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On the Sustainable Choice of Alloying Elements for Strength of Aluminum-Based Alloys

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Abstract: Aluminum alloys are today entirely recyclable and are seen as a sustainable material. However, there are limitations in the use of aluminum from material strength and cost perspective. Nickel, copper and rare earth metals are alloying elements that may provide strength at room and elevated temperatures. These are, however, often seen as harmful from a sustainability viewpoint. Additionally, these alloying elements are commonly costly. The current paper makes an analysis of the sustainability–strength dimension of alloying, together with a cost perspective, to guide alloy producers and alloy users in making an educated choice of direction for future materials and material development.

Keywords: aluminum; alloys; alloying element; cost; strength; sustainability; embodied energy; CO₂-footprint; water usage

1. Introduction

Lightweight components and weight reduction have significant impacts on energy used and greenhouse gas emissions from transport in and between cities. City transport emissions are partly related to wealth, but the underlying factors are automobile dependence and public transport systems [1]. The energy usage, CO₂-footprint as well as gaseous and particle emissions in cities poses a problem and dramatic changes are currently taking place in the transport industry with stricter regulations on emission from legislation and requirements [2]. Legislations and societal trends have put considerable pressure on the transport industry to change towards fully or partially electrified drive trains. The electrification of the drive trains will reduce particle emissions, but the CO₂-footprint is high dependent on the nature of the electricity generation and material production. Serrenho et al. [3] analyzed the effect of vehicle weight reduction and concluded that during the transition to a fossil-free electricity generation, weight reduction of vehicles could produce greater cumulative emissions savings by 2050 than those obtained by the electrification alone. It can safely be concluded that to maximize energy and fuel utilization, lightweight designs and material selection are of great importance. In this aspect aluminum and magnesium alloys are the most effective engineering solutions due to their low densities. Cost and recycling methods available makes aluminum superior for the circular economy [4].

In the alloy development of aluminum, there are a number of alloying principles to achieve strength for both wrought and cast alloys [5–7]. The typical mechanisms used are (1) grain refinement,

(2) precipitation hardening, (3) solution hardening, and for multiphase microstructures there are (4) load bearing effects, (5) thermal expansion mismatch effects and (6) dispersion hardening effects. As the material starts to deform, there will also be effects from deformation hardening in individually deforming phases and effects from modulus mismatch in multiphase systems [6,7]. All this results in a complex solution for alloying systems including effects from processing in the as processed state and effects from heat treatments. Most of the alloying work is focused on optimizing these effects while most of the sustainable analysis concentrates on the use of the materials in components. No significant effort is made on sustainable alloying, meaning how to select or prioritize for a sustainable selection for a specific purpose such as yield strength or tensile strength.

In alloying, there is, from a business perspective, always the issue of cost, and in its purest sense, this is the cost per kg for alloying elements. From a sustainability standpoint, this may also be part of the sustainability measure. Sustainable measures including cost or geopolitical matters also have several different measures. Being able to operate in a long-term perspective, price volatility of the alloying elements is important [8]. On the country level, sourcing and impacts on the environment and the geographical aspects are measured using the Herfindahl–Hirschmann index (HHI) [8]. All these latter have also been generated to cover larger geopolitical aspects of sustainability. For the alloy developer, these matters may be important, but the immediate and overhanging issues are more related to resource efficiency, energy usage and carbon footprint, related to the global warming issues drawn out in the Charney report [9]. As a consequence of this light-weighting, all transports are critical to addressing the global warming issues [3].

The current study takes as a starting point that aluminum is suitable for making designs lighter. In this, strength is essential, and in vehicles, crash safety is also of importance, and as such a suitable measure used to contextualize alloy development is the tensile strength contribution of the alloying elements. The work is delimited to what the alloy manufacturer can control and that is the embodied energy, CO₂-footprint and water usage. The effect of alloying element cost is also addressed in the paper. The result will be a ranking of the possible elements to achieve best possible strength in the as-fabricated state (-F or -O states) with the long-term aim to avoid secondary processing as these add cost, emissions and resources.

2. Methodology

In the current study, data from literature and databases was taken to allow for a generalized analysis of the effectiveness of the alloying elements and the associated environmental loading. A series of indexes were generated as a measure of the environmental impact of these elements to guide the development of alloys for a sustainable future, divided into three main directions of discussion.

