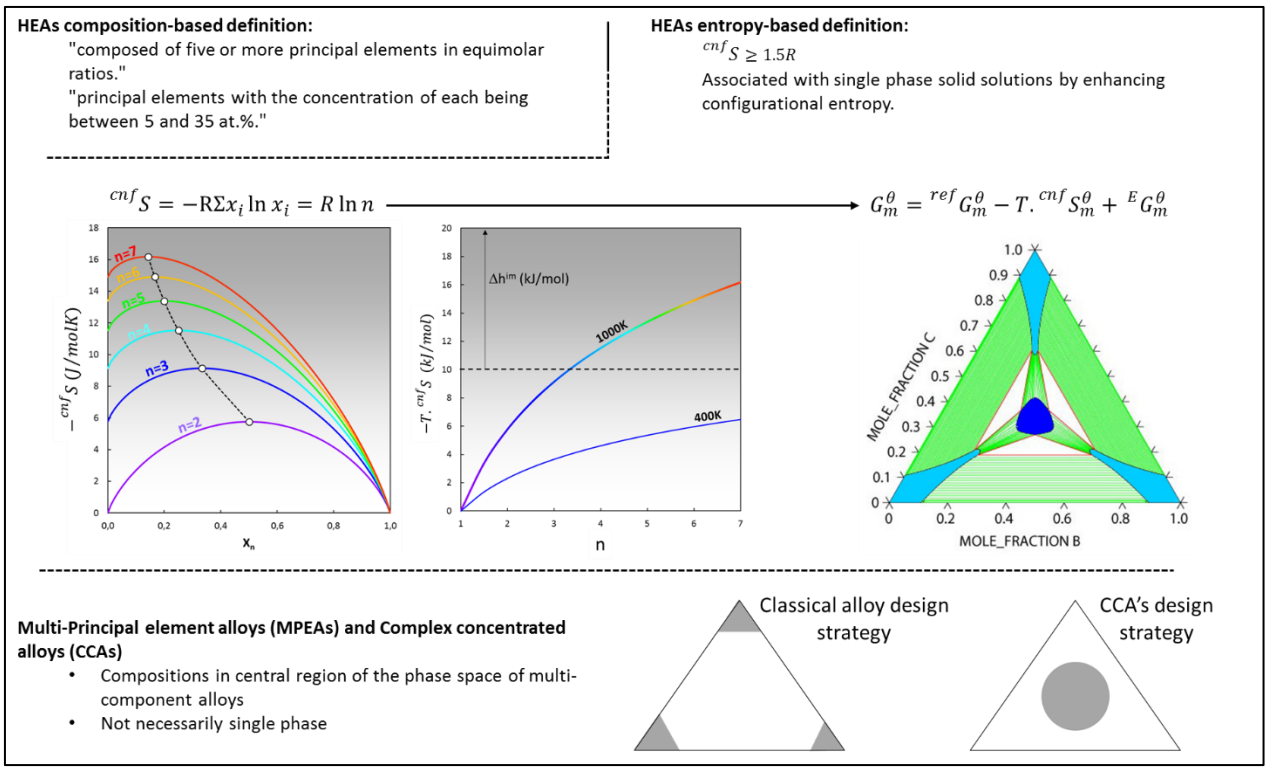


Figure 1: A schematic displaying the effect of configurational entropy on the stabilization of single-phase solid solution around the equiatomic composition, where x_i is the molar fraction of component i, n the number of components in equiatomic proportion, G the Gibbs free energy of a phase t (ref, cnf and E stand for reference, configurational and excess, respectively). In the resulting ternary system calculated from the association of three binaries with a miscibility gap, single solid solution phases are displayed in blue, while green and white denote binary and ternary phase fields. Δh^{im} represents the enthalpy of formation of intermetallic compounds. According [4], 50% of intermetallics have Δh^{im} above 10 kJ/mol. It appears that configurational entropy can compete with enthalpy at high temperature. Finally, the distinguishing feature of the alloying concept behind HEAs and CCAs that is the exploration of the vast interior region of the composition space is illustrated in contrast with the classical design strategy that focuses on the peripheral regions of phase diagrams.

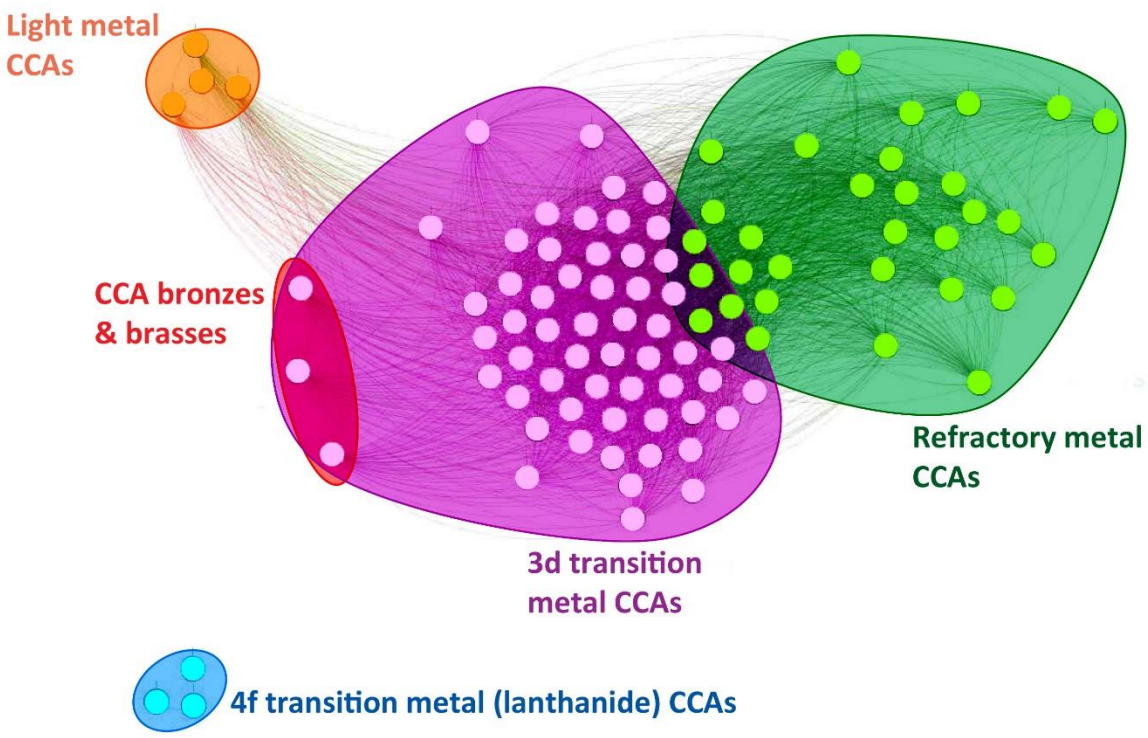


Figure 2: Alloy network analysis (ANA) of 110 equiatomic CCAs. Each node is a unique alloy and a line connecting two nodes indicates sharing of one or more common element. Nodes (alloys) that often share many elements are spaced closely together into specific alloy families. See text for additional description of this plotting method.

