TUNING FORKS FOR VIBRANT TEACHING

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Editor's Note: A hypertext-enhanced version of this article, including sound files of the tuning forks, is available on-line at www.tms.org/pubs/journals/JOM/0511/Burleigh-0511.html.

Metals make up the crucial components for machines, instruments, and structures. Engineering students should have an instinctive feel for the properties of the different metals, but for most students, the metals all blur together. The average student cannot distinguish between galvanized steel and stainless steel, between aluminum and tin, or between gold and polished brass. With the exception of the copper alloys, most metals have the same dull metallic appearance.

It is unfortunate that in our teaching we do not use the other senses to illustrate the differences between metals. To remedy this, with a grant from The Center of Teaching Excellence (Eastern New Mexico University, Portales, New Mexico), the authors had two sets of tuning forks computer-numerical-control machined from 17 alloys and one polymer (Figure 1). These tuning forks are used in classroom demonstrations to give the students a feel for the different densities, atomic weights, elastic moduli, and melting points of the various metals. Differences can be felt in the weight and flexibility, and heard from the differences in resonant frequency, harmonics, and dampening of the different forks. By handling the tuning forks, the students use their hands and ears in addition to their eyes to comprehend differences in the metals (Table I). See the sidebar for background on this project.

Each of the tuning forks has a distinctive ring. The dense copper alloys have a lower pitch, while the stiff steel alloys have a higher pitch. One can hear clear differences between brass, bronze, copper, and copper-beryllium. The free machining brass with 3% lead has the lowest pitch. Interestingly, steel and 6061 aluminum sound similar because steel's threefold increase in stiffness is compensated for by its threefold increase in density. The polycarbonate does not resonate at all, nor does the pure tin because it bends every time it is tapped to resonate. Magnesium, zinc, and aluminum-bronze dampen out within a few seconds. The Monel (Ni-Cu) and the Inconel (Ni-Cr) resonate loud and long. Hardened A6 tool steel resonates at a lower frequency than annealed A6 tool steel. Several metals, including zirconium, titanium, and Inconel, resonate with harmonics.

In the classroom, T. David Burleigh quizzes his students on the ranking of the copper, aluminum, and steel in terms of density and elastic modulus. In one class, only one student in five knew aluminum was the least dense, next was steel, and copper was the most dense. Only one student in five knew aluminum had the lowest elastic modulus, next was copper, and the highest was steel. The next week in class, the tuning forks were passed around and the students listened to the different frequencies, pinched the prongs to feel the different stiffness, and felt the weight of the forks in their hands. The same quiz was given at the end of this class, and there was significant improvement. Five out of seven students knew the correct ranking for the density and four

BACKGROUND

Fifteen years ago at Alcoa Technical Center, Roberto Rioja presented each of his team members with two aluminum tuning forks, one made from alloy 7075 and the other from the aluminum-lithium alloy developed by his team members. This new aerospace aluminum-lithium alloy (now registered as 2099) had a 6% lower density and a 10% higher stiffness (higher elastic modulus) than alloy 7075. The tuning forks looked the same, and some people could feel the weight difference between the two forks, but when the forks were struck and reverberated, everyone could hear the higher pitch in the aluminum-lithium fork. T. David Burleigh was amazed at hearing the differences in the two alloys and has never forgotten it.

There are almost 100 metallic elements, and when combined, the number of commercial alloys reaches the tens of thousands. Teachers use the periodic table, tables of data,[1] and Ashby Charts[2] to teach material properties. These tables and charts are greeted with glassy eyes by the students. The students learn to use the tables, but retain very little basic understanding of the different metals. The authors of this article wanted a hands-on teaching tool to reinforce the students' understanding and intuition about metals.

The tone of a tuning fork is a function of the dimensions, the density, and the elastic modulus of the metal from which it is machined.[3–5] The original dimensions of the forks used by the authors were taken from a steel tuning fork with a frequency of 256 Hz (middle C). The computer numerical control milling machine was programmed to machine all forks to the same dimensions, within 25 to 50 micrometers. If the dimensions are kept the same, but the metal is changed, then a different frequency will result from the different densities and the elastic moduli.

$$f = k\sqrt{\frac{E}{\rho}} \qquad \text{(A)}$$

In Equation A, the resonant frequency f is related to the dimensions k, the elastic modulus E, and the density ρ. The density of a metal is a function of its crystal structure and atomic weight. The elastic modulus is a measure of the stiffness of the metal, that is, how tightly the atoms are bound. Metals with strong atomic bonding are not only stiff, but also have high melting points.

