2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
Education for 130 Years
ASEE
Paper ID #37519

Improving the Quality of Data Graphics in Materials Education

Dr. Barry Dupen, Purdue University Fort Wayne

Dr. Dupen is a Metallurgist and Professor of Mechanical Engineering Technology at Purdue University Fort Wayne (PFW). He has nine years of experience as a metallurgist, materials engineer, and materials laboratory manager in the automotive industry.

Improving the Quality of Data Graphics in Materials Education

Abstract

Materials education is an inherently image-intensive and data-rich endeavor. Educators draw on primary and secondary sources such as journal articles, the news media, and materials handbooks for data graphics (generally, x-y scatter graphs and tables) that help to explain materials concepts. A key purpose of a well-designed graphic is to help the reader compare large sets of data in a compact space and in a short amount of time, helping the reader understand relationships between variables (including uncertainty and scatter). Unfortunately, many data graphics in the materials field are not easy for undergraduates to read. It's difficult enough for students to learn new MS&E concepts without facing unnecessary barriers to learning such as poorly-designed data graphics.

Many data graphics in handbooks, textbooks, and the media show curves with no datapoints. It's necessary in phase diagrams to prevent clutter and confusion, but students can benefit by seeing datapoints on S/N fatigue curves and in graphs of Charpy impact energy vs. temperature. In such graphs, data points help students understand the degree of scatter that is normally found in these mechanical tests.

Some limitations of graphing software can be overcome by changing default settings on fonts, standard symbols, line thicknesses, hard-to-read vertically-oriented text, or a legend that fails to list symbols in the same order as they appear on the graph. Other limitations are best overcome by converting a graph to artwork.

This paper demonstrates ways to improve the quality of engineering graphs used in materials education by comparing many examples of as-published data graphics with improved versions. The examples are drawn from graphs used in a freshman introductory materials and processes class as well as six junior/senior level materials classes taught for a minor in materials engineering technology.

Background

I have taught nine different materials courses for undergraduate mechanical engineering technology students over the past two decades at Purdue University Fort Wayne. Two of these courses are required: a second-semester freshman class, and a junior-level class. The rest of the courses serve as technical electives, typically taken by juniors and seniors. Students can earn a minor in materials if they take enough of these classes. Upon graduation, my students are most likely to work as process engineers or manufacturing engineers, so they need to understand the practical side of materials and processes – not the “S” but the “E” in “MS&E”.

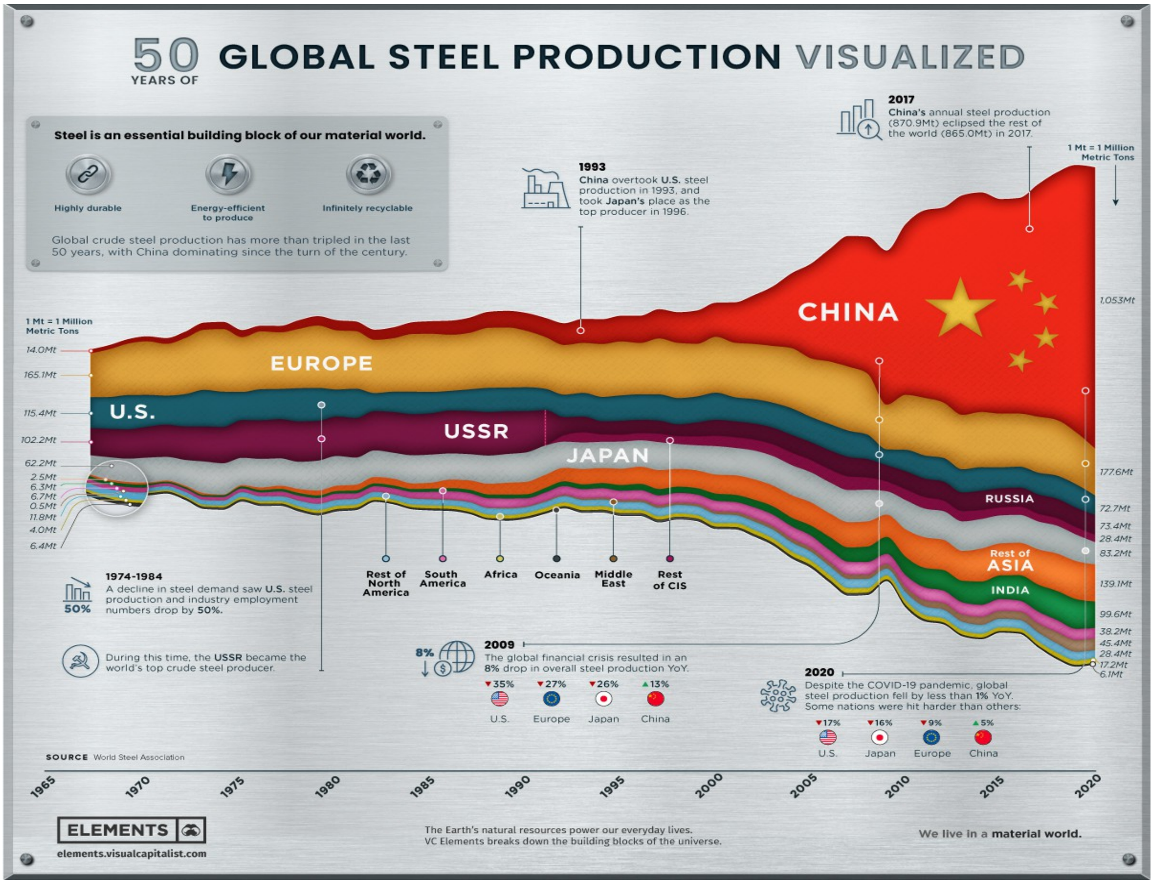
In developing slideshows and handouts to support these courses, I started by scanning and printing the graphs that students needed. I assigned homework problems requiring students to interpret graphs from their textbook and handouts, and to use the information to solve materials engineering problems. It quickly became apparent that students struggled to interpret some of the graphs, and the main reason seemed to be the design of the graphs.

In an ideal world, I would have collected data on student understanding of graphical data before and after implementing these changes, but in practice the changes have been gradual over many years. The only evidence of better student understanding is anecdotal. This paper is more of a "how-to" guide, not a study measuring the success of a pedagogical method.

Data Graphic Design

Data graphics expert Edward Tufte explains that well-designed data graphics should show large datasets in a small space and in a coherent way, enabling the reader to compare different pieces of data without confusion. [1] If the design of the data graphic causes the reader to be confused, then the graphic should be redesigned.

One way to display production quantities for multiple products over time is to stack the data so the largest value is the sum of all other values. This graph from *Visual Capitalist* stacks the steel production of nations and global regions. [2] Although the dominance of China in steel production is clear, changes in steel production for other countries are difficult to discern.



50 YEARS OF GLOBAL STEEL PRODUCTION VISUALIZED

Steel is an essential building block of our material world.

Global crude steel production has more than tripled in the last 50 years, with China dominating since the turn of the century.

1993
China overtook **U.S.** steel production in 1993, and took **Japan's** place as the top producer in 1996.

2017
China's annual steel production (870.9Mt) eclipsed the rest of the world (865.0Mt) in 2017.

1974-1984
A decline in steel demand saw **U.S.** steel production and industry employment numbers drop by **50%**.

During this time, the **USSR** became the world's top crude steel producer.

2009
The global financial crisis resulted in an **8%** drop in overall steel production YoY.

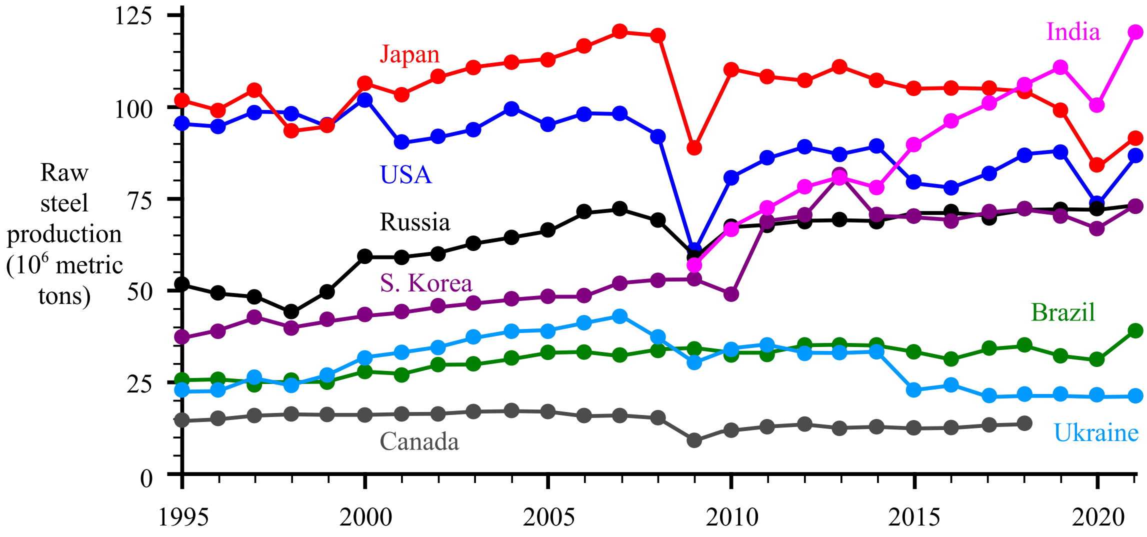
2020
Despite the COVID-19 pandemic, global steel production fell by less than **1%** YoY. Some nations were hit harder than others:

SOURCE World Steel Association

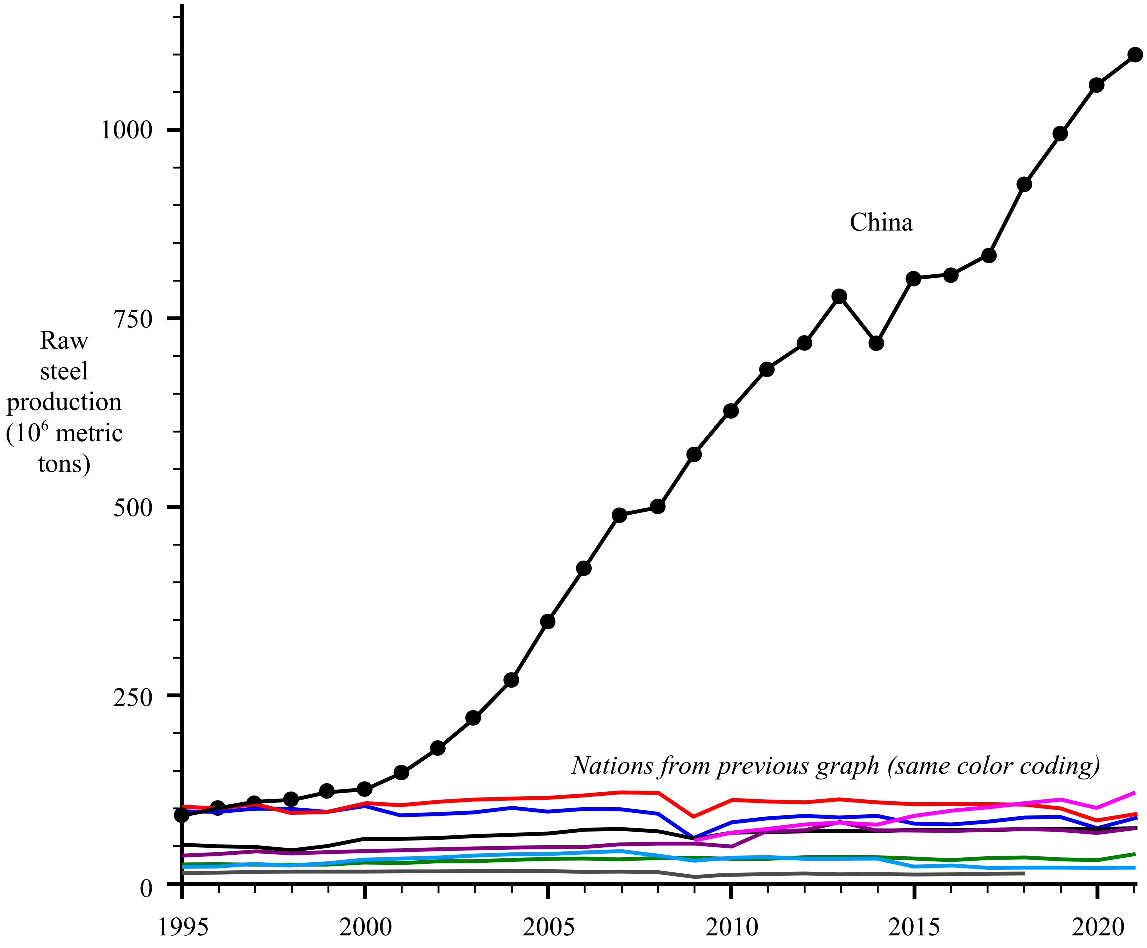
The Earth's natural resources power our everyday lives.
VC Elements breaks down the building blocks of the universe.

We live in a **material world.**

The USGS National Minerals Information Center publishes steel production data on its website. [3] Using this information, we can compare steel production for many countries over time as shown below. Now it is easier to see that steel production in South Korea saw a step-function increase after the Great Recession, and steel production in India has doubled in the last decade.



Now let's expand the vertical scale and add China's steel production to the graph.



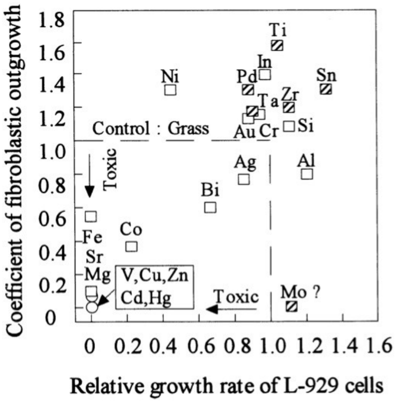
This graph worries some of my materials students, until they learn that China's steel production is used almost entirely for domestic use. Construction of new cities in China has driven high demand for steel and concrete.