2.1. Alloying Element Strength Contribution

As the strength contribution is very complex and for the development of a comprehensive measure, two different approaches to the generation of the index were taken with inspiration taken from the typical contributions from solution hardening and precipitation hardening and composite structures [6,7].

The linear approach related more to particle precipitation and second phase generation:

$$\sigma = \sum_i a_i x_i. \quad (1)$$

The square root approach related more to solution hardening effects of the alloying:

$$\sigma = \sum_i a_i \sqrt{x_i} \quad (2)$$

where a_i is the strength coefficient, and x_i is the weight per cent of the alloying addition for element i . The strength coefficient is essential for the remainder of the discussion as a high strength coefficient opens the possibility for a maximum outcome with a minimum of addition. It should here be noted that the aim is not to describe solution precipitation nor to describe precipitation hardening but to create an index allowing to one to contextualize the environmental impact of the strength contribution of the content of an alloying element. The choice of property is also important and for the current case this was the ultimate tensile strength or UTS, which was chosen as it contains failure behavior implicitly through deformation hardening during the plastic elongation to failure. Data was also chosen in the as-fabricated state (-F or -O states), as heat treatment and secondary processing should be avoided in the ideal case to minimize cost and environmental impact. The data used is collated in the Appendix A Table A1.

2.2. Environmental Alloying Efficiency Index for Alloying Elements

To construct a measure to guide the alloy developers in the selection of alloying element candidates, the contribution to strength must be leveraged by the environmental load. In doing this, the strength coefficient for each element i , should be divided with the environmental load for each one of the loads, (1) embodied energy, b_i , (MJ/kg $_i$), (2) CO $_2$ -footprint, c_i , (kgCO $_2$ /kg $_i$) and water usage, d_i , (l/kg $_i$). The three measures E1 $_i$ (MPa.kg $_i$ /(MJ % element i)), characterizing energy efficiency for element i , E2 $_i$ (MPa. kg $_i$ /(kgCO $_2$ % element i)), characterizing carbonfootprint for element i , and E3 $_i$ (MPa. kg $_i$ /(l % element i)), characterizing water usage for element i , can thus be expressed as:

$$E1_i = \frac{a_i}{b_i} \quad (3)$$

$$E2_i = \frac{a_i}{c_i} \quad (4)$$

$$E3_i = \frac{a_i}{d_i} \quad (5)$$

2.3. Environmental Alloying Efficiency Index with Alloying Element Cost Weighting

The creation of a new set of environmental impact indices contextualized with the element's ability to generate strength with cost weighting for each alloying element, M_i , (RMB/kg) can be constructed as:

$$EM1_i = \frac{a_i}{b_i M_i} \quad (6)$$

$$EM2_i = \frac{a_i}{c_i M_i} \quad (7)$$

$$EM3_i = \frac{a_i}{d_i M_i} \quad (8)$$

Here EM1 $_i$ (MPa.kg $_i^2$ /(RMB MJ % element i)) signifies, as E1 $_i$, the ability to generate strength with the smallest impact through the embodied energy but now also including alloying element cost. EM2 $_i$ (MPa. kg $_i^2$ /(RMB kgCO $_2$ % element i)) signifies, as E2 $_i$, the ability to generate strength with the smallest impact through the CO $_2$ -footprint but also taking cost-effectiveness into account. Similarly, EM3 $_i$ (MPa. kg $_i^2$ /(RMB l % element i)) signifies, as E3 $_i$, the effect of the impact on water usage when cost-effectiveness is considered.

3. Results and Discussion

The results and discussion section is divided into three main subsections. The first subsection is an analysis of the strength contribution, and the second part is the environmental impact. The third and last take the environmental impact and add cost to the analysis.

3.1. Alloying Element Strength Contribution

The relationship between the alloying element and the resulting tensile strength were obtained by using data from the ASM Handbook on typical compositions and tensile strengths at room temperature, Table A1, in the Appendix A. This was made for material in the as-cast state for cast alloys and in the as-fabricated state for wrought alloys. The data for alloys in the heat-treated state were omitted, as the primary target for the current report was non-heat-treated materials due to the fact that in the effort to reduce environmental impact, adding additional processing steps, such as a heat treatment, would increase the embodied energy and thus also the CO₂-footprint.