Table I. Tuning Fork Material Information and Resonant Frequencies

UNS	Trade Name	E (GPa)	Density (g/cm^3)	Liquidus Temp. (°C)	Composition	Frequency (Hz)
PC	Polycarbonate	2.0	1.2		C H	—
L130xx	Pure tin	49.9	7.28	232	Sn 99.9%	—
Z3xxxx	Zn	104.5	7.1	420	Zn 95%	(d)
C36000	Free cutting brass 360		8.50	930–950	60Cu-37Zn-3Pb	129
C26000	Yellow brass (cartridge)	100.6		930–950	70Cu-30Zn	156+950
C11000	Copper 110	129.8	8.94	1,084	Cu 99%	190
C81400	CDA 954, Al-Bronze			550–640	Cu-11Al-4Fe-2.5maxNi	190+1,400 (d)
R60702	Zr 702	98	6.51	1,855	Zr-4.5maxHf	200+1,250
C17200	Brush alloy 190	131	8.25	880–950	Cu-1.9Be	206+1,400
N04400	Monel 400	185	8.83	1,300	65Ni-30Cu-1Mn-1.5Fe	233
M11310	AZ31	44.7	1.78	600–640	Mg-3Al-1Zn	255 (d)
R50400	Ti grade 2	120	4.51	1,665	Ti-max: 0.25 O-0.3Fe-0.1C-0.03Ni-0.015H	256+1,630
S30300	Stainless 303	193	8.0	1,400–1,420	Fe-18Cr-9Ni-2Mn-1Si-0.15C-0.6Mo-max:0.2P-0.15S	260
N06625	Inconel 625	208	8.44	1,290	Ni-22Cr-9Mo-4Nb-0.3Ti-0.3Al	260+1,400
A96061	6061-T6	68.9	2.70	575–630	Al-1.0Mg-0.6Si-Mn	260+1,600
T30106	A6 tool steel (hard)	200	7.84	1,530	Fe-2.2Mn-1.2Mo-1.1Cr-0.7C	266
G10180	1018 steel	350–490	7.9	1,500–1,530	Fe-0.18C-0.7Mn	267+1,666
T30106	A6 tool steel (soft)	>200	~7.84	1,450	Fe-2.2Mn-1.2Mo-1.1Cr-0.7C	276

(d) dampens

out of seven knew the correct ranking for elastic modulus (stiffness).

The tuning forks have been used for many hands-on demonstrations, in classrooms, and at career fairs. As students discover the differences among tuning forks, the instructor can draw out the different metal properties, such as color, weight, pitch, volume, stiffness, and dampening. At Dexter High School in Dexter, New Mexico, a student, upon hearing the different forks, commented, "That's why bells are made from brass!" At Alamo Navajo High School in Magdalena, New Mexico, a student remarked, "Oh, you mean all the metals are different?"

Many high school science teachers have asked where they can buy a similar set of tuning forks. Unfortunately the cost for materials and machining (about $60 per fork) is prohibitive for most. Anyone interested in helping to defray the manufacturing costs of the forks in order to allow distribution to high schools should contact the authors.

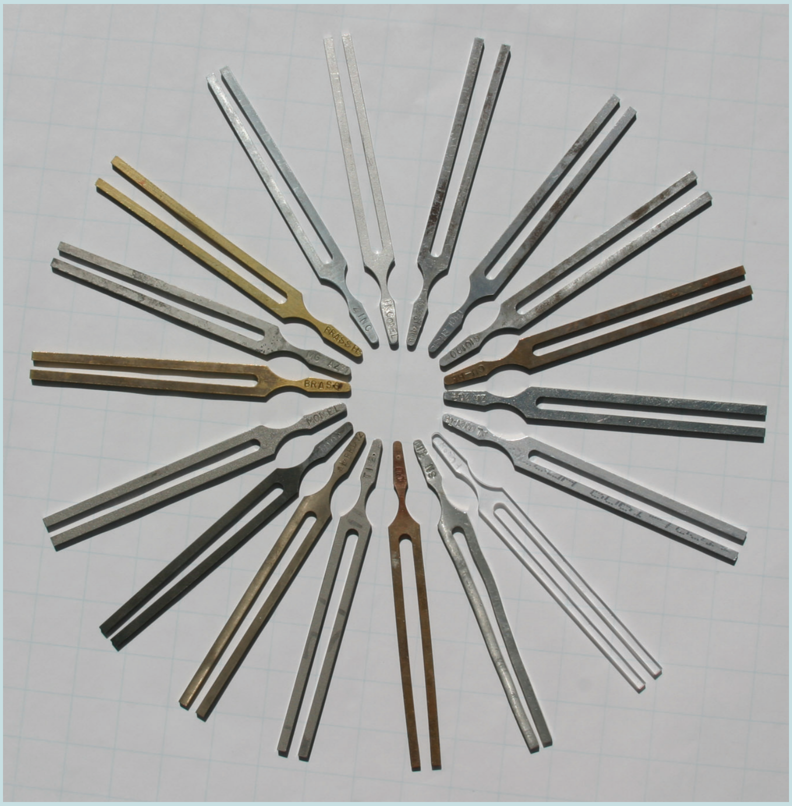

Figure 1. The 18 different tuning forks.

The use of the tuning forks in the university classroom and with high school outreach programs has been successful and is ongoing. By handling tuning forks made from various metals, the students can see, hear, and feel the differences in properties. The use of several senses reinforces the learning and makes it much more enjoyable than reading the metals' properties in a textbook.

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