Use of Shading for Emphasis

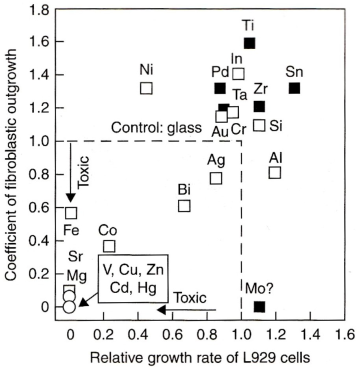
Shading example: Metal Toxicity

Shading can emphasize particular zones on a graph. The graph on the left from *JOM* shows the relative toxicity of various metallic elements in biological culture. [4] L-929 fibroblast cells are mouse cells used in toxicity assessment; the greater the growth, the less toxic the environment. Toxicity is defined as a growth rate on the substrate less than the growth rate on a control surface (normalized to 1.0).

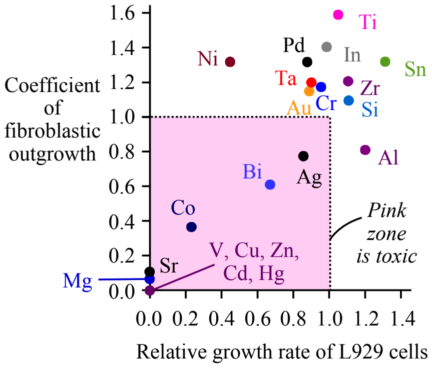
JOM



ASM Handbook



Redrawn

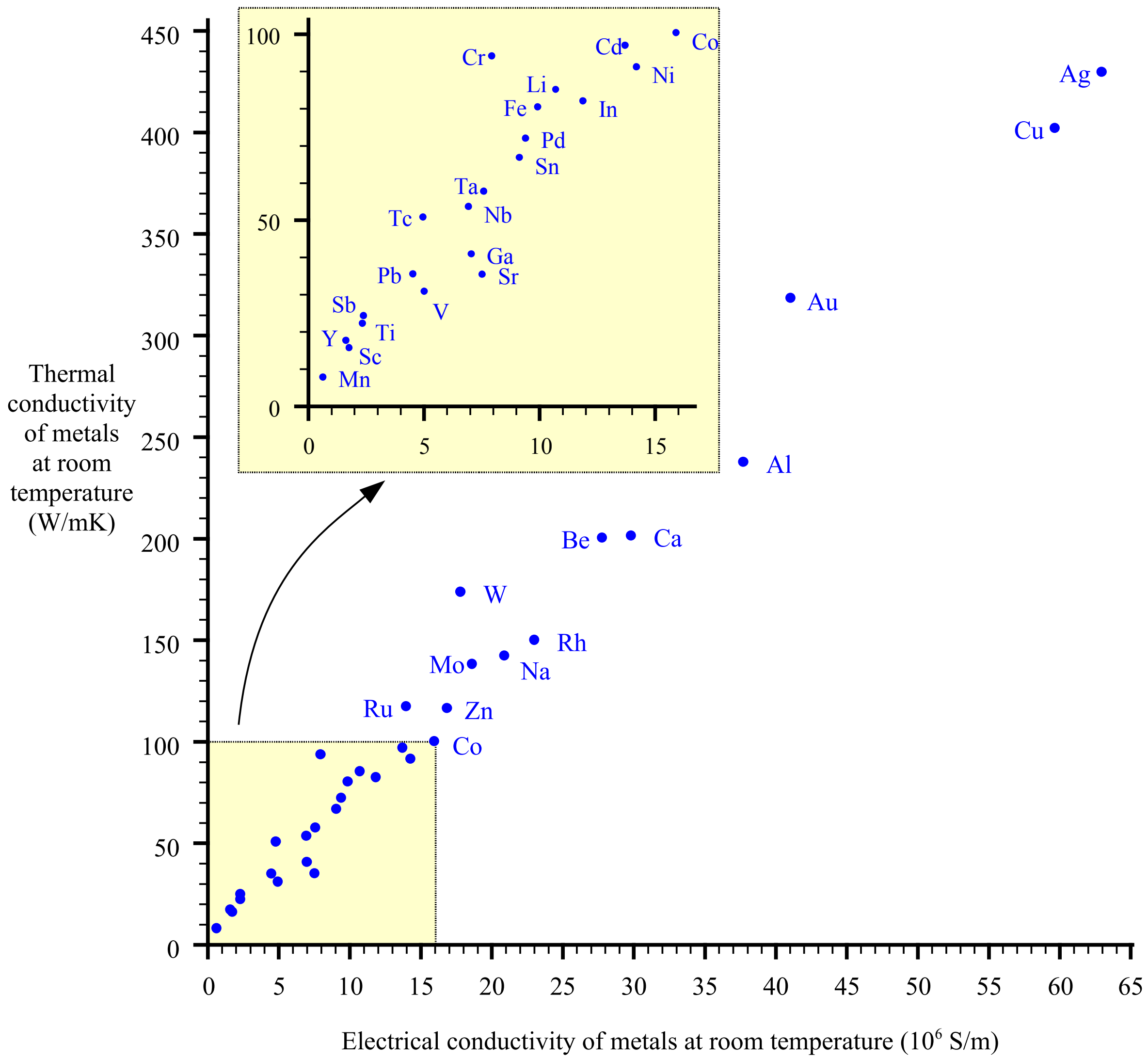


The *JOM* graph is reproduced in Vol. 23 of the *ASM Handbook* with one spelling change (the control surface is *glass,* meaning that the growth rate of L929 cells is measured relative to their growth rate on a glass plate) and a formatting improvement (shorter and more closely spaced dashes in the dashed line). [5] Cross-hatched squares are now black squares, although there is no explanation of the difference between hollow and dark squares in either the original paper or in the *ASM Handbook*. There is also no explanation of why two datapoints are displayed as circles, while 17 datapoints are displayed as squares.

We can improve on these graphs with color coding to distinguish the different elements, and by shading the toxic zone. While not necessary, color-coding the substrate datapoints and labels can help with readability.

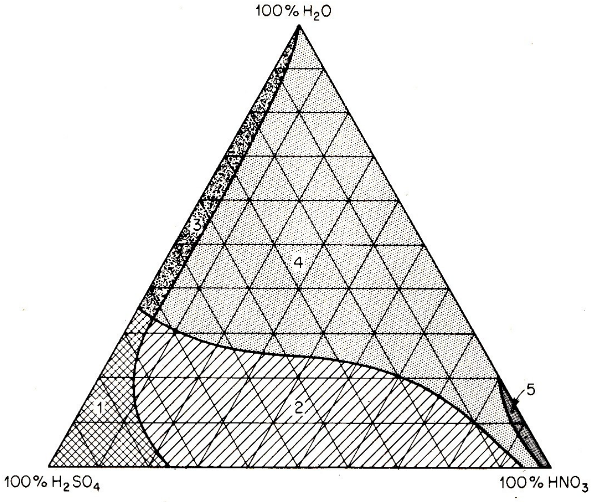
Shading example: Conductivity of Metals

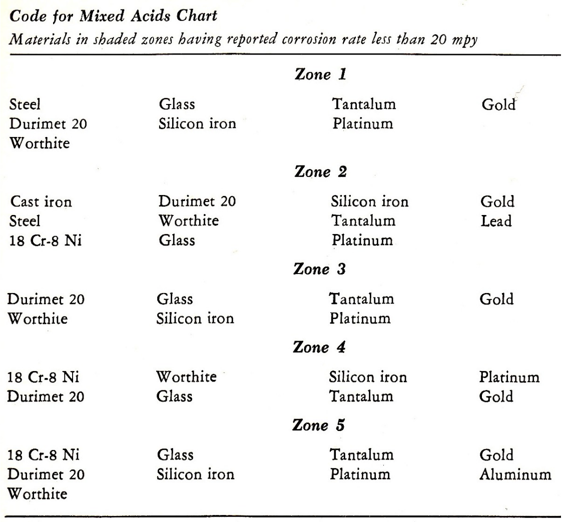
Electrical conductivity and thermal conductivity of metals both depend on electron movement. In 1853, Gustav Wiedemann and Rudolph Franz discovered the ratio of thermal to electrical conductivity was constant for most metals at a given temperature, and we can demonstrate their findings by plotting thermal vs. electrical conductivity on an x-y scatter graph. Since the data range extends over two orders of magnitude, we can either use logarithmic scales or we can use shading to magnify a corner of a graph, where datapoints are clustered too tightly to properly label the values. There is no need to repeat the axis titles for the inset graph.



Use of Color

Prior to affordable color printing of textbooks and handbooks, illustrators relied on crosshatching to distinguish between different zones in a data graphic. This ternary diagram from Fontana & Greene's *Corrosion Engineering* shows the corrosion resistance of glass and metals to a mixture of sulfuric and nitric acids at room temperature. [6] Materials with a corrosion rate less than 20 mils per year (0.5 mm per year) are defined as corrosion-resistant. The table at the right lists the materials that meet this definition within each zone.



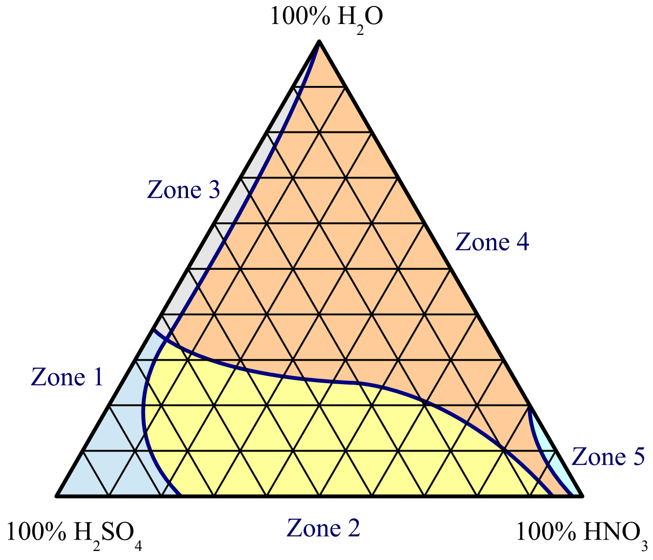


Code for Mixed Acids Chart

Materials in shaded zones having reported corrosion rate less than 20 mpy

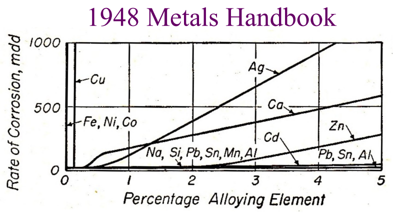
		Zone 1	
Steel Durimet 20 Worthite	Glass Silicon iron	Tantalum Platinum	Gold
		Zone 2	
Cast iron Steel 18 Cr-8 Ni	Durimet 20 Worthite Glass	Silicon iron Tantalum Platinum	Gold Lead
		Zone 3	
Durimet 20 Worthite	Glass Silicon iron	Tantalum Platinum	Gold
		Zone 4	
18 Cr-8 Ni Durimet 20	Worthite Glass	Silicon iron Tantalum	Platinum Gold
		Zone 5	
18 Cr-8 Ni Durimet 20 Worthite	Glass Silicon iron	Tantalum Platinum	Gold Aluminum

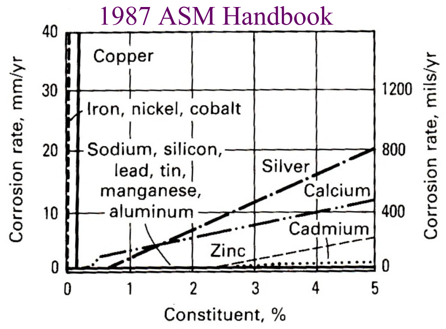
Replacing crosshatching with color improves the readability of the graph. Redesigning the table makes it easier to compare one material with another. Another design choice could be to eliminate the zone labels from the diagram and table, relying on color alone.

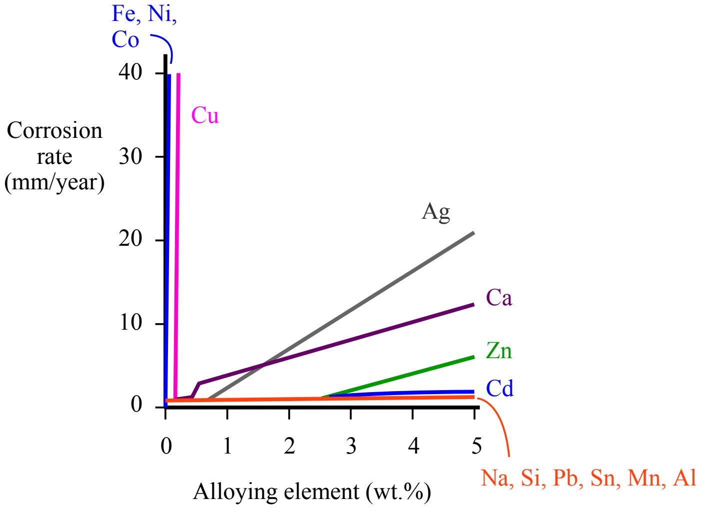


	Zones on the diagram				
	1	2	3	4	5
Gold	✓	✓	✓	✓	✓
Platinum	✓	✓	✓	✓	✓
Tantalum	✓	✓	✓	✓	✓
Glass	✓	✓	✓	✓	✓
Silicon iron	✓	✓	✓	✓	✓
Alloy 20	✓	✓	✓	✓	✓
Worthite	✓	✓	✓	✓	✓
18Cr, 8Ni stainless		✓		✓	✓
Steel	✓	✓			
Cast iron		✓			✓
Aluminum					✓
Lead		✓			

The corrosion rates of magnesium alloys in a 3% NaCl solution were published in graphical form in the *Metals Handbook* and the *ASM Handbook* 39 years apart. [7, 8] Although no actual datapoints appear on these graphs, the original study included 5,000 alloy specimens. [9] Notice the corrosion units have changed from mdd (mils per square decimeter per day) to mm/year. The older graph places the Na/Si/Pb/Sn/Mn/Al label closer to its line, while the 1987 graph uses different line styles to differentiate alloying elements.


