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(54) **HIGH PERFORMANCE AISIMGCU CASTING ALLOY**

HOCHLEISTUNGS-ALSIMGCU-GUSS-LEGIERUNG

ALLIAGE DE MOULAGE PAR COULÉE D'ALSIMGCU À HAUTE PERFORMANCE

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Description**Field**

- 5 [0001] The present invention relates to aluminum alloys, and more particularly, to aluminum alloys used for making cast products.

Background

- 10 [0002] Aluminum alloys are widely used, e.g., in the automotive and aerospace industries, due to a high performance-to-weight ratio, favorable corrosion resistance and other factors. Various aluminum alloys have been proposed in the past that have characteristic combinations of properties in terms of weight, strength, castability, resistance to corrosion, cost, etc. Improvements in alloys to exhibit an improved combination of properties, e.g., that render them more suitable for one or more applications, remain desirable.
- 15 [0003] Lumley R N et al: "Rapid Heat Treatment of Aluminum High-Pressure Diecastings", Metallurgical and Materials Transactions A, Springer-Verlag, New York, vol 40, no. 7, 2 May 2009, pages 1716-1726, concerns the thermal treatment of a series of common high-pressure diecasting aluminum alloys. It discloses an alloy having 9.3 wt.-% Si, 0.73 wt.-% Cu, 0.41 wt.-% Mg, 0.31 wt.-% Zn, 0.79 wt.-% Fe, 0.21 wt.-% Mn, less than 0.2 wt.-% other elements and balance aluminum.

Summary

- 25 [0004] The disclosed subject matter relates to improved aluminum casting alloys (also known as foundry alloys) and methods for producing same. More specifically, the present application relates to an aluminum casting alloy having a composition as defined in claim 1.
- [0005] In one approach, the aluminum casting alloy includes 1.35 - 2.0 wt. % copper and 0.27 - 0.445 wt. % magnesium.
- [0006] In one approach, the aluminum casting alloy includes 0.5 - 0.75 wt. % copper and 0.395 - 0.53 wt. % magnesium.
- [0007] In one approach, the aluminum casting alloy includes 0.75 - 1.35 wt. % copper and 0.335 - 0.505 wt. % magnesium.
- 30 [0008] In one approach the aluminum casting alloy includes copper and magnesium such that $5.0 \leq (\text{Cu}+10\text{Mg}) \leq 5.5$.
- [0009] In one approach, the aluminum casting alloy includes copper and magnesium such that $5.1 \leq (\text{Cu}+10\text{Mg}) \leq 5.4$.
- [0010] In one approach, the aluminum casting alloy contains ≤ 0.01 wt. silver.
- [0011] In one approach, the aluminum casting alloy contains 0.05 - 1.0 wt. % silver.
- 35 [0012] In one approach, the aluminum casting alloy is subjected to a solution heat treatment at TH followed by a cold water quench, where TH ($^{\circ}\text{C}$) = $570 - 10.48*\text{Cu} - 71.6*\text{Mg} - 1.3319*\text{Cu}*\text{Mg} - 0.72*\text{Cu}*\text{Cu} + 72.95*\text{Mg}*\text{Mg}$, based on Mg and Cu content in wt%, within the range defined by a lower limit for TH : $\text{TQ} = 533.6 - 20.98*\text{Cu} + 88.037*\text{Mg} + 33.43*\text{Cu}*\text{Mg} - 0.7763*\text{Cu}*\text{Cu} - 126.267*\text{Mg}*\text{Mg}$ and an upper limit for TH : $\text{TS} = 579.2 - 10.48*\text{Cu} - 71.6*\text{Mg} - 1.3319*\text{Cu}*\text{Mg} - 0.72*\text{Cu}*\text{Cu} + 72.95*\text{Mg}*\text{Mg}$.
- [0013] In one approach, the casting aluminum casting alloy contains 0.1 - 0.12 wt. % titanium.
- 40 [0014] In one approach, the casting aluminum casting alloy contains 0.12 - 0.14 wt. % vanadium.
- [0015] In one approach, the casting aluminum casting alloy contains 0.08 - 0.19 wt. % zirconium.
- [0016] In one approach, the casting aluminum casting alloy contains 0.14 - 0.3 wt. % manganese.
- [0017] In one approach, the casting aluminum casting alloy contains 0.15 - 0.57 wt. % iron.
- [0018] In one approach, the casting aluminum casting alloy contains 0.1 - 0.12 wt. % vanadium.
- 45 [0019] In one approach, the casting aluminum casting alloy contains 0.11 - 0.13 wt. % zirconium.
- [0020] In one approach, the casting aluminum casting alloy contains 0.27 - 0.3 wt. % nickel.
- [0021] In one approach, the casting aluminum casting alloy contains 0.15 - 0.33 wt. % iron.
- [0022] In one approach, the casting aluminum casting alloy contains 0.03 - 0.15 wt. % manganese.
- [0023] In one approach, the casting aluminum casting alloy contains 0.05 - 0.2 wt. % hafnium.
- 50 [0024] In one approach, the casting aluminum casting alloy contains 0.1 - 0.12 wt. % vanadium.
- [0025] In one approach, the casting aluminum casting alloy contains 0.012 - 0.04 wt. % zirconium.

Brief Description of the Drawings

- 55 [0026]

Figure 1 is a graph of phase equilibria involving (Al) and liquid in an Al-Cu-Mg-Si system.

Figure 2 is a graph of the effect of Cu additions on the solidification path of Al-9%Si-0.4%Mg-0.1%Fe alloy.

Figure 3 is a graph of the effect of Cu content on phase fractions in Al-9%-0.4%Mg-0.1%Fe-x%Cu alloys.
 Figure 4 is a graph of the effect of Cu and Mg content on the Q-phase formation temperature of Al-9%Si-Mg-Cu alloys.
 Figure 5 is a graph of the effect of Mg and Cu content on the equilibrium solidus temperature of Al-9%Si-Mg-Cu alloys.
 Figure 6 is a graph of the effect of Mg and Cu content on the equilibrium solidus temperature (T_S) and Q-phase formation temperature (T_Q) of Al-9%Si-Mg-Cu alloys.
 Figure 7 is a graph of the effect of zinc and silicon on the fluidity of Al-x%Si-0.5%Mg-y%Zn alloys
 Figure 8 is an SEM (scanning electron micrograph) @200X magnification, showing spherical Si particles and undissolved Fe-containing particles.
 Figures 9a-b are photographs of undissolved Fe-containing particles in the investigated alloys.
 Figures 10a-d are graphs of the effect of aging condition on tensile properties of the Al-9Si-0.5Mg alloy.
 Figures 11a-d are graphs of the effect of Cu on tensile properties of the Al-9%Si-0.5%Mg alloy.
 Figures 12a-d are graphs of the effect of Cu and Zn on tensile properties of the Al-9%Si-0.5%Mg alloy.
 Figures 13a-d are graphs of the effect of Mg content on tensile properties of the Al-9%Si-1.25%Cu-Mg alloy.
 Figures 14a-d are graphs of the effect of Ag on tensile properties of the Al-9%Si-0.35%Mg-1.75%Cu alloy.
 Figures 15a-d are graphs of tensile properties for six alloys aged for different times at an elevated temperature, as described in the disclosure.
 Figure 16 is a graph of Charpy impact energy (CIE) vs. yield strength for five alloys aged for different times at an elevated temperature.
 Figure 17 is a graph of S-N fatigue curves of selected alloys aged at 155°C for 15 hours. Smooth, Axial; stress ratio = -1.
 Figure 18 is a graph of S-N fatigue curves of selected alloys aged at 155°C for 60 hours. Smooth, Axial; stress ratio = -1.
 Figure 19a-d - 23a-d are optical micrographs of cross-sections of samples of five alloys as cast and machined and aged for two different time periods at an elevated temperature after 6-hour ASTM G110.
 Figure 24 is a graph of depth of attack of selected alloys aged for different time periods on the as-cast and machined surfaces after a 6-hour G110 test.
 Figure 25 is a graph of Mg and Cu content correlated to strength and ductility for Al-9Si-Mg-Cu alloys.
 Figure 26 is a graph of tensile properties of a specific alloy (alloy 9) after exposure to high temperatures.
 Figures 27a and 27b are scanning electron micrographs of a cross-section of a sample of alloy 9 prior to exposure to high temperatures.
 Figures 28a-e are a series of scanning electron micrographs of a cross-section of alloy 9 after exposure to increasing temperatures correlated to a tensile property graph of alloy 9 and A356 alloy.
 Figure 29 is a graph of yield strength at room temperature for various alloys.
 Figure 30 is a graph of yield strength after exposure to 175 °C for various alloys.
 Figure 31 is a graph of yield strength after exposure to 300 °C for various alloys.
 Figure 32 is a graph of yield strength after exposure to 300 °C for various alloys.
 Figure 33 is a graph of yield strength after exposure to 300 °C for various alloys.
 Figure 34 is a graph of yield strength after exposure to 300 °C for various alloys.

Detailed Description of Exemplary Embodiments

EXAMPLE 1: High Performance AlSiCuMg Cast Alloys

1.1 Alloy Development Methods Based on Computational Thermodynamics

[0027] To improve the performances of Al-Si-Mg-Cu cast alloys, a novel alloy design method was used and is described as follows:

In Al-Si-Mg-Cu casting alloys, increasing Cu content can increase the strength due to higher amount of θ' -Al₂Cu and Q' precipitates but reduce ductility, particularly if the amount of un-dissolved constituent Q-phase increases. Figure 1 shows the calculated phase diagram of the Al-Cu-Mg-Si quaternary system, as shown in X. Yan, Thermodynamic and solidification modeling coupled with experimental investigation of the multicomponent aluminum alloys. University of Wisconsin-Madison, 2001, which is incorporated in its entirety by reference herein. Figure 1 shows the three phase equilibria in ternary systems and the four phase equilibria quaternary monovariant lines. Points A, B, C, D, E and F are five phase invariant points in the quaternary system. Points T1 to T6 are the four-phase invariant points in ternary systems and B1, B2 and B3 are the three phase invariant points in binary systems. The formation of Q-phase (AlCuMgSi) constituent particles during solidification is almost inevitable for an Al-Si-Mg alloy containing Cu since Q-phase is involved in the eutectic reaction (invariant reaction B). If these Cu-containing Q-phase particles cannot be dissolved during solution heat treatment, the strengthening effect of Cu will be reduced and the ductility of the casting will also suffer.

[0028] In order to minimize/eliminate un-dissolved Q-phase (AlCuMgSi) and maximize solid solution/precipitation strengthening, the alloy composition, solution heat treatment and aging practice should be optimized. In accordance

with the present disclosure, a thermodynamic computation was used to select alloy composition (mainly Cu and Mg content) and solution heat treatment for avoiding un-dissolved Q-phase particles. Pandat thermodynamic simulation software and the PanAluminum database LLC, CompuTherm, Pandat Software and PanAluminum Database. <http://www.compuTherm.com> were used to calculate these thermodynamic data.

[0029] The inventors of the present disclosure recognize that adding Cu to Al-Si-Mg cast alloys will change the solidification sequence. Figure 2 shows the predicted effect of 1% Cu (all compositions in this report are in weight percent) on the solidification path of Al-9%Si-0.4%Mg-0.1%Fe. More particularly, the solidification temperature range is significantly increased with the addition of 1% Cu due to the formation of Cu-containing phases at lower temperatures. For the Al-9%Si-0.4%Mg-0.1%Fe-1%Cu alloy, Q-AlCuMgSi formed at ~538°C and θ -Al₂Cu phase formed at ~510°C. The volume fraction of each constituent phase and their formation temperatures are also influenced by the Cu content.

[0030] Figure 3 shows the predicted effect of Cu content on phase fractions in Al-9%Si-0.4%Mg-0.1%Fe-x%Cu alloys. As the Cu content increases, the amount of θ -Al₂Cu and Q-AlCuMgSi increases while the amount of Mg₂Si and π -AlFeMgSi decreases. In alloys with more than 0.7% Cu, Mg₂Si phase will not form during solidification. The amount of Q-AlCuMgSi is also limited by the Mg content in the alloy if the Cu content is more than 0.7%.

[0031] The Q-AlCuMgSi phase formation temperature (T_Q) in Al-9%Si-Mg-Cu alloys is a function of Cu and Mg content. The "formation temperature" of a constituent phase is defined as the temperature at which the constituent phase starts to form from the liquid phase. Figure 4 shows the predicted effects of Cu and Mg content on the formation temperature of Q-AlCuMgSi phase. The formation temperature of Q-AlCuMgSi phase decreases with increasing Cu content; but increases with increasing Mg content.

[0032] In accordance with the present disclosure, in order to completely dissolve all the as-cast Q-AlCuMgSi phase particles, the solution heat treatment temperature (T_H) needs to be controlled above the formation temperature of the Q-AlCuMgSi phase, i.e., $T_H > T_Q$. The upper limit of the solution heat treatment temperature is the equilibrium solidus temperature (T_S) in order to avoid re-melting. As a practical measure, the solution heat treatment temperature is controlled to be at least 5 to 10°C below the solidus temperature to avoid localized melting and creation of metallurgical flaws known in the art as rosettes. Hence, in practice, the following relationship is established:

$$T_S - 10^\circ\text{C} > T_H > T_Q \quad (1)$$

[0033] In accordance with the present disclosure, to achieve this criterion, the alloy composition, mainly the Cu and Mg contents, should be selected so that the formation temperature of Q-AlCuMgSi phase is lower than the solidus temperature. Figure 5 shows the predicted effects of Cu and Mg content on the solidus temperature of Al-9%Si-Cu-Mg alloys. As expected, the solidus temperature decreases as the Cu and Mg content increases. It should be noted that Mg content increases the formation temperature of the Q-AlCuMgSi phase but decreases the solidus temperature as indicated in Figure 6. The Q-AlCuMgSi phase formation temperature surface and the ($T_S - 10^\circ\text{C}$) surface (10°C below the solidus temperature surface) are superimposed in Figure 6. These two surfaces intersect along the curve A-B-C. The area that meets the criterion of Equation (1) is on the right hand side of curve A-B-C, i.e., $T_Q < T_S - 10^\circ\text{C}$. Projection of the curve A-B-C to the Cu-Mg composition plane yields the center line $\text{Cu} + 10\text{Mg} = 5.25$ of the preferred composition boundary, as shown in Figure 25. The lower boundary, $\text{Cu} + 10\text{Mg} = 4.73$, was defined by the intersection of the Q-AlCuMgSi phase formation temperature surface and the ($T_S - 15^\circ\text{C}$) surface (15°C below the solidus temperature surface). The upper boundary, $\text{Cu} + 10\text{Mg} = 5.78$, was defined by the intersection of the Q-AlCuMgSi phase formation temperature surface and the ($T_S - 5^\circ\text{C}$) surface (5°C below the solidus temperature surface). For Al-9%Si-0.1%Fe-x%Cu-y%Mg alloys, Q-AlCuMgSi phase particles can be completely dissolved during solution heat treatment when the Cu and Mg contents are controlled within these boundaries.

[0034] In accordance with the present disclosure, the Mg and Cu content to maximize the alloy strength and ductility is shown in Figure 25.

[0035] The preferred relationship of Mg and Cu content is defined by:

$$\text{Cu} + 10\text{Mg} = 5.25 \text{ with } 0.5 < \text{Cu} < 2.0.$$

[0036] The upper bound is $\text{Cu} + 10\text{Mg} = 5.8$ and the lower bound is $\text{Cu} + 10\text{Mg} = 4.7$.

[0037] The foregoing approach allows the selection of a solutionization temperature by (i) calculating the formation temperature of all dissolvable constituent phases in an aluminum alloy; (ii) calculating the equilibrium solidus temperature of an aluminum alloy; (iii) defining a region in Al-Cu-Mg-Si space where the formation temperature of all dissolvable constituent phases is at least 10°C below the solidus temperature. The Al-Cu-Mg-Si space is defined by the relative % composition of each of Al, Cu, Mg and Si and the associated solidus temperatures for the range of relative composition. For a given class of alloy, e.g., Al-Cu-Mg-Si, the space may be defined by the solidus temperature associated with

relative composition of two elements of interest, e.g., Cu and Mg, which are considered relative to their impact on the significant properties of the alloy, such as tensile properties. In addition, the solutionizing temperature may be selected to diminish the presence of specific phases, e.g., that have a negative impact on significant properties, such as, tensile properties. The alloy, e.g., after casting, may be heat treated by heating above the calculated formation temperature of the phase that needs to be completely dissolved after solution heat treatment, e.g., the Q- AlCuMgSi phase, but below the calculated equilibrium solidus temperature. The formation temperature of the phase that needs to be completely dissolved after solution heat treatment and solidus temperatures may be determined by computational thermodynamics, e.g., using Pandat™ software and PanAluminum™ Database available from CompuTherm LLC of Madison, WI.

1.2 Composition selection for tensile bar casting

[0038] Based on the foregoing analysis, several Mg and Cu content combinations were selected as given in Table 3. Additionally, studies by the present inventors have indicated that an addition of zinc with a concentration greater than 3wt% to Al-Si-Mg-(Cu) alloys can increase both ductility and strength of the alloy. As shown in Figure 7, zinc can also increase the fluidity of Al-Si-Mg alloys. Thus, an addition of zinc (4wt%) was also evaluated. It has also been reported L. A. Angers, Development of Advanced I/M 2xxx Alloys for High Speed Civil Transport Applications, Alloy Technology Division Report No. AK92, 1990-04-16 that an addition of Ag can accelerate age-hardening of high Cu-containing (>~1.5wt%) aluminum alloys, and increase the tensile strength at room temperature and elevated temperature. An addition of Ag (0.5wt%) was also included in alloys with higher Cu content such as 1.75wt% Cu. Hence, ten alloy compositions were selected for evaluation. The target compositions of these alloys are given in Table 3. It should be noted that alloy 1 in Table 3 is the baseline alloy, A359.

Table 3. Target Compositions

Alloy		Target Composition (wt%)								
		Si	Cu	Mg	Zn	Ag	Fe	Sr*	Ti	B
1	Al-9Si-0.5Mg	9	0	0.5	0		<0.1	0.0125	0.04	0.003
2	Al-9Si-0.35Mg-0.75Cu-4Zn	9	0.75	0.35	4		<0.1	0.0125	0.04	0.003
3	Al-9Si-0.45Mg-0.75Cu-4Zn	9	0.75	0.45	4		<0.1	0.0125	0.04	0.003
4	Al-9Si-0.45Mg-0.75Cu	9	0.75	0.45	0		<0.1	0.0125	0.04	0.003
5	Al-9Si-0.5Mg-0.75Cu	9	0.75	0.5	0		<0.1	0.0125	0.04	0.003
6	Al-9Si-0.35Mg-1.25Cu	9	1.25	0.35	0		<0.1	0.0125	0.04	0.003
7	Al-9Si-0.45Mg-1.25Cu	9	1.25	0.45	0		<0.1	0.0125	0.04	0.003
8	Al-9Si-0.55Mg-1.25Cu	9	1.25	0.55	0		<0.1	0.0125	0.04	0.003
9	Al-9Si-0.35Mg-1.75Cu	9	1.75	0.35	0		<0.1	0.0125	0.04	0.003
10	Al-9Si-0.35Mg-1.75Cu-0.5Ag	9	1.75	0.35	0	0.5	<0.1	0.0125	0.04	0.003

[0039] A modified ASTM tensile-bar mold was used for the casting. A lubricating mold spray was used on the gauge section, while an insulating mold spray was used on the remaining portion of the cavity. Thirty castings were made for each alloy. The average cycle time was about two minutes. The actual compositions investigated are listed in Table 4, below.

Table 4. Actual Compositions

Alloy		Actual Composition (wt%)								
		Si	Cu	Mg	Zn	Ag	Fe	Sr*	Ti	B
1	Al-9Si-0.5Mg	8.87	0.021	0.48	0		0.079	0.0125	0.05	0.003
2	Al-9Si-0.35Mg-0.75Cu-4Zn	9.01	0.75	0.37	4.03		0.077	0.0125	0.031	0.003
3	Al-9Si-0.45Mg-0.75Cu-4Zn	9.09	0.75	0.46	4.02		0.081	0.0125	0.04	0.003
4	Al-9Si-0.45Mg-0.75Cu	9.18	0.76	0.45			0.083	0.0125	0.042	0.003
5	Al-9Si-0.5Mg-0.75Cu	9.02	0.77	0.49			0.081	0.0125	0.013	0.003

(continued)

Alloy		Actual Composition (wt%)								
		Si	Cu	Mg	Zn	Ag	Fe	Sr*	Ti	B
6	Al-9Si-0.35Mg-1.25Cu	9.02	1.25	0.34			0.088	0.0125	0.03	0.003
7	Al-9Si-0.45Mg-1.25Cu	9.11	1.28	0.44			0.082	0.0125	0.04	0.003
8	Al-9Si-0.55Mg-1.25Cu	8.99	1.27	0.53			0.1	0.0125	0.04	0.003
9	Al-9Si-0.35Mg-1.75Cu	9.29	1.83	0.37			0.08	0.0125	0.048	0.003
10	Al-9Si-0.35Mg-1.75Cu-0.5Ag	8.88	1.78	0.35		0.5	0.081	0.0125	0.044	0.003

The actual compositions are very close to the target compositions. The hydrogen content (single testing) of the castings is given in Table 5.

Table 5. Hydrogen Content of the Castings

Alloy		H Content (ppm)
1	Al-9Si-0.5Mg	0.14
2	Al-9Si-0.35Mg-0.75Cu-4Zn	0.11
3	Al-9Si-0.45Mg-0.75Cu-4Zn	0.19
4	Al-9Si-0.45Mg-0.75Cu	0.11
5	Al-9Si-0.5Mg-0.75Cu	0.14
6	Al-9Si-0.35Mg-1.25Cu	0.15
7	Al-9Si-0.45Mg-1.25Cu	0.13
8	Al-9Si-0.55Mg-1.25Cu	0.16
9	Al-9Si-0.35Mg-1.75Cu	0.13
10	Al-9Si-0.35Mg-1.75Cu-0.5Ag	Not measured
Note: alloy 3 was degassed with porous lance; all other alloys were degassed using a rotary degasser.		

1.3 The preferred solution heat treat temperature as a function of Cu and Mg

[0040] To dissolve all the Q-AlCuMgSi phase particles, the solution heat treatment temperature should be higher than the Q-AlCuMgSi phase formation temperature. Table 6 lists the calculated final eutectic temperature, Q-phase formation temperature and solidus temperature using the targeted composition of the ten alloys investigated.

Table 6. Calculated Final Eutectic Temperature, Q-phase Formation Temperature and Solidus Temperature for Ten Investigated Casting Alloys

Alloy		Final eutectic temperature, C	Q-phase forming temperature, C	Solidus temperature, C
1	Al-9Si-0.5Mg	560	-	563
2	Al-9Si-0.35Mg-0.75Cu-4Zn	470	518	540
3	Al-9Si-0.45Mg-0.75Cu-4Zn	470	518	543
4	Al-9Si-0.45Mg-0.75Cu	510	541	554
5	Al-9Si-0.5Mg-0.75Cu	510	541	553
6	Al-9Si-0.35Mg-1.25Cu	510	533	552
7	Al-9Si-0.45Mg-1.25Cu	510	536	548

(continued)

Alloy		Final eutectic temperature, C	Q-phase forming temperature, C	Solidus temperature, C
8	Al-9Si-0.55Mg-1.25Cu	510	538	545
9	Al-9Si-0.35Mg-1.75Cu	510	528	543
10	Al-9Si-0.35Mg-1.75Cu-0.5Ag	510	526	543

Based on the above mentioned information, two solution heat treatment practices were defined and used. Alloys 2, 3, 9 and 10 had lower solidus temperature and/or lower final eutectic/Q-phase formation temperature than others. Hence a different SHT practice was used.

[0041] The practice I for alloys 2, 3, 9 and 10 was:

- 1.5 hour log heat-up to 471°C
- 2 hour soak at 471°C
- 0.5 hour ramp up to 504°C
- 4 hour soak at 504°C
- 0.5 hour ramp up to T_H
- 6 hour soak at T_H
- CWQ (Cold Water Quench)

and practice II for other six alloys was:

- 1.5 hour log heat-up to 491°C
- 2 hour soak at 491°C
- 0.25 hour ramp up to 504°C
- 4 hour soak at 504°C
- 0.5 hour ramp up to T_H
- 6 hour soak at T_H
- CWQ (Cold Water Quench)

[0042] The final step solution heat treatment temperature T_H was determined from following equation based on Mg and Cu content:

$$T_H (^{\circ}\text{C}) = 570 - 10.48 \cdot \text{Cu} - 71.6 \cdot \text{Mg} - 1.3319 \cdot \text{Cu} \cdot \text{Mg} - 0.72 \cdot \text{Cu} \cdot \text{Cu} + 72.95 \cdot \text{Mg} \cdot \text{Mg}, \quad (2)$$

Where, Mg and Cu are magnesium and copper contents, in wt%

[0043] A lower limit for T_H is defined by:

$$T_Q = 533.6 - 20.98 \cdot \text{Cu} + 88.037 \cdot \text{Mg} + 33.43 \cdot \text{Cu} \cdot \text{Mg} - 0.7763 \cdot \text{Cu} \cdot \text{Cu} - 126.267 \cdot \text{Mg} \cdot \text{Mg} \quad (3)$$

[0044] An upper limit for T_H is defined by:

$$T_S = 579.2 - 10.48 \cdot \text{Cu} - 71.6 \cdot \text{Mg} - 1.3319 \cdot \text{Cu} \cdot \text{Mg} - 0.72 \cdot \text{Cu} \cdot \text{Cu} + 72.95 \cdot \text{Mg} \cdot \text{Mg} \quad (4)$$

[0045] The microstructure of the solution heat treated specimens was characterized using optical and SEM microscopy. There were no un-dissolved Q-phase particles detected in all the Cu-containing alloys investigated. Figure 8 shows the microstructure of the Al-9%Si-0.35%Mg-1.75%Cu alloy (alloy #9) in the T6 temper. Si particles were all well-spheroidized. Some un-dissolved particles were identified as β -AlFeSi, π -AlFeMgSi and $\text{Al}_7\text{Cu}_2\text{Fe}$ phases. The morphologies of these un-dissolved phases are shown in Figure 9 at higher magnification.