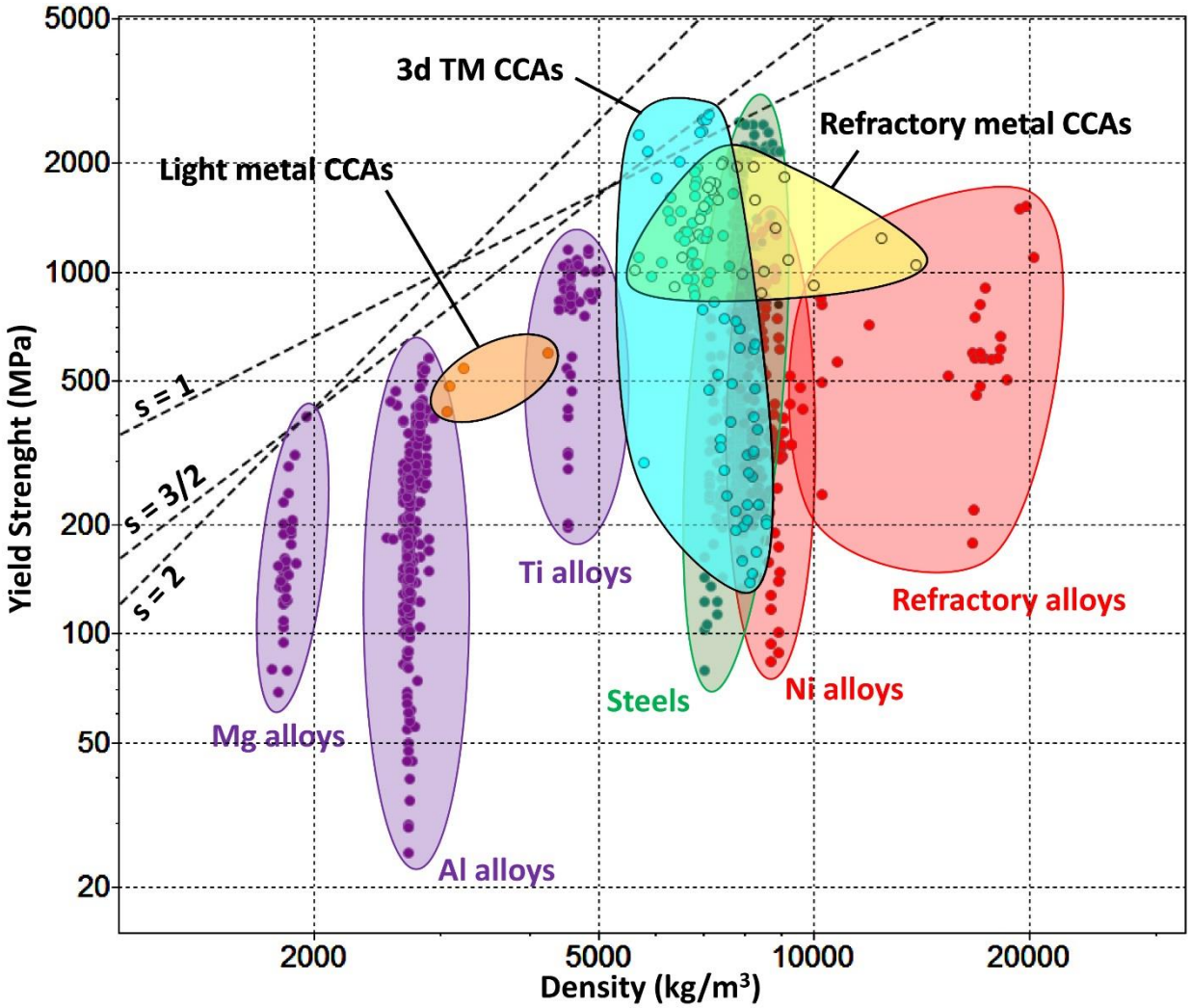
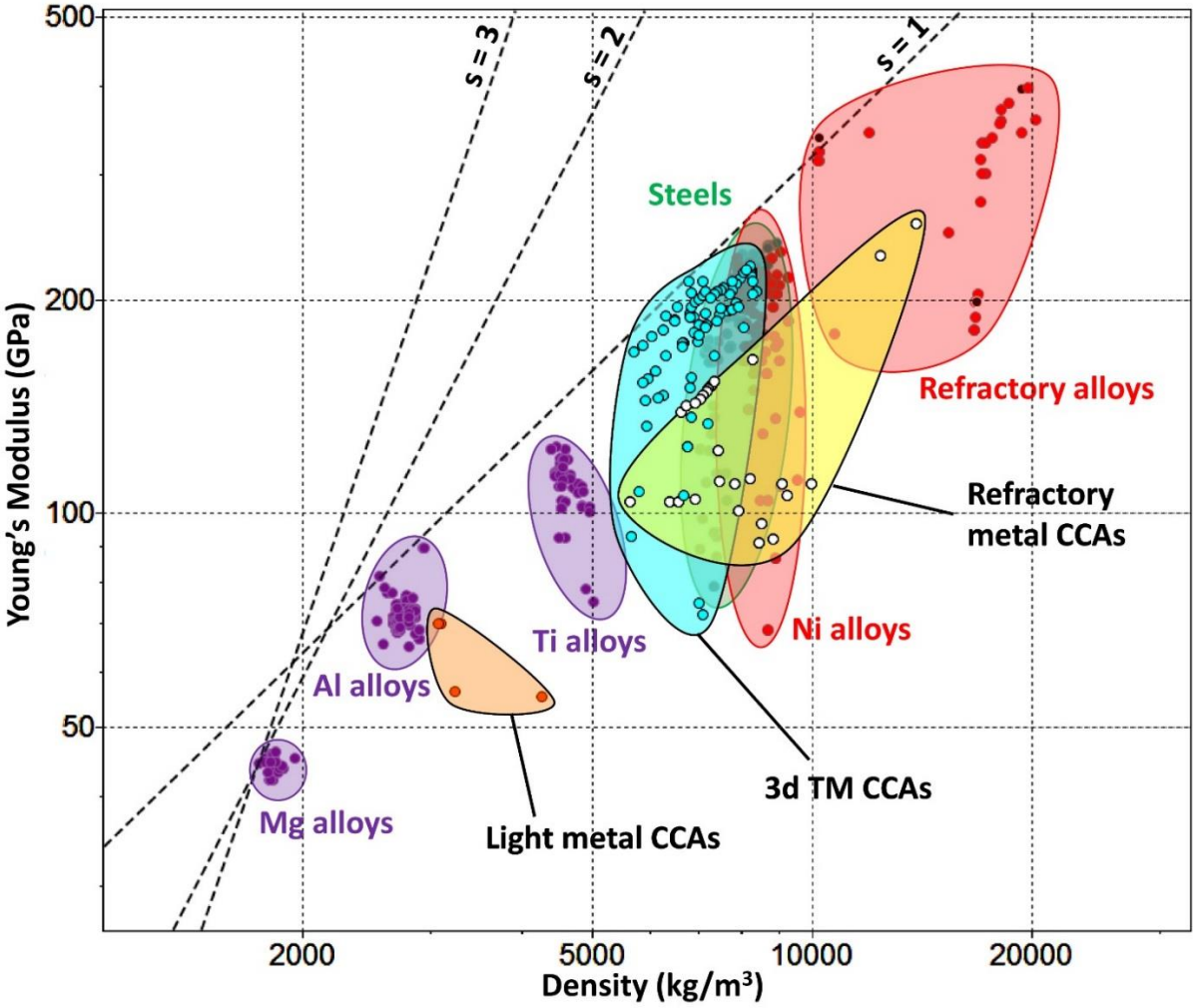
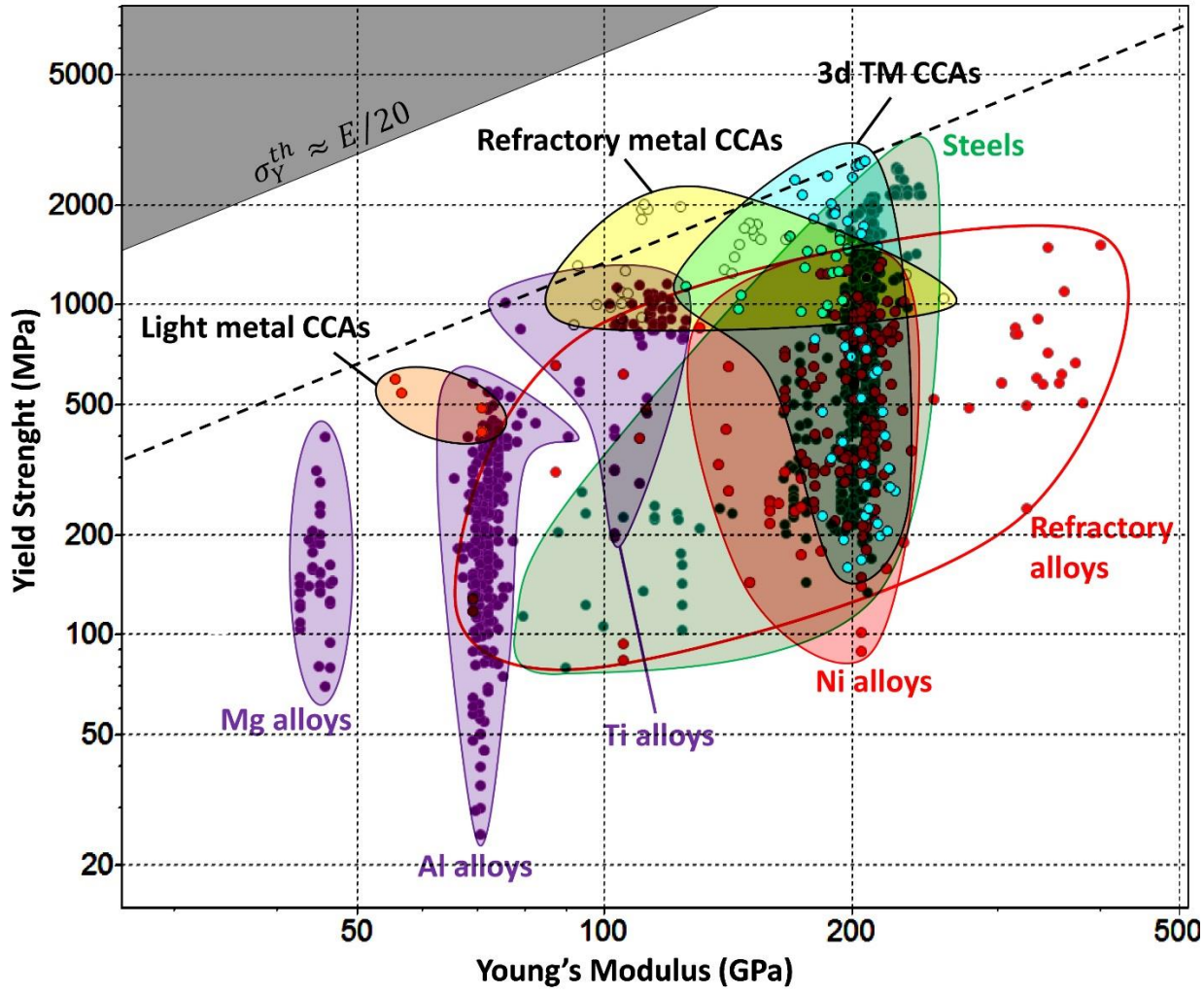


Figure 3: Materials property space for room temperature yield strength vs density of conventional metal alloys and CCAs. 3d transition metal CCAs are shown by teal-colored bubbles, refractory metal CCAs are shown by yellow bubbles and light metal CCAs are shown by orange bubbles. The dashed lines give performance indices for uniaxial loading (slope, s = 1), beam bending (s = 3/2) and panel bending (s = 2). See the text for additional discussion of this plot. This chart was made with the CES EduPack database, Level 3 Aerospace edition and the CCA database from the present work. It displays data for about 1220 commercial and 120 multi-principle element alloys.