1948 Metals Handbook


1987 ASM Handbook



Color makes the graph easier to read. In the redrawn graph, most data labels lie outside the frame of the axes, improving readability. A further improvement would be the addition of data points, but given the age of the original graph, the data may not be available (or reliable).

Linear Scales

Numerical data in textbooks and handbooks are presented as tables to save space. Plotting the numbers along a line can help students understand the dispersion of data within the dataset. A good example is the *c*/*a* ratios of the HCP metals in this table, from Smith's *Structure and Properties of Engineering Alloys*. [10]

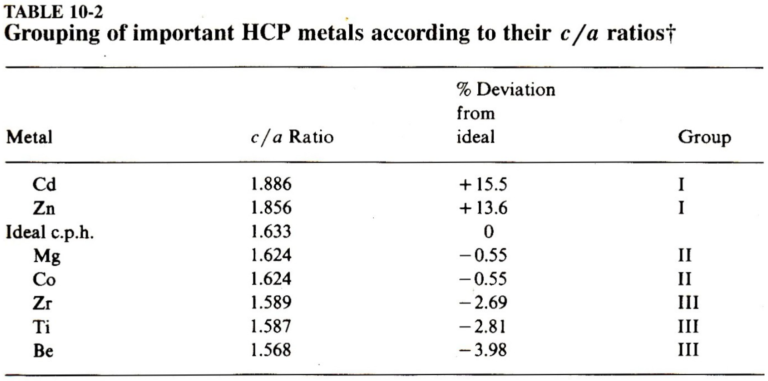
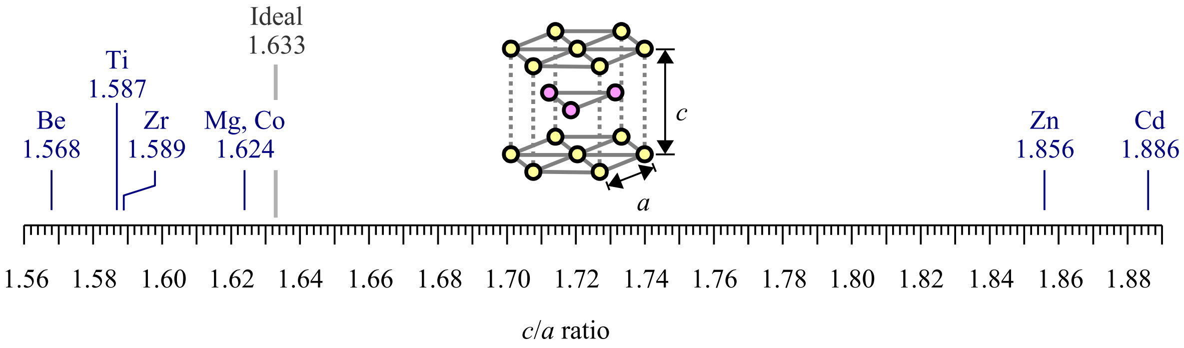


TABLE 10-2
Grouping of important HCP metals according to their *c*/*a* ratios†

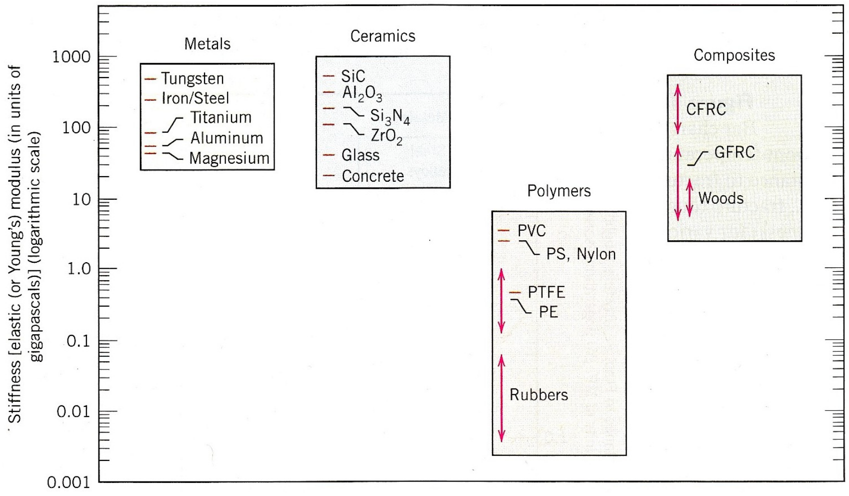
Metal	*c*/*a* Ratio	% Deviation from ideal	Group
Cd	1.886	+15.5	I
Zn	1.856	+13.6	I
Ideal c.p.h.	1.633	0	
Mg	1.624	−0.55	II
Co	1.624	−0.55	II
Zr	1.589	−2.69	III
Ti	1.587	−2.81	III
Be	1.568	−3.98	III

In this table, the "ideal" ratio assumes equally spaced atoms within an ideal ball-model crystal structure. Although HCP metals tend to be difficult to deform at room temperature (magnesium being a prime example), HCP α-titanium is formable because it has a lower *c*/*a* ratio than the ideal value, enabling slip. This linear scale and model of the HCP structure will help students visualize the *c*/*a* ratio for several metals.



Linear scale example: Young's modulus

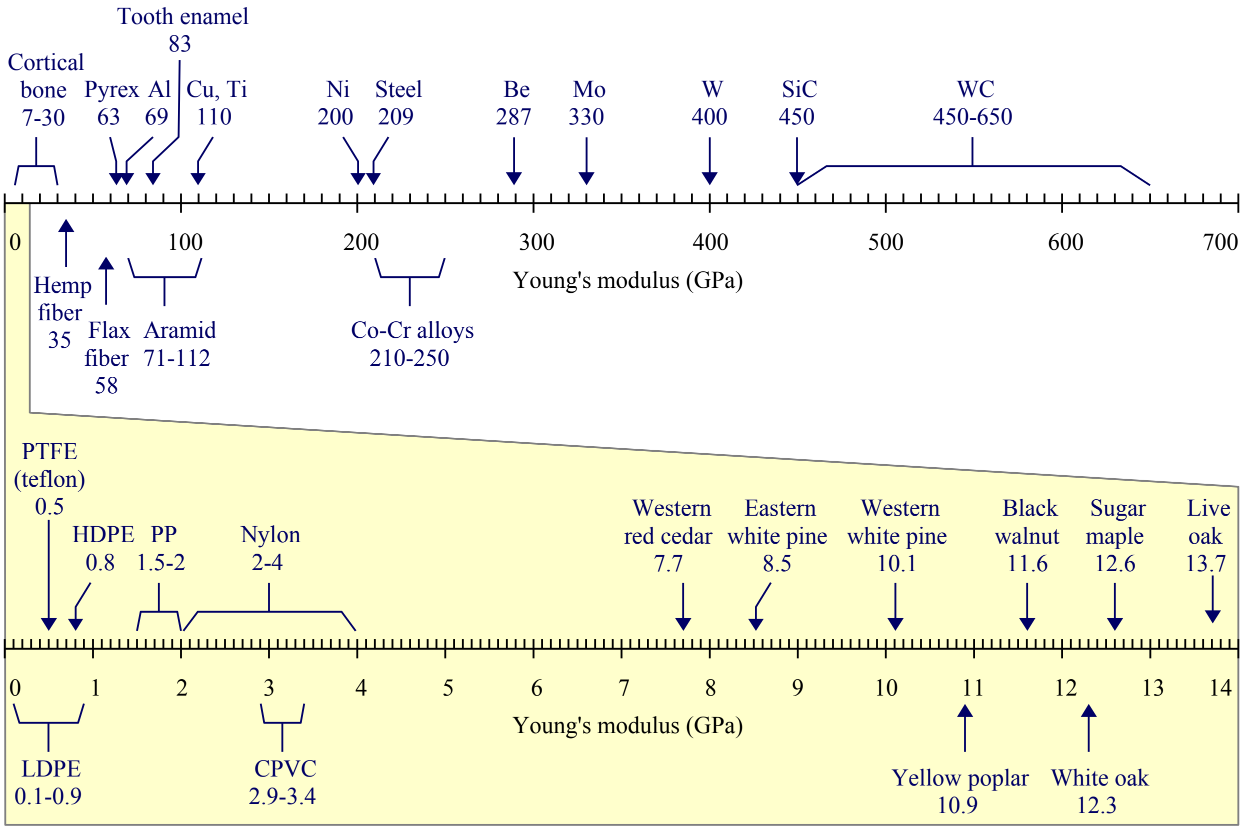
Young's modulus of engineering materials varies by five orders of magnitude from soft rubber to hard intermetallic compounds. One approach is to plot the data on logarithmic scales. Callister & Rethwisch use this approach for four classes of materials. [11]



Placing each class of material in a separate block makes it easier for the reader to compare one class of materials with another. Having scales along both left and right edges allows the reader to use a straightedge to estimate numerical values.

We use logarithmic scales in science and engineering graphics because they allow large ranges of data to be displayed in a small space. Some first-year students have a harder time reading values on a logarithmic scale than on a linear scale. As an alternative, we can present Young's modulus values on a linear scale with a magnified section for low-modulus materials.

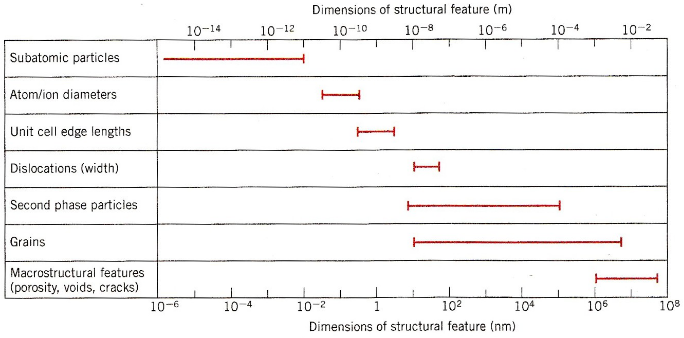
The following graph used in my freshman-level materials and processes class helps students grasp the range of values from human bone to tungsten carbide. The numbers represent the values, and the arrows point to where the values lie on the linear scale. Students may have read that ceramics are stiffer than metals, but the linear scale shows that Pyrex is not as stiff as aluminum, and titanium is close to the stiffness of tooth enamel – an important consideration for dental implants. Students can see that some materials have about the same stiffness (copper & titanium, nickel & steel). Aramid fibers such as Kevlar have the same stiffness as some metals. Most polymers and wood occupy the leftmost 2% of the upper scale, so this section is magnified in the lower scale. Yellow shading helps students recognize that the lower scale is a small portion of the upper scale.



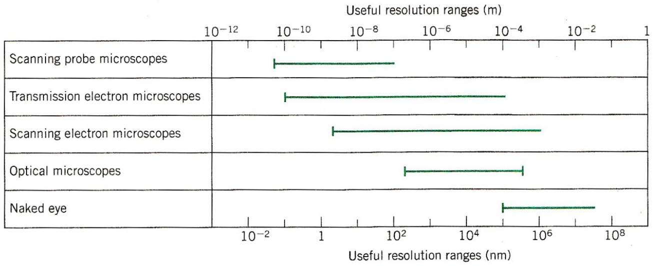
Linear scale example: Size Comparisons

Two bar charts provided by Brazilian professors Sidnei Paciornik and Carlos Pérez Bergmann appear in Callister and Rethwisch, showing the sizes of submicroscopic, microscopic, and macroscopic features along with the useful resolution of various types of microscope. [12]

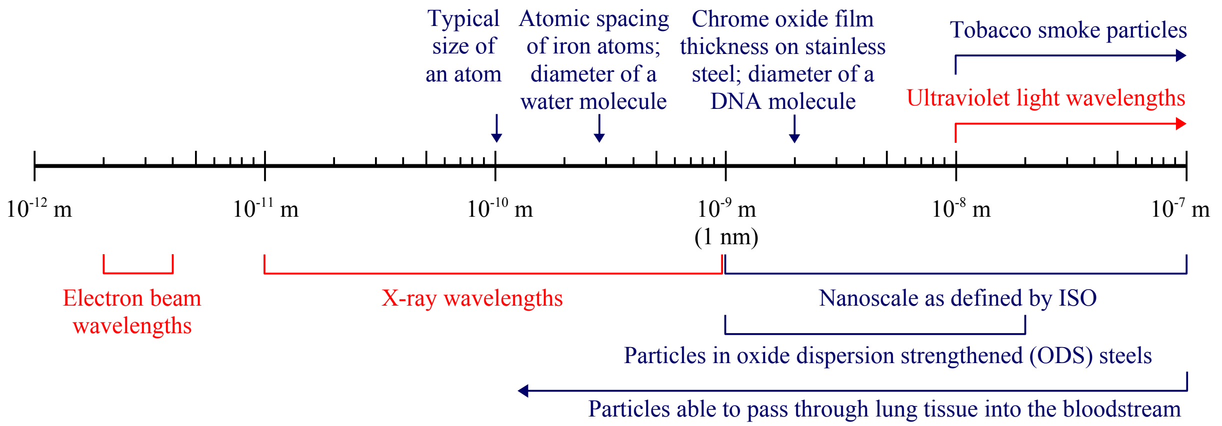
One odd thing about these bar charts is they are presented independently, using different scales – that is, they don't line up. Another oddity is the log scales themselves: there are tick marks exactly halfway between each power of 10...not what anyone expects on a logarithmic scale.