1.4 Experimental Results

1.4.1 Property characterization

[0046] Tensile properties were evaluated according to the ASTM B557 method. Test bars were cut from the modified ASTM B108 castings and tested on the tensile machine without any further machining. All the tensile results are an average of five specimens. Toughness of selected alloys was evaluated using the un-notched Charpy Impact test, ASTM E23-07a. The specimen size was 10mm X 10mm X 55mm machined from the tensile-bar casting. Two specimens were measured for each alloy.

[0047] Smooth S-N fatigue test was conducted according to the ASTM E606 method. Three stress levels, 100 MPa, 150 MPa, and 200 MPa were evaluated. The R ratio was -1 and the frequency was 30 Hz. Three replicated specimens were tested for each condition. Test was terminated after about 10^7 cycles. Smooth fatigue round specimens were obtained by slightly machining the gauge portion of the tensile bar casting.

[0048] Corrosion resistance (type-of-attack) of selected conditions was evaluated according to the ASTM G110 method. Corrosion mode and depth-of-attack on both the as-cast surface and machined surface were assessed.

[0049] All the raw test data including tensile, Charpy impact and S-N fatigue are given in Tables 7 to 9. A summary of the findings is given in the following sections.

Table 7. Mechanical properties of various alloys aged at 155°C for different times*

Alloy	Aged at 155°C for 15hrs					Aged at 155°C for 30hrs					Aged at 155°C for 60hrs				
	UTS (MPa)	TYS (MPa)	E (%)	Q (MPa)		UTS (MPa)	TYS (MPa)	E (%)	Q (MPa)		UTS (MPa)	TYS (MPa)	E (%)	Q (MPa)	
1. Al-9Si-0.5Mg	405.8	323.3	8.3	543.2		398.5	326.5	6.5	520.4		398.7	340.2	5.3	507.7	
2. Al-9Si-0.35Mg-0.75Cu-4Zn	431.5	342.0	5.5	542.6		433.5	358.0	4.5	531.5		446.8	366.0	6.5	568.7	
3. Al-9Si-0.45Mg-0.75Cu-4Zn	460.5	370.5	5.5	571.6		469.0	378.5	7.0	595.8		465.3	390.7	5.0	570.2	
4. Al-9Si-0.45Mg-0.75Cu	451.5	339.0	6.5	573.4		450.5	354.8	5.0	555.3		464.0	373.5	6.5	585.9	
5. Al-9Si-0.5Mg-0.75Cu	426.0	317.3	8.0	561.5		442.8	348.2	6.7	566.4		442.5	364.5	6.0	559.2	
6. Al-9Si-0.35Mg-1.25Cu	411.2	299.2	7.3	540.2		436.3	326.3	7.0	563.1		446.5	342.8	6.5	568.4	
7. Al-9Si-0.45Mg-1.25Cu	424.3	328.0	4.8	525.8		453.8	353.0	5.8	567.7		455.3	375.8	4.0	545.6	
8. Al-9Si-0.55Mg-1.25Cu	444.8	336.5	6.0	561.6		460.3	365.3	4.8	561.8		475.8	385.0	4.8	577.3	
9. Al-9Si-0.35Mg-1.75Cu	465.7	325.0	9.0	608.8		459.5	355.3	5.5	570.6		478.8	386.3	5.0	583.6	
10. Al-9Si-0.35Mg-1.75Cu-0.5Ag	463.3	343.0	7.5	594.5		471.7	364.5	6.3	591.9		471.0	389.3	4.5	569.0	

* Averaged value from five tensile specimens.
The Quality Index, Q = UTS + 150 log(E).

Table 8. Charpy impact test results for some selected alloys

Alloy	Energy (ft-lbs)			
	155°C/15hrs		155°C/60hrs	
	specimen 1	Specimen 3	Specimen 7	Specimen 9
1. Al-9Si-0.5Mg	6	27	23	27
3. Al-9Si-0.45Mg-0.75Cu-4Zn	17	18	10	12
4. Al-9Si-0.45Mg-0.75Cu	32	15	28	13
7. Al-9Si-0.45Mg-1.25Cu	27	12	7	12
9. Al-9Si-0.35Mg-1.75Cu	16	15	8	9

Table 9. S-N fatigue results for some selected alloys aged at 155C for 60 hours (Smooth, Axial; stress ratio = -1)

Alloy	Stress (MPa)	Cycles to Failure	
		155C/15hrs	155C/60hrs
1. Al-9Si-0.5Mg	100	1680725	1231620
1. Al-9Si-0.5Mg	100	1302419	272832
1. Al-9Si-0.5Mg	100	4321029	1077933
1. Al-9Si-0.5Mg	150	71926	148254
1. Al-9Si-0.5Mg	150	242833	42791
1. Al-9Si-0.5Mg	150	153073	56603
1. Al-9Si-0.5Mg	200	16003	54623
1. Al-9Si-0.5Mg	200	8654	30708
1. Al-9Si-0.5Mg	200	36597	39376
3. Al-9Si-0.45Mg-0.75Cu-4Zn	100	160572	248032
3. Al-9Si-0.45Mg-0.75Cu-4Zn	100	298962	131397
3. Al-9Si-0.45Mg-0.75Cu-4Zn	100	120309	394167
3. Al-9Si-0.45Mg-0.75Cu-4Zn	150	120212	12183
3. Al-9Si-0.45Mg-0.75Cu-4Zn	150	70152	42074
3. Al-9Si-0.45Mg-0.75Cu-4Zn	150	190200	31334
3. Al-9Si-0.45Mg-0.75Cu-4Zn	200	38369	18744
3. Al-9Si-0.45Mg-0.75Cu-4Zn	200	29686	14822
3. Al-9Si-0.45Mg-0.75Cu-4Zn	200	39366	11676
4. Al-9Si-0.45Mg-0.75Cu	100	485035	575446
4. Al-9Si-0.45Mn-0.75Cu	100	4521553	233110
4. Al-9Si-0.45Mg-0.75Cu	100	3287495	940229
4. Al-9Si-0.45Mg-0.75Cu	150	170004	141654
4. Al-9Si-0.45Mg-0.75Cu	150	110500	234640
4. Al-9Si-0.45Mg-0.75Cu	150	688783	238478
4. Al-9Si-0.45Mg-0.75Cu	200	108488	22686
4. Al-9Si-0.45Mg-0.75Cu	200	40007	36390
4. Al-9Si-0.45Mg-0.75Cu	200	51678	20726
7. Al-9Si-0.45Mg-1.25Cu	100	1115772	1650686

(continued)

Alloy	Stress (MPa)	Cycles to Failure	
		155C/15hrs	155C/60hrs
7. Al-9Si-0.45Mg-1.25Cu	100	318949	1744140
7. Al-9Si-0.45Mg-1.25Cu	100	468848	484262
7. Al-9Si-0.45Mg-1.25Cu	150	102341	232171
7. Al-9Si-0.45Mg-1.25Cu	150	145766	106741
7. Al-9Si-0.45Mg-1.25Cu	150	63720	226188
7. Al-9Si-0.45Mg-1.25Cu	200	41686	21873
7. Al-9Si-0.45Mg-1.25Cu	200	20709	58819
7. Al-9Si-0.45Mg-1.25Cu	200	52709	4367
9. Al-9Si-0.35Mg-1.75Cu	100	2159782	2288145
9. Al-9Si-0.35Mg-1.75Cu	100	354677	1011473
9. Al-9Si-0.35Mg-1.75Cu	100	4258369	783758
9. Al-9Si-0.35Mg-1.75Cu	150	281867	164554
9. Al-9Si-0.35Mg-1.75Cu	150	135810	188389
9. Al-9Si-0.35Mg-1.75Cu	150	100053	146740
9. Al-9Si-0.35Mg-1.75Cu	200	24014	48506
9. Al-9Si-0.35Mg-1.75Cu	200	30695	8161
9. Al-9Si-0.35Mg-1.75Cu	200	62211	31032

1.4.2 Mechanical Properties at room temperature

1.4.2.1 Effect of aging temperature on tensile properties

[0050] The effect of artificial aging temperature on tensile properties was investigated using the baseline alloy 1-Al-9%Si-0.5%Mg. After a minimum 4 hours of natural aging, the tensile bar castings were aged at 155°C for 15, 30, 60 hours and at 170°C for 8, 16, 24 hours. Three replicate specimens were used for each aging condition.

[0051] Figure 10 shows the tensile properties of the baseline A359 alloy (Al-9%Si-0.5%Mg) at various aging conditions. Low aging temperature (155°C) tends to yield higher quality index than the high aging temperature (170°C). Thus, the low aging temperature at 155°C was selected, even though the aging time is longer to obtain improved properties.

2.4.2.2 Effects of alloy elements on tensile properties

[0052] Figure 11 compares the tensile properties of baseline Al-9%Si-0.5%Mg alloy and Al-9%Si-0.5%Mg-0.75%Cu alloy. The addition of 0.75%Cu to Al-9%Si-0.5%Mg alloy increases the yield strength by ~20 MPa and ultimate tensile strength by ~40 MPa while maintaining the elongation. The average quality index of the Cu-containing alloy is ~560 MPa, which is much higher than the baseline alloy with an average of ~520 MPa.

[0053] Figure 12 compares the tensile properties of four cast alloys, 1, 2, 3 and 4. Alloy 1 is the baseline alloy. Alloy 2-4 all contain 0.75%Cu with various amounts of Mg and/or Zn. Alloys 3 and 4 contain 0.45%Mg, while alloy 2 contains 0.35%Mg and alloy 1 contains 0.5%Mg. Alloys 2 and 3 also have 4%Zn. A preliminary assessment of these four alloys indicates that Mg and Zn increase alloy strength without sacrificing ductility. A direct comparison between alloys 3 and 4 indicates that by adding 4%Zn to the Al-9%Si-0.45%Mg-0.75%Cu alloy, both ultimate tensile strength and yield strength are increased while maintaining the elongation. The 4%Zn addition also increases the aging kinetics as indicated in Figure 12. When aged at 155°C for 15 hours, yield strength of about 370 MPa can be achieved for the Al-9%Si-0.45%Mg-0.75%Cu-4%Zn alloy, which is about 30MPa higher than that of the alloy without Zn.

[0054] Figure 13 shows the effect of Mg content (0.35-0.55wt%) on the tensile properties of the Al-9%Si-1.25%Cu-Mg alloys (Alloys 6-8). The tensile properties of the baseline alloy Al-9%Si-0.5%Mg are also included for comparison.

Mg content showed significant influence on the tensile properties. With increasing Mg content, both yield strength and tensile strength were increased, but the elongation was decreased. The decrease of elongation with increasing Mg content could be related to higher amount of π -AlFeMgSi phase particles even if all the Q-AlCuMgSi phase particles were dissolved. The impact of Mg content on quality indexes of the Al-9%Si-1.25%Cu-Mg alloys was overall found to be insignificant.

[0055] Figure 14 shows the effect of Ag (0.5wt%) on the tensile properties of Al-9%Si-0.35%Mg-1.75%Cu alloy. An addition of 0.5wt% Ag had very limited impact on strength, elongation and quality index of the Al-9%Si-0.35%Mg-1.75%Cu alloy. It should be noted that the quality index of the Al-9%Si-0.35%Mg-1.75%Cu (without Ag) alloy is ~60MPa higher than the baseline alloy, A359 (Alloy 1)

[0056] Figures 15a-15d show the tensile properties of five promising alloys in accordance with the present disclosure along with the baseline alloy Al-9Si-0.5Mg (alloy 1). These five alloys achieve the target tensile properties, i.e., 10-15% increase in tensile and maintaining similar elongation as A356/A357 alloy. The alloys are: Al-9%Si-0.45%Mg-0.75%Cu (Alloy 4), Al-9%Si-0.45%Mg-0.75%Cu-4%Zn (Alloy 3), Al-9%Si-0.45%Mg-1.25%Cu (Alloy 7), Al-9%Si-0.35%Mg-1.75%Cu (Alloy 9), and Al-9%Si-0.35%Mg-1.75%Cu-0.5%Ag (Alloy 10).

[0057] Based on the data, it is believed that the following tensile properties can be obtained with alloys aged at 155°C for time ranged from 15 to 60 hrs.

Ultimate tensile strength:	450-470MPa
Tensile yield strength:	360-390MPa
Elongation:	5-7%
Quality index:	560-590MPa

[0058] These properties are much higher than A359 (Alloy 1) and are very similar to A201 (Al4.6Cu0.35Mg0.7Ag) cast alloy (UTS 450MPa, TYS 380MPa, Elongation 8%, and Q 585 MPa) ASM Handbook Volume 15, Casting, ASM International, December 2008. On the other hand, the castability of these Al-9%Si-Mg-Cu alloys is much better than A201 alloy. The A201 alloy has a poor castability due to its high tendency of hot cracking and Cu macro-segregation. Additionally, the material cost of A201 with 0.7wt% Ag is also much higher than those embodiments in accordance with the present disclosure that are Ag-free.

[0059] Based on the tensile property results, four alloys without Ag (Alloys 3, 4, 7 and 9) with promising tensile properties along with baseline alloy, A359 (Alloy 1) were selected for further investigation. Charpy impact, S-N fatigue and general corrosion tests were conducted on these five alloys aged at 155°C for 15 hours and 60 hours.

1.4.4 Charpy impact tests

[0060] Figure 16 shows the results of the individual tests by plotting Charpy impact energy vs. tensile yield strength. The filled symbols are for specimens aged at 155°C for 15 hours and open symbols are for specimens aged at 155°C for 60 hours. Tensile yield strength increases as the aging time increases, while the Charpy impact energy decreases with increasing aging time. The results indicate that most alloys/aging conditions follow the expected strength/toughness relationship. However, the results indeed show a slight degradation of the strength/toughness relationship with higher Cu content such as 1.25 and 1.75wt%.

1.4.5 S-N fatigue tests

[0061] Aluminum castings are often used in engineered components subject to cycles of applied stress. Over their commercial lifetime millions of stress cycles can occur, so it is important to characterize their fatigue life. This is especially true for safety critical applications, such as automotive suspension components.

[0062] Figures 17 and 18 show the S-N fatigue test results of five selected alloys aged at 155°C for 15 and 60 hours, respectively. During these tests a constant amplitude stress ($R = -1$) was applied to the test specimens. Three different stress levels, 100MPa, 150MPa and 200MPa were applied. The total number of cycles to failure was recorded.

[0063] When aged at 155°C for 15 hours, all the Cu-containing alloys showed better fatigue performance (higher number of cycles to failure) than the baseline A359 alloy at higher stress levels (>150MPa). At lower stress levels (<125MPa), the fatigue lives of the Al-9Si-0.45Mg-0.75Cu and Al-9Si-0.35Mg-1.75Cu alloys are very similar to the A359 alloy, while the fatigue life of the Al-9Si-0.45Cu-0.75Cu-4Zn alloy (alloy 3) was lower than the A359 alloy. The lower fatigue life of this alloy could result from the higher hydrogen content of the casting, as stated previously.

[0064] Increasing aging time (higher tensile strength) tended to decrease the number of cycles to failure. For example, as the aging time increased from 15 hours to 60 hours, the average number of cycles to failure at 150 MPa stress level decreased from ~323,000 to ~205,000 for the Al-9%Si-0.45%Mg-0.75%Cu alloy and from ~155,900 to ~82,500 for the

A359 alloy. The result could be a general trend of the strength/fatigue relationship of Al-Si-Mg-(Cu) casting alloys. Again, alloy 3 showed a lower fatigue performance than others.

1.4.6 Corrosion tests - ASTM G110

[0065] Figures 19 to 23 show optical micrographs of the cross-sectional views after 6-hour ASTM G110 tests for five selected alloys of both the as-cast surfaces and machined surfaces. The mode of corrosion attack was predominantly interdendritic corrosion. The number of corrosion sites was generally higher in the four Cu-containing compositions than in the Cu-free baseline alloy.

[0066] More particularly, Figs. 19a-d show optical micrographs of cross-sections of Al-9%Si-0.5%Mg after a 6-hour ASTM G110 test: a) of the alloy as cast and aged 15 hours at 155°C; b) of the alloy as cast and aged 60 hours at 155°C; c) of the alloy with a machined surface and aged 15 hours at 155°C; and d) of the alloy with a machined surface and aged 60 hours at 155°C.

[0067] Figs. 20a-d show optical micrographs of cross-sections of Al-9%Si-0.35%Mg-0.75%Cu-4%Zn after a 6-hour ASTM G110 test: a) of the alloy as cast and aged 15 hours at 155°C; b) of the alloy as cast and aged 60 hours at 155°C; c) of the alloy with a machined surface and aged 15 hours at 155°C; and d) of the alloy with a machined surface and aged 60 hours at 155°C.

[0068] Figs. 21a-d show optical micrographs of cross-sections of Al-9%Si-0.45%Mg-0.75%Cu after a 6-hour ASTM G110 test: a) of the alloy as cast and aged 15 hours at 155°C; b) of the alloy as cast and aged 60 hours at 155°C; c) of the alloy with a machined surface and aged 15 hours at 155°C; and d) of the alloy with a machined surface and aged 60 hours at 155°C.

[0069] Figs. 22a-d show optical micrographs of cross-sections of Al-9%Si-0.45%Mg-1.25%Cu after a 6-hour ASTM G110 test: a) of the alloy as cast and aged 15 hours at 155°C; b) of the alloy as cast and aged 60 hours at 155°C; c) of the alloy with a machined surface and aged 15 hours at 155°C; and d) of the alloy with a machined surface and aged 60 hours at 155°C.

[0070] Figs. 23a-d show optical micrographs of cross-sections of Al-9%Si-0.35%Mg-1.75%Cu after a 6-hour ASTM G110 test: a) of the alloy as cast and aged 15 hours at 155°C; b) of the alloy as cast and aged 60 hours at 155°C; c) of the alloy with a machined surface and aged 15 hours at 155°C; and d) of the alloy with a machined surface and aged 60 hours at 155°C.

[0071] Figure 24 shows the depth of attack after the 6-hour ASTM G110 test. There is no clear difference or trend among the alloys. Aging time did not show obvious impact on the depth of attack either, while some differences were found between the as-cast surfaces and the machined surfaces. In general, the corrosion attack was slightly deeper on the machined surface than the as-cast surface of the same sample.

[0072] Overall, the additions of Cu or Cu+Zn do not change the corrosion mode nor increase the depth-of -attack of the alloys. It is believed that all the alloys evaluated have similar corrosion resistance as the baseline alloy, A359.

[0073] The present disclosure has described Al-Si-Cu-Mg alloys that can achieve high strength without sacrificing ductility. Tensile properties including 450-470MPa ultimate tensile strength, 360-390MPa yield strength, 5-7 % elongation, and 560-590MPa Quality Index were obtained. These properties exceed conventional 3xx alloys and are very similar to that of the A201 (2xx+Ag) Alloy, while the castabilities of the new Al-9Si-MgCu alloys are much better than that of the A201 alloy. The new alloys showed better S-N fatigue resistance than A359 (Al-9Si-0.5Mg) alloys. Alloys in accordance with the present disclosure have adequate fracture toughness and general corrosion resistance.

EXAMPLE 2: Cast Alloys for Applications at Elevated Temperatures

[0074] Because alloys such as those described in the present disclosure may be utilized in applications wherein they are exposed to high temperatures, such as in engines in the form of engine blocks, cylinder heads, pistons, etc., it is of interest to assess how such alloys behave when exposed to high temperatures. Figure 26 shows a graph of tensile properties of an alloy in accordance with the present disclosure, namely, Al-9Si-0.35Mg-1.75Cu (previously referred to as alloy 9, e.g., in Figure 15) after exposure to various temperatures. As noted, for each test generating data in the graph, the exposure time of the alloys was 500 hours at the indicated temperature. The samples were also tested at the temperature indicated. As shown in the graph, the yield strength of the alloy diminished significantly at temperatures above 150°C. In accordance with the present disclosure, the metal was analyzed to ascertain features associated with the loss in strength due to exposure to increased temperatures.

[0075] Figures 27a and 27b show scanning electron microscope (SEM) micrographs of a cross-section of a sample of alloy 9 prior to exposure to high temperatures, with 27b being an enlarged view of the portion of the micrograph of 31a indicated as "A". As shown in Figure 27a, the grain boundaries are visible, as well as, Si and AlFeSi particles. The predominately Al portion shown in Figure 27b shows no visible precipitate at 20,000X magnification.

[0076] Figures 28a-e show a series of scanning electron microscope (SEM) micrographs of a cross-section of alloy

C00 (previously referred to as alloy 9, e.g., in Figure 15) of the same scale as the micrograph shown in Figure 27b after exposure to increasing temperatures as shown by the correlation of the micrographs to the data points on the tensile property graph G of alloy 9. The tensile characteristics of A356 alloy in the given temperature range are also shown in graph G for comparison. As can be appreciated from the sequence of micrographs, exposure of alloy 9 to increasing temperatures results in continuously increasing prominence of precipitate particles, which are larger, and which exhibit divergent geometries.

[0077] The inventors of the present disclosure recognized that certain alloying elements, viz., Ti, V, Zr, Mn, Ni, Hf, and Fe could be introduced to the C00 alloy (previously referred to as alloy 9, e.g., in Figure 15) of the present disclosure in small amounts to produce an alloy that resists strength degradation at elevated temperatures.

[0078] The following table (Table 10) show 18 alloys utilizing additive elements in small quantities to the C00 alloy (previously referred to as alloy 9, e.g., in Figure 15) for the purpose of developing improved strength at elevated temperatures.

Table 10. Alloy Compositions

Alloy	Actual Composition (wt%)											
	Fe	Si	Mn	Cu	Mg	Sr	Ti	B	V	Zr	Ni	Hf
C00	0.08	9.29	0	1.83	0.37	0.0125	0.05		0	0	0	0
C01	0.15	9.3	0.002	1.82	0.002	0.008	0.11	0.0047	0.012	0.002	0	0
C02	0.15	9.35	0.002	1.82	0.39	0.008	0.11	0.0043	0.012	0.002	0	0
C03	0.15	9.05	0.002	1.77	0.37	0.007	0.11	0.0051	0.13	0.002	0	0
C04	0.16	8.95	0.002	1.77	0.36	0.006	0.1	0.0026	0.1	0.091	0	0
C05	0.16	8.86	0.002	1.76	0.36	0.005	0.1	0.0016	0.13	0.15	0	0
C06	0.16	8.54	0.002	1.72	0.35	0.004	0.1	0.005	0.13	0.18	0	0
C07	0.16	9.31	0.15	1.8	0.34	0.004	0.11	0.0044	0.025	0.016	0	0
C08	0.16	9.32	0.16	1.84	0.34	0.004	0.11	0.0051	0.025	0.017	0	0
C09	0.17	9.1	0.28	1.8	0.33	0.003	0.11	0.005	0.025	0.016	0	0
C10	0.32	9.26	0.3	1.83	0.34	0.003	0.11	0.0045	0.024	0.017	0	0
C11	0.49	8.96	0.3	1.78	0.32	0.003	0.12	0.0055	0.11	0.016	0	0
C12	0.56	8.97	0.3	1.79	0.32	0.002	0.1	0.0039	0.11	0.12	0	0
C13	0.15	9.28	0.003	1.82	0.33	0.0125	0.1	0.005	0.0012	0.002	0.28	0
C14	0.2	9.28	0.004	1.81	0.33	0.004	0.1	0.0026	0.012	0.002	0.28	0
C15	0.31	9.27	0.03	1.82	0.33	0.004	0.1	0.0032	0.012	0.002	0.28	0
C16	0.32	9.14	0.1	1.79	0.32	0.003	0.1	0.0032	0.012	0.003	0.27	0.1
C17	0.32	8.88	0.12	1.75	0.3	0.003	0.1	0.0031	0.11	0.013	0.26	0.1
C18	0.32	8.89	0.14	1.76	0.3	0.003	0.1	0.003	0.11	0.036	0.27	0.1

Table 11 shows the mechanical properties of the foregoing alloys, viz., ultimate tensile strength (UTS), total yield strength (TYS) and Elongation % at 300 °C, 175° C and room temperature (RT).