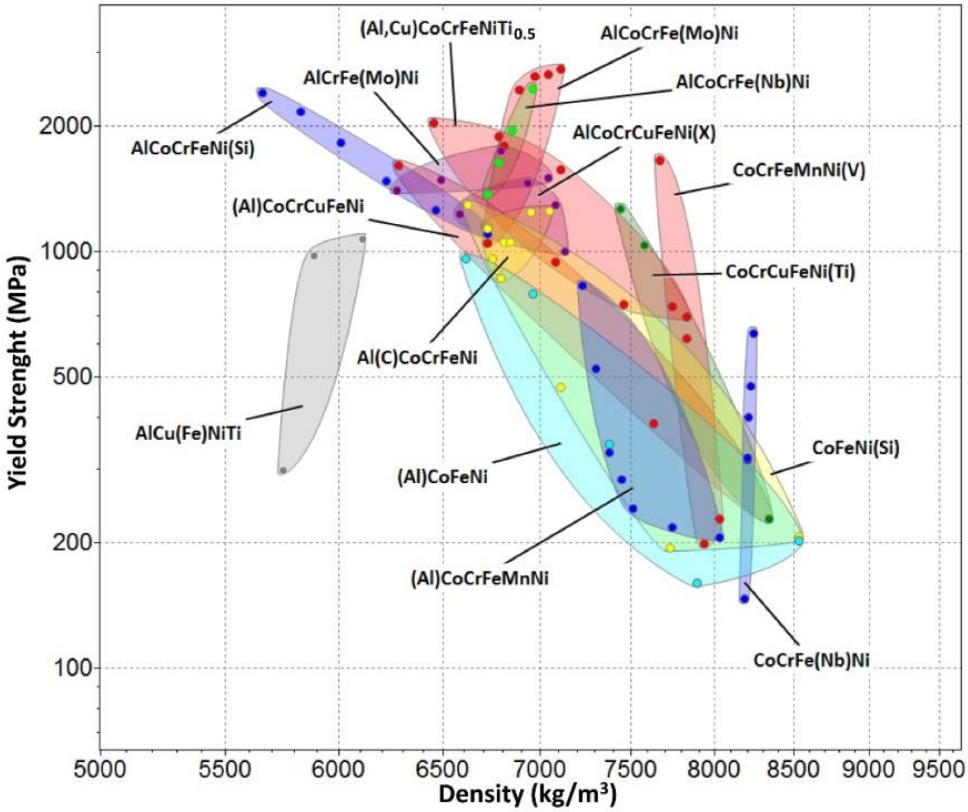

500
200
100
50
Young's Modulus (GPa)
2000
5000
10000
20000
Density (kg/m³)
s = 3
s = 2
s = 1
Steels
Refractory alloys
Refractory metal CCAs
Ni alloys
Ti alloys
Al alloys
Mg alloys
Light metal CCAs
3d TM CCAs

(a)

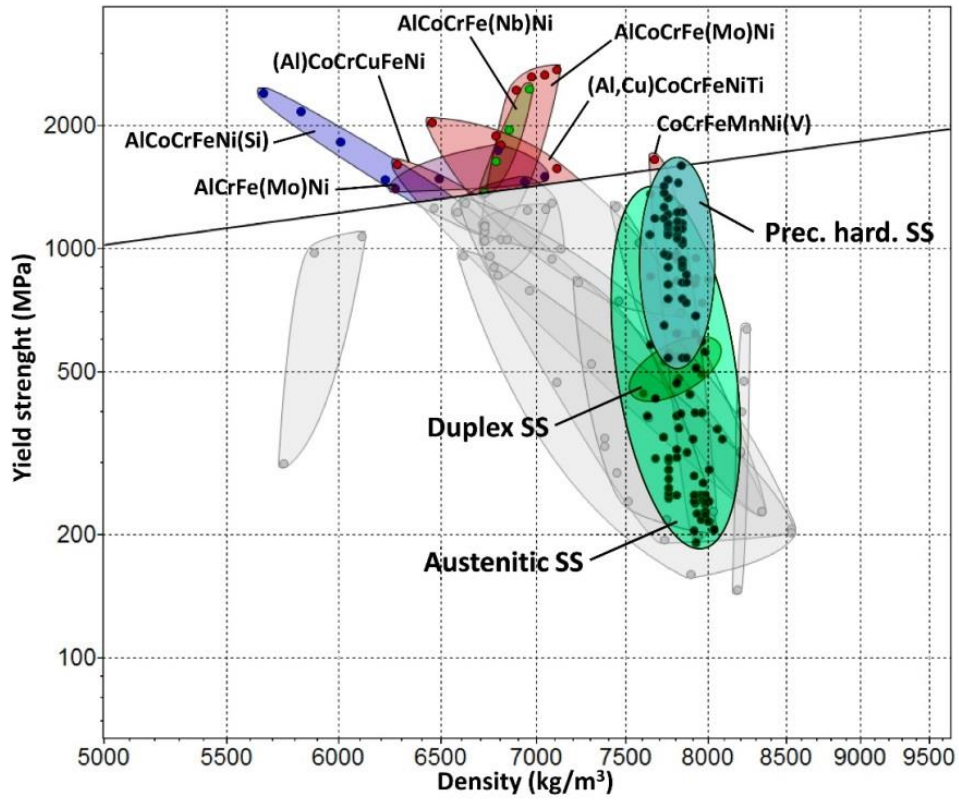


(b)

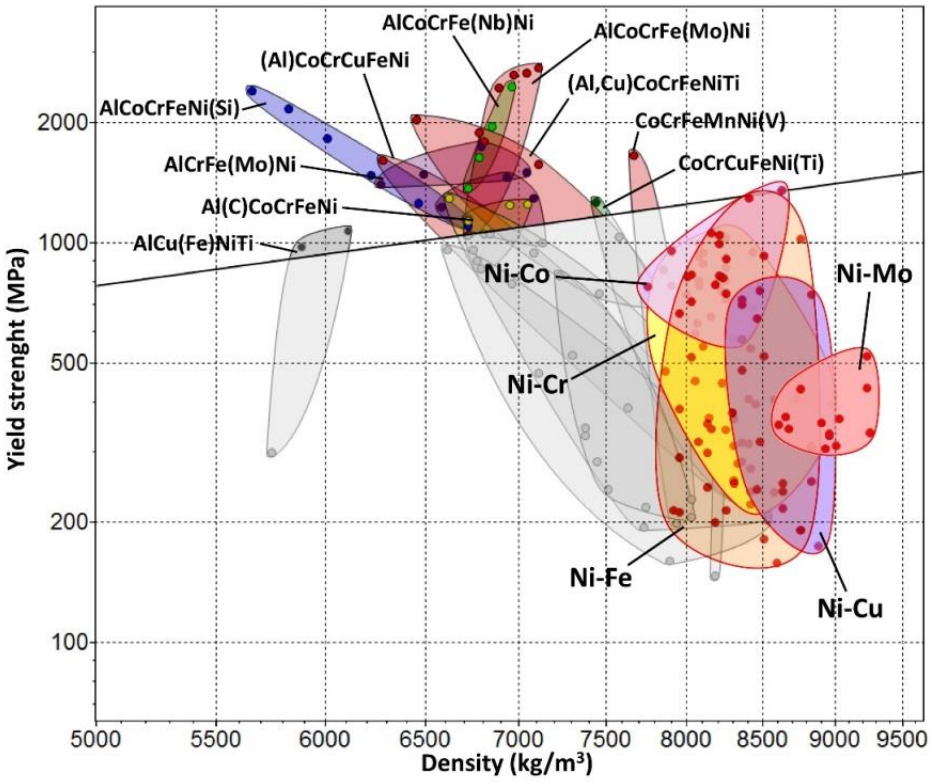
Figure 4: (a) Materials property space for room temperature Young's modulus vs density of conventional metal alloys and CCAs. 3d transition metal CCAs are shown by teal-colored bubbles and refractory metal CCAs are shown by yellow bubbles. The dashed lines give performance indices for uniaxial tension (slope, s = 1), beam bending (s = 2) and panel bending (s = 3). See the text for additional discussion of this plot. This chart was made with the CES EduPack database, Level 3 Aerospace edition and the CCA database from the present work. It displays data for about 1220 commercial and 115 multi-principle element alloys. (b) Room temperature yield strength plotted against Young's modulus for conventional metal alloys and CCAs. The contour (dashed line) shows the ratio of the yield strength over the Young's modulus.