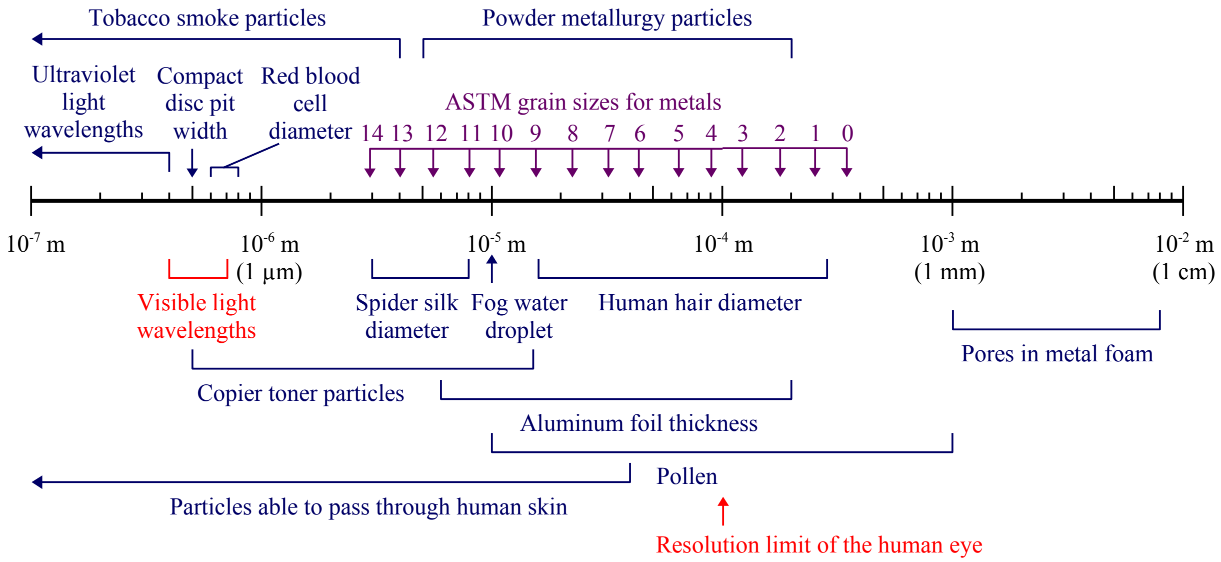


(a)



Another way to present the data is to put the sizes of objects on the same graph as the wavelengths of light, as shown below. Here, the scales are expanded to include more information. The first scale runs from 1 picometer to 100 nanometers, while the second scale runs from 100 nm to 1 cm. Light wavelengths and resolutions are given in red type.



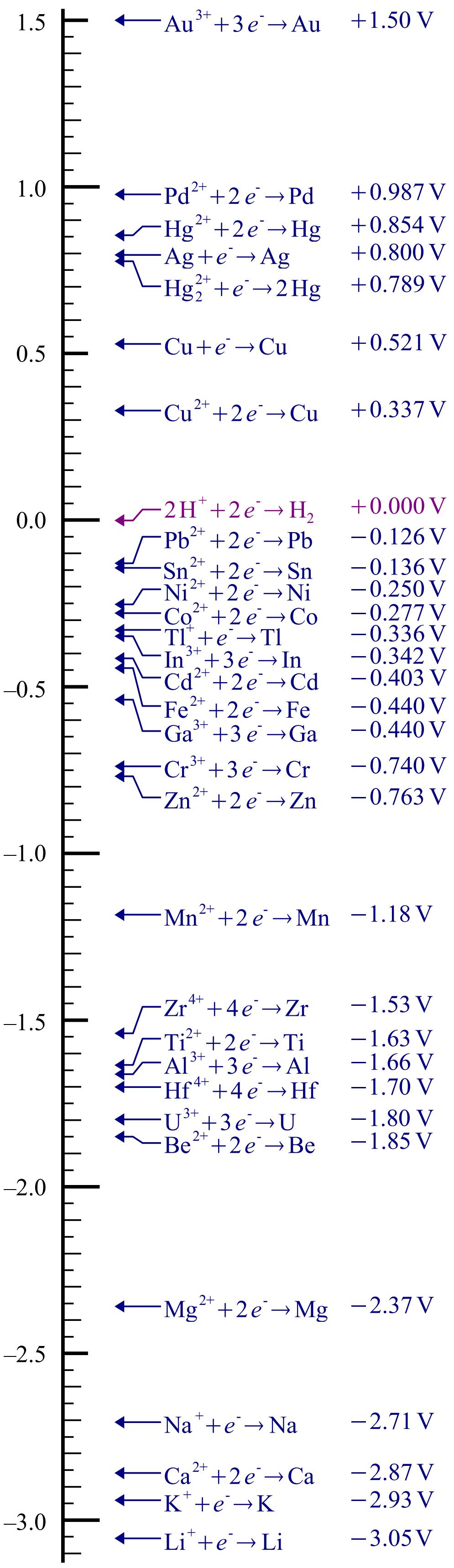


There is more detail here to provide students with a sense of scale. Common items like water molecules, water droplets, human hair, and aluminum foil are shown with materials items such as ASTM grain sizes in magenta type, powder metallurgy particles, and the thickness of the protective chrome oxide layer on stainless steels.

Linear scale example: Galvanic corrosion

Electromotive force data for elements corroding in seawater are usually presented in a table like the one below, sorted by voltage. Displaying the data on a linear scale at the right shows where the data clumps, and where there are gaps. Visually, it's easy to compare voltage differences based on distance along the scale.

$Au^{3+} + 3e^- \rightarrow Au$	+1.50 V
$Pd^{2+} + 2e^- \rightarrow Pd$	+0.987 V
$Hg^{2+} + 2e^- \rightarrow Hg$	+0.854 V
$Ag + e^- \rightarrow Ag$	+0.800 V
$Hg_2^{2+} + e^- \rightarrow 2\,Hg$	+0.789 V
$Cu + e^- \rightarrow Cu$	+0.521 V
$Cu^{2+} + 2e^- \rightarrow Cu$	+0.337 V
$2H^+ + 2e^- \rightarrow H_2$	+0.000 V
$Pb^{2+} + 2e^- \rightarrow Pb$	−0.126 V
$Sn^{2+} + 2e^- \rightarrow Sn$	−0.136 V
$Ni^{2+} + 2e^- \rightarrow Ni$	−0.250 V
$Co^{2+} + 2e^- \rightarrow Co$	−0.277 V
$Tl^{+} + e^- \rightarrow Tl$	−0.336 V
$In^{3+} + 3e^- \rightarrow In$	−0.342 V
$Cd^{2+} + 2e^- \rightarrow Cd$	−0.403 V
$Fe^{2+} + 2e^- \rightarrow Fe$	−0.440 V
$Ga^{3+} + 3e^- \rightarrow Ga$	−0.440 V
$Cr^{3+} + 3e^- \rightarrow Cr$	−0.740 V
$Zn^{2+} + 2e^- \rightarrow Zn$	−0.763 V
$Mn^{2+} + 2e^- \rightarrow Mn$	−1.18 V
$Zr^{4+} + 4e^- \rightarrow Zr$	−1.53 V
$Ti^{2+} + 2e^- \rightarrow Ti$	−1.63 V
$Al^{3+} + 3e^- \rightarrow Al$	−1.66 V
$Hf^{4+} + 4e^- \rightarrow Hf$	−1.70 V
$U^{3+} + 3e^- \rightarrow U$	−1.80 V
$Be^{2+} + 2e^- \rightarrow Be$	−1.85 V
$Mg^{2+} + 2e^- \rightarrow Mg$	−2.37 V
$Na^{+} + e^- \rightarrow Na$	−2.71 V
$Ca^{2+} + 2e^- \rightarrow Ca$	−2.87 V
$K^{+} + e^- \rightarrow K$	−2.93 V
$Li^{+} + e^- \rightarrow Li$	−3.05 V



Linear scale example: Forging Temperatures for Magnesium Alloys

A linear graph can help the reader think critically about statements made in a textbook or handbook. This table from Vol. 14 of the *ASM Handbook* lists recommended forging temperatures for 10 magnesium alloys. [13] The accompanying text says that magnesium alloys are often forged within 55°C of the solidus temperature (except for high zinc alloys containing a low-temperature eutectic), but we cannot tell that from this table.

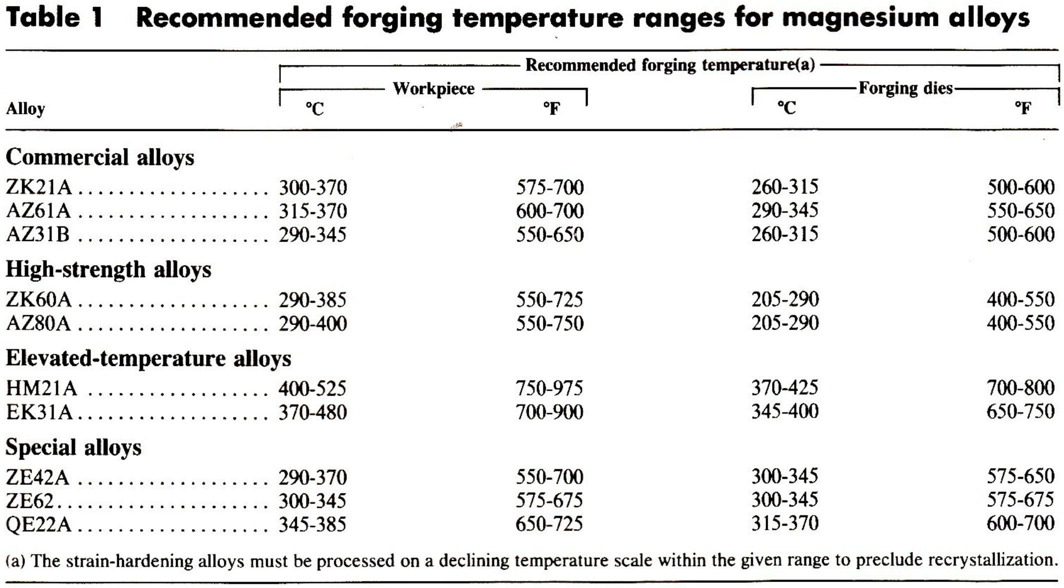


Table 1 Recommended forging temperature ranges for magnesium alloys

Alloy	Recommended forging temperature(a)			
	Workpiece		Forging dies	
	°C	°F	°C	°F
Commercial alloys				
ZK21A	300-370	575-700	260-315	500-600
AZ61A	315-370	600-700	290-345	550-650
AZ31B	290-345	550-650	260-315	500-600
High-strength alloys				
ZK60A	290-385	550-725	205-290	400-550
AZ80A	290-400	550-750	205-290	400-550
Elevated-temperature alloys				
HM21A	400-525	750-975	370-425	700-800
EK31A	370-480	700-900	345-400	650-750
Special alloys				
ZE42A	290-370	550-700	300-345	575-650
ZE62	300-345	575-675	300-345	575-675
QE22A	345-385	650-725	315-370	600-700

(a) The strain-hardening alloys must be processed on a declining temperature scale within the given range to preclude recrystallization.

A redesigned graphic shows the numbers on a linear scale, and includes the solidus temperatures for these alloys. Forging temperatures are shown in magenta text, while solidus temperatures are in dark blue text. It is clear that forging is *not* done within 55°C of the solidus temperature.

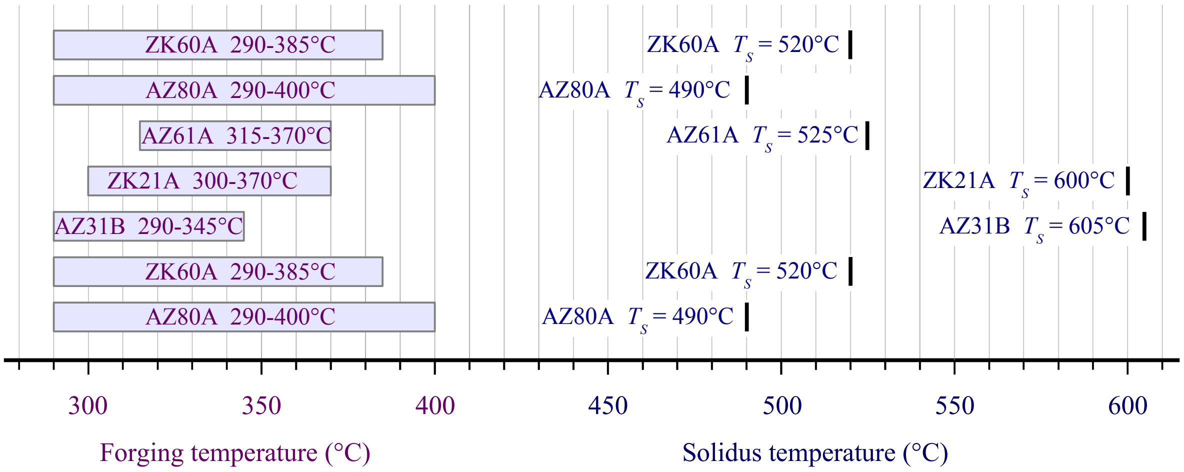


Table Design

This table from *Selection of Engineering Materials and Adhesives* demonstrates a common readability problem with wide tables published in textbooks and handbooks. [14] The reader may need to use a straightedge to figure out which stainless steel alloy corresponds with the second X in the pipe column.