Table 11. Mechanical Properties at Various Temperatures

Alloy	300C								
	UTS(ksi)			TYS(ksi)			Elongation(%)		
C00	8.2	8.4	8.3	6	6.3	6	49	54	29.5
C01	9.3	9.5	9.6	6.5	6.4	6.7	63	54.5	49.5
C02	10	10.3	9	6.9	7.2	6.5	51.5	40.5	40.5
C03	8.8	10.2	10.6	6.8	7.2	7.5	52	43.5	56.5
C04	10.4	10.3	11.7	7.9	7.4	8	47.5	47	41.5
C05	10.8	10.7	11.1	8.5	8	8.2	47	41.5	36.5
C06	11	9.3	11.2	7.7	7.1	8.5	35	36	42.5
C07	10.5	10.6	10.3	8.1	8	7.7	53	40	43.5
C08	10	9.7	10.6	7.5	6.7	7.9	39	40.5	36.5
C09	10.3	10.8	11.7	7.5	7.8	8.6	35	35	36
C10	10.7	10.7	11.3	8.1	8	8.3	37	40	33
C11	11	11.3	10.5	7.9	8.1	7.7	27.5	30.5	34.5
C12	11.7	10.8	11.4	8.2	7.9	8.2	33	28.5	34.5
C13	10.2	9	9.4	7.5	6.9	7	45.5	53	40
C14	9.3	9.2	9.9	6.6	6.6	6.9	56	44	42.5
C15	10	9.8	10	7.2	7.2	7.2	46.5	32	31.5
C16	10.3	10.3	10.1	7.7	7.5	7.5	44.5	36.5	34.5
C17	10.5	9.4	10	7.5	7.2	7.2	46.5	42.5	29.5
C18	10.1	11.4	11.3	7.5	8.6	8.2	29	28.5	25.5

Alloy	175C									RT					
	UTS(ksi)			TYS(ksi)			Elongation(%)			UTS(ksi)		TYS(ksi)		Elongation(%)	
C00	34.8	33.7	37.1	28.8	27.8	31	8.5	10.5	10.5	58.4	56.5	47.7	52.4	4	4
C01	28.1	31	29.4	21.4	23.7	21.8	16.6	24	14.9	37.7	38.4	20.1	20.9	9	12
C02	43.6	46.2	46.1	38	39.6	40.2	6.9	5.1	5.1	60.2	56.7		46.2	3	3
C03	44.9	43.1	45.4	40.6	37.4	39.8	0.6	7.4	4	50.5	59.8	48.7	50.3	3	5.5
C04	46.5	46.5	48.3	40.6	41	42.8	6.9	9.1	4.6	58.7	57.5	49.7	48.1	3	1
C05	40	47.4	47	35.4	40.7	39.9	2.9	5.1	5.1	52.4	58.2	51.1	47.7	1	3
C06	44.3	43.6	46.6	38.4	37.4	40.9	5.7	8	3.4	57.9	59.1	48.2	48.8	3	4
C07	48.3	46.7	43	41.6	40.8	38	6.3	2.3	6.9	57	58.3	48.1		3.5	3.5
C08	49.3	41.8	42.6	41.2	36.5	36.6	6.3	2.3	6.9	58.6	52	46.2	48.2	3.5	3
C09	39	45.2	43.9	33.7	39.2	38.6	3.4	3.4	2.3	52	58.1	47.9	48.5	3	3
C10	35.7	43.6	48.6	30.9	37.3	41.9	2.3	3.4	2.3	55	55.6	47.7	49.6	3	3
C11	42.4	42.5	47.6	36.5	35.8	41.1	1.1	2.3	2.3	54.1	52.6	49.3	49.1	3	3
C12	37.9	37.3	37.3	35.3	31.7	31.2	1.1	1.7	4	50.2	52.7	48.5	50.6	1	1.5
C13	45.3	45.2	41.3	39.2	38.2	35	2.9	6.3	8	56.3	58.5	48.1	45.9	2.5	8
C14	34.3	38.6	45.7	32.3	32.4	39	0.6	9.1	5.1	61.3	57.1	44.3	44.5	8	4
C15	40.1	45.2	44.7	34.2	38.5	37.6	2.9	5.1	3.4	56.7	55.8	45.9	47.1	4	4
C16	42.3	41.6	41.7	35.4	35.2	35.9	4	5.1	2.3	57.4	53.7	46.4	46	4	3
C17	42.6	38.4	39.5	21.8	38	34.2	14.9	6.9	2.3	57.2	56.1	47.1	46.9	3	3
C18	37.2	41.4	41.5	35.1	34.6	34.7	1.1	5.1	3.4	48.5	50.6	45.1	46.9	2	2

[0079] Figure 29 shows a graph of yield strength at room temperature for foregoing alloys. A356 is shown for comparison. In addition, a department of energy (DOE) published target for strength improvement is shown for comparison [Predictive Modeling for Automotive Light weighting Applications and Advanced Alloy Development for Automotive and Heavy-Duty Engines, Issue by Department of Energy on 03/22/2012]. As can be appreciated, the C00 alloy is comparable in strength at room temperature to alloys C02-C18, all of which substantially exceed the strength of the A356 alloy and the DOE target properties. Alloy C01 - without substantial quantities of Mg, has a far lower yield strength.

[0080] Figure 30 is a graph of yield strength after exposure to 175 °C for 500 hours for the foregoing alloys. The C00,

as well as A356 are shown for comparison. As can be appreciated, the C00 alloy substantially exceeds the strength of the A356 alloy. Alloys C02-C18), all show marked improvement over both A356 and C00.

[0081] Figure 31 is a graph of yield strength after exposure to 300°C for 500 hours for the foregoing alloys. C00, as well as A356 are shown for comparison. Figure 32 shows is a graph of yield strength after exposure to 300°C for various alloys. More particularly, adjacent alloys (going in the direction of the arrows) show the result of an additional element or the increase in quantity of an element. The highest result in the graph of Figure 32 is for C00 + 0.1T + 0.16Fe + 0.13V + 0.15Zr. The addition of more Zr (to 0.18%) to this combination results in decreased performance.

[0082] Figure 33 is a graph of yield strength after exposure to 300 °C for various alloys for 500 hours. The graphs show improvements due to the addition of Ti, Fe and Mn to the C00 composition, with the maximum performance noted relative to C00 + 0.11Ti + 0.32Fe + 0.3Mn. The addition of V to the foregoing reduces performance and the further addition of 0.12 Zr brings performance almost back to the maximum level.

[0083] Figure 34 is a graph of yield strength after exposure to 300 °C for various alloys, i.e., due to the addition of elements to the C00 composition. The optimal performance is noted relative to C00 + 0.1Ti + 0.28Ni + 0.32 Fe + 0.14Mn + 0.1Hf + 0.11V + 0.04Zr.

Claims

1. An aluminum casting alloy consisting of:

8.5 - 9.5 wt. % silicon;
0.5 - 2.0 wt. % copper (Cu);
wherein the alloy includes

- i. 1.35 - 2.0 wt. % copper and 0.27 - 0.445 wt. % magnesium, or
- ii. 0.5 - 0.75 wt. % copper and 0.395 - 0.53 wt. % magnesium, or
- iii. 0.75 - 1.35 wt. % copper and 0.335 - 0.505 wt. % magnesium;

0.27 - 0.53 wt. % magnesium (Mg);

wherein the aluminum casting alloy includes copper and magnesium such that $4.7 \leq (\text{Cu}+10\text{Mg}) \leq 5.8$;

up to 0.25 wt. % zinc;
up to 1.0 wt. % silver;
up to 1.0 wt. % nickel
up to 1.0 wt. % hafnium
up to 1.0 wt. % manganese
up to 1.0 wt. % iron;
up to 0.30 wt. % titanium;
up to 0.30 wt. % zirconium;
up to 0.30 wt. % vanadium;
up to 0.10 wt. % of one or more of strontium, sodium and antimony;
other elements being ≤ 0.04 wt. % each and ≤ 0.12 wt. % in total;

the balance being aluminum.

2. The aluminum casting alloy of Claim 1, wherein the aluminum casting alloy includes copper and magnesium such that $5.0 \leq (\text{Cu}+10\text{Mg}) \leq 5.5$,

3. The aluminum casting alloy of Claim 1, wherein the aluminum casting alloy includes copper and magnesium such that $5.1 \leq (\text{Cu}+10\text{Mg}) \leq 5.4$.

4. The aluminum casting alloy of Claim 1, wherein the alloy contains ≤ 0.01 wt. silver

5. The aluminum casting alloy of Claim 1, wherein the alloy contains 0.05 - 1.0 wt. % silver.

6. The casting alloy of Claim 1, wherein the alloy includes 0.1 - 0.12 wt. % titanium.

7. The casting alloy of Claim 6, wherein the alloy includes 0.12 - 0.14 wt. % vanadium
8. The casting alloy of Claim 7, wherein the alloy includes 0.08 - 0.19 wt. % zirconium.
9. The casting alloy of Claim 6, wherein the alloy includes 0.14 - 0.3 wt. % manganese, or wherein the alloy includes 0.14 - 0.3 wt. % manganese and 0.15 - 0.57 wt. % iron, or wherein the alloy includes 0.14 - 0.3 wt. % manganese, 0.15 - 0.57 wt. % iron and 0.1 - 0.12 wt. % vanadium, or wherein the alloy includes 0.14 - 0.3 wt. % manganese, 0.15 - 0.57 wt. % iron, 0.1 - 0.12 wt. % vanadium and 0.11 - 0.13 wt. % zirconium.
10. The casting alloy of Claim 6, wherein the alloy includes 0.27 - 0.3 wt. % nickel, or wherein the alloy includes 0.27 - 0.3 wt. % nickel and 0.15 - 0.33 wt. % iron, or wherein the alloy includes 0.27 - 0.3 wt. % nickel, 0.15 - 0.33 wt. % iron, 0.03 - 0.15 wt. % manganese, or wherein the alloy includes 0.27 - 0.3 wt. % nickel, 0.15 - 0.33 wt. % iron, 0.03 - 0.15 wt. % manganese and 0.05 - 0.2 wt. % hafnium, or wherein the alloy includes 0.27 - 0.3 wt. % nickel, 0.15 - 0.33 wt. % iron, 0.03 - 0.15 wt. % manganese and 0.1 - 0.12 wt. % vanadium, or wherein the alloy includes 0.27 - 0.3 wt. % nickel, 0.15 - 0.33 wt. % iron, 0.03 - 0.15 wt. % manganese, 0.1 - 0.12 wt. % vanadium and 0.012 - 0.04 wt. % zirconium.
11. The aluminum casting alloy of any one of Claims 1 to 10, wherein the alloy is subjected to solution heat treat at T_H followed by a cold water quench, where the preferred T_H ($^{\circ}\text{C}$) = $570 - 10.48 \cdot \text{Cu} - 71.6 \cdot \text{Mg} - 1.3319 \cdot \text{Cu} \cdot \text{Mg} - 0.72 \cdot \text{Cu} \cdot \text{Cu} + 72.95 \cdot \text{Mg} \cdot \text{Mg}$, based on Mg and Cu content in wt%, within the range defined bar a lower limit for T_H : $T_Q = 533.6 - 20.98 \cdot \text{Cu} + 88.037 \cdot \text{Mg} + 33.43 \cdot \text{Cu} \cdot \text{Mg} - 0.7763 \cdot \text{Cu} \cdot \text{Cu} - 126.267 \cdot \text{Mg} \cdot \text{Mg}$ and an upper limit for T_H : $T_S = 579.2 - 10.48 \cdot \text{Cu} - 71.6 \cdot \text{Mg} - 1.3319 \cdot \text{Cu} \cdot \text{Mg} - 0.72 \cdot \text{Cu} \cdot \text{Cu} + 72.95 \cdot \text{Mg} \cdot \text{Mg}$.

Patentansprüche

1. Eine Aluminiumgusslegierung bestehend aus:

8,5-9,5 Gew. % Silizium;
0,5-2,0 Gew. % Kupfer (Cu);
wobei die Legierung

- i. 1,35-2,0 Gew. % Kupfer und 0,27-0,445 Gew. % Magnesium, oder
- ii. 0,5-0,75 Gew. % Kupfer und 0,395-0,53 Gew. % Magnesium, oder
- iii. 0,75-1,35 Gew. % Kupfer und 0,335-0,505 Gew. % Magnesium enthält;

0,27-0,53 Gew. % Magnesium (Mg);

wobei die Aluminiumgusslegierung Kupfer und Magnesium derart enthält, dass $4,7 \leq (\text{Cu} + 10 \text{ Mg}) \leq 5,8$;

bis zu 0,25 Gew. % Zink;
bis zu 1,0 Gew. % Silber;
bis zu 1,0 Gew. % Nickel;
bis zu 1,0 Gew. % Hafnium;
bis zu 1,0 Gew. % Mangan;
Bis zu 1,0 Gew. % Eisen;
bis zu 0,3 Gew. % Titan;
bis zu 0,3 Gew. % Zirkonium;
bis zu 0,3 Gew. % Vanadium;
bis zu 0,1 Gew. % eines oder mehrerer von Strontium, Natrium und Antimon;
andere Elemente jeweils $\leq 0,04$ Gew. % und in Summe $\leq 0,12$ Gew. %;

der Rest Aluminium.

2. Die Aluminiumgusslegierung nach Anspruch 1, wobei die Aluminiumgusslegierung Kupfer und Magnesium derart enthält, dass $5,0 \leq (\text{Cu} + 10 \text{ Mg}) \leq 5,5$.
3. Die Aluminiumgusslegierung nach Anspruch 1, wobei die Aluminiumgusslegierung Kupfer und Magnesium derart

enthält, dass $5,1 \leq (\text{Cu} + 10 \text{ Mg}) \leq 5,4$.

4. Die Aluminiumgusslegierung nach Anspruch 1, wobei die Legierung $\leq 0,01$ Gew. % Silber enthält.
5. Die Aluminiumgusslegierung nach Anspruch 1, wobei die Legierung 0,05-1,0 Gew. % Silber enthält.
6. Die Aluminiumgusslegierung nach Anspruch 1, wobei die Legierung 0,1-0,12 Gew. % Titan enthält.
7. Die Gusslegierung nach Anspruch 6, wobei die Legierung 0,12-0,14 Gew. % Vanadium enthält.
8. Die Gusslegierung nach Anspruch 7, wobei die Legierung 0,08-0,19 Gew. % Zirkonium enthält.
9. Die Gusslegierung nach Anspruch 6, wobei die Legierung 0,14-0,3 Gew. % Mangan enthält, oder wobei die Legierung 0,14-0,3 Gew. % Mangan und 0,15-0,57 Gew. % Eisen enthält, oder wobei die Legierung 0,14-0,3 Gew. % Mangan, 0,15-0,57 Gew. % Eisen und 0,1-0,12 Gew. % Vanadium enthält, oder wobei die Legierung 0,14-0,3 Gew. % Mangan, 0,15-0,57 Gew. % Eisen, 0,1-0,12 Gew. % Vanadium und 0,11-0,13 Gew. % Zirkonium enthält.
10. Die Gusslegierung nach Anspruch 6, wobei die Legierung 0,27-0,3 Gew. % Nickel enthält, oder wobei die Legierung 0,27-0,3 Gew. % Nickel und 0,15-0,33 Gew. % Eisen enthält, oder wobei die Legierung 0,27-0,3 Gew. % Nickel, 0,15-0,33 Gew. % Eisen und 0,03-0,15 Gew. % Mangan enthält, oder wobei die Legierung 0,27-0,3 Gew. % Nickel, 0,15-0,33 Gew. % Eisen, 0,03-0,15 Gew. % Mangan und 0,05-0,2 Gew. % Hafnium enthält, oder wobei die Legierung 0,27-0,3 Gew. % Nickel, 0,15-0,33 Gew. % Eisen, 0,03-0,15 Gew. % Mangan und 0,1-0,12 Gew. % Vanadium enthält, oder wobei die Legierung 0,27-0,3 Gew. % Nickel, 0,15-0,33 Gew. % Eisen, 0,03-0,15 Gew. % Mangan, 0,1-0,12 Gew. % Vanadium und 0,012-0,04 Gew. % Zirkonium enthält.
11. Die Aluminiumgusslegierung nach einem der Ansprüche 1 bis 10, wobei die Legierung einer Lösungsglühbehandlung bei T_H gefolgt von einem Abschrecken mit kaltem Wasser unterzogen wird, wobei bevorzugt T_H ($^{\circ}\text{C}$) = $570 - 10,48 * \text{Cu} - 71,6 * \text{Mg} - 1,3319 * \text{Cu} * \text{Mg} - 0,72 * \text{Cu} * \text{Cu} + 72,95 * \text{Mg} * \text{Mg}$, basierend auf einem Mg und Cu Gehalt in Gew. %, innerhalb eines Bereichs, der definiert ist durch eine Untergrenze für T_H : $T_Q = 533,6 - 20,98 * \text{Cu} + 88,037 * \text{Mg} + 33,43 * \text{Cu} * \text{Mg} - 0,7763 * \text{Cu} * \text{Cu} - 126,267 * \text{Mg} * \text{Mg}$ und einer Obergrenze für T_H : $T_S = 579,2 - 10,48 * \text{Cu} - 71,6 * \text{Mg} - 1,3319 * \text{Cu} * \text{Mg} - 0,72 * \text{Cu} * \text{Cu} + 72,95 * \text{Mg} * \text{Mg}$, ist.

Revendications

1. Alliage de fonderie d'aluminium constitué de :

8,5 à 9,5 % en poids de silicium ;
 0,5 à 2,0 % en poids de cuivre (Cu) ;
 l'alliage comprenant :

- i. de 1,35 à 2,0 % en poids de cuivre et de 0,27 à 0,445 % en poids de magnésium, ou
- ii. de 0,5 à 0,75 % en poids de cuivre et de 0,395 à 0,53 % en poids de magnésium, ou
- iii. de 0,75 à 1,35 % en poids de cuivre et de 0,335 à 0,505 % en poids de magnésium ;

0,27 à 0,53 % en poids de magnésium (Mg) ;
 l'alliage de fonderie d'aluminium comprenant du cuivre et du magnésium de sorte que $4,7 \leq (\text{Cu} + 10 \text{ Mg}) \leq 5,8$;
 jusqu'à 0,25 % en poids de zinc ;
 jusqu'à 1,0 % en poids d'argent ;
 jusqu'à 1,0 % en poids de nickel ;
 jusqu'à 1,0 % en poids de hafnium ;
 jusqu'à 1,0 % en poids de manganèse ;
 jusqu'à 1,0 % en poids de fer ;
 jusqu'à 0,30 % en poids de titane ;
 jusqu'à 0,30 % en poids de zirconium ;
 jusqu'à 0,30 % en poids de vanadium ;
 jusqu'à 0,10 % en poids d'un ou plusieurs parmi le strontium, le sodium et l'antimoine ;
 les autres éléments étant $\leq 0,04$ % en poids chacun et $\leq 0,12$ % en poids au total ;

le reste étant de l'aluminium.

2. Alliage de fonderie d'aluminium selon la revendication 1, dans lequel l'alliage de fonderie d'aluminium comprend du cuivre et du magnésium tel que $5,0 \leq (\text{Cu}+10\text{Mg}) \leq 5,5$.
3. Alliage de fonderie d'aluminium selon la revendication 1, dans lequel l'alliage de fonderie d'aluminium comprend du cuivre et du magnésium tel que $5,1 \leq (\text{Cu}+10\text{Mg}) \leq 5,4$.
4. Alliage de fonderie d'aluminium selon la revendication 1, dans lequel l'alliage contient $\leq 0,01$ % en poids d'argent.
5. Alliage de fonderie d'aluminium selon la revendication 1, dans lequel l'alliage contient de 0,05 à 1,0 % en poids d'argent.
6. Alliage de fonderie d'aluminium selon la revendication 1, dans lequel l'alliage contient de 0,1 à 0,12 % en poids de titane.
7. Alliage de fonderie d'aluminium selon la revendication 6, dans lequel l'alliage contient de 0,12 à 0,14 % en poids de vanadium.
8. Alliage de fonderie d'aluminium selon la revendication 7, dans lequel l'alliage contient de 0,08 à 0,19 % en poids de zirconium.
9. Alliage de fonderie d'aluminium selon la revendication 6, dans lequel l'alliage contient de 0,14 à 0,3 % en poids de manganèse, ou dans lequel l'alliage comprend de 0,14 à 0,3 % en poids de manganèse et de 0,15 à 0,57 % en poids de fer, ou dans lequel l'alliage comprend de 0,14 à 0,3 % en poids de manganèse, de 0,15 à 0,57 % en poids de fer et de 0,1 à 0,12 % en poids de vanadium, ou dans lequel l'alliage comprend de 0,14 à 0,3 % en poids de manganèse, de 0,15 à 0,57 % en poids de fer, de 0,1 à 0,12 % en poids de vanadium et de 0,11 à 0,13 % en poids de zirconium.
10. Alliage de fonderie d'aluminium selon la revendication 6, dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel, ou dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel et de 0,15 à 0,33 % en poids de fer, ou dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel, de 0,15 à 0,33 % en poids de fer et de 0,03 à 0,15 % en poids de manganèse, ou dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel, de 0,15 à 0,33 % en poids de fer, de 0,03 à 0,15 % en poids de manganèse et de 0,05 à 0,2 % en poids de hafnium, ou dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel, de 0,15 à 0,33 % en poids de fer, de 0,03 à 0,15 % en poids de manganèse et de 0,1 à 0,12 % en poids de vanadium, ou dans lequel l'alliage contient de 0,27 à 0,3 % en poids de nickel, de 0,15 à 0,33 % en poids de fer, de 0,03 à 0,15 % en poids de manganèse, de 0,1 à 0,12 % en poids de vanadium et de 0,012 à 0,04 % en poids de zirconium.
11. Alliage de fonderie d'aluminium selon l'une quelconque des revendications 1 à 10, dans lequel l'alliage est soumis à un traitement thermique en solution à T_H suivi par une trempe dans de l'eau froide, où la T_H préférée ($^{\circ}\text{C}$) = $570-10,48*\text{Cu}-71,6*\text{Mg}-1,3319*\text{Cu}*\text{Mg}-0,72*\text{Cu}*\text{Cu}+72,95*\text{Mg}*\text{Mg}$, par rapport à la teneur en Mg et Cu en % en poids, dans la plage définie par une limite inférieure pour T_H : $T_Q = 533,6-20,98*\text{Cu}+88,037*\text{Mg}+33,43*\text{Cu}*\text{Mg}-0,7763*\text{Cu}*\text{Cu}-126,267*\text{Mg}*\text{Mg}$ et une limite supérieure pour T_H : $T_S = 579,2-10,48*\text{Cu}-71,6*\text{Mg}-1,3319*\text{Cu}*\text{Mg}-0,72*\text{Cu}*\text{Cu}+72,95*\text{Mg}*\text{Mg}$.