The coefficients were obtained using the generalized reduced gradient solver in Excel with a multi-start option of a population of 10,000 to compensate for the potential shortcomings of the solver. The optimization target was to minimize the sum of squares for the whole population. The linear solution showed a value of 92% of that of the root equation of why the linear solution was deemed superior. The results for the linear approach are shown in Figure 1a and for the root approach are shown in Figure 1b. The actual prediction quality is reasonable to use the coefficient a_i in the following analysis for quantitative contextualization.

Figure 1. Actual values versus predicted values for (a) the linear approach and (b) the root approach.

The actual values for the strength coefficients using the linear model are collated in Table 1. It should here be noted that these values were for room temperature and tensile strength. A negative value indicated that when using that alloying element, a reduction of the room temperature strength was the result. It should here be noted that Er, Y and Fe were particularly harmful to the room temperature properties. Ni also had a negative influence, as well as Be. All elements with a negative strength coefficient counteract the effort in increasing the strength of the material and as such, should be avoided. The elements with a negative influence were not part of the analysis as the general intent was to avoid negative influence. There were naturally novel alloy design concepts for which the current description failed to describe with higher Fe contents, such as the CastaductTM alloy [10]. This was a limitation of the current study and it was only valid for modification and development of existing alloys.

Table 1. The obtained values of the strength coefficient, a_i , for the linear approach.

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Ni
a_i (MPa./% element i)	93.54	12.72	−33.98	7.01	45.41	31.97	98.24	−12.27
Element	Zn	Ti	Be	Sn	Ce	La	Y	Er
a_i (MPa./% element i)	12.30	0.01	−0.91	6.30	64.98	31.61	−47.75	−54.95

3.2. Environmental Load From Alloying Elements

The data for the environmental loads were chosen such that the geopolitical aspects were not considered in this first step, but rather the matter that would have a substantial effect on energy usage and carbon footprint as these are intimately connected through the energy source used [3]. In this part,

the assumption of the use of the best available technology (BAT) was made. Water is also one of the more critical resources and therefore, the use of water was also brought into the analysis. All data were taken from the Cambridge Engineering Selector (CES) software [8].

The chosen measures for the environmental load were (1) embodied energy, b_i , (MJ/kg_i), (2) CO₂-footprint, c_i , (kgCO₂/kg_i) and water usage, d_i , (l/kg_i). The data available were collated in Table 2, also indicating the data chosen for the current analysis.

Table 2. Environmental impact in the form of the three environmental loads from the different alloying element and the chosen value for the current study. The chosen data according to the assumption of best available technology (BAT) are the values in parentheses [8].

Element	b_i Embodied Energy (MJ/kg) Primary Production	c_i CO ₂ Footprint (kg/kg). Primary Production	d_i Water Usage (L/kg). Pure Element
Si	116–128 (116)	4.78–5.27 (4.78)	23.2–25.7 (23.2)
Fe	23.2–25.6 (23.2)	2.18–2.4 (2.18)	44.9–49.6 (44.9)
Cu	56.1–61.9 (51.6)	3.44–3.79 (3.44)	297–328 (297)
Mn	55.8–61.5 (55.8)	3.8–4.19 (3.8)	231–256 (231)
Mg	310–342 (310)	44.2–48.7 (44.2)	930–1030 (930)
Cr	550–606 (550)	20–22.1 (20)	451–498 (451)
Ni	159–175 (159)	11.2–12.3 (11.2)	79–377 (79)
Zn	44–48.5 (44)	3.46–3.82 (3.46)	327–361 (361)
Ti	559–616 (559)	31.6–34.9 (34.9)	(110)
Be	6080–67,000 (6080)	821–905 (821)	340–379 (340)
Zr	1530–1690 (1530)	98.1–108 (98.1)	262–289 (262)
Ce	493–544 (493)	32.4–35.8 (32.4)	52.4–57.9 (52.4)
La	258–284 (258)	16.7–18.4 (16.7)	52.7–58.2 (52.7)
Y	1400–1540 (1400)	84.8–93.5 (84.8)	52.4–57.9 (52.4)
Er	2810–3100 (2810)	188–207 (188)	52.7–58.2 (52.7)

3.3. Environmental Alloying Efficiency Index for Alloying Elements

The environmental efficiency indexes for alloying elements are shown in Figure 2 for the index $E1_i$, Figure 3 for index $E2_i$ and Figure 4 for index $E3_i$.