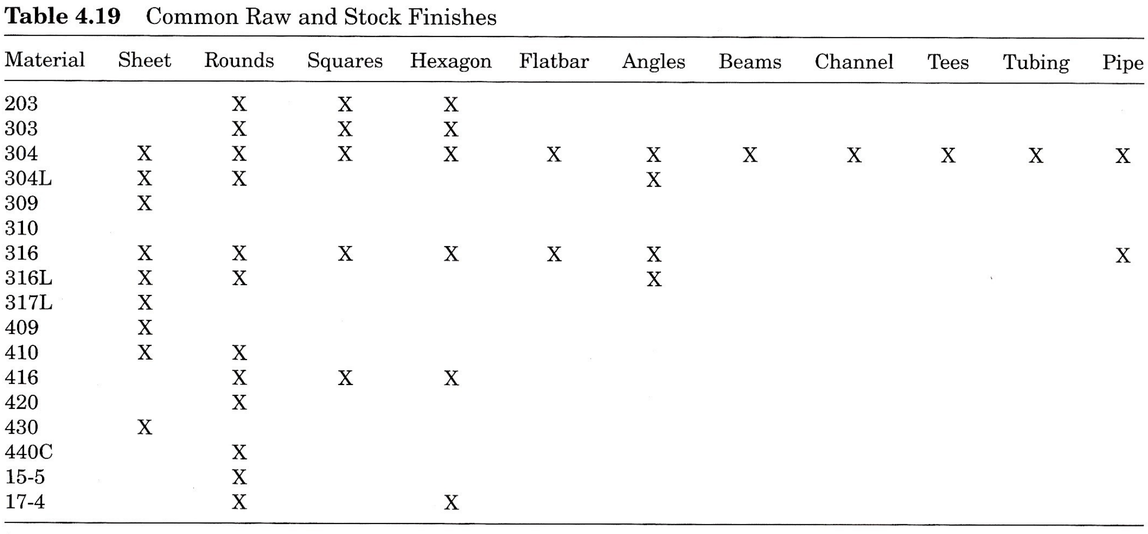


Table 4.19 Common Raw and Stock Finishes

Material	Sheet	Rounds	Squares	Hexagon	Flatbar	Angles	Beams	Channel	Tees	Tubing	Pipe
203		X	X	X							
303		X	X	X							
304	X	X	X	X	X	X	X	X	X	X	X
304L	X	X				X					
309	X										
310											
316	X	X	X	X	X	X					X
316L	X	X				X					
317L	X										
409	X										
410	X	X									
416		X	X	X							
420		X									
430	X										
440C		X									
15-5		X									
17-4		X		X							

A better solution is to use light gridlines or shading (like the *Consumer Reports* automobile reliability tables).

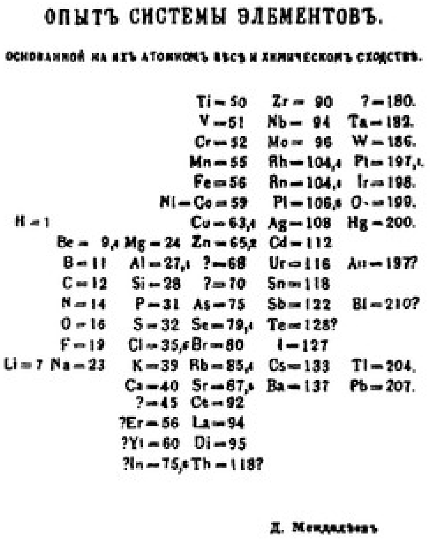
Material	Sheet	Rounds	Squares	Hexagon	Flatbar	Angles	Beams	Channel	Tees	Tubing	Pipe
203		X	X	X							
303		X	X	X							
304	X	X	X	X	X	X	X	X	X	X	X
304L	X	X				X					
309	X										
310											
316	X	X	X	X	X	X					X
316L	X	X				X					
317L	X										
409	X										
410	X	X									
416		X	X	X							
420		X									
430	X										
440C		X									
15-5		X									
17-4		X		X							

Now it is clear that the second X in the pipe column is Type 316 stainless steel. The table says that Type 310 stainless steel is not available in any of these forms...an error, because it is sold as sheet, plate, pipe, and bar form.

Colored Graphical Tables for Qualitative Data

Mendeleev first published his periodic table of the elements in black and white, oriented 90° to the common format used today. [15] He included atomic numbers only, but modern periodic tables may include each element's group, period, atomic mass, nobility, valence, bonding, etc.

Some authors fit as much information into a single periodic table as possible, using color shading, solid and hollow text, and colored text. This approach makes sense for the inside cover of a book or for a wall poster. Another approach is to create a series of smaller tables, each using color shading to indicate one qualitative property.



ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,1.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

For example, this periodic table distinguishes metals from metalloids and nonmetals.

🟧 H																	🟧 He
🟪 Li	🟪 Be											🟨 B	🟧 C	🟧 N	🟧 O	🟧 F	🟧 Ne
🟪 Na	🟪 Mg											🟪 Al	🟨 Si	🟧 P	🟧 S	🟧 Cl	🟧 Ar
🟪 K	🟪 Ca	🟪 Sc	🟪 Ti	🟪 V	🟪 Cr	🟪 Mn	🟪 Fe	🟪 Co	🟪 Ni	🟪 Cu	🟪 Zn	🟪 Ga	🟨 Ge	🟨 As	🟧 Se	🟧 Br	🟧 Kr
🟪 Rb	🟪 Sr	🟪 Y	🟪 Zr	🟪 Nb	🟪 Mo	🟪 Tc	🟪 Ru	🟪 Rh	🟪 Pd	🟪 Ag	🟪 Cd	🟪 In	🟪 Sn	🟨 Sb	🟨 Te	🟧 I	🟧 Xe
🟪 Cs	🟪 Ba	🟪 Lu	🟪 Hf	🟪 Ta	🟪 W	🟪 Re	🟪 Os	🟪 Ir	🟪 Pt	🟪 Au	🟪 Hg	🟪 Tl	🟪 Pb	🟪 Bi	🟪 Po	🟨 At	🟧 Rn
🟪 Fr	🟪 Ra	🟪 Lr	🟪 Rf	🟪 Db	🟪 Sg	🟪 Bh	🟪 Hs	Mt	Ds	Rg	🟪 Cn	Nh	🟪 Fl	Mc	Lv	Ts	Og

🟪 La	🟪 Ce	🟪 Pr	🟪 Nd	🟪 Pm	🟪 Sm	🟪 Eu	🟪 Gd	🟪 Tb	🟪 Dy	🟪 Ho	🟪 Er	🟪 Tm	🟪 Yb
🟪 Ac	🟪 Th	🟪 Pa	🟪 U	🟪 Np	🟪 Pu	🟪 Am	🟪 Cm	🟪 Bk	🟪 Cf	🟪 Es	🟪 Fm	🟪 Md	🟪 No

🟪 Metal
🟨 Metalloid
🟧 Nonmetal

This periodic table distinguishes room-temperature phases.

🟧 H																	🟧 He
🟪 Li	🟪 Be											🟪 B	🟪 C	🟧 N	🟧 O	🟧 F	🟧 Ne
🟪 Na	🟪 Mg											🟪 Al	🟪 Si	🟪 P	🟪 S	🟧 Cl	🟧 Ar
🟪 K	🟪 Ca	🟪 Sc	🟪 Ti	🟪 V	🟪 Cr	🟪 Mn	🟪 Fe	🟪 Co	🟪 Ni	🟪 Cu	🟪 Zn	🟪 Ga	🟪 Ge	🟪 As	🟪 Se	🟨 Br	🟧 Kr
🟪 Rb	🟪 Sr	🟪 Y	🟪 Zr	🟪 Nb	🟪 Mo	🟪 Tc	🟪 Ru	🟪 Rh	🟪 Pd	🟪 Ag	🟪 Cd	🟪 In	🟪 Sn	🟪 Sb	🟪 Te	🟪 I	🟧 Xe
🟪 Cs	🟪 Ba	🟪 Lu	🟪 Hf	🟪 Ta	🟪 W	🟪 Re	🟪 Os	🟪 Ir	🟪 Pt	🟪 Au	🟨 Hg	🟪 Tl	🟪 Pb	🟪 Bi	🟪 Po	🟪 At	🟧 Rn
🟪 Fr	🟪 Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

🟪 La	🟪 Ce	🟪 Pr	🟪 Nd	🟪 Pm	🟪 Sm	🟪 Eu	🟪 Gd	🟪 Tb	🟪 Dy	🟪 Ho	🟪 Er	🟪 Tm	🟪 Yb
🟪 Ac	🟪 Th	🟪 Pa	🟪 U	🟪 Np	🟪 Pu	🟪 Am	🟪 Cm	🟪 Bk	🟪 Cf	🟪 Es	🟪 Fm	🟪 Md	🟪 No

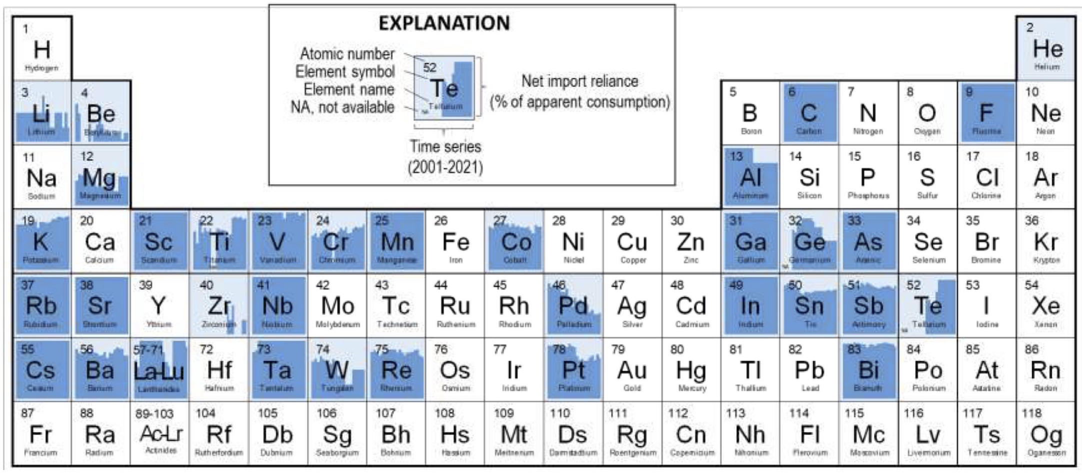
🟪 Solid
🟨 Liquid
🟧 Gas

This periodic table marks the elements that are commonly added to steels.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Other properties that lend themselves to this type of display include radioactivity, toxicity, and relative cost. USGS publishes a periodic table that shows the U.S. reliance on imports for 32 individual elements and the lanthanides as a class, over a 20 year span. [3] Notable omissions include iron, nickel, copper, and zinc.



Colored graphical table example: Galvanic corrosion

New editions in the *ASM Handbook* series are printed in color, thanks to the availability of affordable high-speed color laserprinting. The 1987 edition of the *ASM Handbook* on corrosion was printed in black and white, making it more challenging for the authors to present qualitative data in an easy-to-read format. A case in point is this table comparing seawater corrosion rates of galvanic couples in a qualitative sense (only the top few rows are shown here). [16]

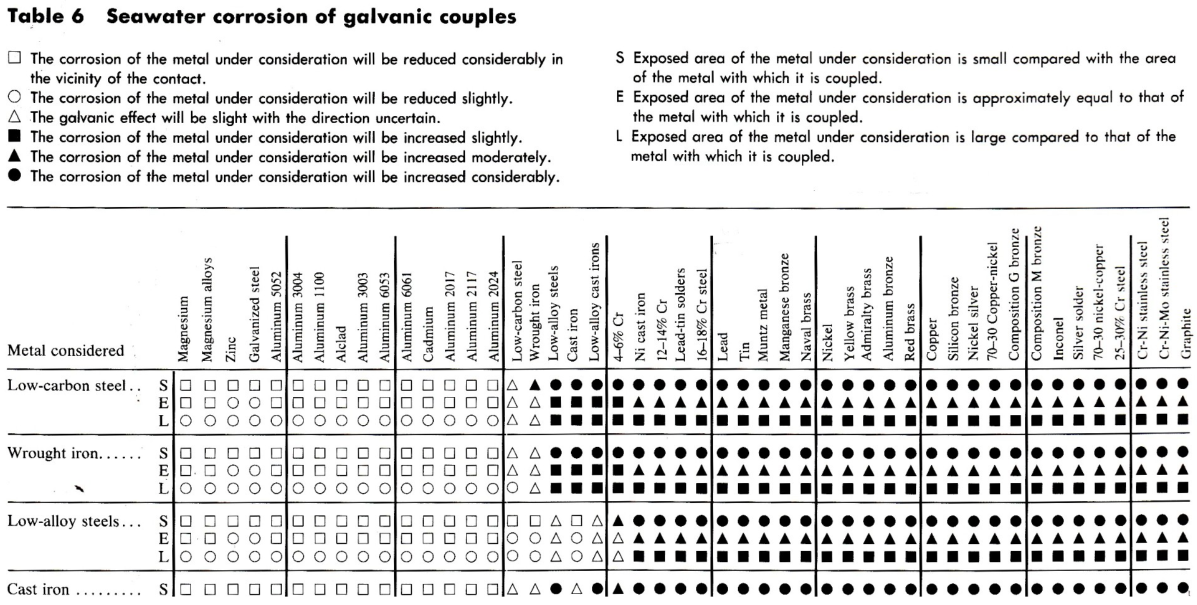


Table 6 Seawater corrosion of galvanic couples

□ The corrosion of the metal under consideration will be reduced considerably in the vicinity of the contact.
○ The corrosion of the metal under consideration will be reduced slightly.
△ The galvanic effect will be slight with the direction uncertain.
■ The corrosion of the metal under consideration will be increased slightly.
▲ The corrosion of the metal under consideration will be increased moderately.
● The corrosion of the metal under consideration will be increased considerably.

S Exposed area of the metal under consideration is small compared with the area of the metal with which it is coupled.
E Exposed area of the metal under consideration is approximately equal to that of the metal with which it is coupled.
L Exposed area of the metal under consideration is large compared to that of the metal with which it is coupled.