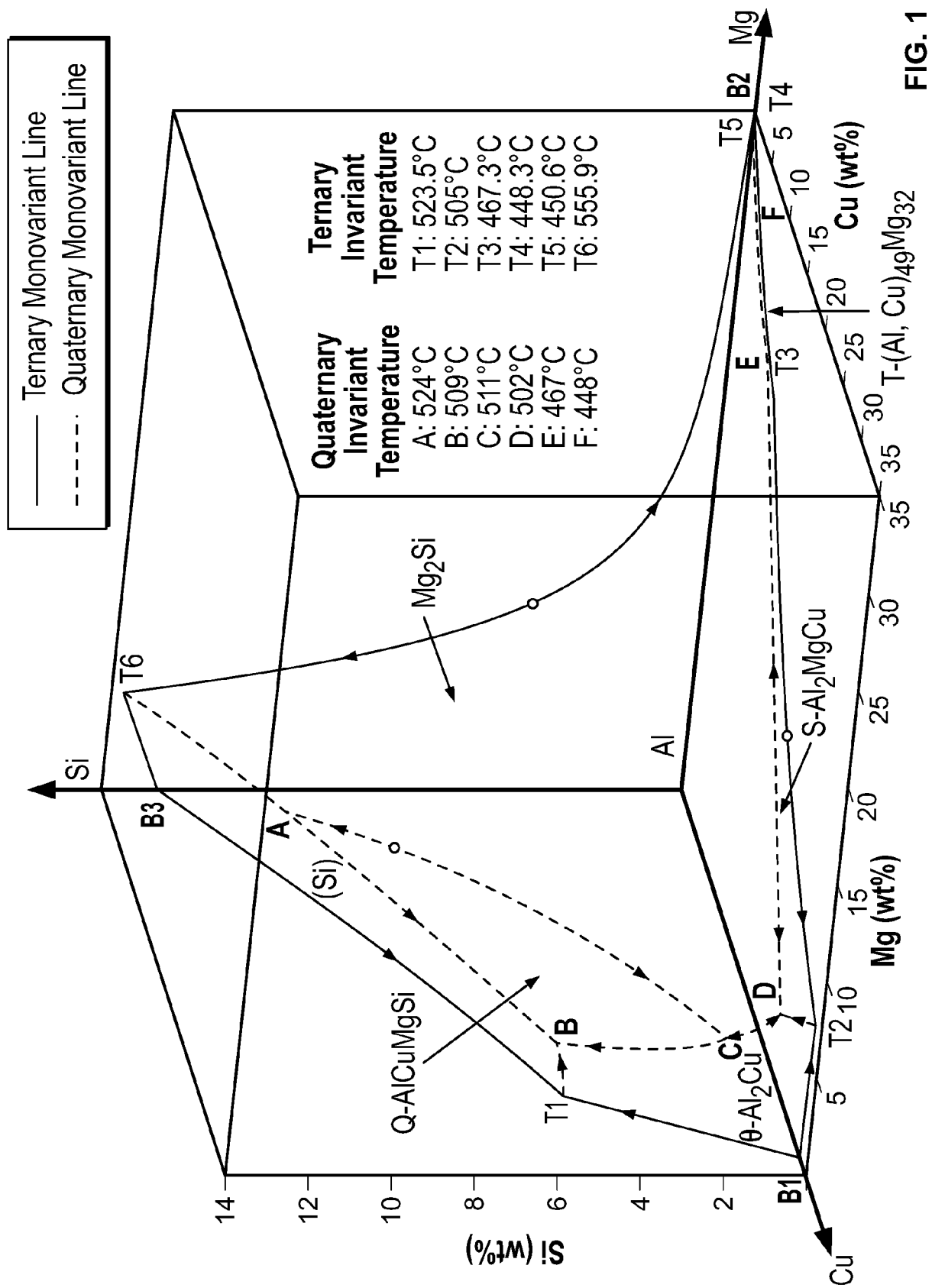


FIG. 1

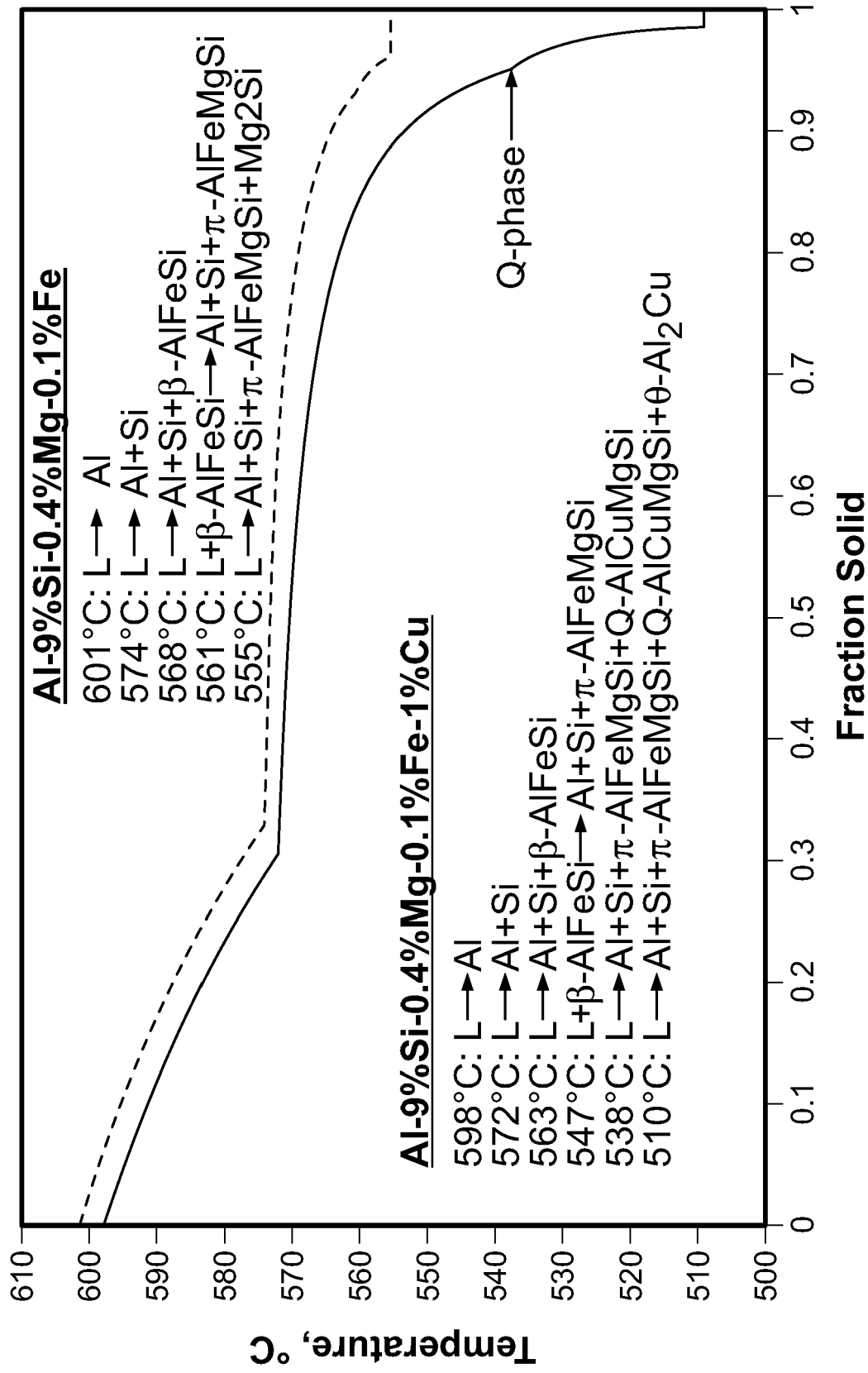


FIG. 2

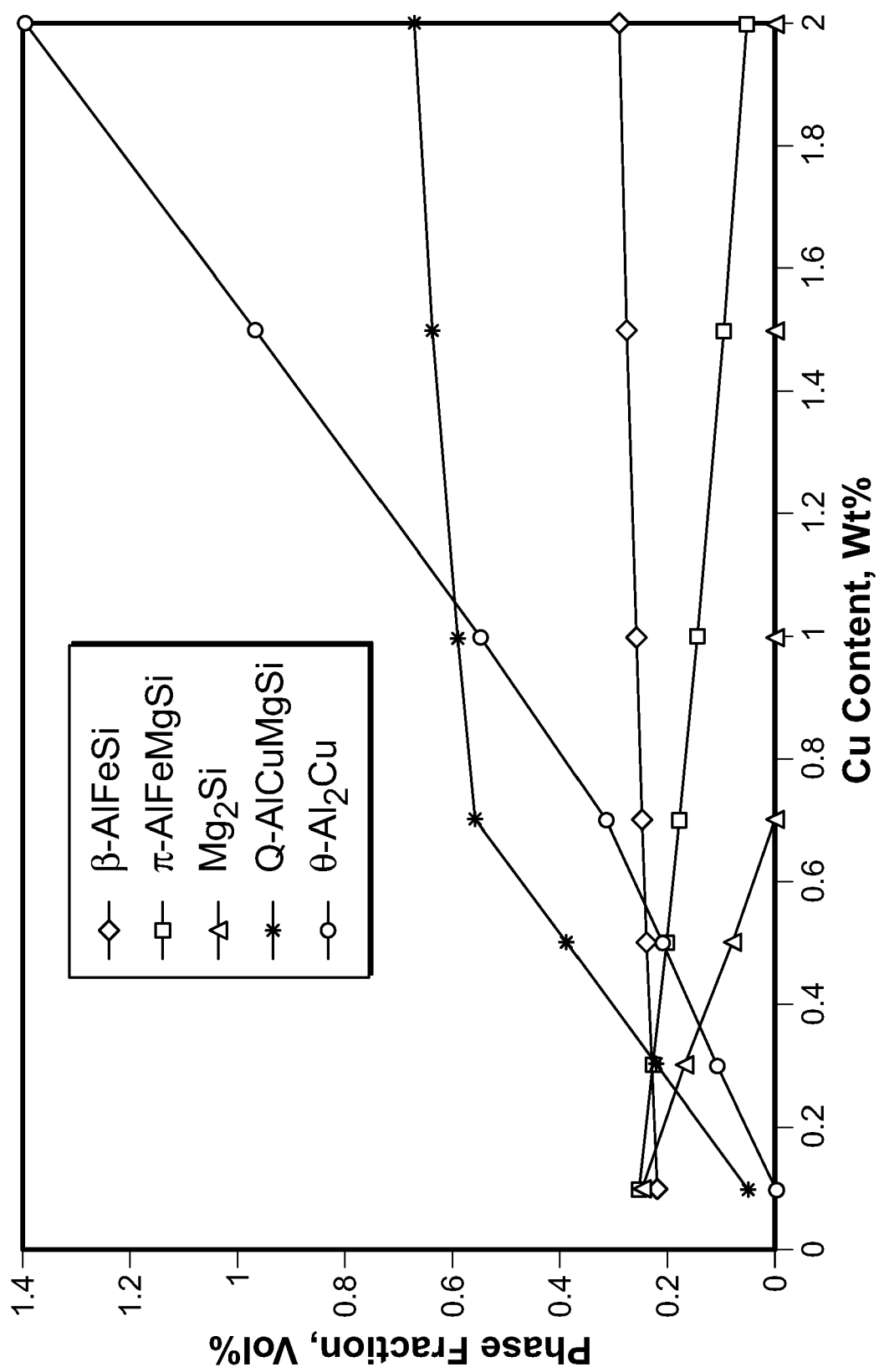


FIG. 3

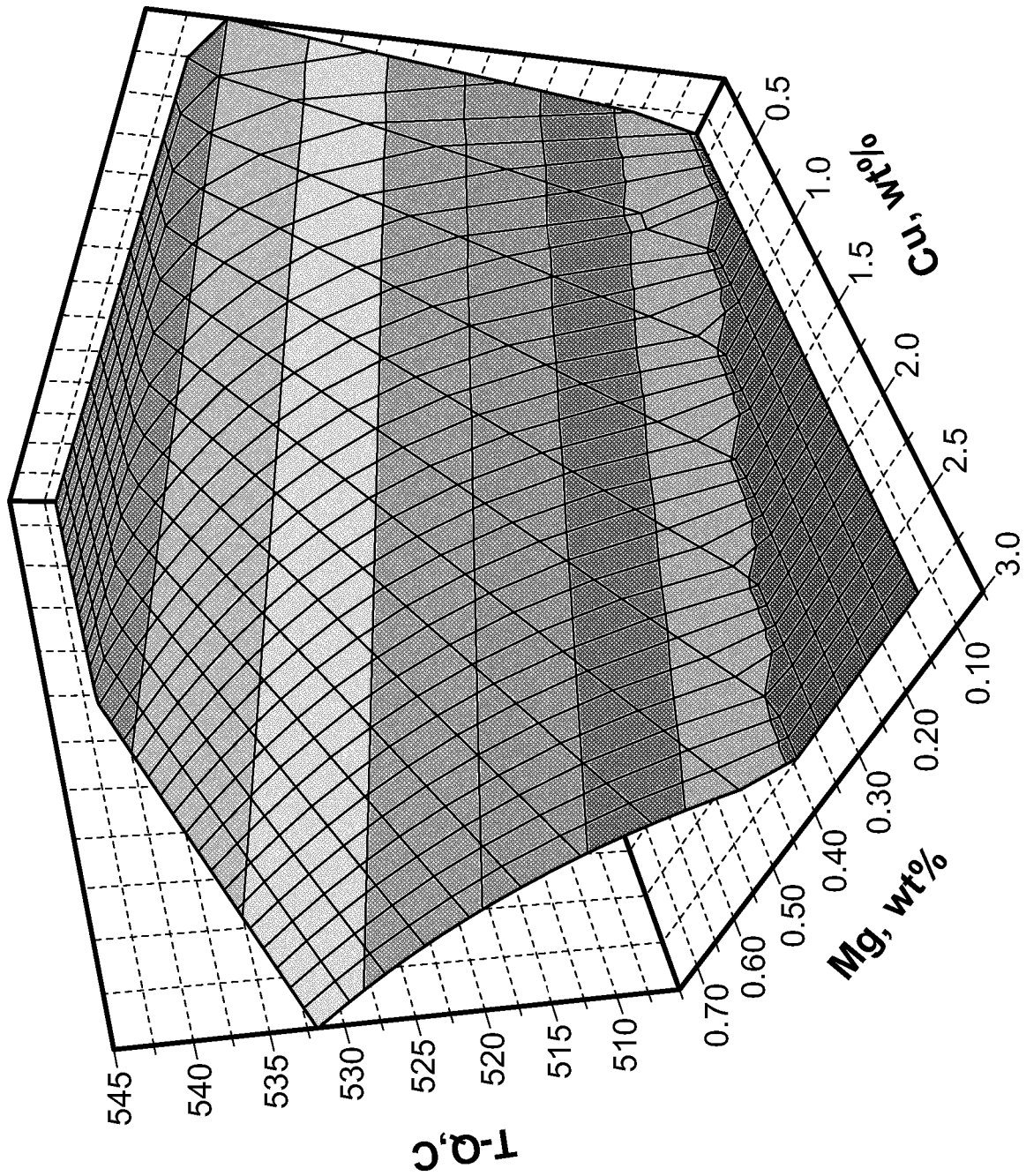


FIG. 4

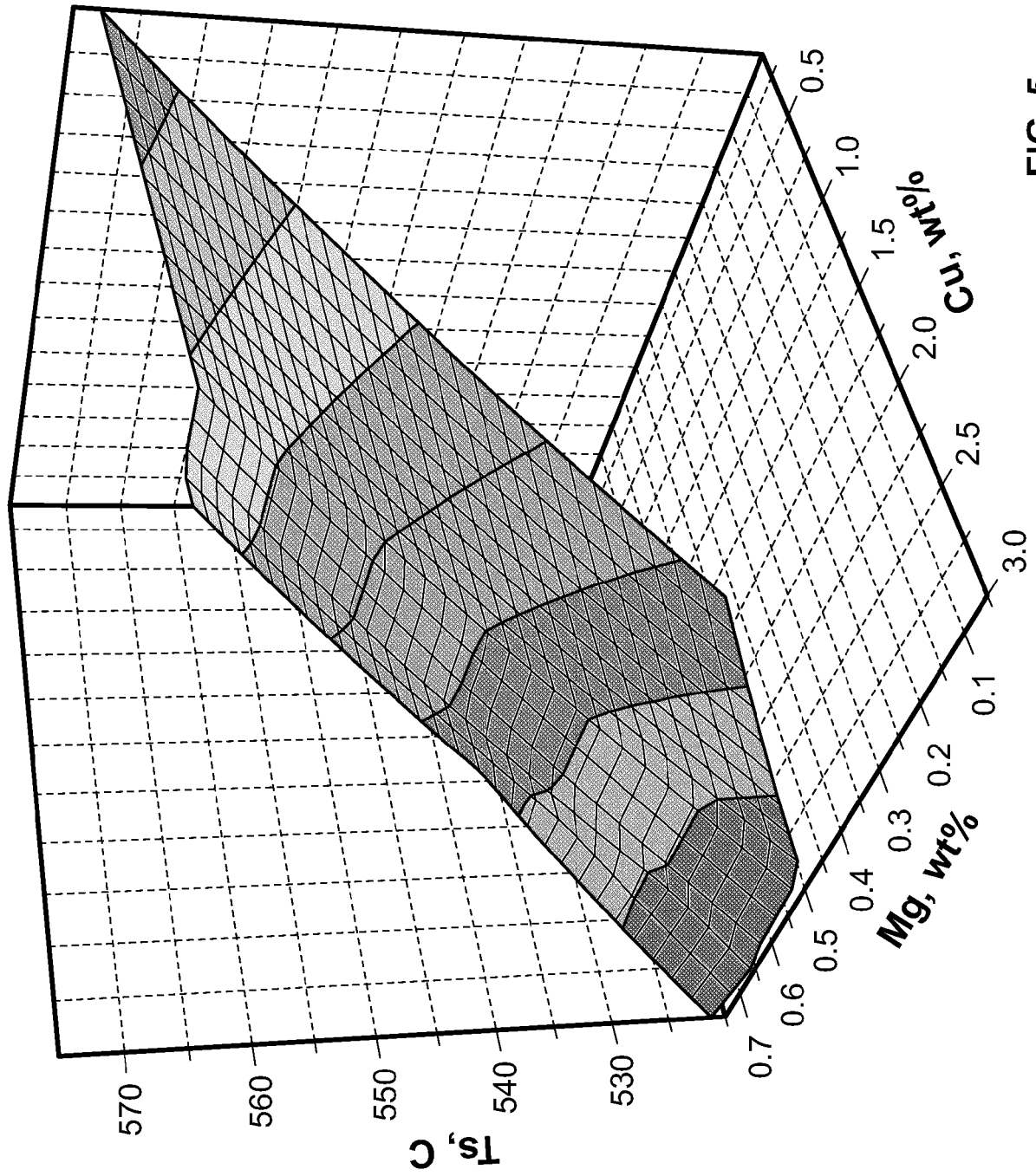


FIG. 5

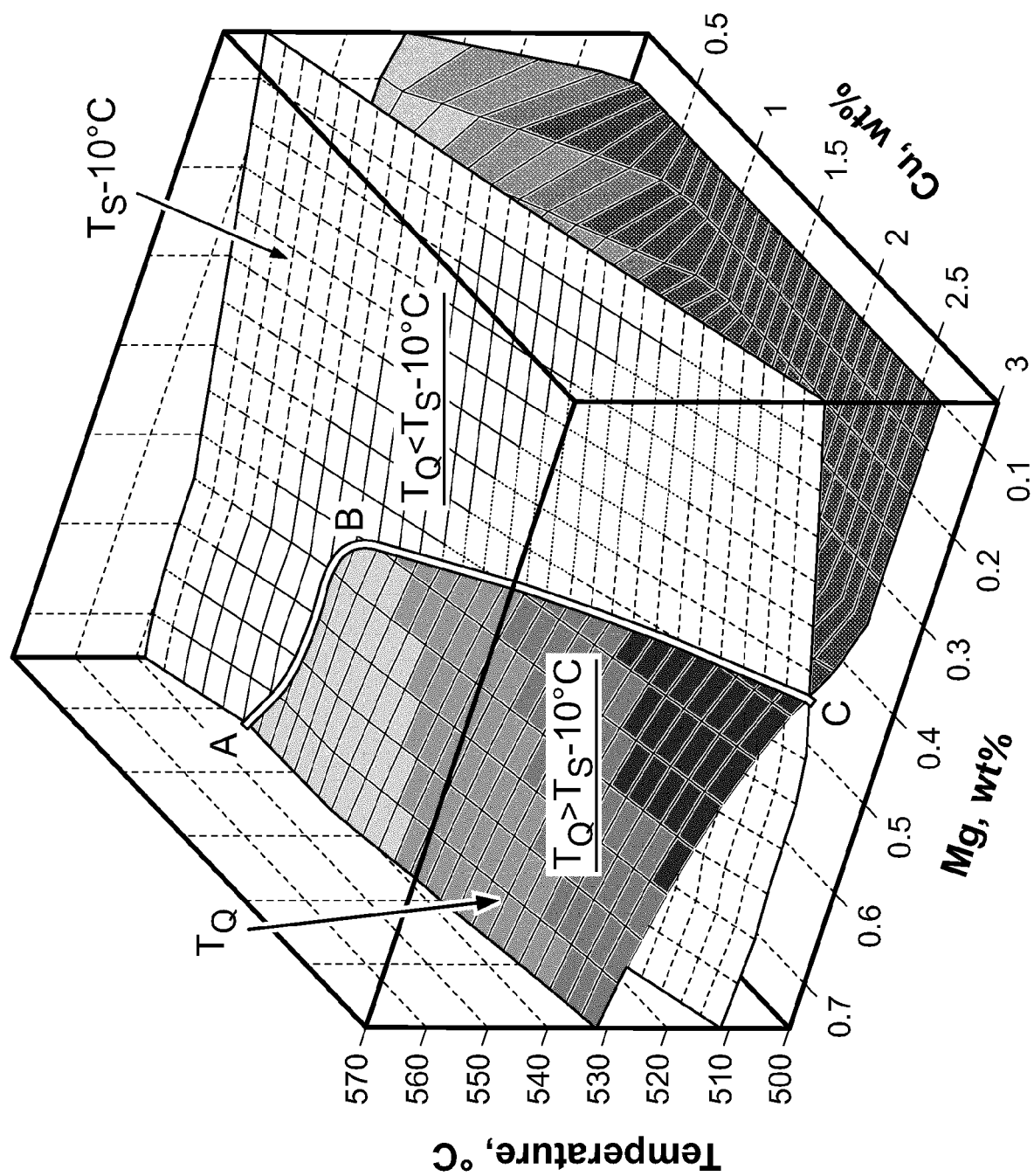


FIG. 6

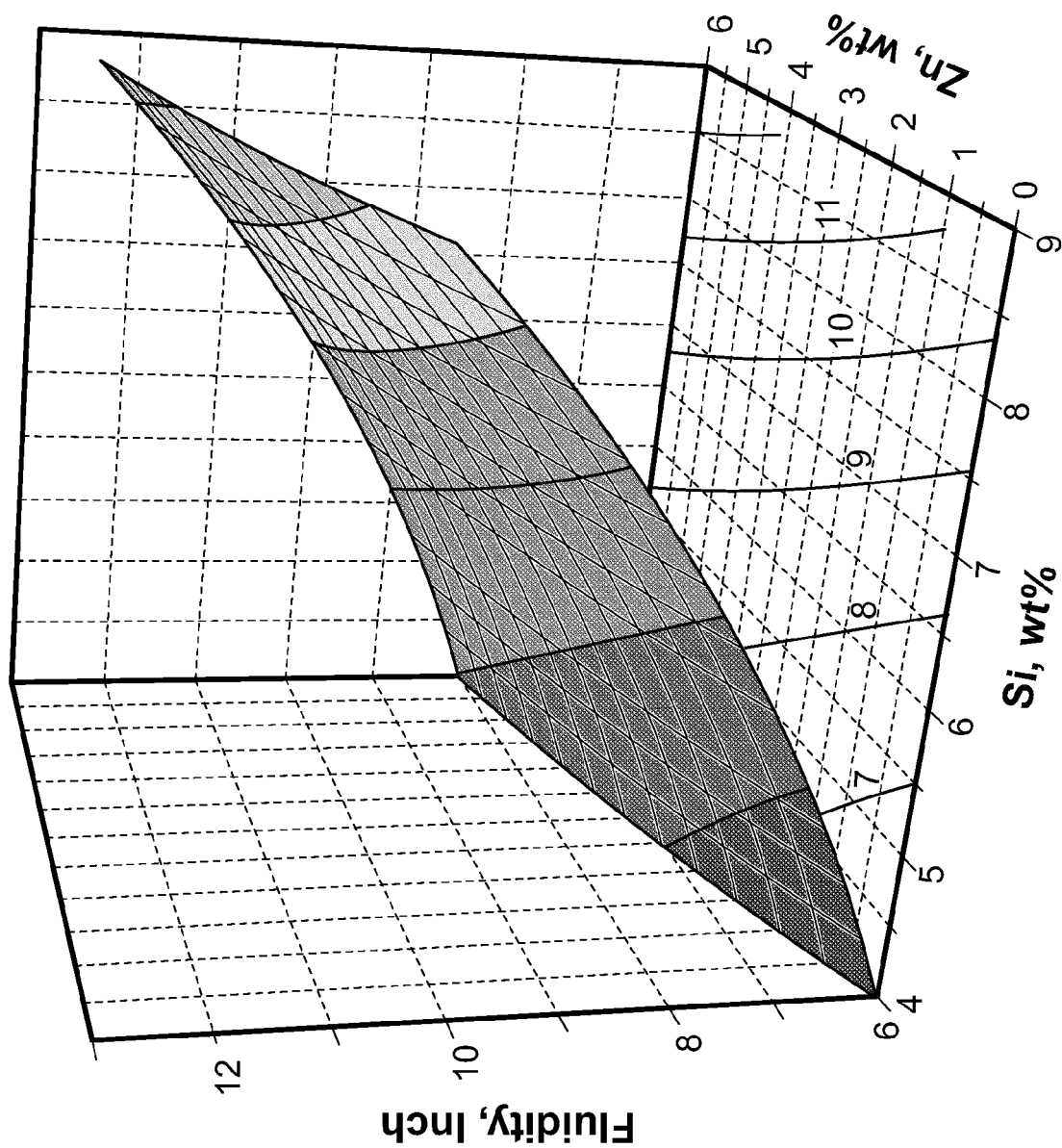


FIG. 7