(Al,Cu)CoCrFeNiTi0.5
AlCoCrFe(Mo)Ni
AlCrFe(Mo)Ni
AlCoCrFe(Nb)Ni
AlCoCrFeNi(Si)
AlCoCrCuFeNi(X)
CoCrFeMnNi(V)
(Al)CoCrCuFeNi
CoCrCuFeNi(Ti)
Al(C)CoCrFeNi
AlCu(Fe)NiTi
CoFeNi(Si)
(Al)CoFeNi
(Al)CoCrFeMnNi
CoCrFe(Nb)Ni
Yield Strenght (MPa)
Density (kg/m³)
100
200
500
1000
2000
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500

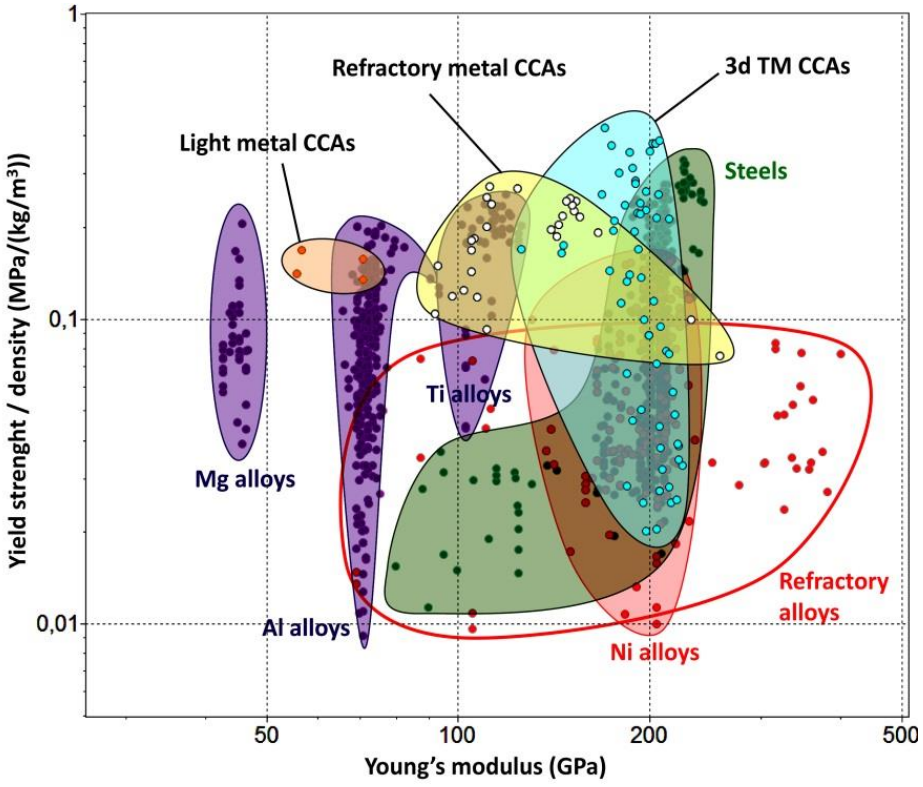
(a)


AlCoCrFe(Nb)Ni
AlCoCrFe(Mo)Ni
(Al)CoCrCuFeNi
(Al,Cu)CoCrFeNiTi
CoCrFeMnNi(V)
AlCoCrFeNi(Si)
AlCrFe(Mo)Ni
Prec. hard. SS
Duplex SS
Austenitic SS
Yield strenght (MPa)
Density (kg/m³)
100
200
500
1000
2000
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500

(b)

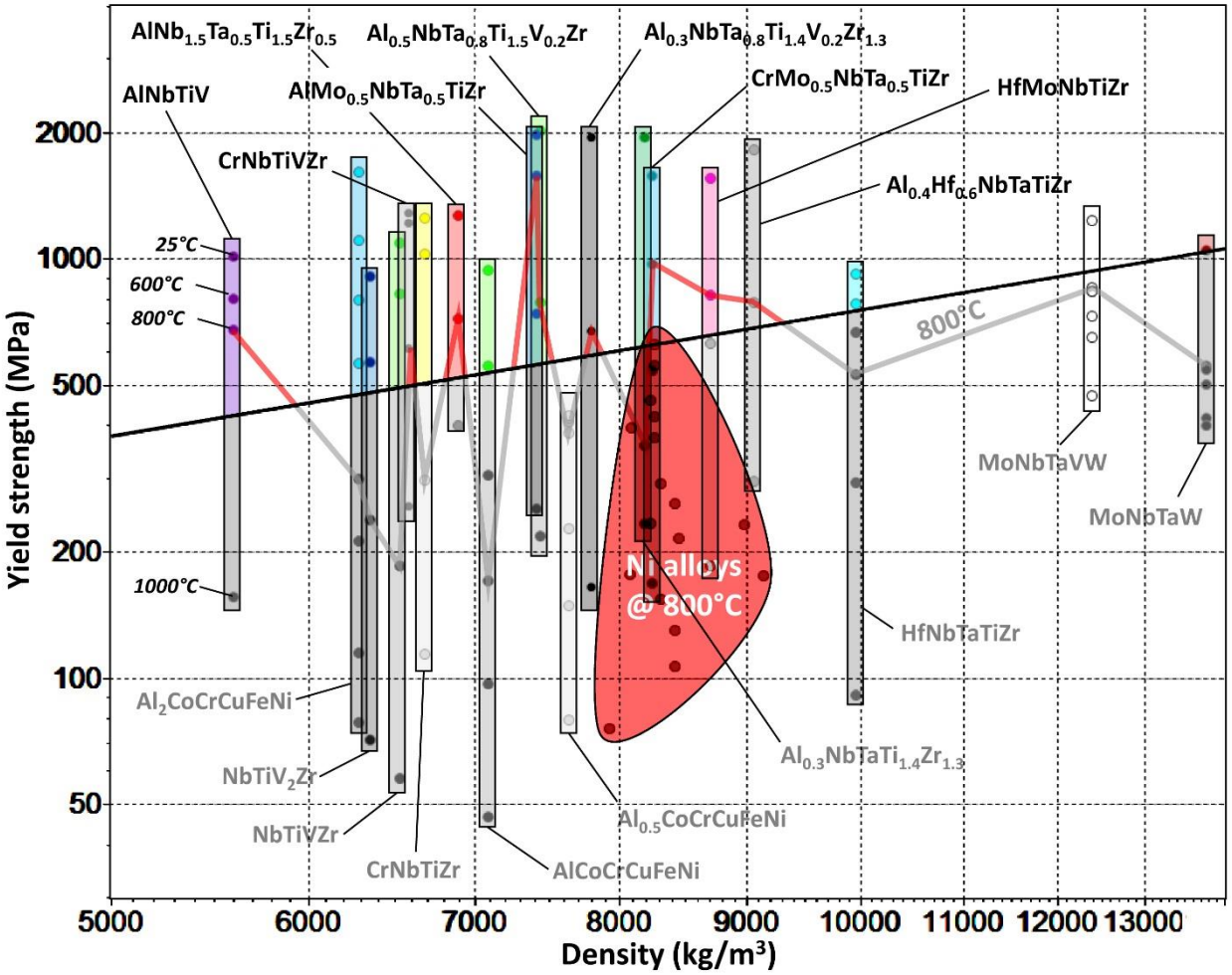

AlCoCrFe(Nb)Ni
AlCoCrFe(Mo)Ni
(Al)CoCrCuFeNi
(Al,Cu)CoCrFeNiTi
AlCoCrFeNi(Si)
CoCrFeMnNi(V)
AlCrFe(Mo)Ni
CoCrCuFeNi(Ti)
Al(C)CoCrFeNi
AlCu(Fe)NiTi
Ni-Co
Ni-Mo
Ni-Cr
Ni-Fe
Ni-Cu
Yield strenght (MPa)
2000
1000
500
200
100
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
Density (kg/m³)

(c)