Metal considered		Magnesium	Magnesium alloys	Zinc	Galvanized steel	Aluminum 5052	Aluminum 3004	Aluminum 1100	Alclad	Aluminum 3003	Aluminum 6053	Aluminum 6061	Cadmium	Aluminum 2017	Aluminum 2117	Aluminum 2024
Low-carbon steel . .	S	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	E	□	□	○	○	□	□	□	□	□	□	□	□	□	□	□
	L	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Wrought iron.	S	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	E	□	□	○	○	□	□	□	□	□	□	□	□	□	□	□
	L	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Low-alloy steels . . .	S	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	E	□	□	○	○	□	□	□	□	□	□	□	□	□	□	□
	L	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Cast iron	S	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□

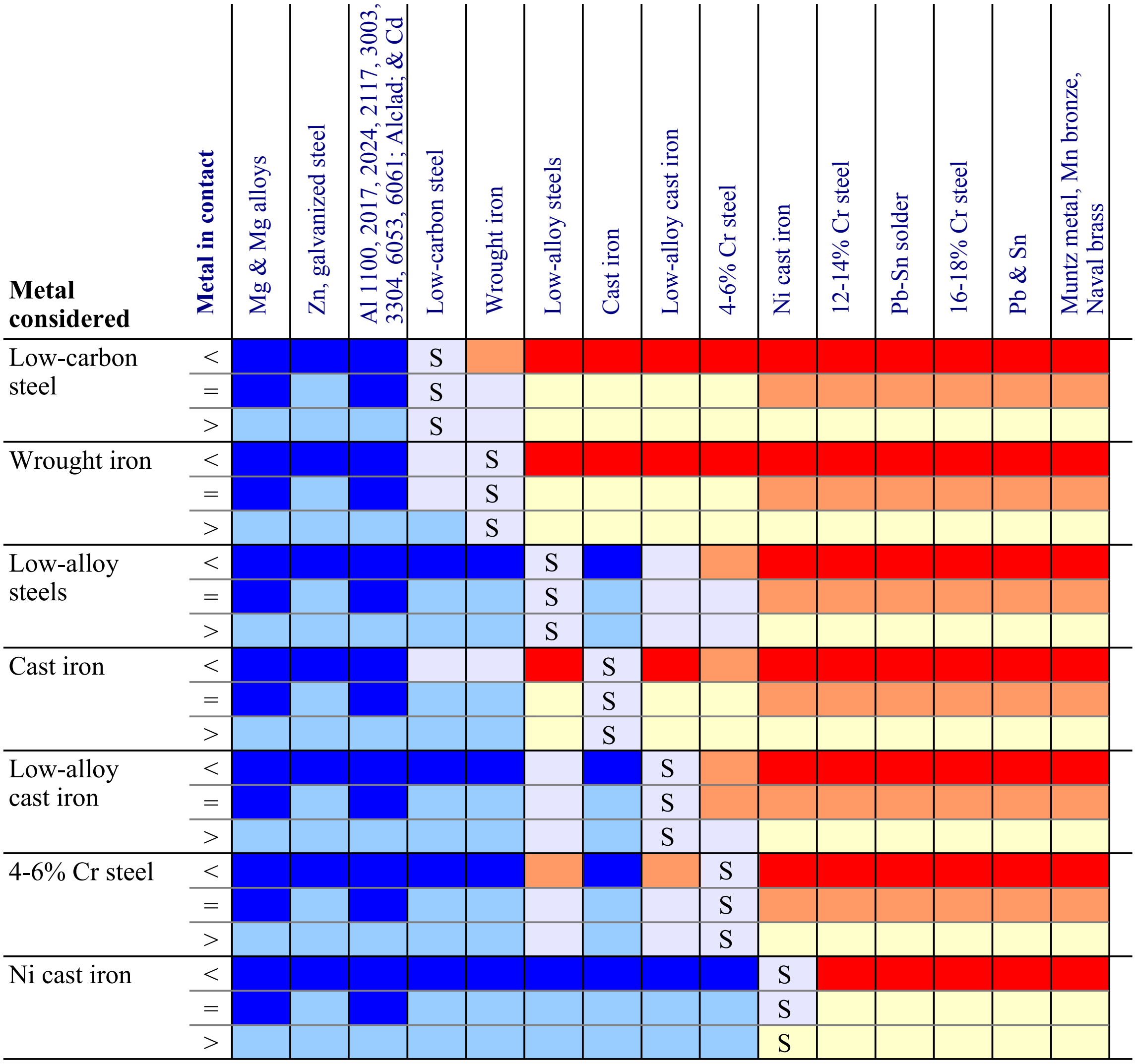
Metal considered		Low-carbon steel	Wrought iron	Low-alloy steels	Cast iron	Low-alloy cast irons	4–6% Cr	Ni cast iron	12–14% Cr	Lead-tin solders	16–18% Cr steel	Lead	Tin	Muntz metal	Manganese bronze	Naval brass
Low-carbon steel . .	S	△	▲	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	△	△	■	■	■	■	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	△	△	■	■	■	■	■	■	■	■	■	■	■	■	■
Wrought iron.	S	△	△	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	△	△	■	■	■	■	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	○	△	■	■	■	■	■	■	■	■	■	■	■	■	■
Low-alloy steels . . .	S	□	□	△	□	△	▲	●	●	●	●	●	●	●	●	●
	E	○	○	△	○	△	△	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	○	○	△	○	△	△	■	■	■	■	■	■	■	■	■
Cast iron	S	△	△	●	△	●	▲	●	●	●	●	●	●	●	●	●

Metal considered		Nickel	Yellow brass	Admiralty brass	Aluminum bronze	Red brass	Copper	Silicon bronze	Nickel silver	70–30 Copper-nickel	Composition G bronze	Composition M bronze	Inconel	Silver solder	70–30 nickel-copper	25–30% Cr steel	Cr-Ni stainless steel	Cr-Ni-Mo stainless steel	Graphite
Low-carbon steel . .	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Wrought iron.	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Low-alloy steels . . .	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	E	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲
	L	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Cast iron	S	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

The table includes a large amount of data in a small space, enabling the reader to compare corrosion rate (six shapes, where hollow = slower corrosion, shaded = accelerated corrosion) under three surface area ratios. Unfortunately, the meaning of the shapes is inconsistent: a hollow square means a significant reduction in corrosion, but a shaded square does not mean a significant increase in corrosion. The letters S, E, and L in the **Metal considered** column indicate that the exposed area of the metal is small, equal, or large relative to the metal it is coupled to...the "metal in contact."

Some materials have identical corrosion behavior (aluminum alloys 1100, 2017, 2024, 2117, 3003, 3304, 6053, 6061), so why use eight columns when one will work?

A redrawn version color-codes fonts used for the metal considered and the metal in contact (blue type). The letter "S" indicates the two metals in the couple are the same. Colored rectangles replace corrosion rate symbols, where, blue represents safety and red represents danger. The **Metal considered** column now uses less than (<) equal (=) or more than (>) symbols to indicate the surface area of the metal in contact, instead of letters S, E, or L.



Metal considered	**Metal in contact**	Mg & Mg alloys	Zn, galvanized steel	Al 1100, 2017, 2024, 2117, 3003, 3304, 6053, 6061; Alclad; & Cd	Low-carbon steel	Wrought iron	Low-alloy steels	Cast iron	Low-alloy cast iron	4-6% Cr steel	Ni cast iron	12-14% Cr steel	Pb-Sn solder	16-18% Cr steel	Pb & Sn	Muntz metal, Mn bronze, Naval brass
Low-carbon steel	<	🟦	🟦	🟦	S	🟧	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	S	⬜	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	S	⬜	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Wrought iron	<	🟦	🟦	🟦	⬜	S	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	⬜	S	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	🔷	S	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Low-alloy steels	<	🟦	🟦	🟦	🟦	🟦	S	🟦	⬜	🟧	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	🔷	🔷	S	🔷	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	🔷	🔷	S	🔷	⬜	⬜	🟨	🟨	🟨	🟨	🟨	🟨
Cast iron	<	🟦	🟦	🟦	⬜	⬜	🟥	S	🟥	🟧	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	🔷	🔷	🟨	S	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	🔷	🔷	🟨	S	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Low-alloy cast iron	<	🟦	🟦	🟦	🟦	🟦	⬜	🟦	S	🟧	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	🔷	🔷	⬜	🔷	S	🟧	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	🔷	🔷	⬜	🔷	S	⬜	🟨	🟨	🟨	🟨	🟨	🟨
4-6% Cr steel	<	🟦	🟦	🟦	🟦	🟦	🟧	🟦	🟧	S	🟥	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	🔷	🔷	⬜	🔷	⬜	S	🟧	🟧	🟧	🟧	🟧	🟧
	>	🔷	🔷	🔷	🔷	🔷	⬜	🔷	⬜	S	🟨	🟨	🟨	🟨	🟨	🟨
Ni cast iron	<	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	S	🟥	🟥	🟥	🟥	🟥
	=	🟦	🔷	🟦	🔷	🔷	🔷	🔷	🔷	🔷	S	🟨	🟨	🟨	🟨	🟨
	>	🔷	🔷	🔷	🔷	🔷	🔷	🔷	🔷	🔷	S	🟨	🟨	🟨	🟨	🟨

🟦	Metal under consideration corrodes **much slower** than normal
🔷	Metal under consideration corrodes **a little slower** than normal
⬜	Nearly no measurable change in corrosion rate
🟨	Metal under consideration corrodes a **little faster** than normal
🟧	Metal under consideration corrodes **moderately faster** than normal
🟥	Metal under consideration corrodes **much faster** than normal

S = same “metal considered” and “metal in contact”

The complete graphical table includes seven more (triple) rows of “metals considered” and five more columns of “metals in contact.” I include a portion of the ASM Handbook version of the table in the handout so students can compare it with the color-coded version. Students tell me they much prefer the new version.

Colored graphical table example: Sulfuric acid resistance

Other types of corrosion also lend themselves to graphical tables. The table below from *Stainless Steels for Design Engineers* comprises 20% of a larger table which shows the resistance of 15 metal alloys to 5 concentrations of sulfuric acid at 6 temperatures [17]. The numbers 0, 1, and 2 represent the corrosion rate:

- 0 = corrosion proof, with a corrosion rate < 0.1 mm/year
- 1 = corrosion resistant, with a corrosion rate 0.1 to 1.0 mm/year
- 2 = serious corrosion, with a corrosion rate > 1.0 mm/year

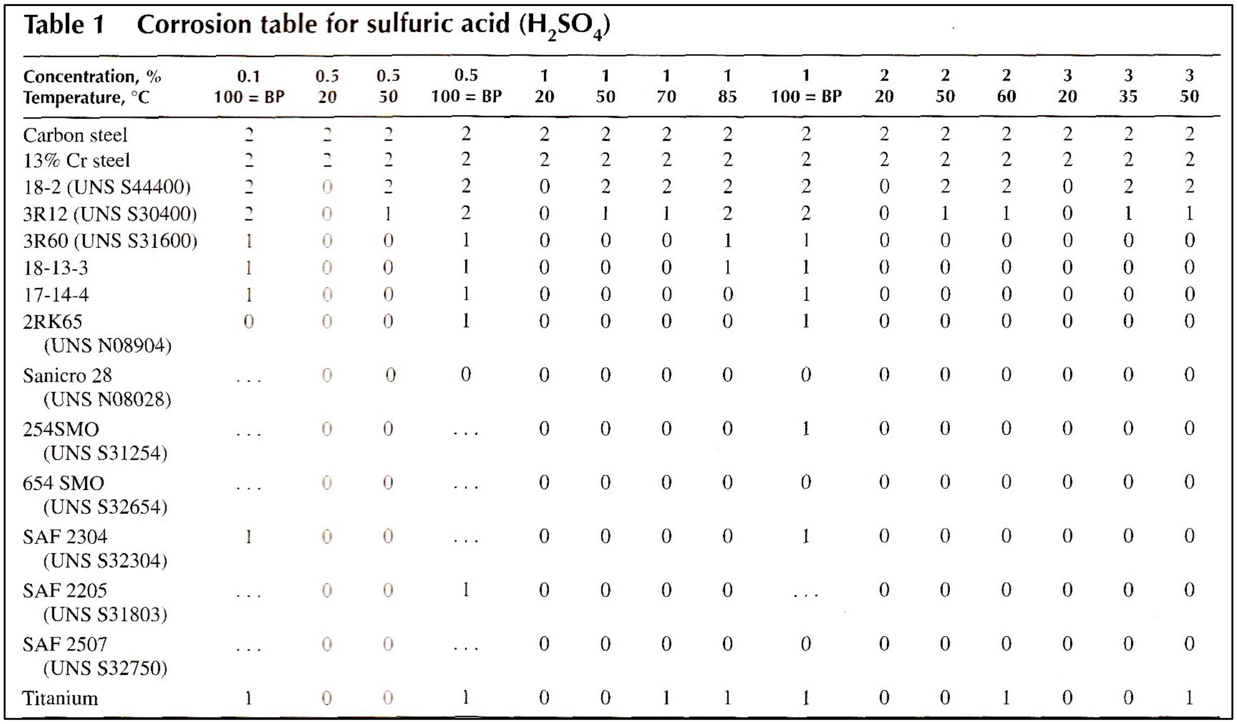
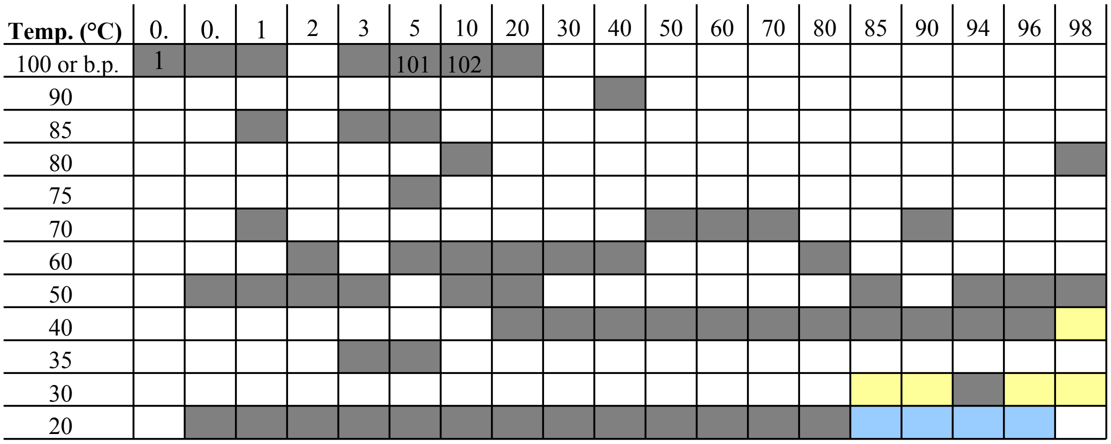


Table 1 Corrosion table for sulfuric acid (H_2SO_4)

Concentration, %	0.1	0.5	0.5	0.5	1	1	1	1	1	2	2	2	3	3	3
Temperature, °C	100 = BP	20	50	100 = BP	20	50	70	85	100 = BP	20	50	60	20	35	50
Carbon steel	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
13% Cr steel	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
18-2 (UNS S44400)	2	0	2	2	0	2	2	2	2	0	2	2	0	2	2
3R12 (UNS S30400)	2	0	1	2	0	1	1	2	2	0	1	1	0	1	1
3R60 (UNS S31600)	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0
18-13-3	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0
17-14-4	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0
2RK65 (UNS N08904)	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
Sanicro 28 (UNS N08028)	. . .	0	0	0	0	0	0	0	0	0	0	0	0	0	0
254SMO (UNS S31254)	. . .	0	0	. . .	0	0	0	0	1	0	0	0	0	0	0
654 SMO (UNS S32654)	. . .	0	0	. . .	0	0	0	0	0	0	0	0	0	0	0
SAF 2304 (UNS S32304)	1	0	0	. . .	0	0	0	0	1	0	0	0	0	0	0
SAF 2205 (UNS S31803)	. . .	0	0	1	0	0	0	0	. . .	0	0	0	0	0	0
SAF 2507 (UNS S32750)	. . .	0	0	. . .	0	0	0	0	0	0	0	0	0	0	0
Titanium	1	0	0	1	0	0	1	1	1	0	0	1	0	0	1

We can take just one of the materials and show the data over the full range of acid concentrations and temperatures. Color shading makes the table easier to read than numerical codes.