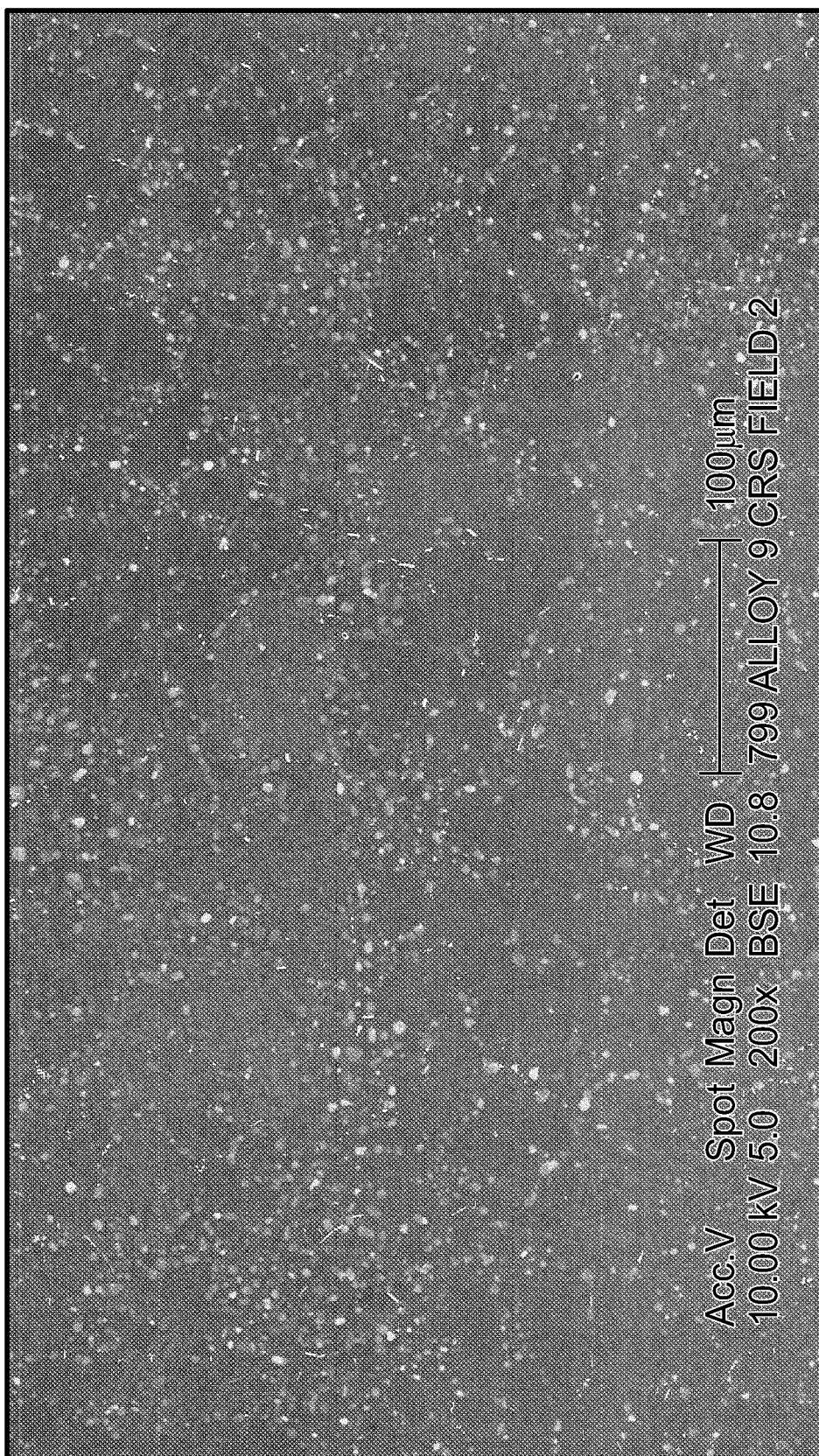


FIG. 8

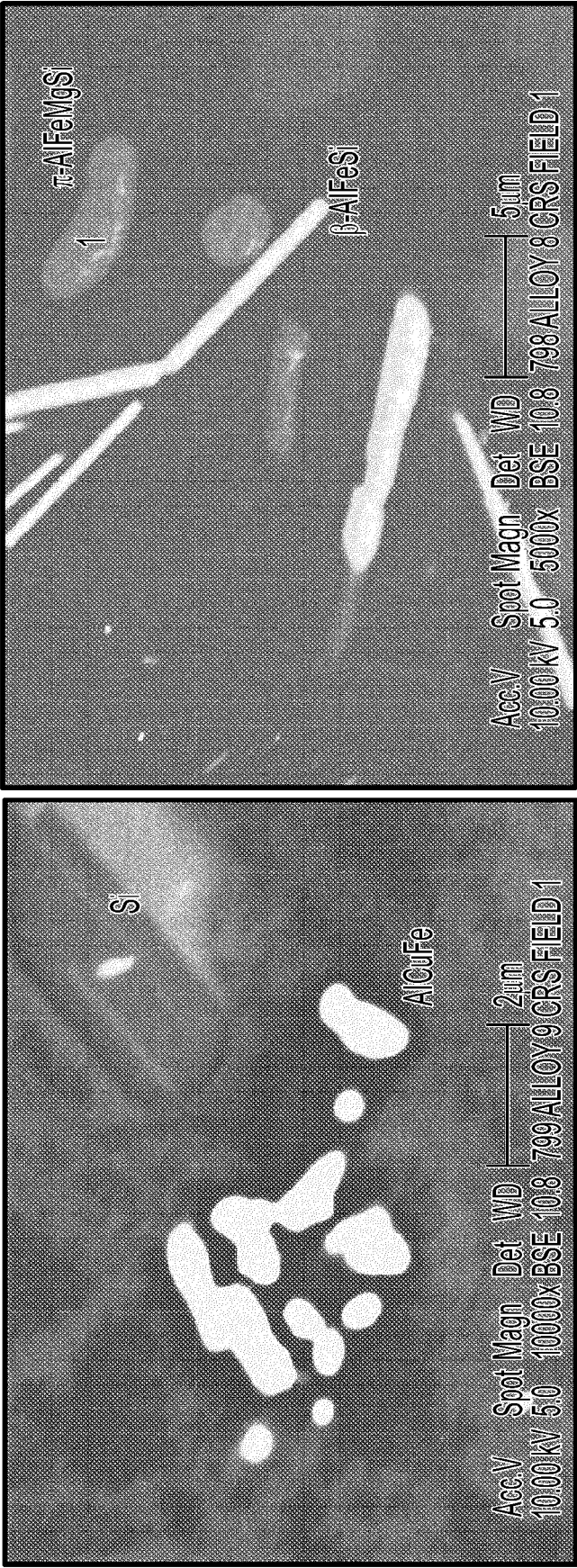


FIG. 9

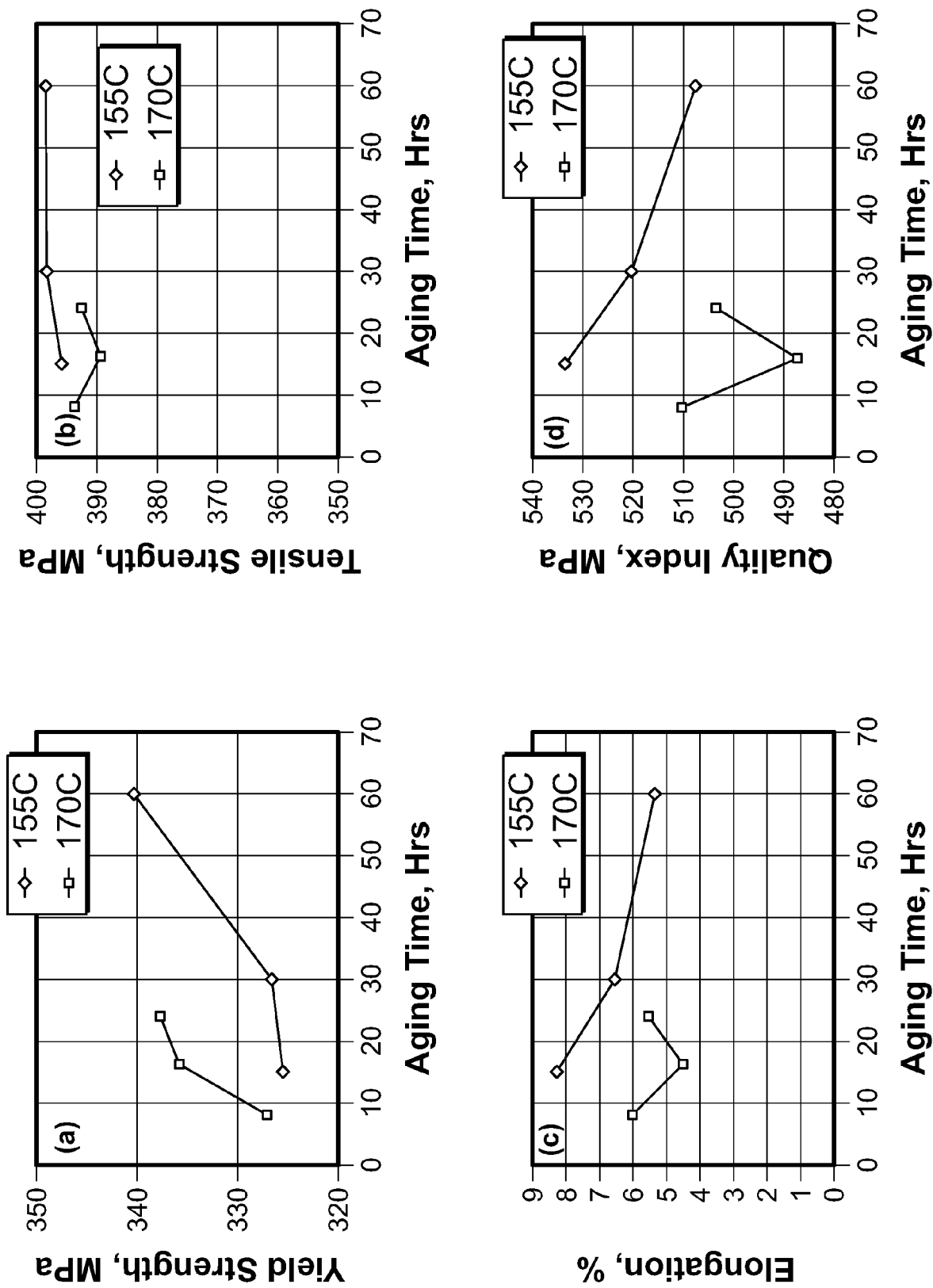


FIG. 10

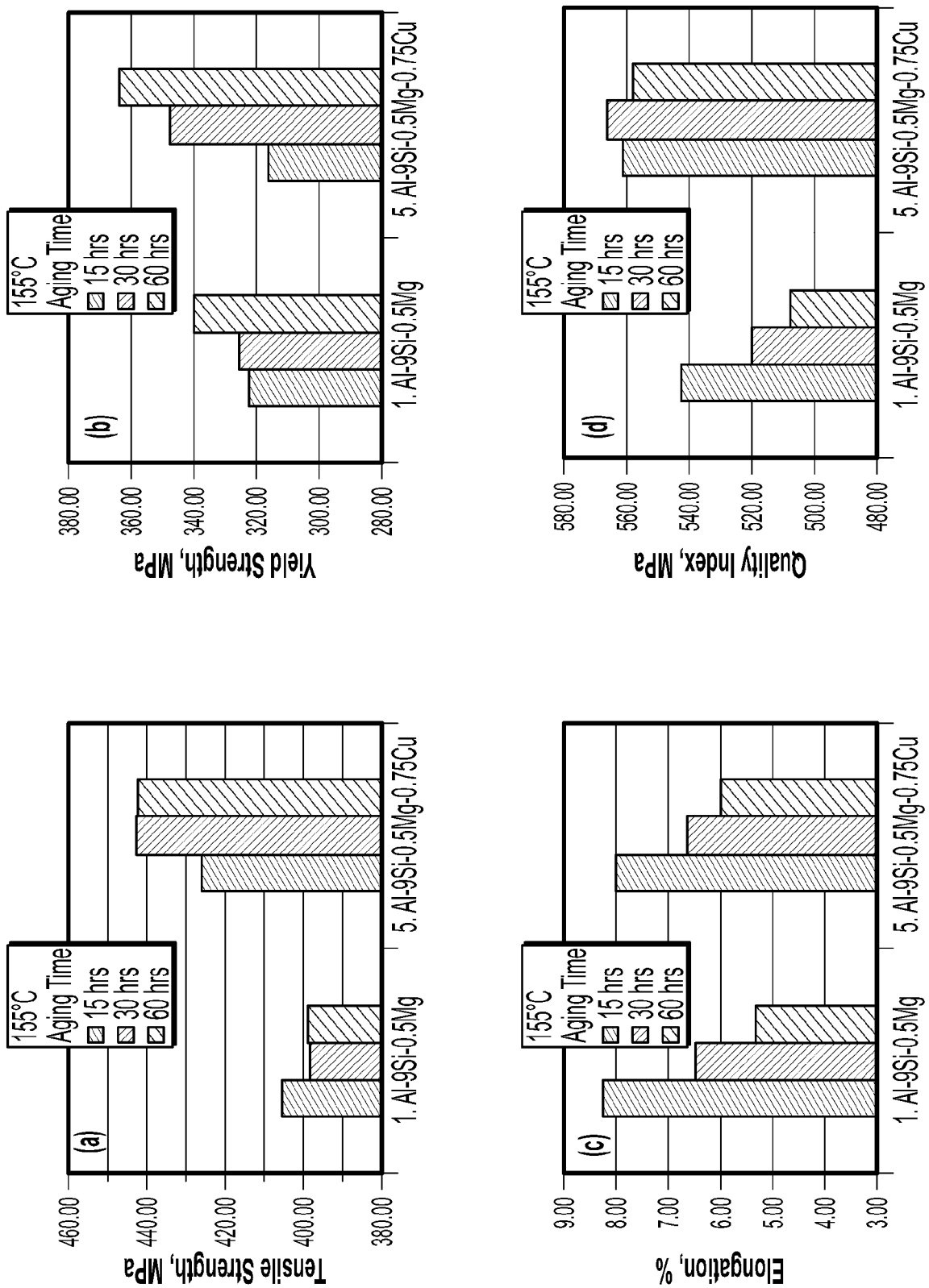


FIG. 11

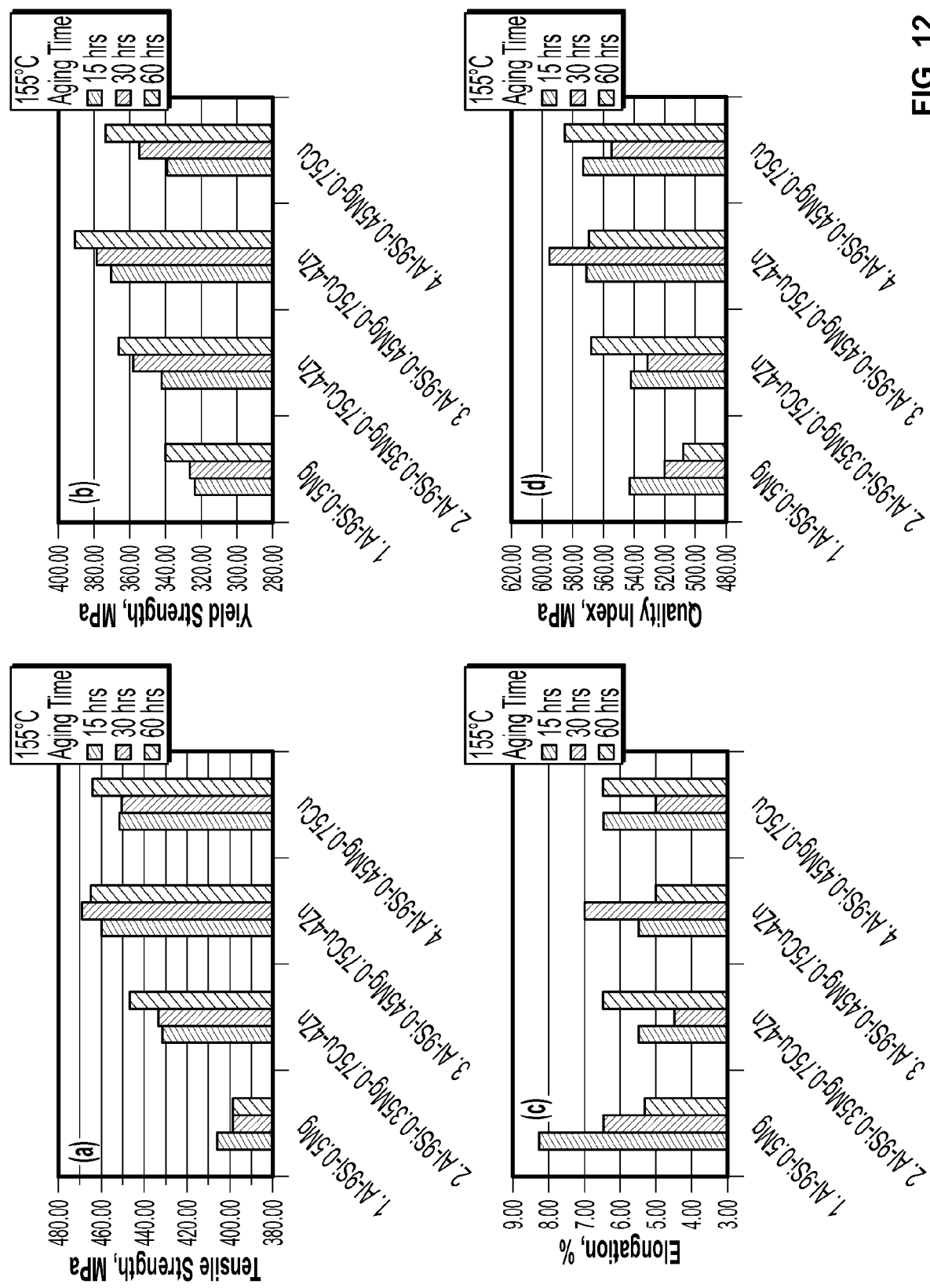


FIG. 12

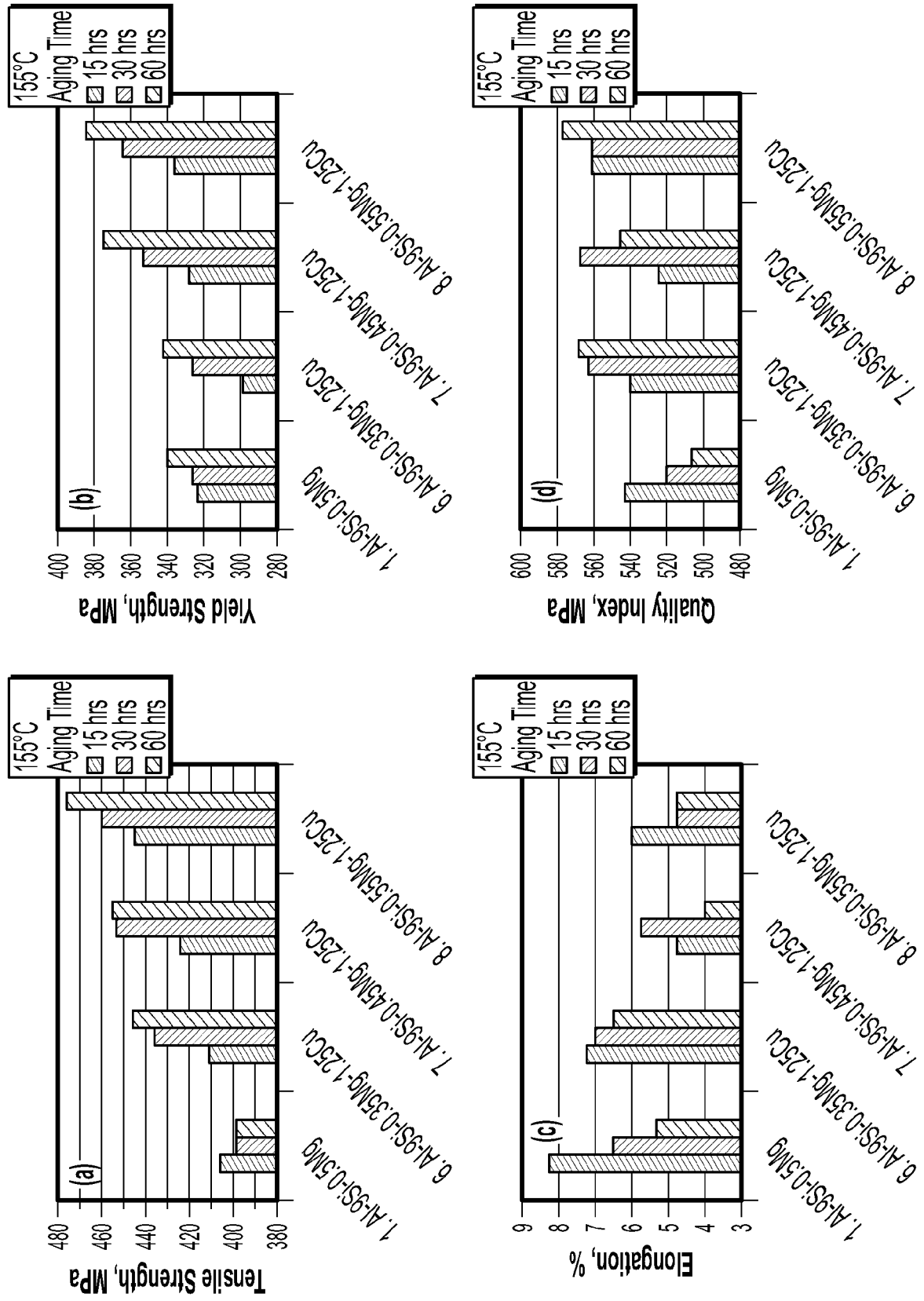
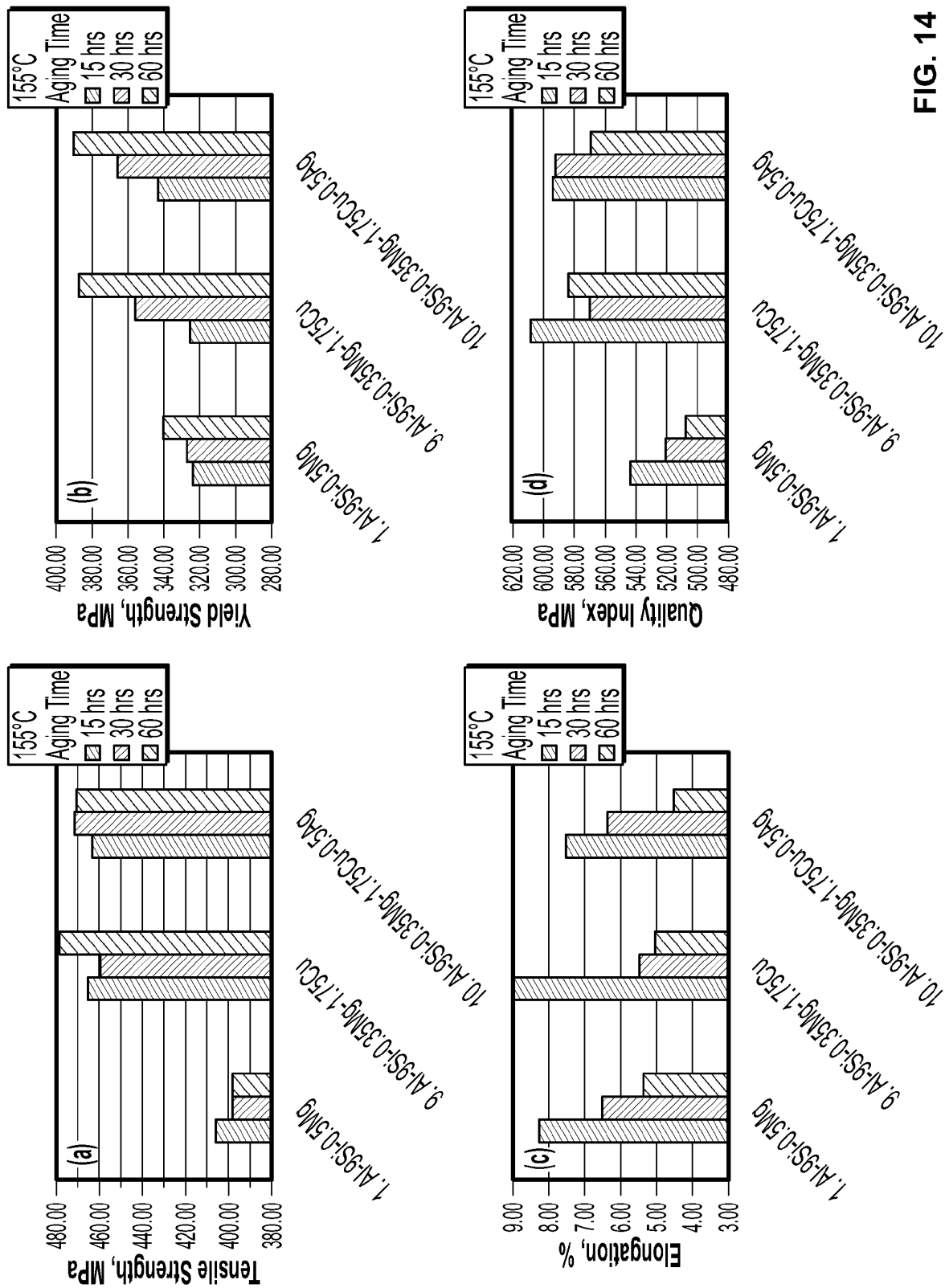
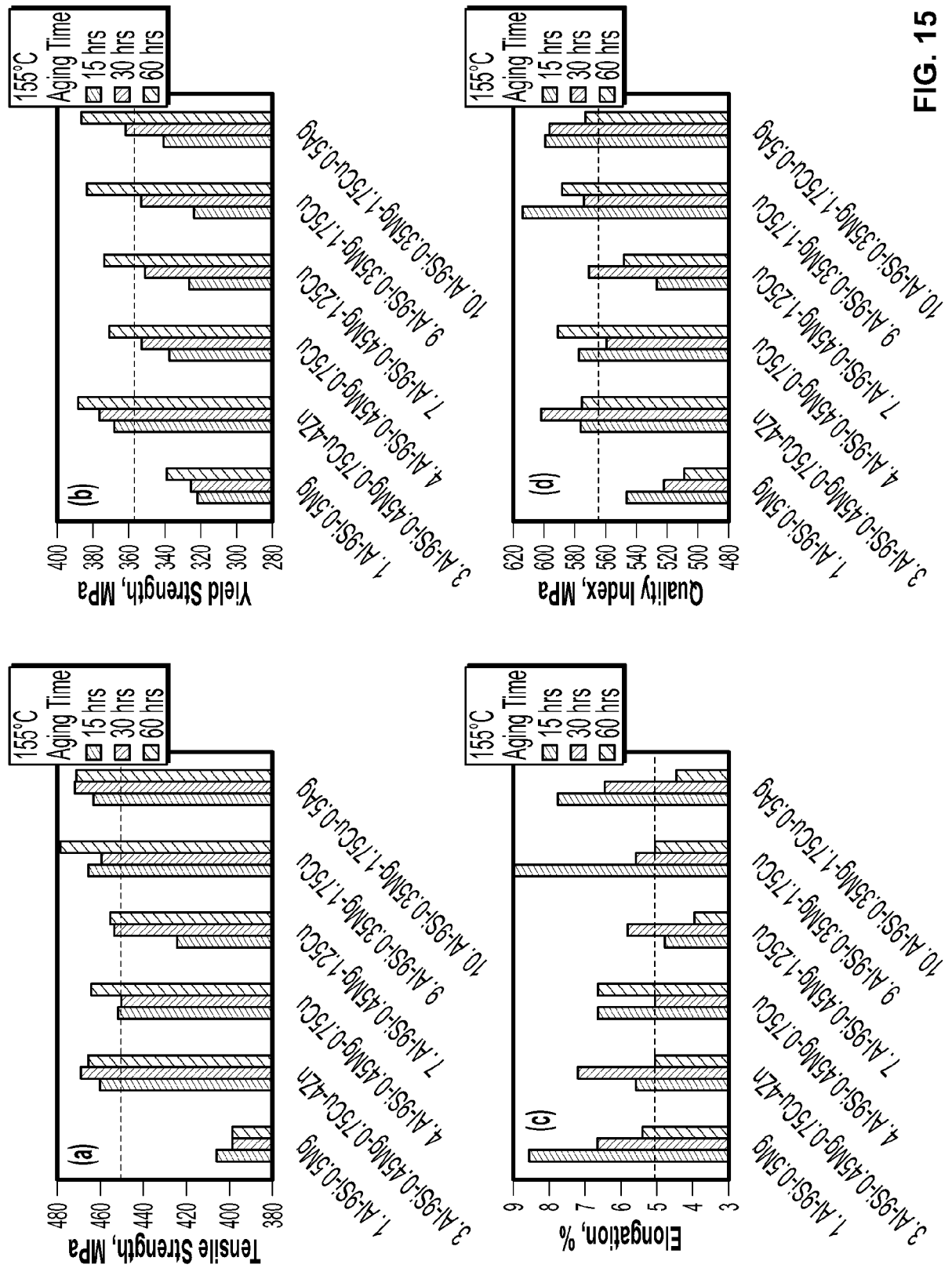