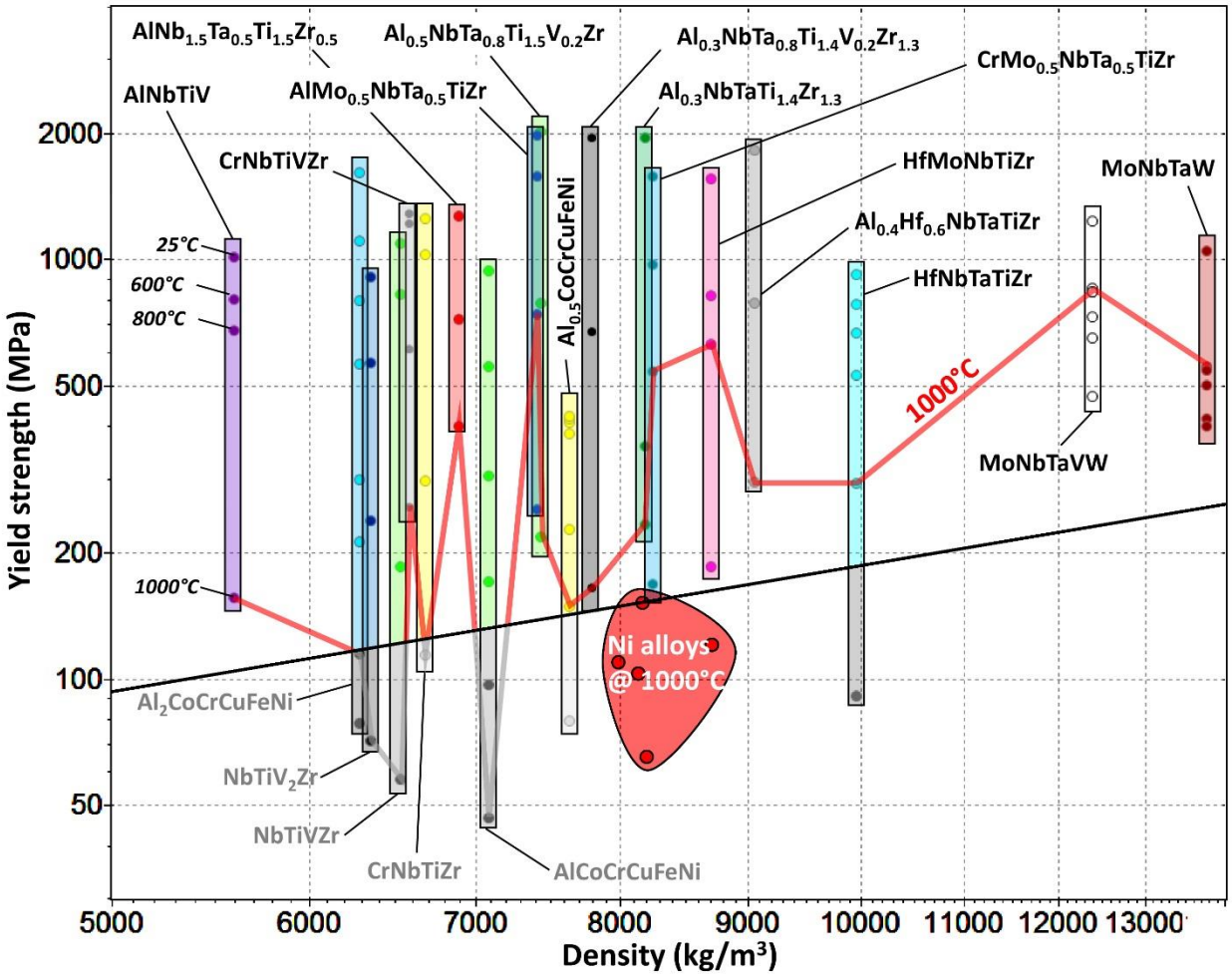

Refractory metal CCAs
3d TM CCAs
Light metal CCAs
Steels
Ti alloys
Mg alloys
Refractory
alloys
Al alloys
Ni alloys
Yield strenght / density (MPa/(kg/m³))
1
0,1
0,01
50
100
200
500
Young's modulus (GPa)

(d)

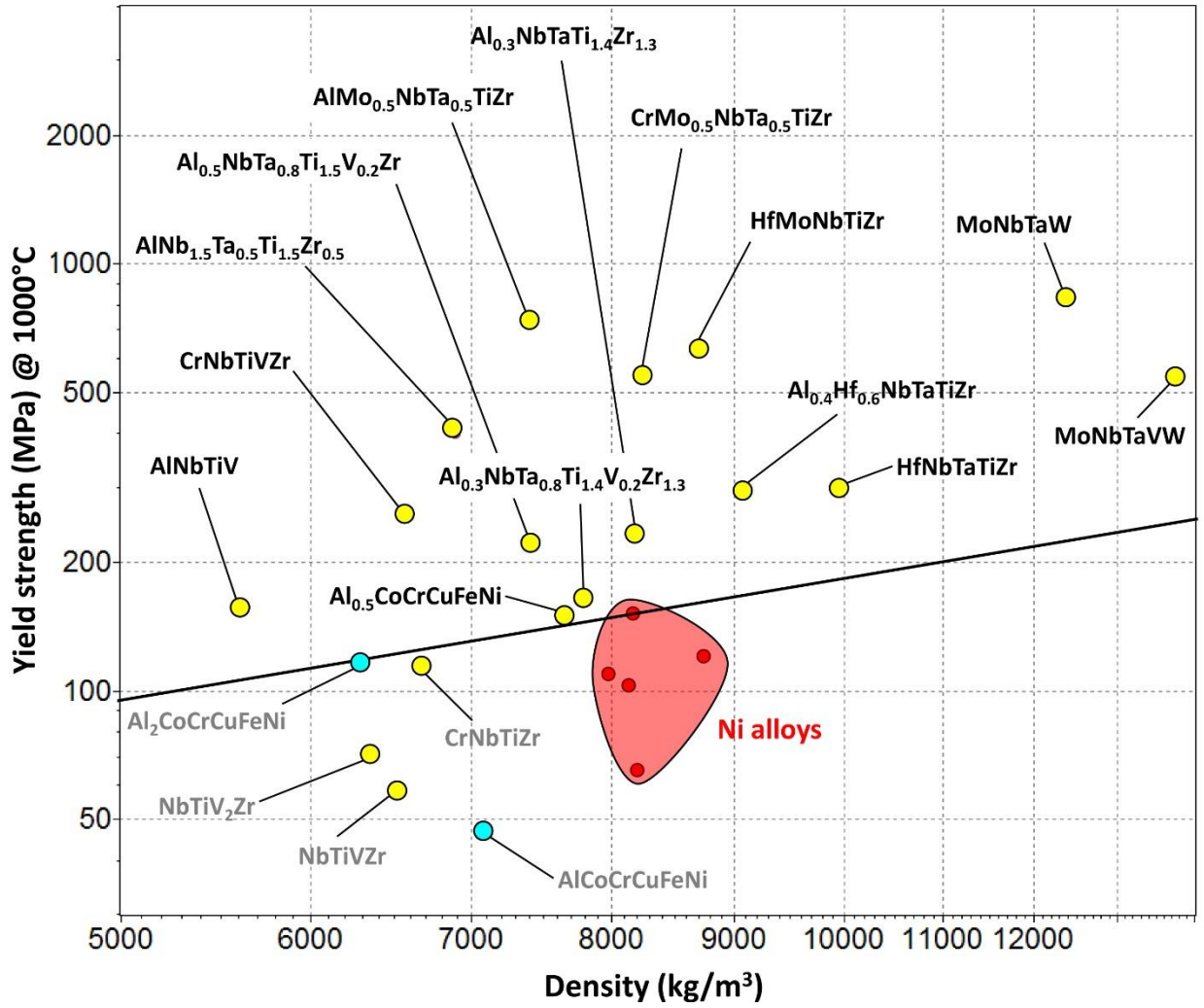
Figure 5: (a) Detailed illustration of 3d transition metal CCA alloy classes in room temperature yield strength vs density property space. 76 alloys are shown. (b) Comparison of 3d transition metal CCA alloy classes with three major classes of commercial stainless steels. Data for 136 stainless steel alloys are shown. (c) Comparison of 3d transition metal CCA alloy classes with selected classes of commercial Nickel alloys. Data for 119 Ni alloys are included. Individual alloys are shown by open and closed circles, and alloy classes are enclosed in bubbles. In (b,c), 3d transition metal CCAs above the performance index line for uniaxial tension (slope, s = 1) are shown in color, whereas those below the line are shown in gray. This chart was made with the CES EduPack database, Level 3 Aerospace edition and the CCA database from the present work. (d) Specific Yield Strength versus Young's modulus for commercial alloys and different family CCAs.