Carbon Steel



Concentration of sulfuric acid (%)

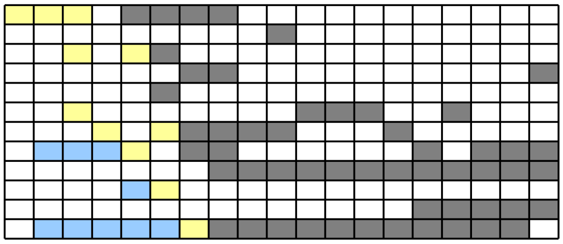
Temp. (°C)	0.	0.	1	2	3	5	10	20	30	40	50	60	70	80	85	90	94	96	98
100 or b.p.	■ 1	■	■		■	■ 101	■ 102	■											
90										■									
85			■		■	■													
80							■												■
75						■													
70			■								■	■	■			■			
60				■		■	■	■	■	■				■					
50		■	■	■	■		■	■							■		■	■	■
40								■	■	■	■	■	■	■	■	■	■	■	🟨
35					■	■													
30															🟨	🟨	■	🟨	🟨
20		■	■	■	■	■	■	■	■	■	■	■	■	■	🟦	🟦	🟦	🟦	

🟦 Corrosion-proof
🟨 Not corrosion-proof, but useful in some cases
■ Serious corrosion – do not use
☐ No data

At a glance we can see that carbon steel is resistant to corrosion at low temperature and very high concentrations...but not under other conditions. Gaps in the experimental data are immediately apparent – we have data for 32% of the possible test conditions. The numbers in the gray boxes along the top row reflect the boiling points of 5% and 10% sulfuric acid solutions, respectively, which are higher than the boiling point of water.

Once one tabular graph is shown, there is no need to repeat the numerical headings on subsequent graphs. We can make smaller graphs using the same grid pattern to help compare one material with another. This smaller graphic shows that titanium is good at low concentrations of sulfuric acid at all temperatures, while it corrodes readily at higher concentrations at all temperatures.

Titanium



🟨	🟨	🟨		■	■	■	■											
									■									
		🟨		🟨	■													
						■	■											■
					■													
		🟨								■	■	■			■			
			🟨		🟨	■	■	■	■				■					
	🟦	🟦	🟦	🟨		■	■							■		■	■	■
							■	■	■	■	■	■	■	■	■	■	■	■
				🟦	🟨													
														■	■	■	■	■
	🟦	🟦	🟦	🟦	🟦	🟨	■	■	■	■	■	■	■	■	■	■	■	

Colored graphical table example: Forming Processes for Stainless Steels

The previous examples included tables using symbols or numbers. This table from Vol. 14 of the *ASM Handbook* uses 4 letters to distinguish the suitability of 8 forming processes for 39 stainless alloys. [18]

Although 4 letters are used, combinations include A-B, B-C, and C-D, so there are actually 7 levels of suitability.

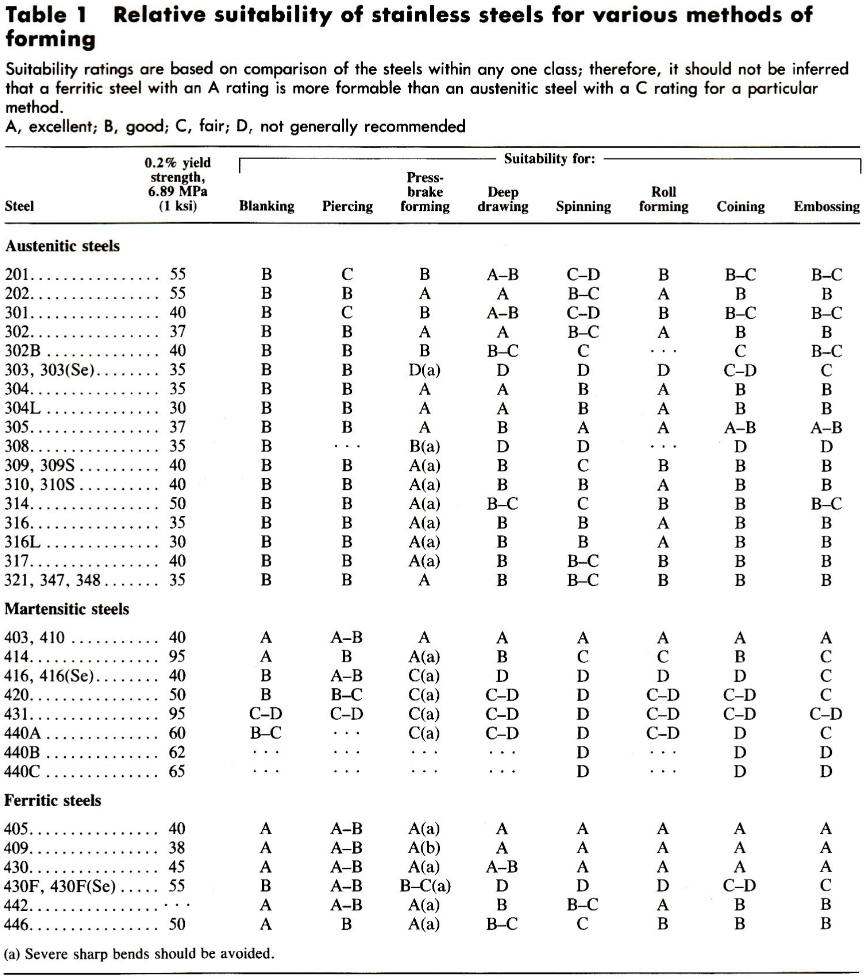


Table 1 Relative suitability of stainless steels for various methods of forming

Suitability ratings are based on comparison of the steels within any one class; therefore, it should not be inferred that a ferritic steel with an A rating is more formable than an austenitic steel with a C rating for a particular method.
A, excellent; B, good; C, fair; D, not generally recommended

Steel	0.2% yield strength, 6.89 MPa (1 ksi)	Suitability for:							
		Blanking	Piercing	Press-brake forming	Deep drawing	Spinning	Roll forming	Coining	Embossing
Austenitic steels									
201	55	B	C	B	A–B	C–D	B	B–C	B–C
202	55	B	B	A	A	B–C	A	B	B
301	40	B	C	B	A–B	C–D	B	B–C	B–C
302	37	B	B	A	A	B–C	A	B	B
302B	40	B	B	B	B–C	C	. . .	C	B–C
303, 303(Se)	35	B	B	D(a)	D	D	D	C–D	C
304	35	B	B	A	A	B	A	B	B
304L	30	B	B	A	A	B	A	B	B
305	37	B	B	A	B	A	A	A–B	A–B
308	35	B	. . .	B(a)	D	D	. . .	D	D
309, 309S	40	B	B	A(a)	B	C	B	B	B
310, 310S	40	B	B	A(a)	B	B	A	B	B
314	50	B	B	A(a)	B–C	C	B	B	B–C
316	35	B	B	A(a)	B	B	A	B	B
316L	30	B	B	A(a)	B	B	A	B	B
317	40	B	B	A(a)	B	B–C	B	B	B
321, 347, 348	35	B	B	A	B	B–C	B	B	B
Martensitic steels									
403, 410	40	A	A–B	A	A	A	A	A	A
414	95	A	B	A(a)	B	C	C	B	C
416, 416(Se)	40	B	A–B	C(a)	D	D	D	D	C
420	50	B	B–C	C(a)	C–D	D	C–D	C–D	C
431	95	C–D	C–D	C(a)	C–D	D	C–D	C–D	C–D
440A	60	B–C	. . .	C(a)	C–D	D	C–D	D	C
440B	62	. . .	. . .	. . .	. . .	D	. . .	D	D
440C	65	. . .	. . .	. . .	. . .	D	. . .	D	D
Ferritic steels									
405	40	A	A–B	A(a)	A	A	A	A	A
409	38	A	A–B	A(b)	A	A	A	A	A
430	45	A	A–B	A(a)	A–B	A	A	A	A
430F, 430F(Se)	55	B	A–B	B–C(a)	D	D	D	C–D	C
442	. . .	A	A–B	A(a)	B	B–C	A	B	B
446	50	A	B	A(a)	B–C	C	B	B	B

(a) Severe sharp bends should be avoided.

A colored graphical table makes it easier to compare alloys for a given metalworking process (Types 403 and 410 martensitic stainless steels are easier to spin than any other type of martensitic stainless), and to compare processes for a given alloy (Type 316 is easier to roll form than to spin). The striped boxes indicate a mixed rating, so an A-B rating appears as blue and yellow stripes. Black boxes indicate missing data.

Alloy system	Yield strength (MPa)	Blanking	Piercing	Press brake forming	Deep drawing	Spinning	Roll forming	Coining	Embossing
Austenitic									
201	380	🟨	🟧	🟨	🟨/🟦	🟥/🟧	🟨	🟧/🟨	🟧/🟨
202	380	🟨	🟨	🟦	🟦	🟧/🟨	🟦	🟨	🟨
301	280	🟨	🟧	🟨	🟨/🟦	🟥/🟧	🟨	🟧/🟨	🟧/🟨
302	260	🟨	🟨	🟦	🟦	🟧/🟨	🟦	🟨	🟨
302B	280	🟨	🟨	🟨	🟧/🟨	🟧	⬛	🟧	🟧/🟨
303, 303(Se)	240	🟨	🟨	🟥 ***	🟥	🟥	🟥	🟧/🟥	🟧
304	240	🟨	🟨	🟦	🟦	🟨	🟦	🟨	🟨
304L	210	🟨	🟨	🟦	🟦	🟨	🟦	🟨	🟨
305	260	🟨	🟨	🟦	🟨	🟦	🟦	🟨/🟦	🟦/🟨
308	240	🟨	⬛	🟨 ***	🟥	🟥	⬛	🟥	🟥
309, 309S	280	🟨	🟨	🟦 ***	🟨	🟧	🟨	🟨	🟨
310, 310S	280	🟨	🟨	🟦 ***	🟨	🟨	🟦	🟨	🟨
314	340	🟨	🟨	🟦 ***	🟧/🟨	🟧	🟨	🟨	🟧/🟨
316	240	🟨	🟨	🟦 ***	🟨	🟨	🟦	🟨	🟨
316L	210	🟨	🟨	🟦 ***	🟨	🟨	🟦	🟨	🟨
317	280	🟨	🟨	🟦 ***	🟨	🟧/🟨	🟨	🟨	🟨
321, 347, 348	240	🟨	🟨	🟦	🟨	🟧/🟨	🟨	🟨	🟨
Martensitic									
403, 410	280	🟦	🟨/🟦	🟦	🟦	🟦	🟦	🟦	🟦
414	660	🟦	🟨	🟦 ***	🟨	🟧	🟧	🟨	🟧
416, 416(Se)	280	🟨	🟦/🟨	🟧 ***	🟥	🟥	🟥	🟥	🟧
420	340	🟨	🟧/🟨	🟧 ***	🟥/🟧	🟥	🟥/🟧	🟥/🟧	🟧
431	660	🟧/🟥	🟥/🟧	🟧 ***	🟥/🟧	🟥	🟥/🟧	🟧/🟥	🟥/🟧
440A	410	🟧/🟨	⬛	🟧 ***	🟥/🟧	🟥	🟥/🟧	🟥	🟧
440B	430	⬛	⬛	⬛	⬛	🟥	⬛	🟥	🟥
440C	450	⬛	⬛	⬛	⬛	🟥	⬛	🟥	🟥
Ferritic									
405	280	🟦	🟨/🟦	🟦 ***	🟦	🟦	🟦	🟦	🟦
409	260	🟦	🟨/🟦	🟦 ***	🟦	🟦	🟦	🟦	🟦
430	310	🟦	🟨/🟦	🟦 ***	🟨/🟦	🟦	🟦	🟦	🟦
430F, 430F(Se)	380	🟨	🟦/🟨	🟧/🟨	🟥	🟥	🟥	🟥/🟧	🟧
442	---	🟦	🟨/🟦	🟦 ***	🟨	🟧/🟨	🟦	🟨	🟨
446	340	🟦	🟨	🟦 ***	🟧/🟨	🟧	🟨	🟨	🟨

🟦 Excellent
🟨 Good
🟧 Fair
🟥 Not recommended
⬛ No data

Comparisons of formability are with respect to other stainless alloys *in the same class* (austenitic, martensitic, or ferritic), not between classes of stainless alloys.