Figure 2. Strengths contribution by alloying per embodied energy, $E1_i$.

Figure 3. Strengths contribution by alloying per embodied energy, E2_i.

Figure 4. Strength contribution by alloying per water usage, E3_i.

As seen in Figure 2 the results for E1_i and the most efficient element to use for high strength with a minimum of environmental impact through embodied energy was Mn with Zn as second followed by Cr. It is worthwhile noting that the common alloying elements Si, Cu and Mg were on par with Ce and La. Important to note here is that this analysis was valid for primary alloys.

CO₂-footprint is more important today following the discovery of the greenhouse effect reported in the so-called Charney report [9]. The findings for the CO₂-footprint followed the same pattern as that of the embodied energy. The most effective alloying element was Mn, followed by Zn and then Cu and Si. The elements Mg, Cr, Ce and La were roughly on par. For the CO₂-footprint, Cu and Si were more beneficial than Mg, Cr, Ce and La, a difference that was less pronounced for the embodied energy.

The results for the water usage was different compared to that of both the embodied energy and CO₂-footprint. Mn and Zn were still among the best elements, but Si was the most effective element with Zn, Cu and La being nearly on par with each other in producing strength with little water.

3.4. Environmental Alloying Efficiency Index with Alloying Element Cost Weighting

Cost of alloys and processes is often a determining factor in enabling the use of a material [11]. In the current analysis, the cost of alloys was based on the Chinese metal market with reference taken in September 2019 (Figure 5). The cost of alloying element (M_i , (RMB/kg)) varied strongly with Fe being the lowest and Be the costliest. It should also be noted that Ce and La were in the same price range as other common alloying materials such as Mg, Cu and Cr, while Y and Er were significantly more costly [12].

Figure 5. Alloying element cost basis for the estimation of influence of cost. Source: Chinese metal market September 2019.

The result for EM1_i, as seen in Figure 6, was only slightly altered from the E1_i results. Mn was the most cost-effective way to improve strength with the least amount of embodied energy and unit cost. Second was Zn and then Si. Mg was slightly above Cr, Cu, Ce and La, which were on par. Repeating the process and studying the outcome for EM2_i signified, as E2_i, the ability to generate strength with the smallest impact through the CO₂-footprint but also taking cost-effectiveness into account; the result was similar to the E1_i results, Figure 7. The variation was, however, higher. Again, Mn was the most cost-effective way to improve strength with the smallest CO₂-footprint and unit cost. Second was Zn, followed by Si and Cu and then Mg, Cr, Ce and La, which were on par.

Figure 6. Embodied energy and strength index with cost weighting, EM1_i.

Figure 7. CO₂-footprint and strength index with cost weighting, EM2_i.

The analysis made above on $E3_i$ compared to that of $E1_i$ and $E2_i$ showed that the effect on the impact on water usage showed a different pattern, which also was the case when studying the outcome for $EM3_i$ when cost-effectiveness was considered, Figure 8. The main difference was that Mn was the best solution when cost-effectiveness was included, but for the environmental impact alone, Si was the preferred element but only by a slim margin compared to Mn. For the $EM3_i$ index, Mn was without competition the superior solution followed by Si and then Cu and La. One order of magnitude lower then followed Mg, Cr and Ce.

Figure 8. Water usage and strength index with cost weighting, $EM3_i$.

4. Conclusions

From an effectiveness standpoint, Mn is the overall preferred element of choice followed by Zn and then Si with and without cost penalty, as seen in Table 3. In the table, the ranking from the derived indices are shown and the sum of the ranking with and without cost is shown. In the analysis of the impact, the overall ranking is shown within parentheses.

Table 3. The ranking using the 6 different indexes derived and the total impact ranking.

