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(54) SUBSTANTIALLY PB-FREE ALUMINUM ALLOY COMPOSITION

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C22C 21/12	(2006.01)

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(57) **ABSTRACT**

A substantially Pb-free aluminum alloy consisting essentially of (in weight percent) Si<0.40; Fe<0.70; Cu 5.0-6.0; Zn<0.30; Bi 0.20-0.80; Sn 0.10-0.50 with the remainder being aluminum and incidental impurities. In one embodiment for applications that are sensitive to cracking from stresses generated during machining, the Bi/Sn ratio (in terms of weight percent) is less than 1.32/1 and producing in a T8 temper. On another embodiment for applications that are not sensitive to cracking from stresses during machining but would benefit from smaller machine chip size and more aggressive material removal rates, the aluminum alloy is produced using a T6 temper. The substantially Pb-free aluminum alloy has mechanical properties that include Ultimate Tensile Strength ≥45.0 KSI/311 MPa, Yield Strength ≥38.0 KSI/262 MPa, and % Elongation ≥10%.

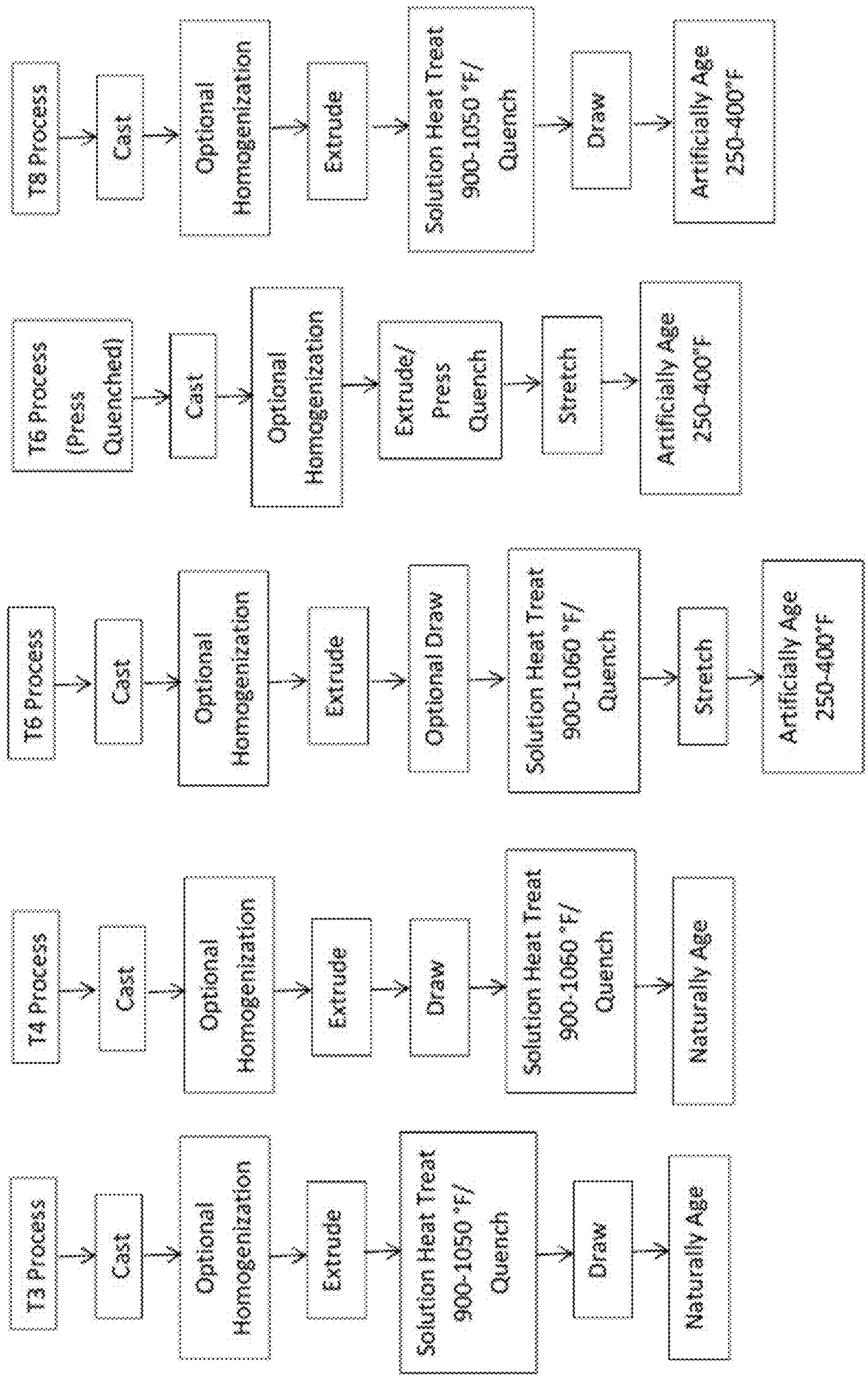
T3 Process
Cast
Optional Homogenization
Extrude
Solution Heat Treat 900-1050 °F/ Quench
Draw
Naturally Age
T4 Process
Cast
Optional Homogenization
Extrude
Draw
Solution Heat Treat 900-1060 °F/ Quench
Naturally Age
T6 Process
Cast
Optional Homogenization
Extrude
Optional Draw
Solution Heat Treat 900-1060 °F/ Quench
Stretch
Artificially Age 250-400°F
T6 Process (Press Quenched)
Cast
Optional Homogenization
Extrude/ Press Quench
Stretch
Artificially Age 250-400°F
T8 Process
Cast
Optional Homogenization
Extrude
Solution Heat Treat 900-1050 °F/ Quench
Draw
Artificially Age 250-400°F