AlNb1.5Ta0.5Ti1.5Zr0.5
Al0.5NbTa0.8Ti1.5V0.2Zr
Al0.3NbTa0.8Ti1.4V0.2Zr1.3
AlNbTiV
AlMo0.5NbTa0.5TiZr
CrMo0.5NbTa0.5TiZr
HfMoNbTiZr
CrNbTiVZr
Al0.4Hf0.6NbTaTiZr
25°C
600°C
800°C
1000°C
800°C
MoNbTaVW
MoNbTaW
Ni alloys
@ 800°C
HfNbTaTiZr
Al2CoCrCuFeNi
Al0.3NbTaTi1.4Zr1.3
NbTiV2Zr
Al0.5CoCrCuFeNi
NbTiVZr
CrNbTiZr
AlCoCrCuFeNi
Yield strength (MPa)
2000
1000
500
200
100
50
5000
6000
7000
8000
9000
10000
11000
12000
13000
Density (kg/m3)

(a)

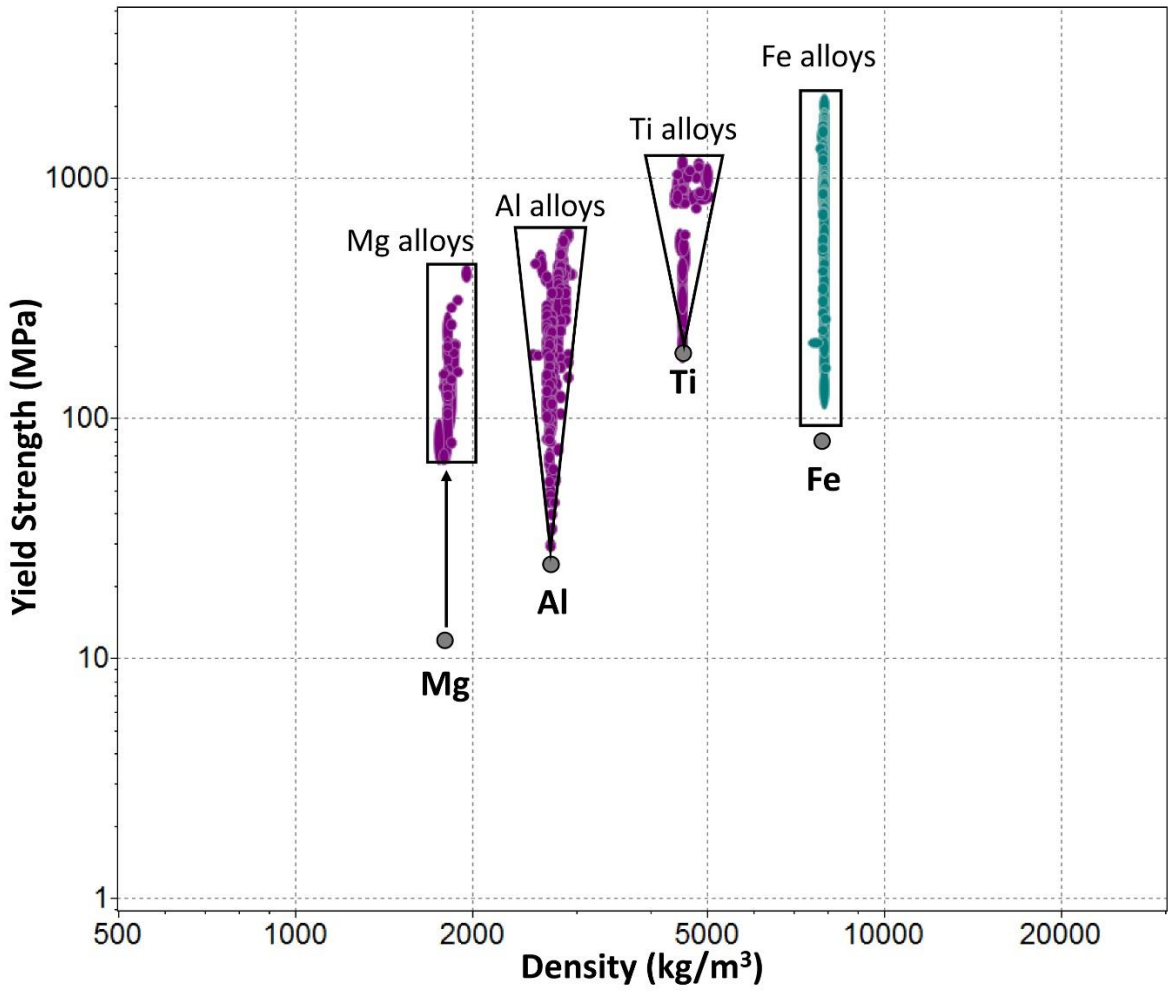

AlNb1.5Ta0.5Ti1.5Zr0.5
Al0.5NbTa0.8Ti1.5V0.2Zr
Al0.3NbTa0.8Ti1.4V0.2Zr1.3
CrMo0.5NbTa0.5TiZr
AlNbTiV
AlMo0.5NbTa0.5TiZr
Al0.3NbTaTi1.4Zr1.3
CrNbTiVZr
HfMoNbTiZr
MoNbTaW
Al0.4Hf0.6NbTaTiZr
25°C
600°C
800°C
Al0.5CoCrCuFeNi
HfNbTaTiZr
1000°C
1000°C
MoNbTaVW
Ni alloys
@ 1000°C
Al2CoCrCuFeNi
NbTiV2Zr
NbTiVZr
CrNbTiZr
AlCoCrCuFeNi
Yield strength (MPa)
2000
1000
500
200
100
50
5000
6000
7000
8000
9000
10000
11000
12000
13000
Density (kg/m3)

(b)

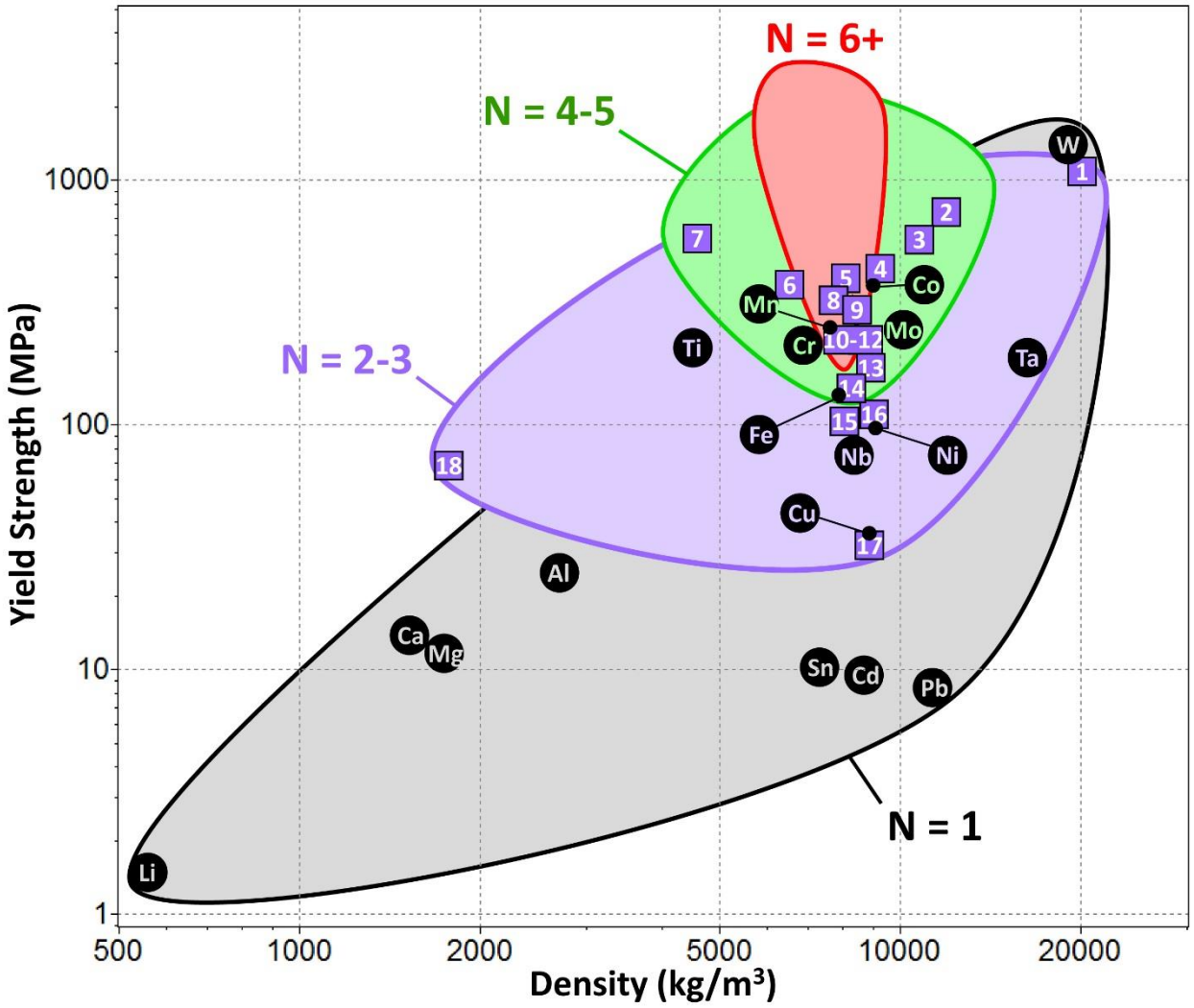


(c)

Figure 6: Materials property space for yield strength vs density as a function of the temperature. Individual CCAs are shown with vertical bars that provide alloy properties at a different temperatures. The red line connects yield strength values of CCAs at 800°C in (a) and 1000°C in (b). In (c) only the data at 1000°C are displayed. Data for 15 Nickel alloys at 800°C and 5 at 1000°C are shown for comparison, they include Ni-Cr Rene 41, Ni-Cr WASPALOY, Ni-Cr INCONEL 718, Ni-Cr INCONEL X-750, Ni-Cr INCONEL 706, Ni-Cr INCONEL 600, Ni-Cr INCONEL 625, Ni-Cr alloy INCONEL 754, Ni-Cr alloy HASTELLOY X, Ni-Co superalloy L605, Ni-Co superalloy HS 188, Ni-Fe alloy Haynes HR-110, and Ni-Fe superalloy N-155. CCA above the performance index line for uniaxial tension (slope, s = 1) display their label above the line. This chart was made with the CES EduPack database, Level 3 Aerospace edition and the CCA database from the present work.

