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Comparing Stainless Steel and Other Metals

Machine Design
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Stainless steel gives parts a clean look, but it's a mismatch for many applications.

Stainless steel is widely used in the food and medical industries because it is easily cleaned and sanitized. Strength and corrosion resistance often make it the material of choice in transportation and processing equipment, engine parts, and firearms. And sometimes, designers specify stainless simply for its appearance, not for its structural properties. However, its benefits don't fit every application.

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In aviation, for instance, its utility is far from clear. Commonly used aerospace metals include water-quenched, AISI 4130 alloy steel, **Aluminum Association** (AA) 2024-T3 Alclad aluminum, AA 7075-T6 Alclad aluminum, AISI 304 austenitic stainless steel, and AISI 440C martensitic stainless steel. Here's how they compare.

Steel strengths

- AISI 4130 alloy steel contains 0.75 to 1.20% chromium and no significant nickel.
- AA 2024-T3 and AA 7075-T6 aluminum are also nickel-free, but AA 7075-T6 contains 0.23% chromium.
- AISI 304 stainless contains 18% chromium and 8% nickel.
- AISI 440C has 16 to 18% chromium and 0.95 to 1.2% carbon.

Steels are generally 66% heavier than aluminum but specific strength, the ratio of strength to density, is the property of interest for aircraft designers. Of the five materials, 440C stainless steel has the highest specific strength, followed by 4130 alloy steel, 7075-T6 aluminum, and 2024-T3 aluminum. AISI 304 stainless steel has the lowest strength-to-weight ratio of the five.

Stainless selection

Type	ALLOYING ELEMENTS: Cr, %		Ni, %		MECHANICAL PROPERTIES: Ultimate tensile strength, ksi		2% yield strength, ksi		Elongation, %		Hardness, HrB		Comments
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	
Austenitic	16	30	3	22	65	325	0	310	0	60	0	96	Prone to stress-corrosion cracking, magnetic after cold working
Ferritic	10.5	27	None		60	125	25	80	16	33	0	100	Not heat treatable, magnetic
Martensitic	4	18	0	2.5	60	285	30	275	3	30	0	97	Heat treatable, magnetic
Precipitation hardening	12.3	18	3	7.8	125	240	95	230	1	15	101	115	Magnetic after heat treatment
Duplex	21	29	2.5	6.5	87	116	58	80	15	30	81	107	

The properties of stainless steels depend on the concentration of chromium and nickel in their compositions. Both elements add corrosion resistance and strength.

Looking at strength, designers should consider two parameters. One is ultimate tensile strength (UTS), the maximum tensile stress a material can endure without tearing. The other is yield strength, the tensile load per unit area required to permanently deform a material. Up to the yield point, deformation is elastic; the material returns to its original shape after the load is removed. Yield strength is usually determined as the intersection of the stress-strain curve with a line parallel to the initial straight-line portion of the curve and offset by 2% strain, often called 2% yield stress.

For both UTS and 2% yield strength, 440C stainless shines over the other steel and aluminum alloys in this comparison. 4130 alloy steel comes in a close second. Aluminums fall at the bottom in terms of UTS, but 304 stainless steel has the lowest 2% yield strength at 42.1 ksi.

Fastener performance

PROPERTY	ALLOY STEEL	STAINLESS STEEL	% DIFFERENCE
Tensile strength, ksi	185	95	51
Yield strength, ksi	163	30	82
Maximum operating temperature (unplated), °F	550	800	31

Another property of interest is elongation, the amount a material lengthens before fracturing. Greater elongation means the material is less prone to fracture, but it often goes hand in hand with lower stiffness. Elongation is usually expressed as a percentage of the length change over the initial measured length.

Here, 304 stainless elongates the most at 55%. 440C stainless has the shortest elongation at 2%. Its martensitic structure makes it strong but brittle.

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Shear strength, the maximum stress a material endures before it fractures, comes into play when components see off-axis forces. Shear strengths are not typically quoted for stainless steels because they are too low to have engineering value. 4130 alloy steel has shear strength around 11 ksi, lower than those for the aluminum alloys.