Element	Rank by $E1_i$	Rank by $EM1_i$	Rank by $E2_i$	Rank by $EM2_i$	Rank by $E3_i$	Rank by $EM3_i$	Impact $E1_i + E2_i + E3_i$	Impact $EM1_i + EM2_i + EM3_i$
Si	7	3	4	3	1	2	12 (3)	8 (3)
Fe	Negative	Negative	Negative	Negative	Negative	Negative	-	-
Cu	4	8	3	4	5	4	12 (3)	16 (4)
Mn	1	1	1	1	2	1	4 (1)	3 (1)
Mg	8	4	8	7	8	7	24 (8)	19 (6)
Cr	3	7	5	6	6	6	14 (5)	19 (6)
Ni	Negative	Negative	Negative	Negative	Negative	Negative	-	-
Zn	2	2	2	2	3	3	7 (2)	7 (2)
Ti	10	10	10	10	10	10	30 (10)	30 (10)
Be	Negative	Negative	Negative	Negative	Negative	Negative	-	-
Sn	9	9	9	9	9	9	27 (9)	27 (9)
Ce	5	5	7	8	7	8	19 (7)	21 (8)
La	6	6	6	5	4	5	16 (6)	16 (4)
Y	Negative	Negative	Negative	Negative	Negative	Negative	-	-
Er	Negative	Negative	Negative	Negative	Negative	Negative	-	-

Mn is the most effective element and has a slight relative advantage based on cost. Zn is not affected by cost while Si, ranked third, has a slight benefit from cost. Copper, which based on environmental impact is ranked third, is punished by cost and drops one position based on cost. It should here be noted that Cu has an ecotoxic nature, which is not reflected in the current analysis. Cr ranked fifth but also has a negative effect based on cost and drops a position when the cost is included. La is ranked sixth and Ce is ranked seventh based on environmental impact. La and Ce are unexpectedly ranked

above Mg, which is ranked eighth. Taking cost into account, Mg and Ce switch place, giving Mg a cost advantage. La has a substantial cost advantage, making it leapfrog to fourth position when taking cost into account. The research on rare earth materials is strong in China [13]. The current analysis shows that there also are advantages in terms of environmental impact and cost benefits to using La and perhaps also Ce instead of Mg in the future alloying concepts. Sn and Ti are the lowest ranking elements and there is only a minimal influence on the strengths of these elements, and their use has primarily others reason than to improve ensile strength

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Appendix A

In the appendix the data used for the fitting to obtain the strengths coefficients are in Table A1.

Table A1. Data used in the fitting of the strength coefficients with compositions in weight %.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Be	Sn	Ce	La	Y	Er	Al	UTS MPa	Ref
1145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	89.6	[14]
1350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	82.7	[14]
2017	0.5	0	4	0.7	0.6	0	0	0	0	0	0	0	0	0	0	94.2	180	[14]
2024	0	0	4.4	0.6	1.5	0	0	0	0	0	0	0	0	0	0	93.5	185	[14]
2024	0	0	4.4	0.6	1.5	0	0	0	0	0	0	0	0	0	0	93.5	180	[14]
2219	0	0	6.3	0.3	0	0	0	0	0.06	0	0	0	0	0	0	93.34	170	[14]
3002	0	0	0	0.15	0.12	0	0	0	0	0	0	0	0	0	0	99.73	90	[14]
3003	0	0	0.12	1.2	0	0	0	0	0	0	0	0	0	0	0	98.68	110	[14]
3003	0	0	0.12	1.2	0	0	0	0	0	0	0	0	0	0	0	98.68	110	[14]
3004	0	0	0	1.2	1	0	0	0	0	0	0	0	0	0	0	97.8	180	[14]
3004	0	0	0	1.2	1	0	0	0	0	0	0	0	0	0	0	97.8	180	[14]
3005	0	0	0	1.2	0.4	0	0	0	0	0	0	0	0	0	0	98.4	130	[14]
3102	0	0	0	0.22	0	0	0	0	0	0	0	0	0	0	0	99.78	95	[14]
3105	0	0	0	0.6	0.5	0	0	0	0	0	0	0	0	0	0	98.9	115	[14]
5005	0	0	0	0	0.8	0	0	0	0	0	0	0	0	0	0	99.2	125	[14]
5010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	115	[14]
5042	0	0	0	0.35	3.5	0	0	0	0	0	0	0	0	0	0	96.15	230	[14]
5050	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	98.6	145	[14]
5051	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	98	165	[14]
5052	0	0	0	0	2.5	0.25	0	0	0	0	0	0	0	0	0	97.25	195	[14]
5056	0	0	0	0.12	5	0.12	0	0	0	0	0	0	0	0	0	94.76	290	[14]
5059	0	0	0	0.9	5.5	0	0	0.62	0	0	0	0	0	0	0	92.98	360	[14]
5083	0	0	0	0.7	4.4	0.15	0	0	0	0	0	0	0	0	0	94.75	290	[14]
5086	0	0	0	0.45	4	0.15	0	0	0	0	0	0	0	0	0	95.4	260	[14]
5154	0	0	0	0	3.5	0.25	0	0	0	0	0	0	0	0	0	96.25	240	[14]
5182	0	0	0	0.35	4.5	0	0	0	0	0	0	0	0	0	0	95.15	275	[14]
5254	0	0	0	0	3.5	0.25	0	0	0	0	0	0	0	0	0	96.25	230	[14]
5383	0	0	0	0.85	4.75	0	0	0	0	0	0	0	0	0	0	94.4	315	[14]
5454	0	0	0	0.8	2.7	0.12	0	0	0	0	0	0	0	0	0	96.38	250	[14]