FIG. 13





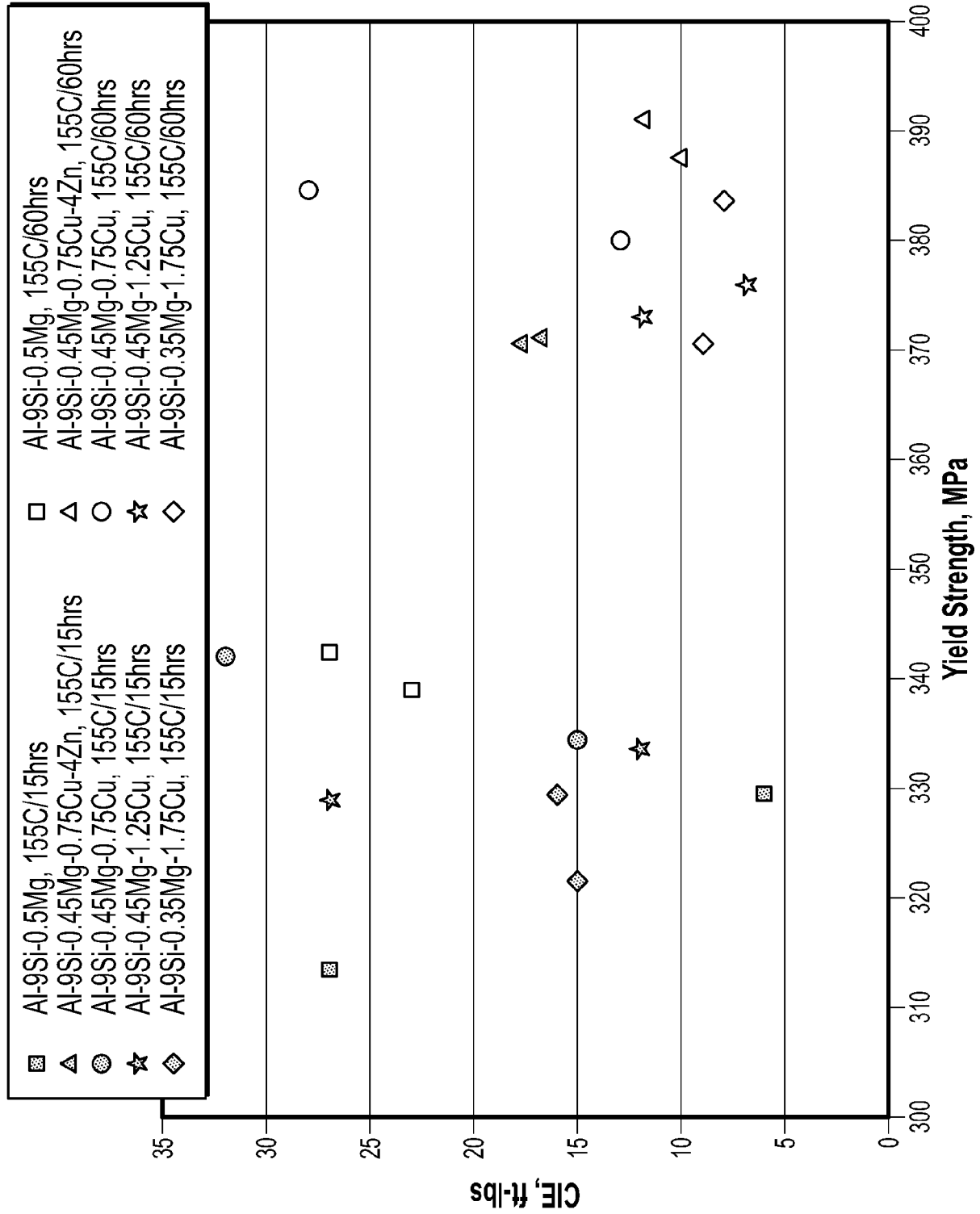


FIG. 16

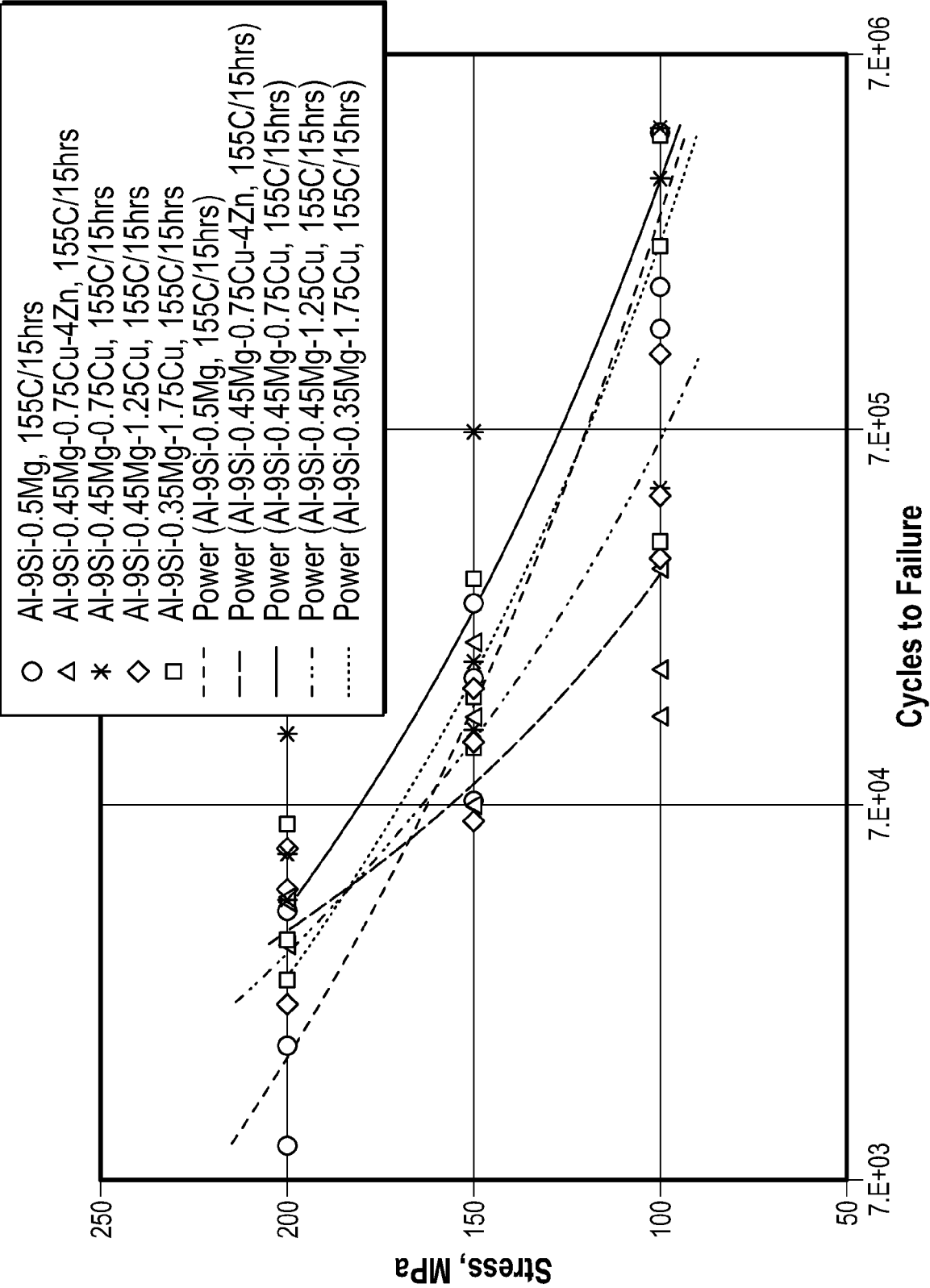
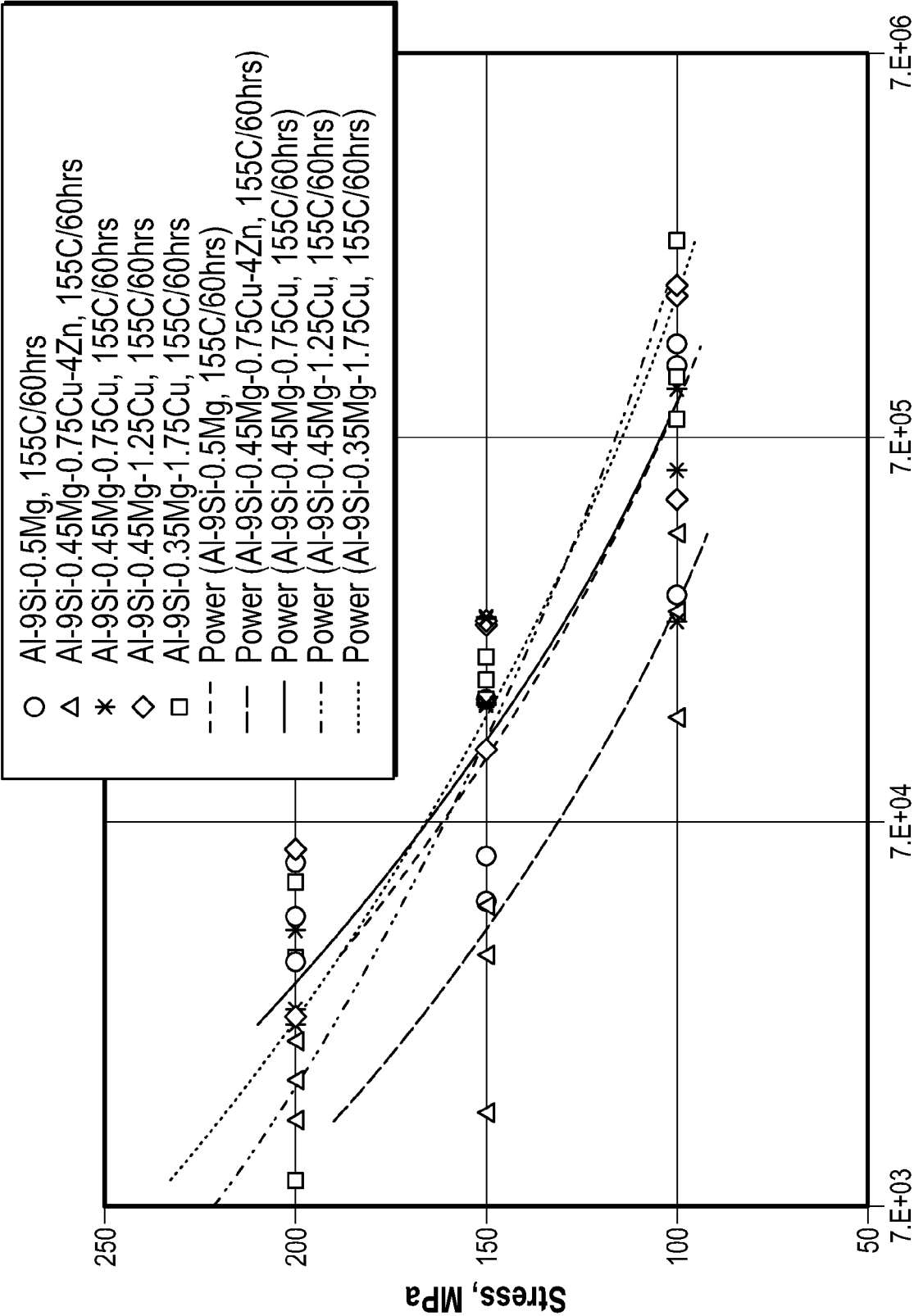


