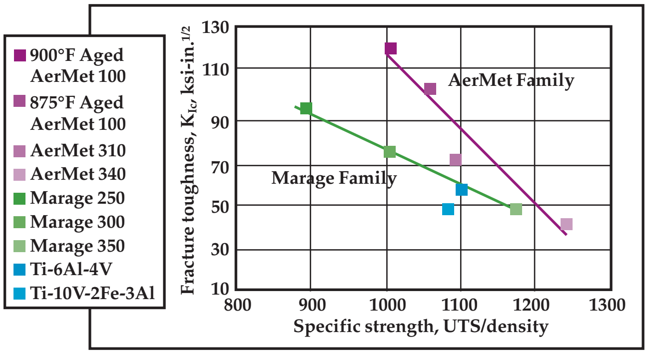

Fig. 7 — Fracture toughness vs. specific strength.

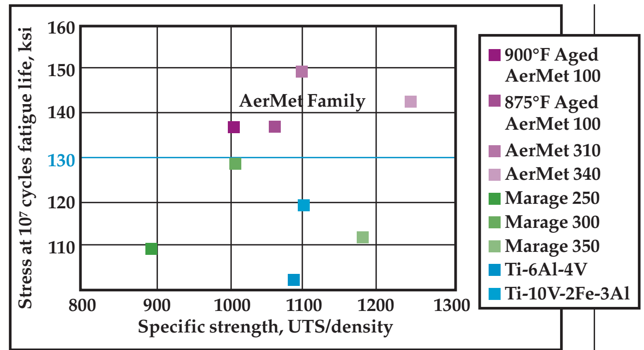

Fig. 8 — Rotating bending (R = –1, Kt =1) fatigue life vs. specific strength.

between the steels, with the Ti-6Al-4V alloy showing better ductility than the Ti-10V-2Fe-3Al alloy.

Toughness measurements

When toughness is critical at very high strength levels, the AerMet alloy family appears to be a better choice than either the maraging steels or titanium alloys. Relative toughness is shown in Fig. 6, where Charpy V-notch impact energy is plotted against specific strength for the two high-strength steel families.

The plots show linear relationships for both the maraging steels and the AerMet alloys. The line for the AerMet alloys lies above and to the right of the line for the maraging steels, showing that for comparable strength levels, an AerMet alloy has superior impact properties. Again, the titanium alloys are superior to the maraging steels (Fig. 6), but inferior to the AerMet alloys.

Similar linear relationships exist for fracture toughness as a function of specific strength, as shown in Fig. 7. Here, AerMet 100 and 310 have superior fracture toughness when compared with Marage 250 and 300, respectively.

At 350 ksi ultimate strength, AerMet 340 and Marage 350 have similar fracture toughness. At similar specific strength levels, the titanium alloys are inferior to the AerMet alloys.

When fatigue life is critical at very high strengths, the AerMet alloy family scores higher than both the titanium alloys and the maraging steels. The superior fatigue properties are seen when the stress at runout is plotted against specific strength in Fig. 8.

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