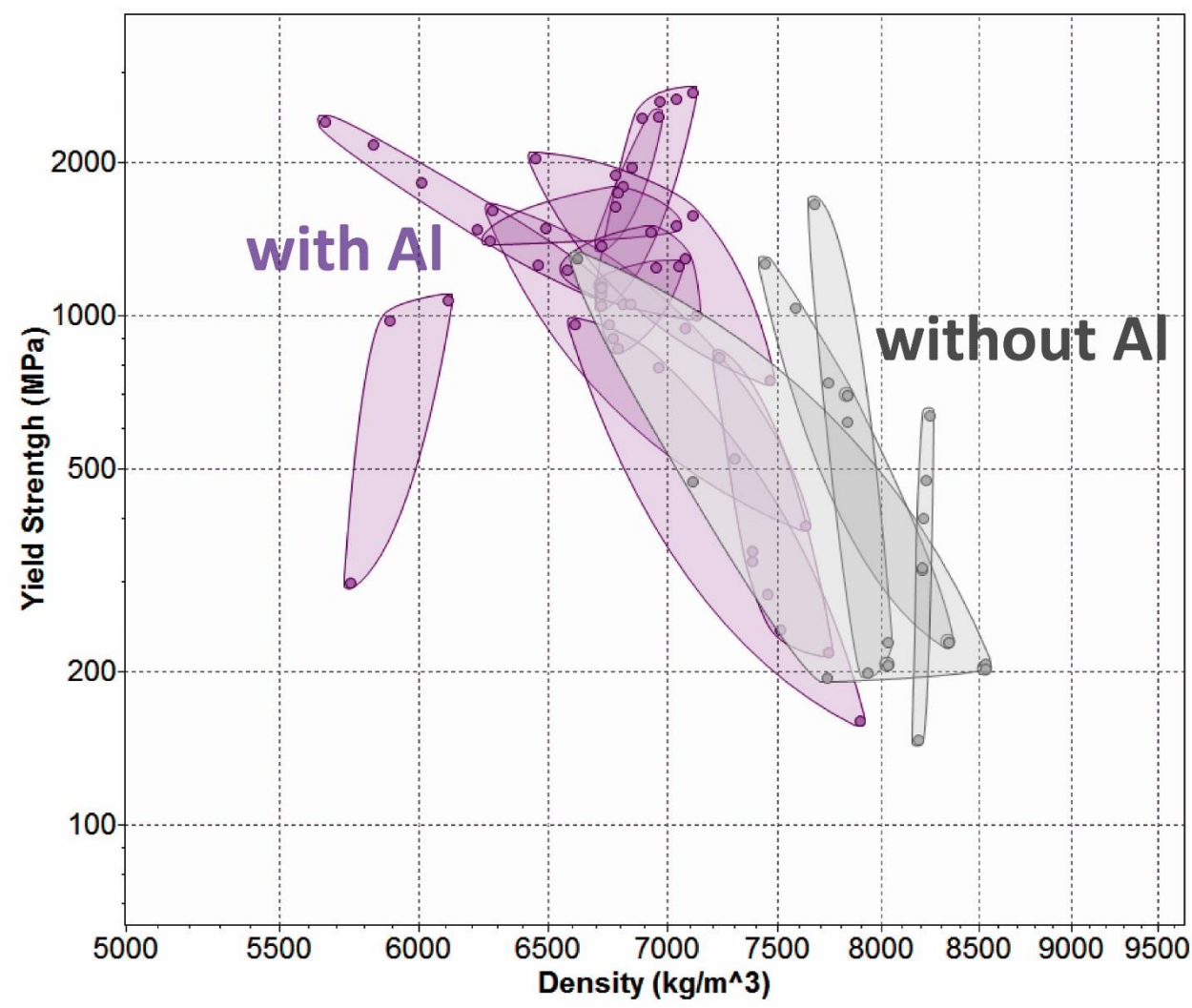

Fe alloys
Ti alloys
Al alloys
Mg alloys
1000
100
10
1
Ti
Fe
Al
Mg
Yield Strength (MPa)
500
1000
2000
5000
10000
20000
Density (kg/m³)

(a)

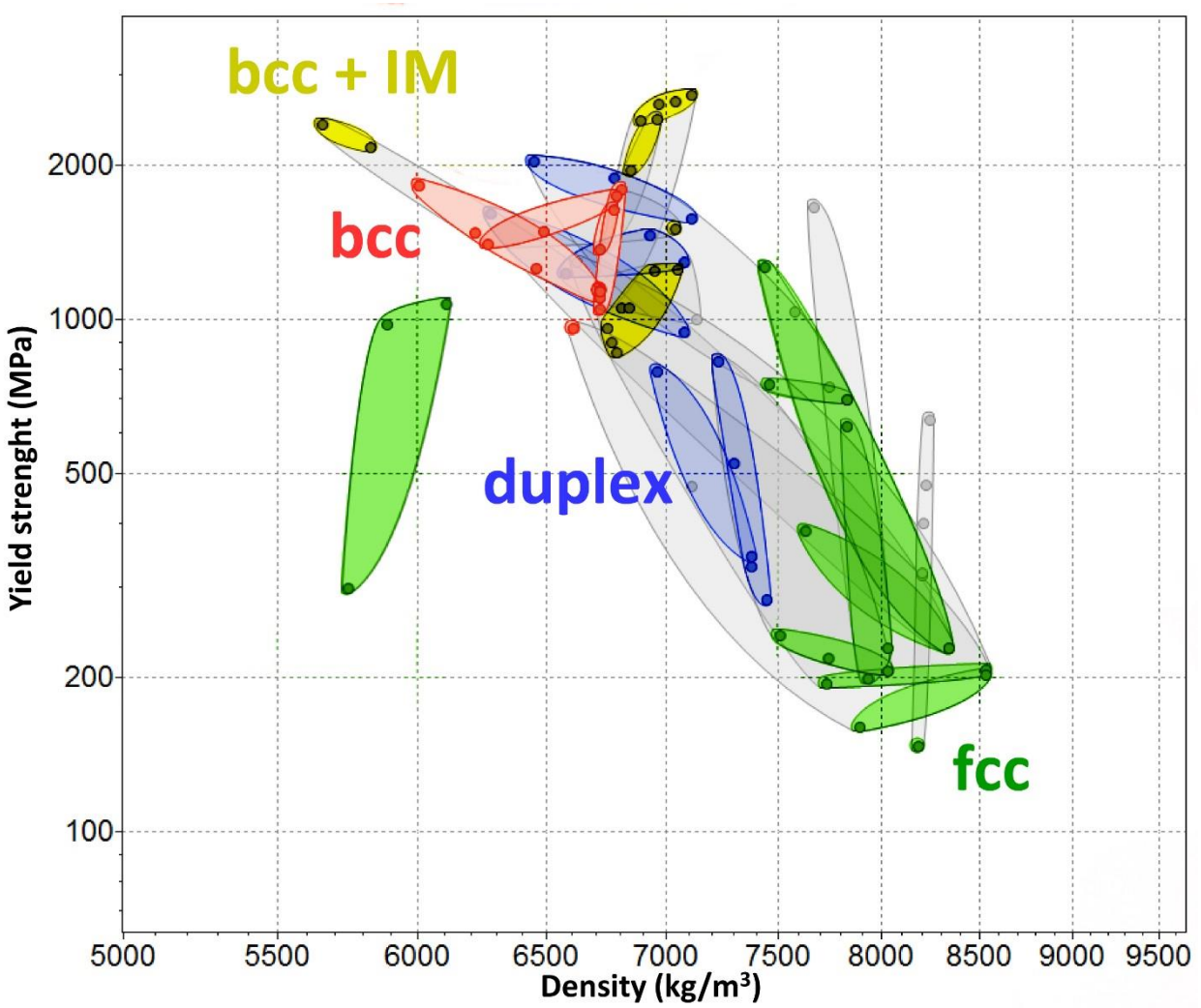


(b)

Figure 7: (a) The effect of alloying on room temperature specific yield strength for Al, Mg, Ti and Fe, and conventional alloys based on these elements. The alloy yield strengths are significantly higher than the base element, while the density changes are marginal. (b) The effect of alloying on room temperature specific yield strength for CCAs as a function of the number of principal elements. The range in densities shrinks while the yield strengths shift to higher values. The unary systems are labelled inside black circles. The binary and ternary systems are: (1) Re-W, (2) Mo-W, (3) Nb-Ta-W, (4) Mo-Ni, (5) Cr-Ni, (6) Ni-Ti, (7) Al-Nb-Ti, (8) Cr-Fe-Ni, (9) Co-Cr-Ni, (10) Fe-Ni, (11) Fe-Mn-Ni, (12) Co-Mn-Ni, (13) Co-Fe-Ni, (14) Cu-Ni, (15) Cu-Zn, (16) Co-Ni, (17) Pb-Sn, and (18) Li-Mg. The quaternaries and above use data from 3d TM CCAs, refractory CCAs, CCA bronzes and brasses, and light metal CCAs.