Yield strength values are presumably for metals in their softest condition.

*** Avoid sharp bends

Creating x-y Scatter Graphs from Tables

Tables are useful for presenting data in a compact form, but oftentimes an x-y scatter graph tells a story better than a table can. For example, this table from Vol. 14 of the *ASM Handbook* lists the pressures required to extrude 4 magnesium alloys at 7 temperatures with an 85% reduction in area. [19] Extrusion pressures are listed first in SI units, then in US Customary units.

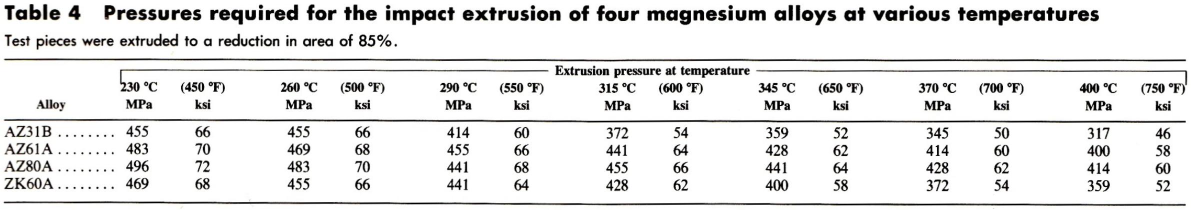


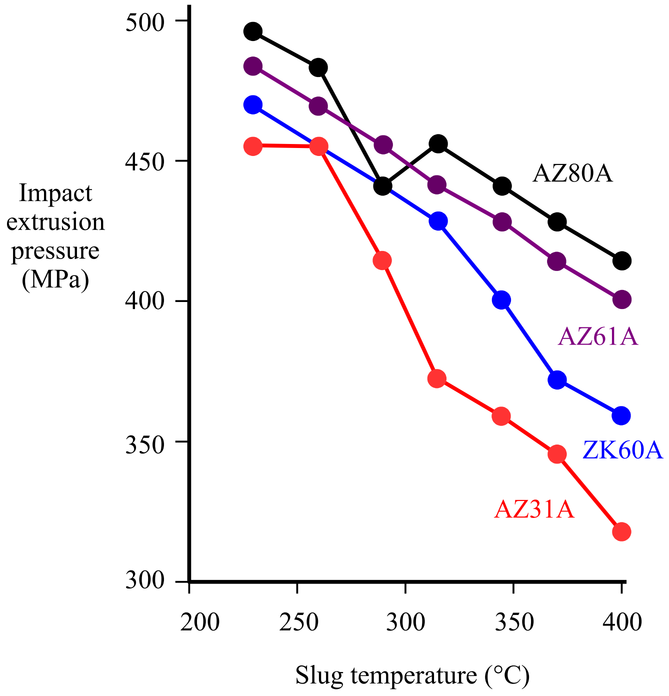
Table 4 Pressures required for the impact extrusion of four magnesium alloys at various temperatures

Test pieces were extruded to a reduction in area of 85%.

Alloy	Extrusion pressure at temperature													
	230 °C	(450 °F)	260 °C	(500 °F)	290 °C	(550 °F)	315 °C	(600 °F)	345 °C	(650 °F)	370 °C	(700 °F)	400 °C	(750 °F)
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi
AZ31B	455	66	455	66	414	60	372	54	359	52	345	50	317	46
AZ61A	483	70	469	68	455	66	441	64	428	62	414	60	400	58
AZ80A	496	72	483	70	441	68	455	66	441	64	428	62	414	60
ZK60A	469	68	455	66	441	64	428	62	400	58	372	54	359	52

An x-y scatter graph of this dataset reveals a typographical error in the table. The black curve for AZ80A drops unexpectedly at 290°C to a value that is 28 MPa too low, then it rises up again at 315°C. Notice that the US Customary value is 68 ksi, which is equivalent to 469 MPa, but the table entry is 441 MPa. The black AZ80A curve should be parallel to the magenta AZ61A curve.

The graph also makes it easier to interpolate values for determining temperature for a given pressure, or for determining pressure for a given temperature.

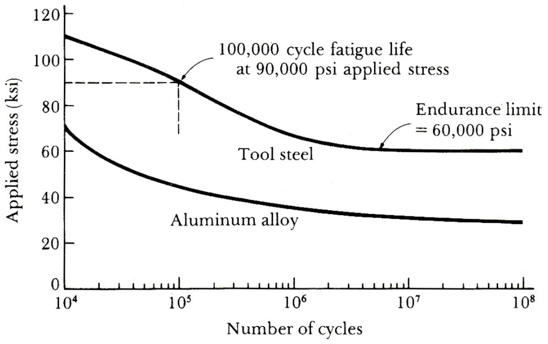


Displaying Scatter

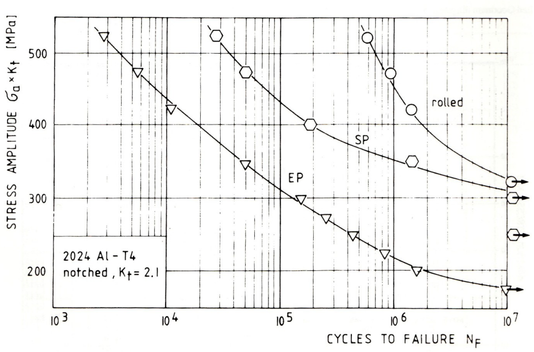
With metals, fatigue and impact tests produce much more scatter than hardness and tensile tests, yet many textbooks present fatigue and impact test results as curves with little or no scatter.

This S-N fatigue graph from Askeland's *The Science and Engineering of Materials* compares the behavior of two materials, showing clear definitions for fatigue life and endurance limit. [20]

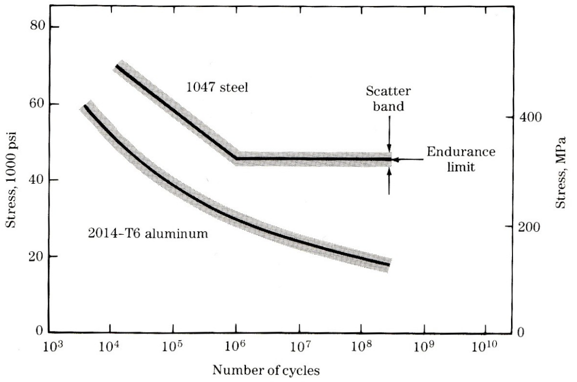
However, there are no datapoints, and no indication of the degree of scatter, potentially causing students to think that there is no scatter. The dashed line implies that the curve is exact. In my previous industrial career, an engineer once asked me whether our test lab was running fatigue tests incorrectly because some samples survived twice as long as others on the same test. I explained that his dataset was too small, and if he had run more samples, the scatter would have been greater (and more realistic).



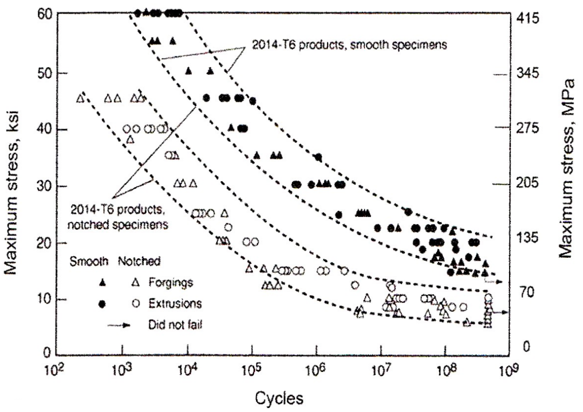
This graph from *Fatigue Data Book: Light Structural Alloys* shows data for rolled, shot peened (SP), and electrolytically polished (EP) 2024-T4 aluminum samples. It is simply not believable, if the points are meant to be actual datapoints. [21]

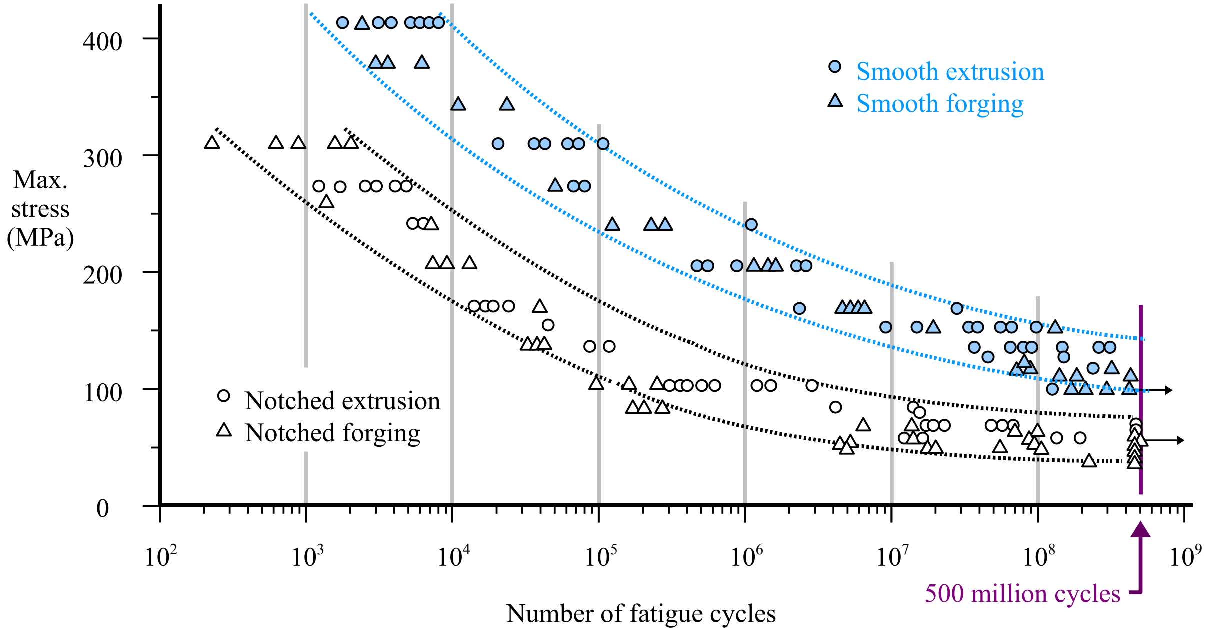


This graph from Smith's *Principles of Materials Science and Engineering* compares two materials and uses gray shading to illustrate the range in scatter for 1047 steel and 2014-T6 aluminum, but there are no actual datapoints. [22] The shading has a suspiciously uniform width. Also, unlike the Askeland graph above, this fatigue graph implies there is a sharp kink in the steel data at the endurance limit.



This graph from Vol. 2B of the *ASM Handbook* compares smooth and notched 2014-T6 aluminum samples in both forged and extruded shapes. [23] It shows that the scatter in cycle life increases as cycle time increases. In early stages, scatter is about one order of magnitude, while at later stages scatter is more than two orders of magnitude. We can further improve the diagram with color, as shown below.





Students can benefit from seeing that fatigue data has scatter which increases in magnitude at higher cycle life, if for no other reason that to avoid the mistake of the engineer described at the beginning of this section.

Conclusions

Graphs prepared for students of materials science, materials engineering, and materials technology should allow readers to compare large sets of data in a small space, without unnecessary complexity or confusion. This paper describes various techniques to improve materials data graphics, which include design approaches, the use of shading and color, linear scales, table design, colored graphical tables, and the display of scatter.

References

[1] Edward R. Tufte, *The Visual Display of Quantitative Information,* Graphics Press, 1983, p.13.

[2] https://elements.visualcapitalist.com/50-years-of-global-steel-production/, accessed January 2022. Visual Capitalist is a media company owned by Jeff Desjardins, specializing in data visualizations showing how materials and energy affect the global economy.

[3] *Mineral Commodity Summaries 2022,* U.S. Geological Survey, 2022. Available at https://pubs.er.usgs.gov/publication/mcs2022.

[4] Mitsuo Miinomi, "Recent Metallic Materials for Biomedical Applications," *JOM,* June 1999, p.32.

[5] *ASM Handbook Vol. 23: Materials for Medical Devices,* ASM International, 2012, p.234.

[6] Mars Fontana and Norbert Greene, *Corrosion Engineering,* McGraw-Hill, 1978, p.250-251. The original source is G.A. Nelson, Shell Development Company.

[7] *Metals Handbook,* 1948 edition, The American Society for Metals, 1948, p.997.

[8] *ASM Handbook Vol. 13: Corrosion,* ASM International, 1987, p.741.

[9] J.D. Hanawalt, C.E. Nelson, and J.A. Peloubet, "Corrosion Studies of Magnesium and its Alloys," *Transactions of AIME*, Vo. 147, .1942, p.273-299.

[10] William F. Smith, *Structure and Properties of Engineering Alloys,* 2nd ed., McGraw-Hill, 1993, p.439.

[11] William Callister & David Rethwisch, *Materials Science and Engineering: An Introduction,* 9th ed., Wiley, 2014, p.7.

[12] Callister & Rethwisch, p.127.

[13] *ASM Handbook Vol. 14: Forming and Forging,* ASM International, 1988, p.259.

[14] Lawrence Fisher, *Selection of Engineering Materials and Adhesives,* CRC Press, 2005, p.203.

[15] Dmitri Mendeleev, 1869 version of his periodic table of the elements (public domain).

[16] *ASM Handbook Vol. 13,* p.773.

[17] Michael F. McGuire, *Stainless Steels for Design Engineers,* ASM International, 2008, p.259-261.

[18] *ASM Handbook Vol. 14*, p.759.

[19] *ASM Handbook Vol. 14*, p.312.

[20] Donald Askeland, *The Science and Engineering of Materials,* Brooks/Cole, 1984, p.137.

[21] *Fatigue Data Book: Light Structural Alloys,* ASM International, 1995, p.20.

[22] William Smith, *Principles of Materials Science and Engineering,* McGraw-Hill, 1986, p.286.

[23] *ASM Handbook Vol. 2B: Properties and Selection of Aluminum Alloys,* ASM International, 2019, p.54.