Hardness is a material's ability to resist scratching or indention. Harder materials may be more durable, but they are also more difficult to machine. 440C stainless and 4130 alloy steel are the two hardest metals in this comparison.

As materials are heated, they expand. The rate of this linear expansion is the coefficient of thermal expansion (CTE). Lower CTEs let designers downplay dimensional changes as temperatures rise. Here, 440C has the lowest CTE of these five alloys at 5.6 × 10-6 in./in./°F between 32 and 212°F.

The highest load that can be repeatedly applied without breaking a material is known as the fatigue or endurance limit. AISI 4130 alloy steel shines at 130 ksi, over three times greater than the next closest alloy, 440C stainless steel.

For more detailed property data, see the accompanying table.

		ALLOY				
PROPERTY	UNITS	AA 2024-T3	AA 7075-T6	AISI 304	AISI 440C	AISI 4130
DENSITY	LB/IN.^{3}	0.100	0.101	0.29	0.28	0.283
SPECIFIC STRENGTH		7.0×10^5	8.2×10^5	2.7×10^5	3.9×10^5	3.4×10^5
ULTIMATE TENSILE STRENGTH	KSI	70	76	85	285	236
0.2% YIELD STRENGTH	KSI	50	67	35	275	212
ELONGATION	%	18	11	55	2	10
HARDNESS	BRINELL	120	150	170	97	197
COEFFICIENT OF THERMAL EXPANSION	10^{-6} IN./IN./°F (32 TO 212°F)	12.9	13.1	9.6	5.6	7

Comparing costs

Mechanical properties are not the only criteria on which materials are judged. Cost counts, too. The lowest-priced uncertified raw material in this analysis is 4130 alloy steel. 2024-T3 aluminum costs 40% more and 7075-T6 aluminum is 42% more expensive. 304 stainless steel only bumps cost up by 37% while 440C stainless steel is 80% more costly than the alloy steel.

This comparative analysis is for stainless steels at the low end of the properties scale. Requirements for higher strength at elevated temperatures and better corrosion resistance add to costs.

While stringent material requirements may elevate costs, machining drives up the expense of finished parts more than that of the material itself. Specifically, surface cutting speed in feet per minute determines how much machine time a processor has to invest in each type of material.

AISI 1212 carbon steel is considered relatively easy to cut. Annealed 4130 alloy steel can only be cut 72% as fast. Annealed 304 and 440C stainless steels have surface cutting speeds 55% and 60% lower than the carbon steel, respectively.

The difference in cutting speeds is partly due to the materials' sulfur content. More sulfur makes alloys more machinable. 1212 carbon steel has 0.16 to 0.23% sulfur compared to 0.04% in 4130 alloy steel and 0.03% in 304 and 440C stainless steels.

In contrast, aluminum alloys like 2024-T3 and 7075-T6 can be machined at over three times the speed of 1212.

Welding is another secondary operation designers should consider when specifying alloys. Some stainless steels are good candidates, others cannot be welded at all.

Like every metal, stainless steel can crack and distort under the heat of a welding gun. Steels can also lose corrosion resistance during welding, leading to rust at the joints. Extra premachining steps to create a weldable surface that will not corrode add to the cost of welding stainless steel.

Corrosion and passivation

Even without welding, stainless steels can corrode unless they are treated, machined, and properly applied. They can suffer from pitting, crevice corrosion, knifeline attack, rouging (formation of iron oxide, hydroxide, or carbonate deposits), intergranular corrosion, stress-corrosion cracking, sulfide stress cracking, and contact corrosion.

Another mode most engineers recognize is galvanic corrosion between two dissimilar materials placed together. For example, stainless-steel fasteners on an aluminum panel quickly corrode.

A common way to avoid galvanic corrosion is with a physical barrier, such as a washer, gasket, finish, or lubricant that prevents the metals from touching.