FIG. 17



Cycles to Failure
FIG. 18

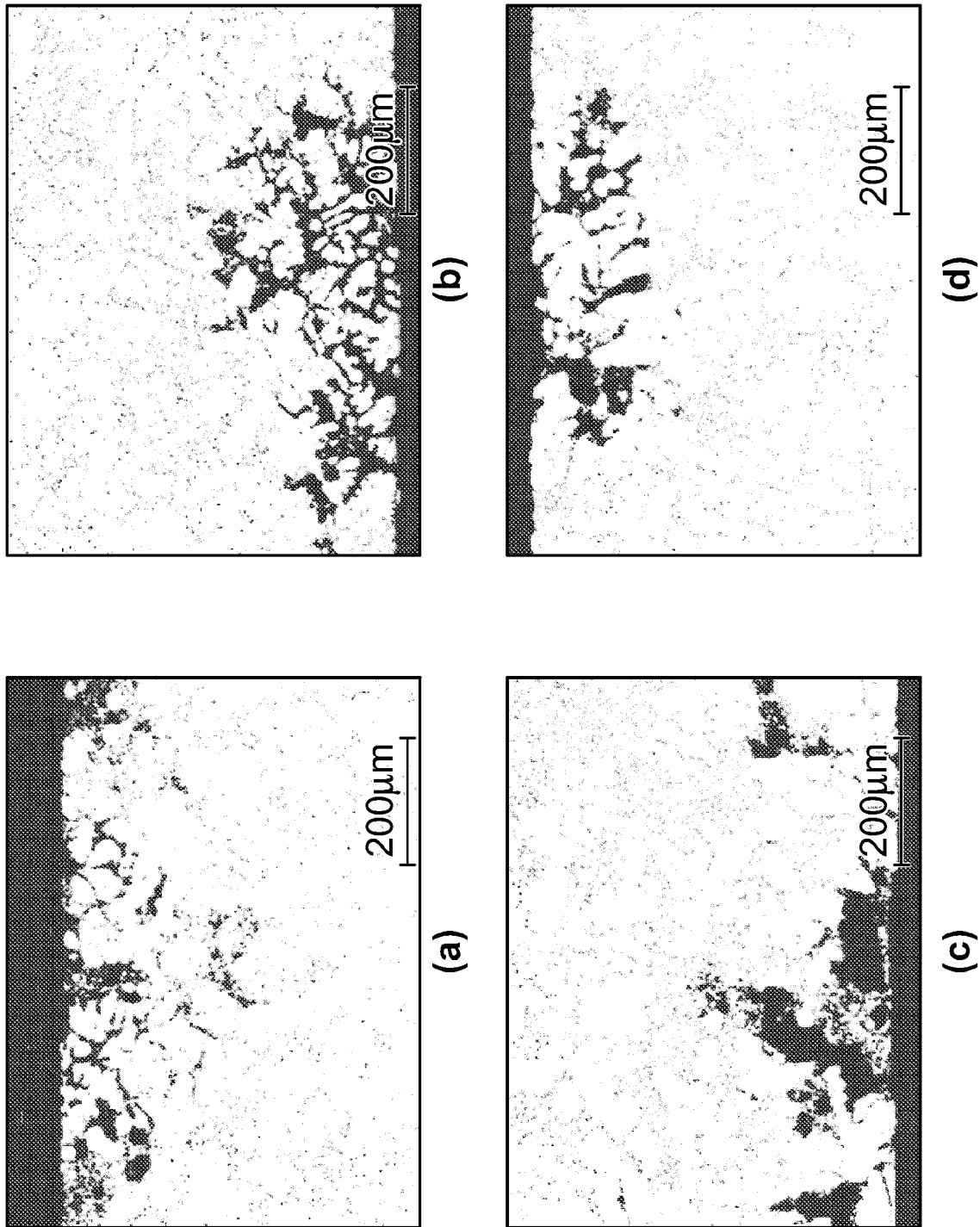


FIG. 19

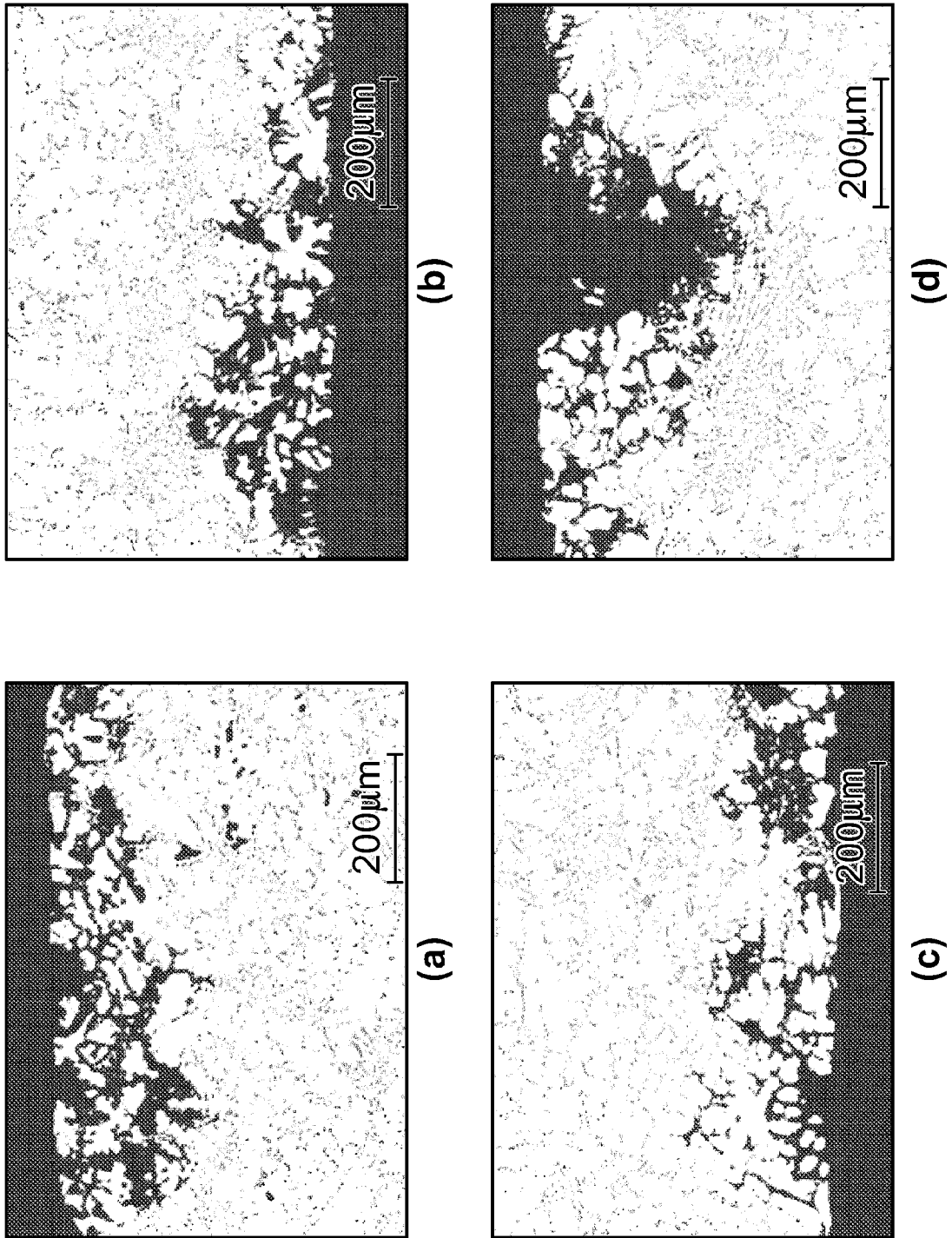


FIG. 20

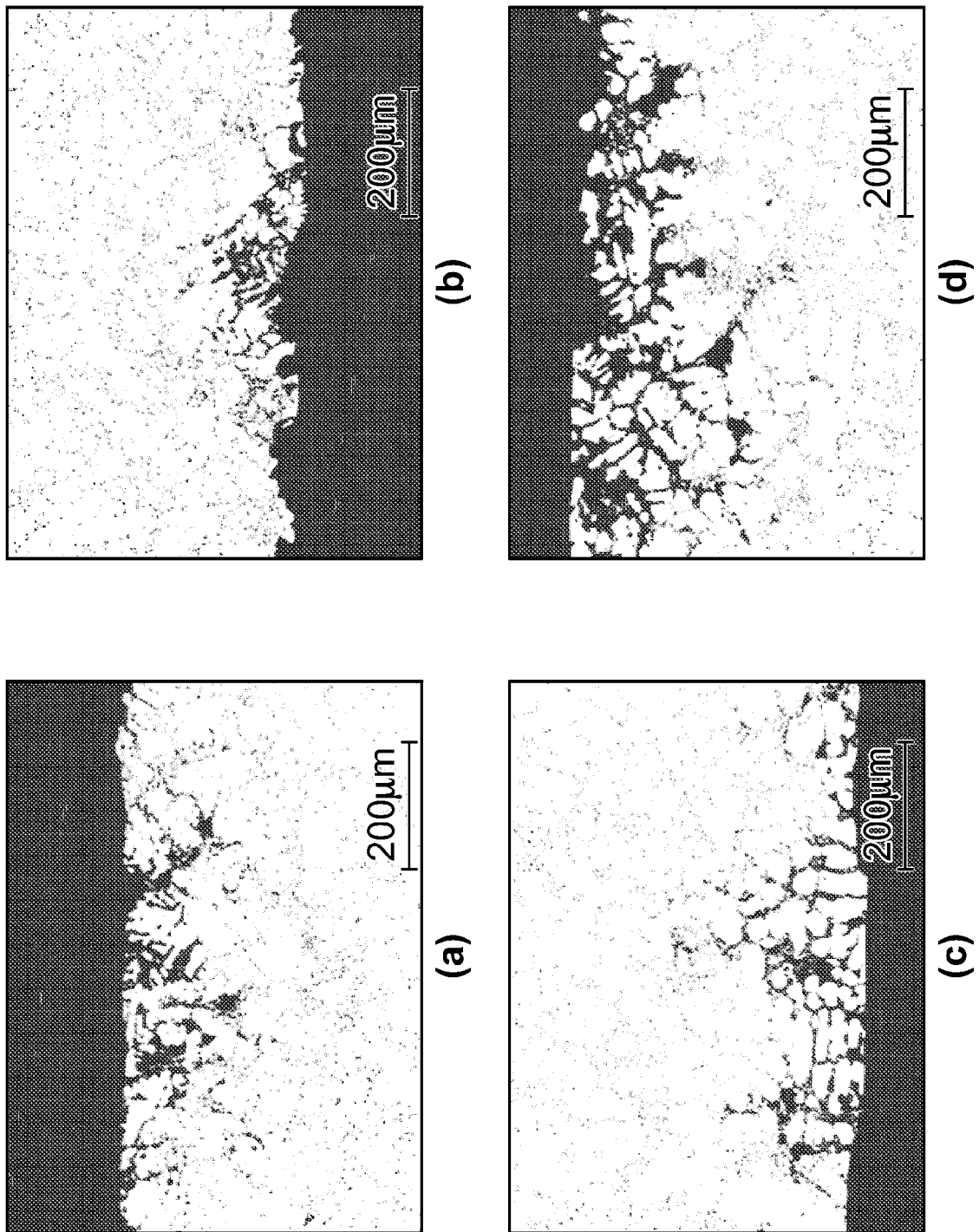


FIG. 21

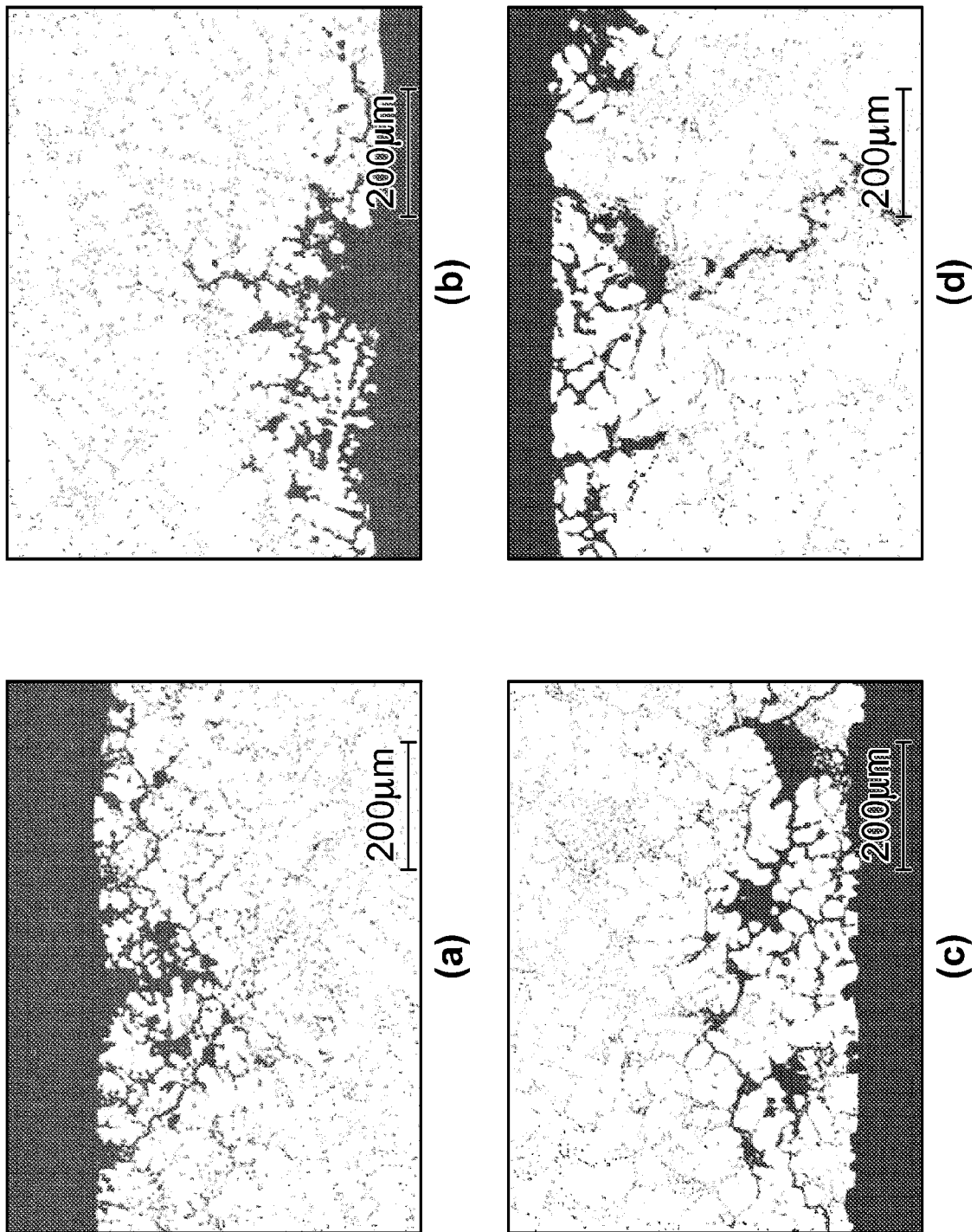


FIG. 22

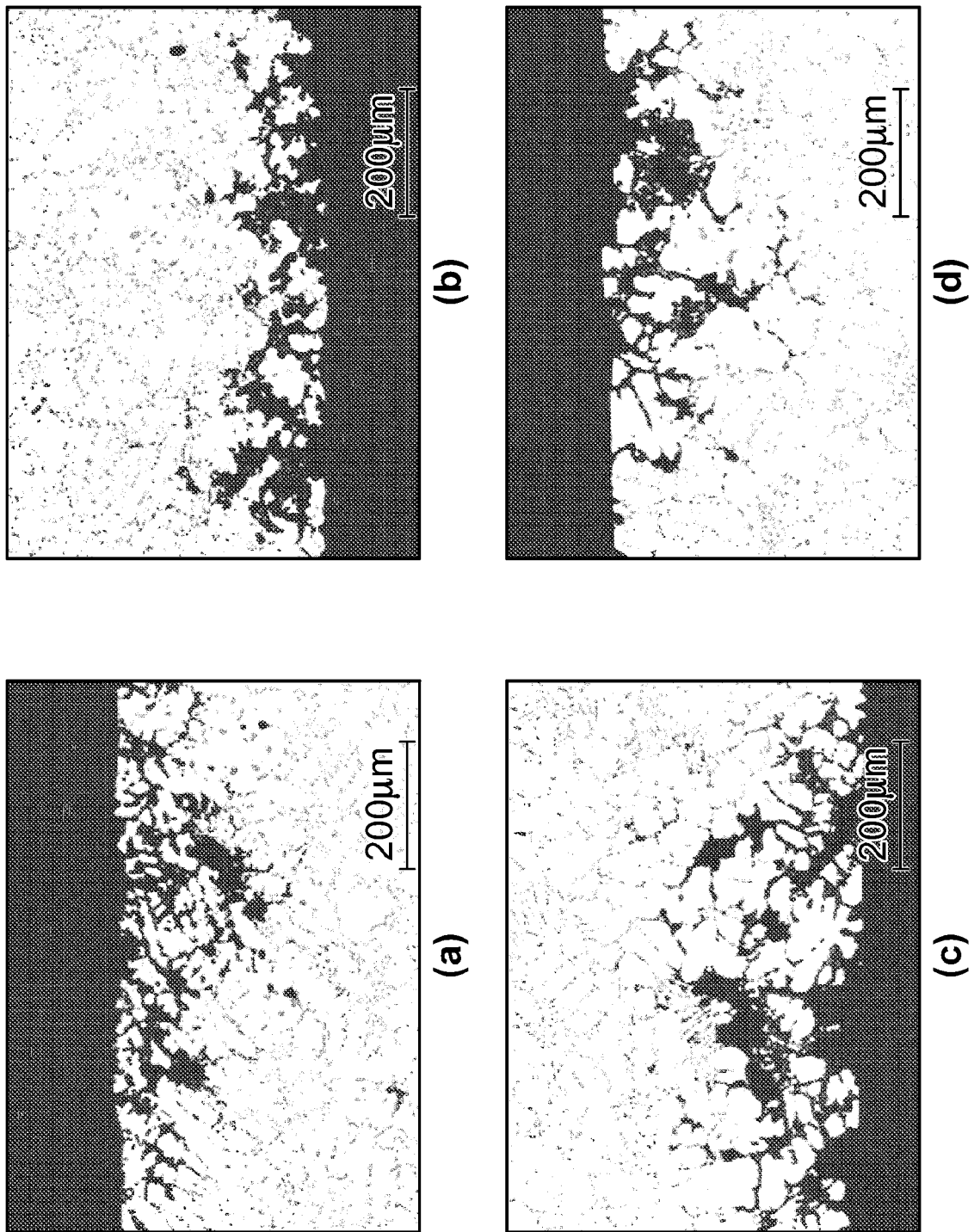


FIG. 23

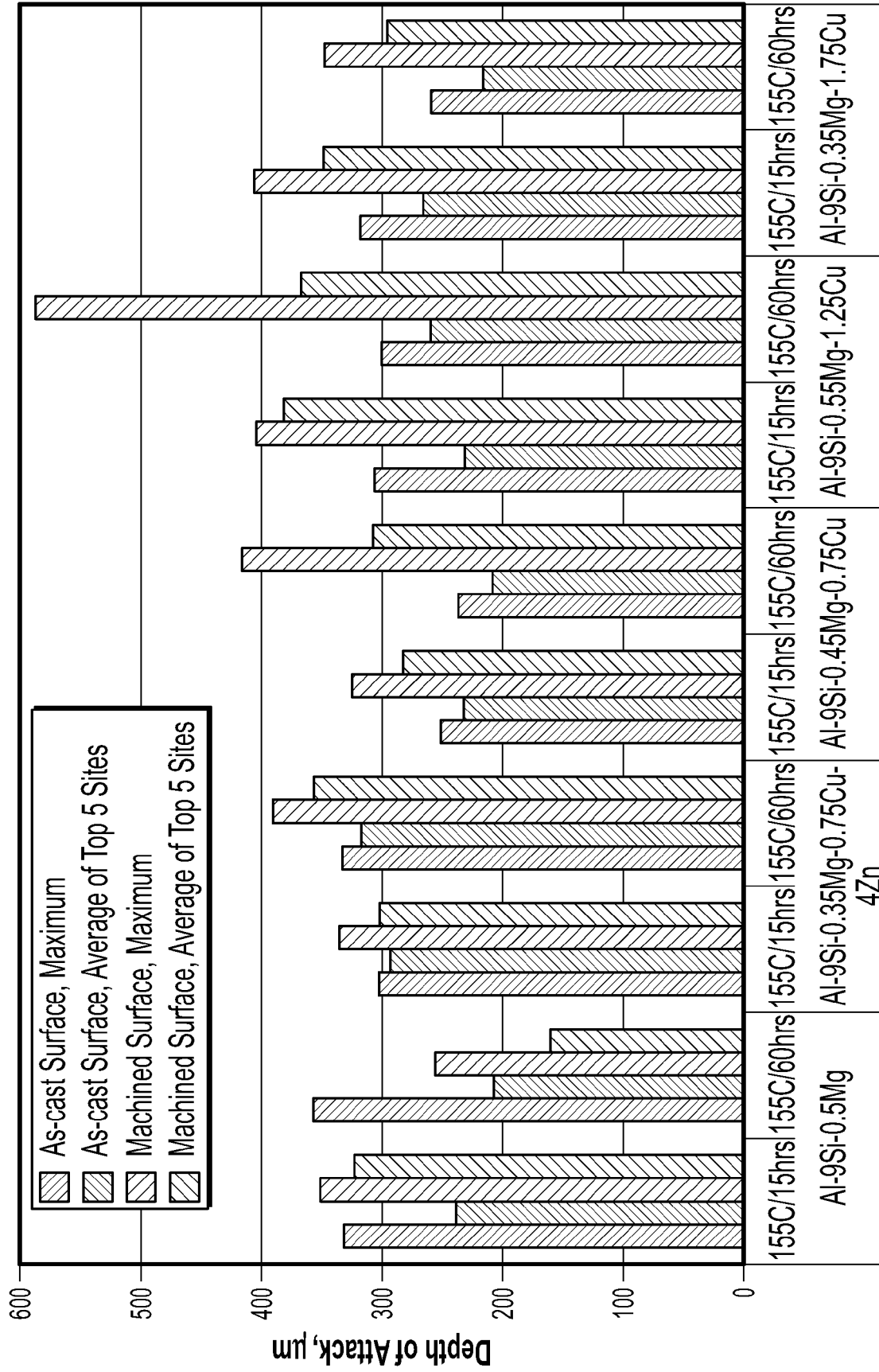


FIG. 24

Al-9Si-Mg-Cu Alloy

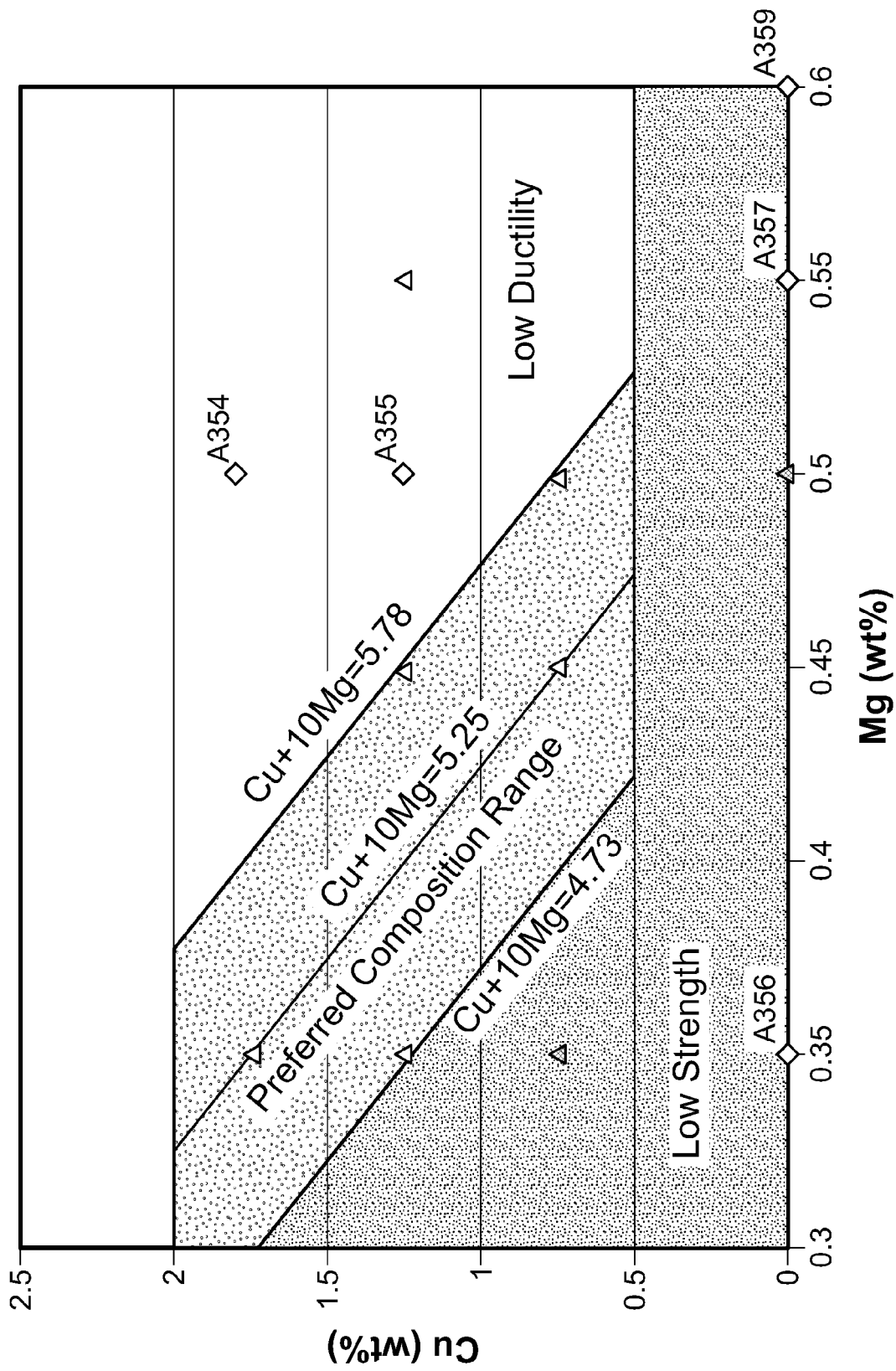


FIG. 25

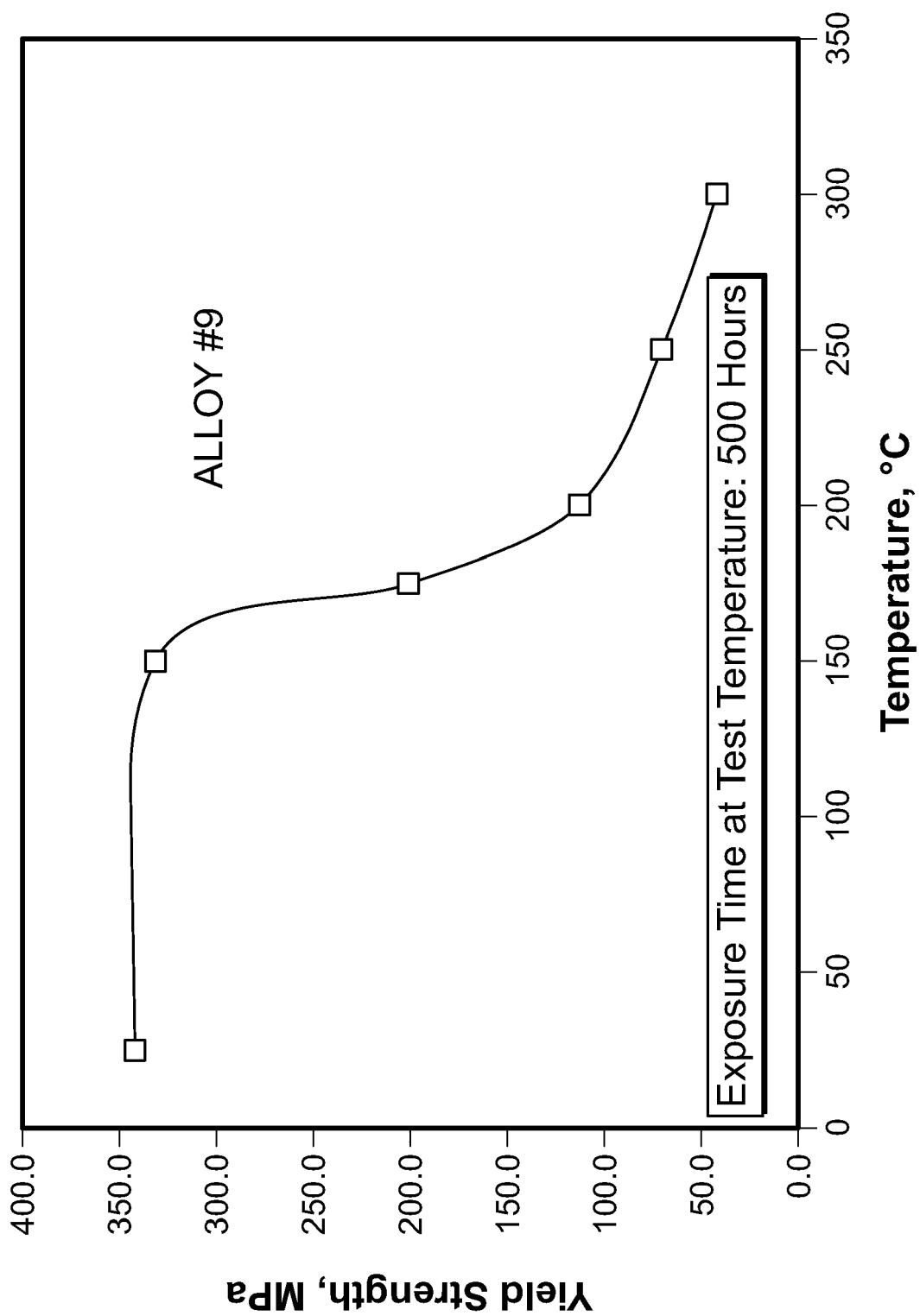


FIG. 26

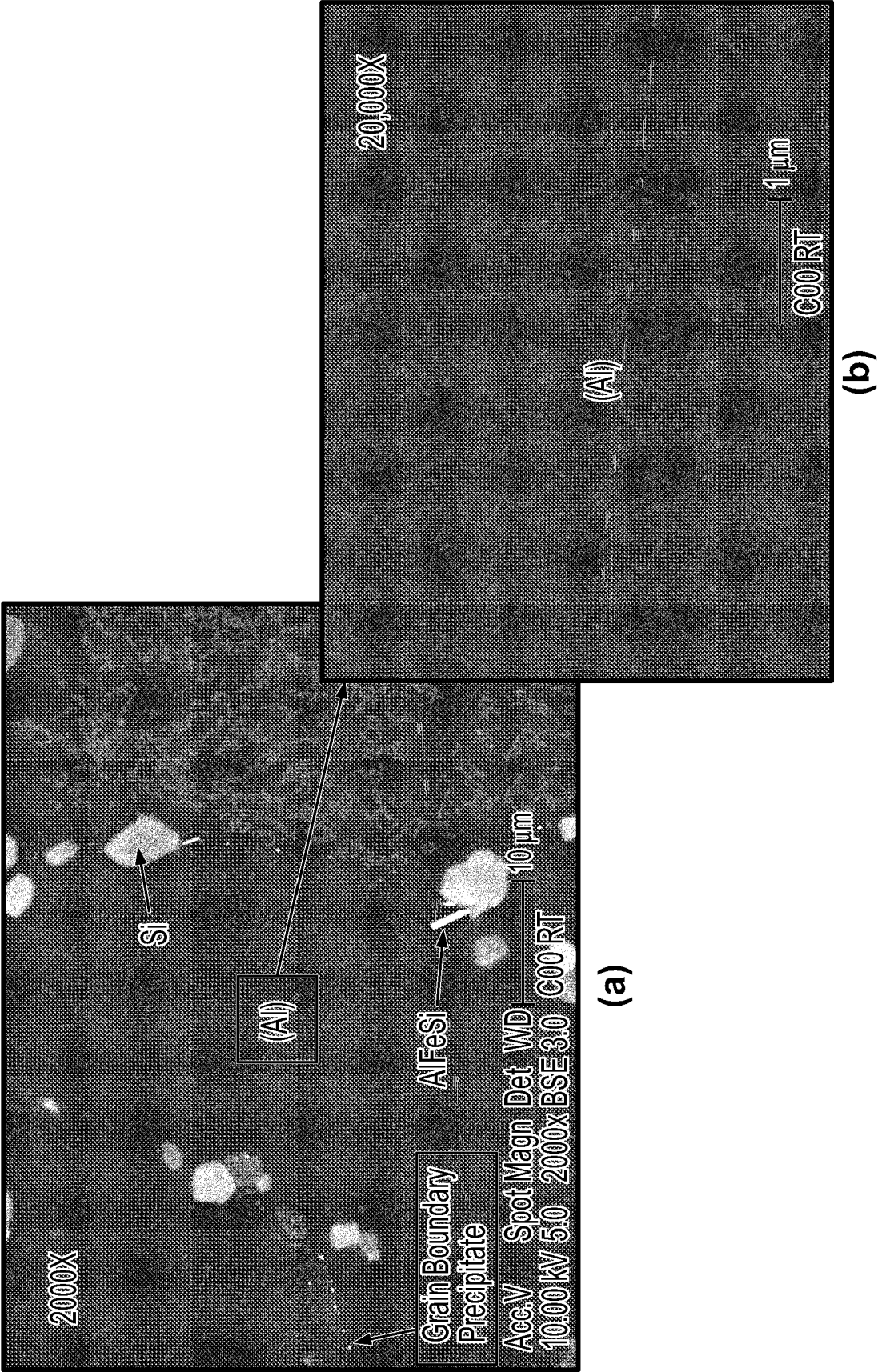


FIG. 27

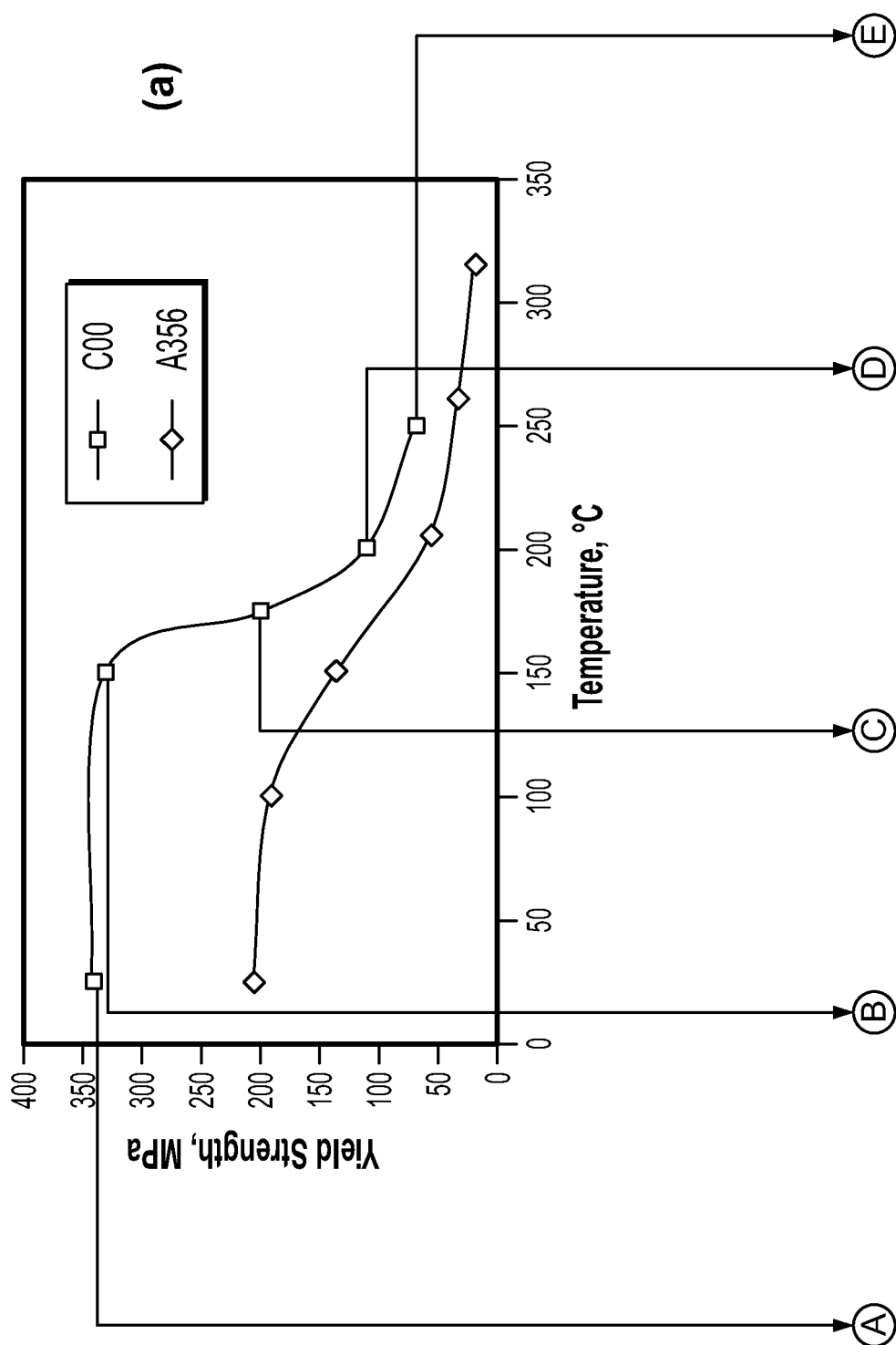


FIG. 28

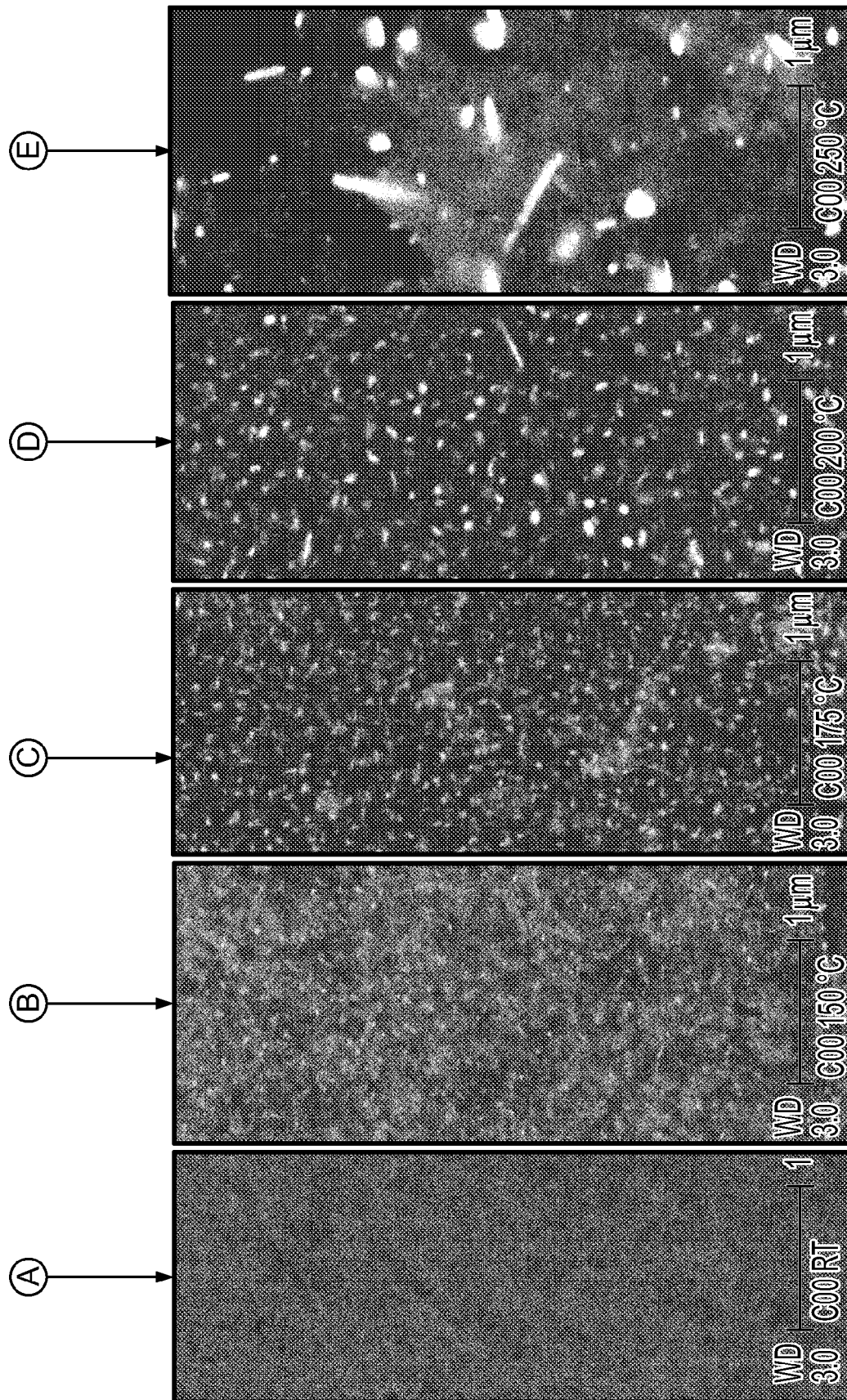


FIG. 28 (Cont.)