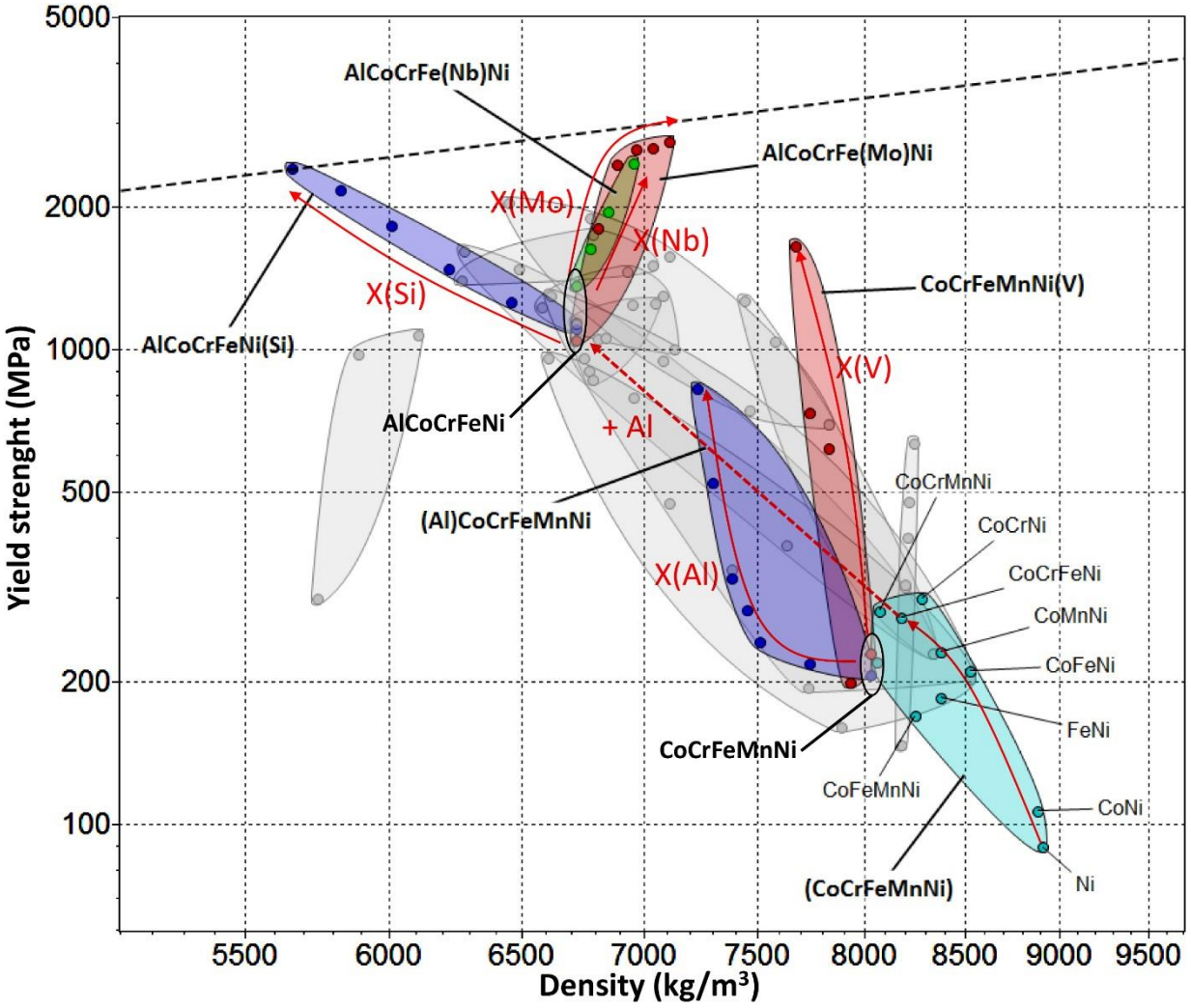

with Al
without Al
Yield Strentgh (MPa)
2000
1000
500
200
100
5000
5500
6000
6500
7000
7500
8000
8500
9000
9500
Density (kg/m^3)

(a)

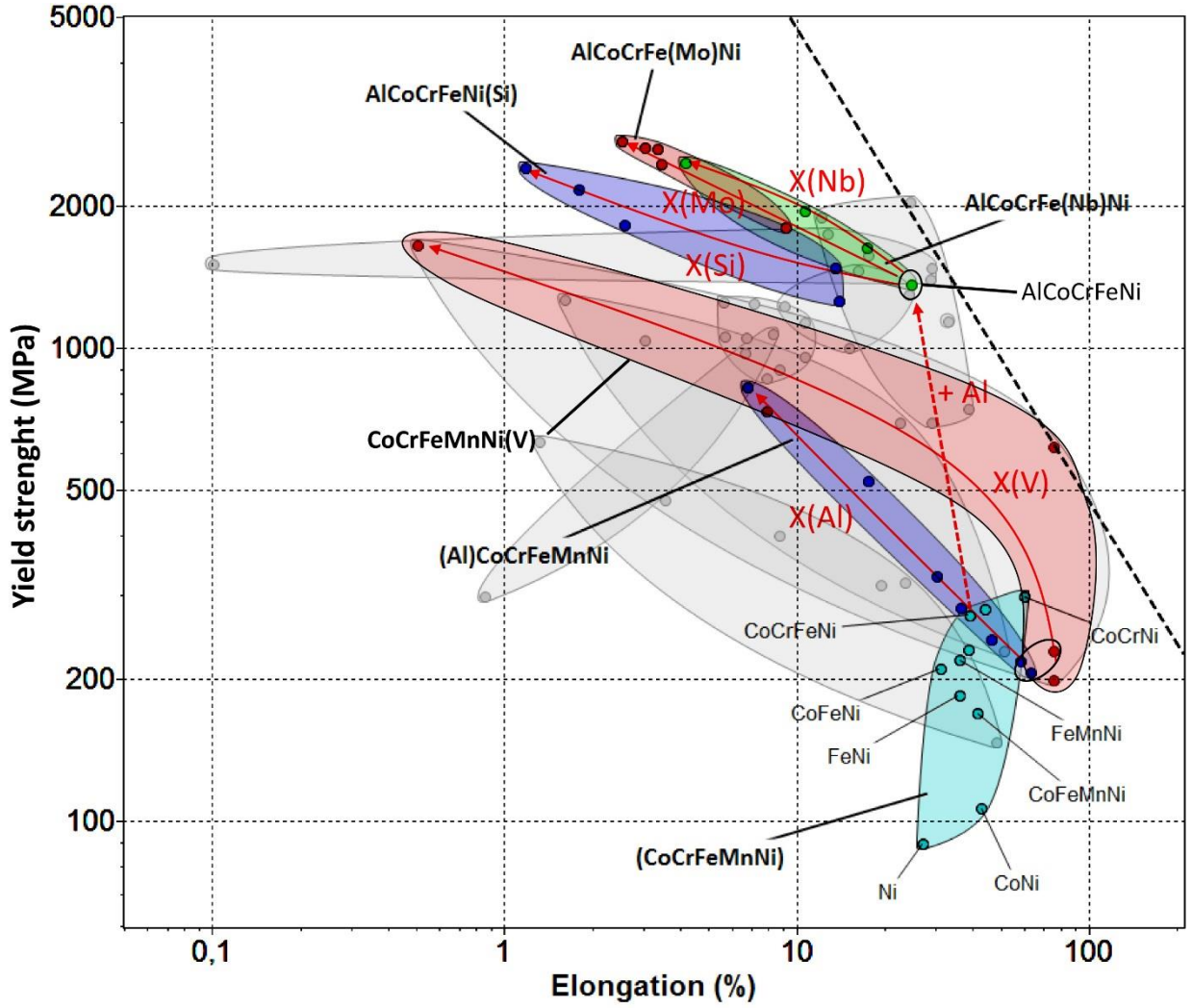


(b)

Figure 8: Materials property space for room temperature yield strength vs density showing the effect of Al addition on (a) the properties and (b) the resulting phases present for 3d TM CCAs.


AlCoCrFe(Nb)Ni
AlCoCrFe(Mo)Ni
X(Mo)
X(Nb)
X(Si)
AlCoCrFeNi(Si)
CoCrFeMnNi(V)
X(V)
AlCoCrFeNi
+ Al
(Al)CoCrFeMnNi
CoCrMnNi
CoCrNi
CoCrFeNi
CoMnNi
CoFeNi
FeNi
X(Al)
CoCrFeMnNi
CoFeMnNi
CoNi
Ni
(CoCrFeMnNi)
Yield strenght (MPa)
Density (kg/m³)
5000
2000
1000
500
200
100
5500
6000
6500
7000
7500
8000
8500
9000
9500

(a)



(b)

Figure 9: Materials property space for (a) room temperature yield strength vs density and (b) room temperature yield strength vs elongation illustrating the influence of Al, Ni, V and Si on the properties of selected 3d TM CCAs. The dashed lines give performance indices for light component in uniaxial tension (slope, s = 1) in (a), and the product of strength and ductility (slope, s = -1) in (b).