Another problem with stainless steel is galling. This typically takes place when stainless-steel fasteners are highly torqued, marring the material's passivating oxide surface film.

Most parts must be passivated in an acid bath after machining and thorough cleaning. Polishing can also prevent materials from rusting, but a polished finish must be kept up through maintenance and waxing throughout the part's life.

What is stainless steel?

The American Iron and Steel Institute (AISI) defines stainless steel as steel that contains 10% or more chromium alone or with other alloying elements. Chromium increases hardness, strength, and corrosion resistance. Nickel gives similar benefits but adds hardness without sacrificing ductility and toughness. It also reduces thermal expansion for better dimensional stability.

The earliest record of corrosion-resistant steel was the Iron Pillar of Delhi, India, circa 400 AD. It is high in phosphorus, which worked with weather conditions to create a protective passivation layer of iron oxides and phosphates.

French metallurgist Pierre Berthier engineered the first documented corrosion-resistant material in 1821 for a cutlery application. Between 1904 and 1911, French researcher Leon Guillet developed alloys that today would be classified as stainless steel. In 1911, German Philip Monnartz documented the connection between chromium content and corrosion resistance.

By 1913, Harry Brearly, a metallurgist in Sheffield, England, working on a corrosion-resistant alloy for gun barrels, was dubbed by some the inventor of stainless steel. The alloy that resulted from his work is today called martensitic stainless steel.

At the same time at **Krupp Iron Works** in Germany, Eduard Maurer and Benno Strauss created an austenitic alloy. In the United States, Christian Dantsizen and Frederick Becket invented ferritic stainless steel.

Stainless steels' main categories are austenitic (200 and 300 Series), ferritic (400 Series), martensitic (400 and 500 Series), precipitation-hardening (PH), and duplex alloys.

Austenitic stainless steels have the best corrosion resistance of all stainless steels because they contain at least 16% chromium. Added nickel and manganese hold the metal in an austenitic microstructure. AISI 304 stainless is a common alloy containing 18% chromium and 8% nickel. These alloys are usually characterized as ductile, weldable, and hardenable by cold forming.

Ferritic stainless steels have 10.5 to 27% chromium and no significant nickel content, lowering their corrosion resistance. They are considered best for high-temperature instead of high-strength applications.

Martensitic alloys contain 12 to 14% chromium, 0.2 to 1% molybdenum, and no significant amount of nickel. They have lower corrosion resistance than austenitic or ferritic alloys, but are considered hard, strong, slightly brittle, and hardenable by heat treatment. A common aircraft-grade martensitic stainless is AISI 440C, which contains 16 to 18% chromium and 0.95 to 1.2% carbon.

PH stainless steels contain around 17% chromium and 4% nickel. This makes them as corrosion resistant as austenitic grades. Unlike austenitic alloys, however, heat treatment strengthens PH steels to levels higher than martensitic alloys.

Duplex stainless steels, as their name indicates, are a combination of two of the main alloy types. The alloys' mixture of 19 to 28% chromium, 0 to 5% molybdenum, and 5 to 7% nickel results in a mixed austenitic and ferritic microstructure. They are stronger than either austenitic and ferritic alloys and have better localized corrosion resistance.

Fastener to fastener

One specific aircraft application for metals is fastening. Fasteners such as NAS 1352 socket-head-cap screws reliably hold aircraft together.

Comparing ASTM A574 alloy-steel fasteners with ASTM F837 stainless-steel fasteners reveals that alloy steel is stronger in tensile and yield strength, whereas stainless steel better handles high temperatures.

Shear strength is not listed because it varies with fastener diameter. For example, however, the single shear strength of an alloy-steel Number 10 fastener is 3,225 lb while a stainless-steel fastener of the same size tolerates 1,280 lb.

Taking this particular example further, a 10-32 × 0.500-in.-long fastener costs 73% more using stainless steel, with less strength but a 69% higher top operating temperature. If an engineer doesn't anticipate the fastener seeing 800°F, it may not be worth the additional cost.

Resources: American Iron and Steel Institute |Ellis & Associates

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