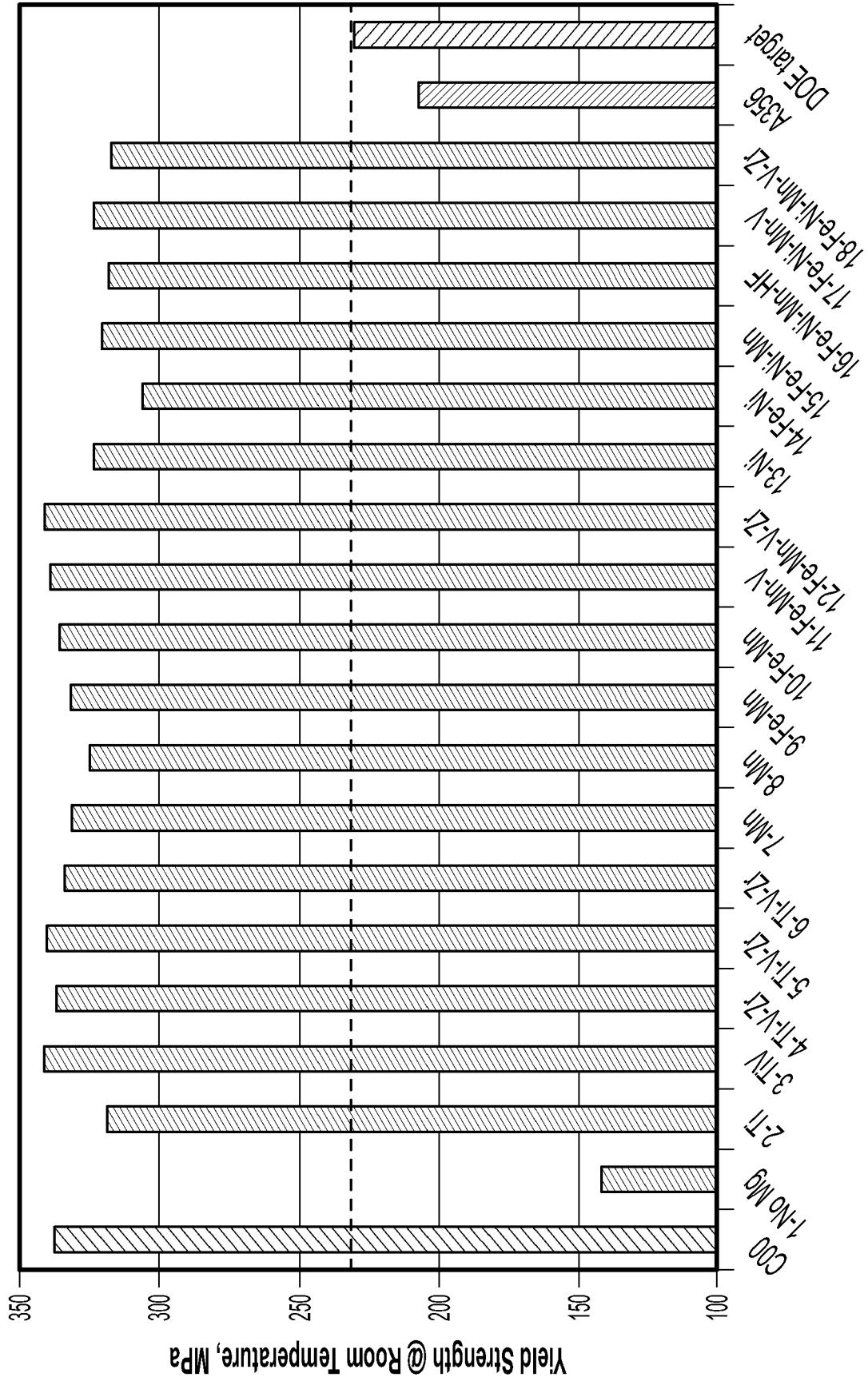


FIG. 29

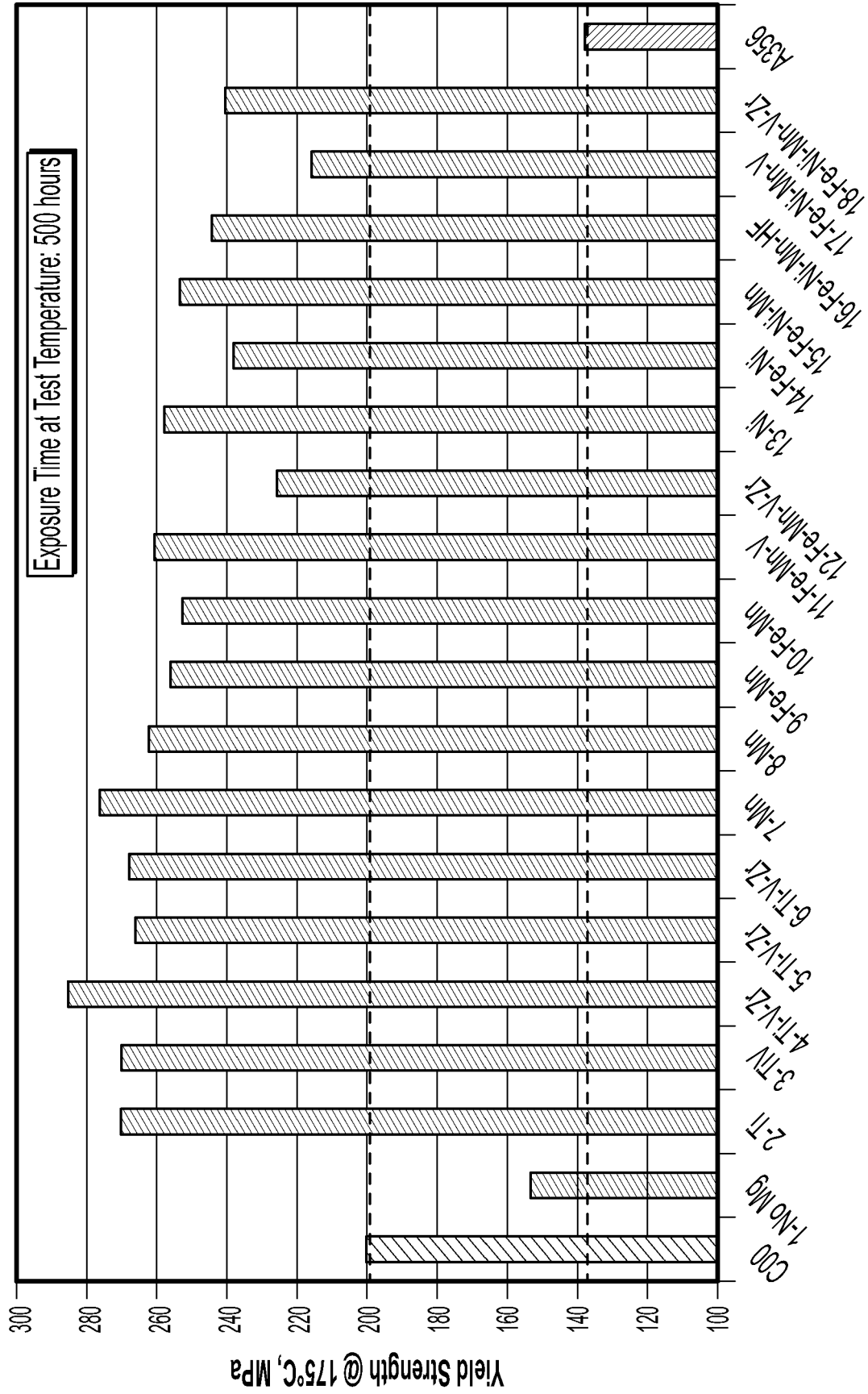


FIG. 30

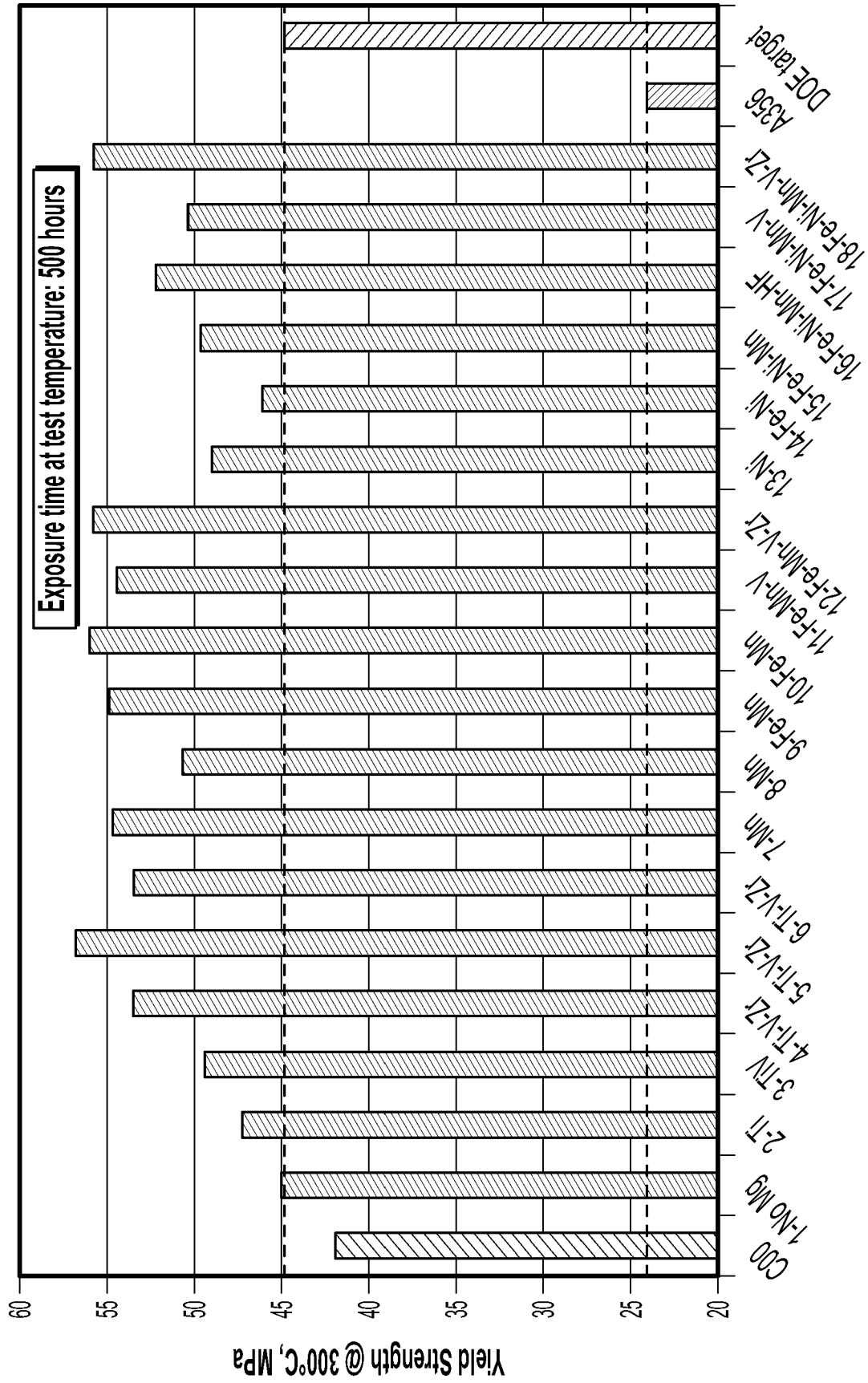


FIG. 31

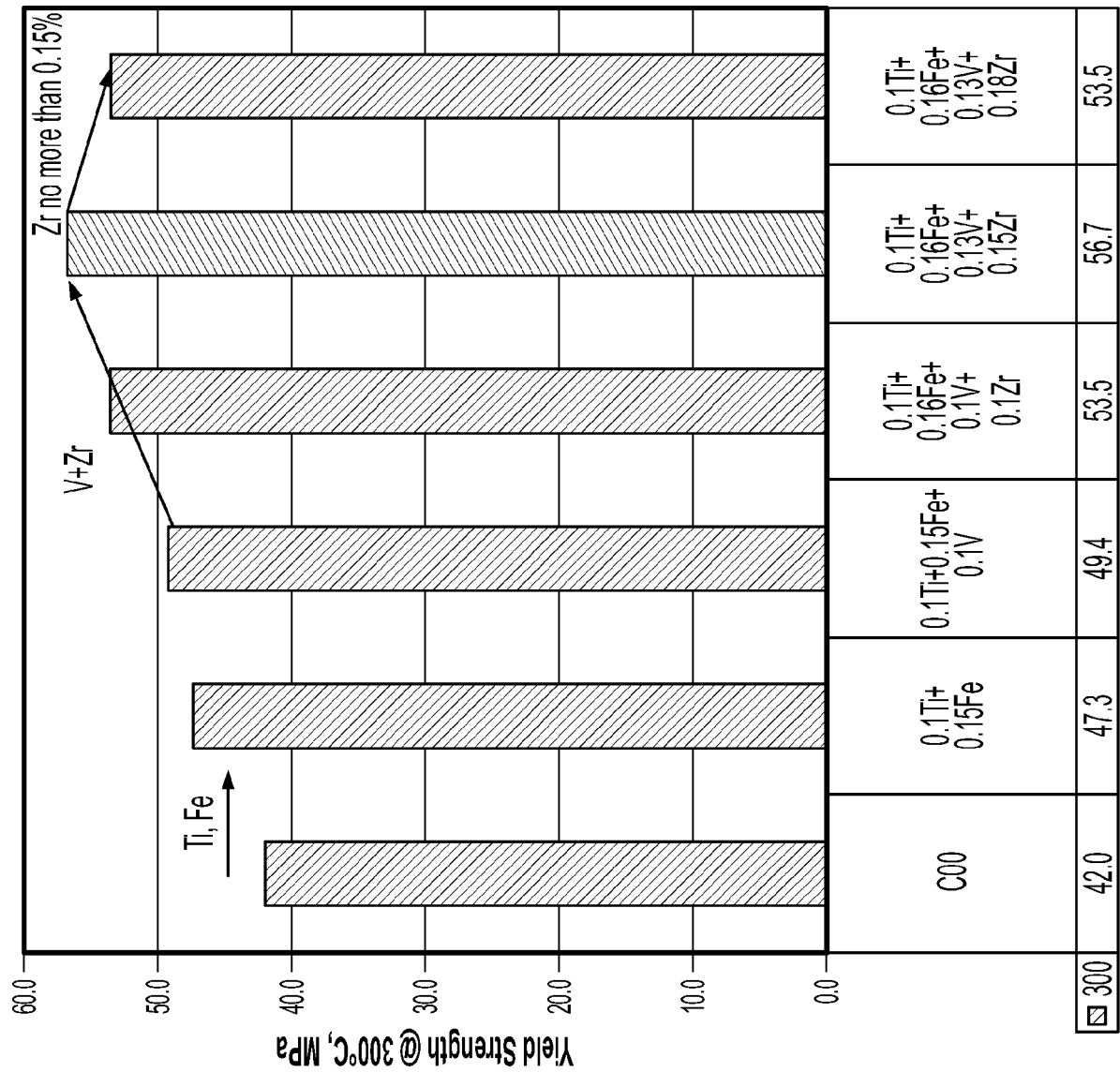


FIG. 32

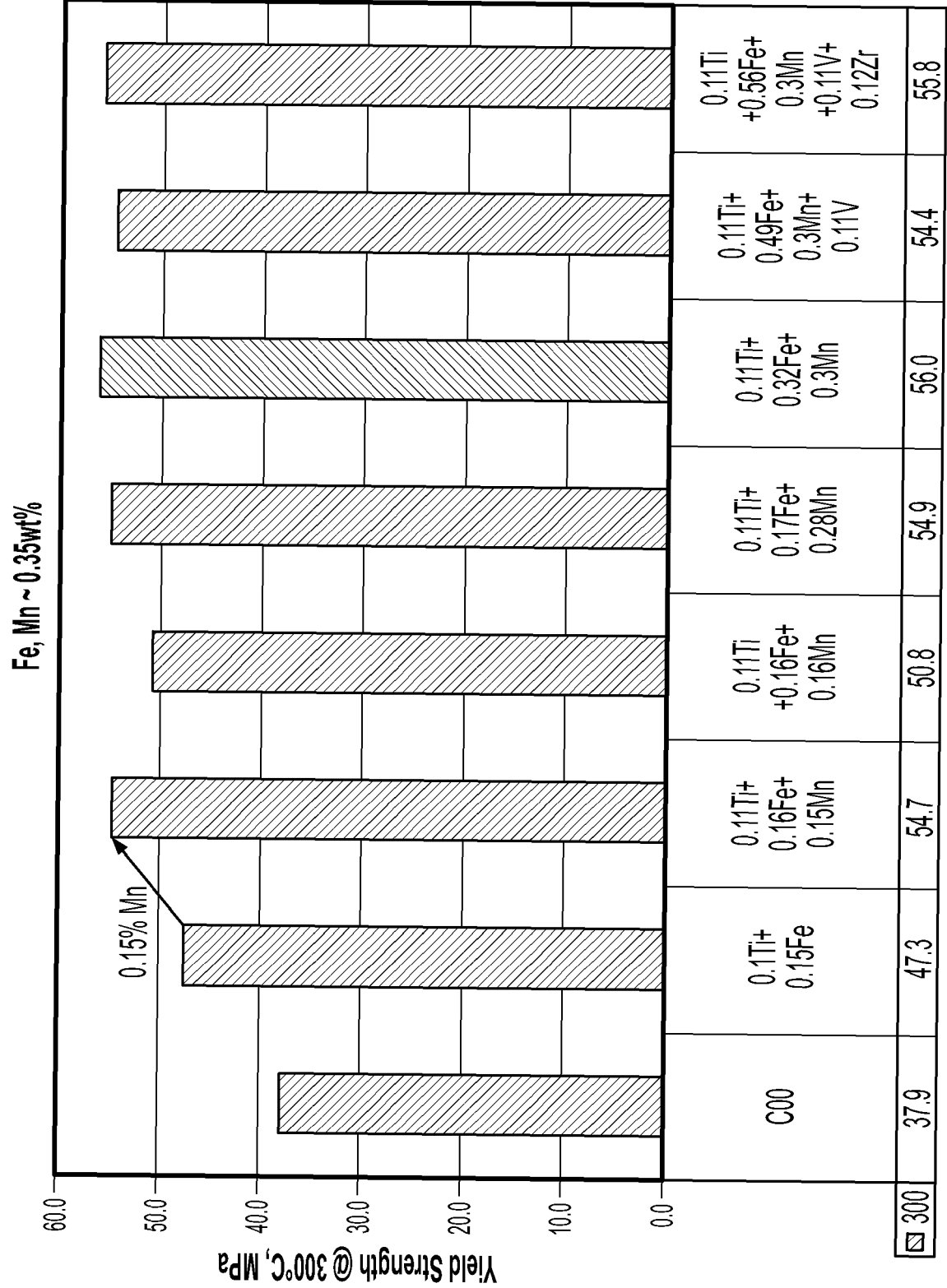


FIG. 33

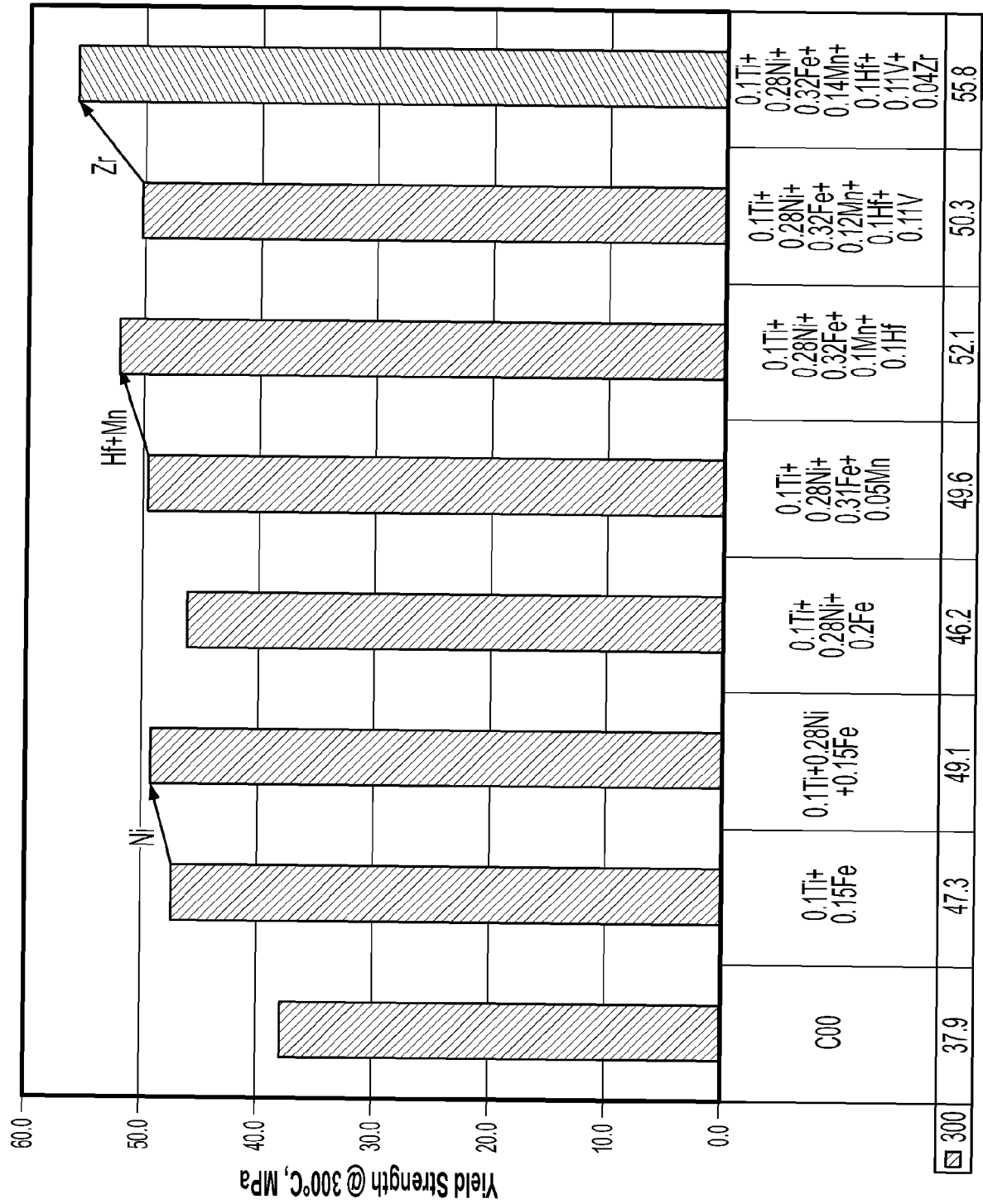


FIG. 34

REFERENCES CITED IN THE DESCRIPTION

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