Table A1. Cont.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Be	Sn	Ce	La	Y	Er	Al	UTS MPa	Ref
5456	0	0	0	0.8	5.1	0.12	0	0	0	0	0	0	0	0	0	93.98	310	[14]
5457	0	0	0	0.3	1	0	0	0	0	0	0	0	0	0	0	98.7	220	[14]
6061	0.6	0	0.28	0	1	0.2	0	0	0	0	0	0	0	0	0	97.92	125	[14]
6061	0.6	0	0.28	0	1	0.2	0	0	0	0	0	0	0	0	0	97.92	115	[14]
6063	0.4	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	98.9	90	[14]
6066	1.4	0	1	0.8	1.1	0	0	0	0	0	0	0	0	0	0	95.7	150	[14]
7075	0	0	1.6	0	2.5	0.23	0	5.6	0	0	0	0	0	0	0	90.07	220	[14]
7178	0	0	2	0	2.8	0.23	0	6.8	0	0	0	0	0	0	0	88.17	230	[14]
7178	0	0	2	0	2.8	0.23	0	6.8	0	0	0	0	0	0	0	88.17	220	[14]
208.0	3	0	4	0	0	0	0	0	0	0	0	0	0	0	0	93	245	[14]
222.0	0	0	10	0	0.25	0	0	0	0	0	0	0	0	0	0	89.75	185	[14]
230	4	1.5	10	0.6	0.25	0	1	1.5	0.25	0	0	0	0	0	0	80.9	205	[14]
240	0	0	8	0.5	6	0	0.5	0	0	0	0	0	0	0	0	85	235	[14]
242	0	0	4	0	1.5	0	2	0	0	0	0	0	0	0	0	92.5	145	[14]
A242.0	0	0	4.1	0	1.4	0.2	2	0	0.14	0	0	0	0	0	0	92.16	185	[14]
295	1.1	0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	94.4	170	[14]
308	5.5	0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	90	195	[14]
319	6	0	3.5	0	0	0	0	0	0	0	0	0	0	0	0	90.5	185	[14]
319	6	0	3.5	0	0	0	0	0	0	0	0	0	0	0	0	90.5	235	[14]
328.0	8	0	1.5	0.4	0.4	0	0	0	0	0	0	0	0	0	0	89.7	170	[14]
333	9	0	3.5	0	0.28	0	0	0	0	0	0	0	0	0	0	87.22	235	[14]
355	5	0	1.25	0	0.5	0	0	0	0	0	0	0	0	0	0	93.25	160	[14]
C355.0	5	0	1.25	0	0.5	0	0	0	0	0	0	0	0	0	0	93.25	185	[14]
356	7	0	0	0	0.32	0	0	0	0	0	0	0	0	0	0	92.68	165	[14]
356	7	0	0	0	0.32	0	0	0	0	0	0	0	0	0	0	92.68	180	[14]
A356.0	7	0	0	0	0.35	0	0	0	0	0	0	0	0	0	0	92.65	160	[14]
A356.0	7	0	0	0	0.35	0	0	0	0	0	0	0	0	0	0	92.65	185	[14]
357	7	0	0	0	0.52	0	0	0	0	0	0	0	0	0	0	92.48	170	[14]
A357.0	7	0	0	0	0.55	0	0	0	0.12	0.055	0	0	0	0	0	92.275	195	[14]
360	9.5	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	90	305	[14]
A360.0	9.5	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	90	315	[14]
380	8.5	0	3.5	0	0	0	0	0	0	0	0	0	0	0	0	88	315	[14]
A380.0	8.5	0	3.5	0	0	0	0	0	0	0	0	0	0	0	0	88	325	[14]
383	10.5	0	2.5	0	0	0	0	0	0	0	0	0	0	0	0	87	310	[14]
384	11.2	0	3.8	0	0	0	0	0	0	0	0	0	0	0	0	85	330	[14]
B390.0	17	0	4.5	0	0.55	0	0	0	0	0	0	0	0	0	0	77.95	315	[14]
413	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88	295	[14]
A413.0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88	290	[14]
443	5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94.8	130	[14]
B443.0	5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94.8	160	[14]
C443.0	5.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	94.8	115	[14]
A444.0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	93	145	[14]
A444.0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	93	165	[14]
512	1.8	0	0	0	4	0	0	0	0	0	0	0	0	0	0	94.2	140	[14]
513	0	0	0	0	4	0	0	1.8	0	0	0	0	0	0	0	94.2	185	[14]
514	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	96	170	[14]
518	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	92	310	[14]
535	0	0	0	0.18	6.8	0	0	0	0.18	0.005	0	0	0	0	0	92.835	240	[14]
535	0	0	0	0.18	6.8	0	0	0	0.18	0.005	0	0	0	0	0	92.835	240	[14]
710	0	0	0.5	0	0.7	0	0	6.5	0	0	0	0	0	0	0	92.3	220	[14]
711	0	1	0.5	0	0.35	0	0	6.5	0	0	0	0	0	0	0	91.65	195	[14]
712	0	0	0	0	0.58	0.5	0	6	0.2	0	0	0	0	0	0	92.72	235	[14]
713	0	0	0.7	0	0.35	0	0	7.5	0	0	0	0	0	0	0	91.45	220	[14]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0	0	0	0	96.84	184	[13]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0.1	0	0	0	96.74	202	[13]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0.2	0	0	0	96.64	203	[13]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0.3	0	0	0	96.54	218	[13]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0.4	0	0	0	96.44	210	[13]
Exp.	0	0.16	0	0	3	0	0	0	0	0	0	0.5	0	0	0	96.34	200	[13]
Exp.	10.86	0.57	2.95	0	0.23	0	0	0.68	0	0	0	0	0	0	0	84.71	160	[15]
Exp.	10.53	0.66	3.36	0	0.29	0	0	0.54	0	0	0	0	0	0.12	0	84.5	220	[15]
Exp.	10.28	0.54	3.03	0	0.35	0	0	0.56	0	0	0	0	0	0.23	0	85.01	240	[15]

Table A1. Cont.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Be	Sn	Ce	La	Y	Er	Al	UTS MPa	Ref
Exp.	10.59	0.66	3.29	0	0.3	0	0	0.63	0	0	0	0	0	0.34	0	84.19	230	[15]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0	92.42	148	[16]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0.2	92.22	158	[16]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0.14	92.28	169	[16]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0.5	91.92	167	[16]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0.6	91.82	155	[16]
Exp.	7.02	0.12	0.005	0.005	0.42	0	0	0	0.01	0	0	0	0	0	0.7	91.72	154	[16]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0	0	0	92.19	230	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.01	0	0	92.18	255	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.03	0	0	92.16	242	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.05	0	0	92.14	249	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.07	0	0	92.12	249	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.1	0	0	92.09	273	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.3	0	0	91.89	272	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	0.5	0	0	91.69	273	[17]
Exp.	7.2	0.09	0.01	0.01	0.49	0	0	0.01	0	0	0	0	1	0	0	91.19	230	[17]
Exp.	11	0.4	1.5	0	0.3	0	0	0	0	0	0	0	0	0	0	86.8	240	[18]
Exp.	11	0.4	1.5	0	0.3	0	0	0	0	0	0	0	0.5	0	0	86.3	245	[18]
Exp.	11	0.4	1.5	0	0.3	0	0	0	0	0	0	0	0.1	0	0	86.7	260	[18]
Exp.	11	0.4	1.5	0	0.3	0	0	0	0	0	0	0	0.2	0	0	86.6	250	[18]
Exp.	0.65	0.13	0.27	0	0.95	0.15	0	0	0	0	2	0	0	0	0	95.85	157	[18]

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