FIG. 1

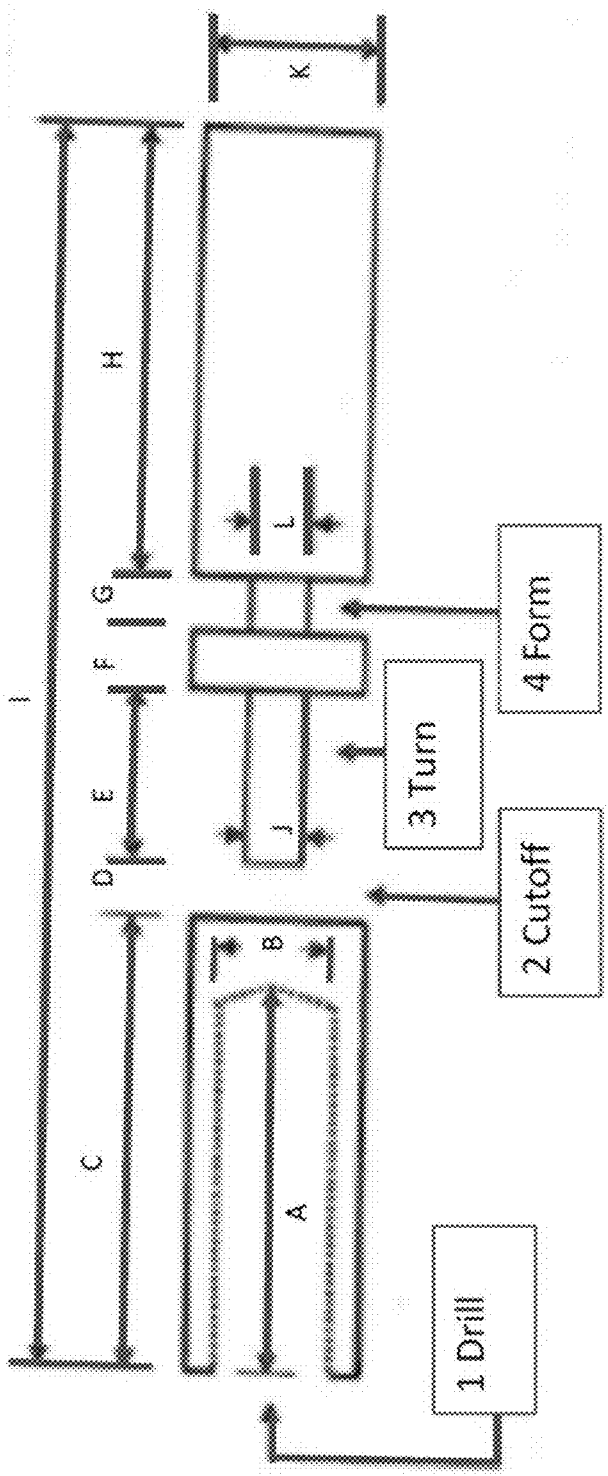

FIG. 2

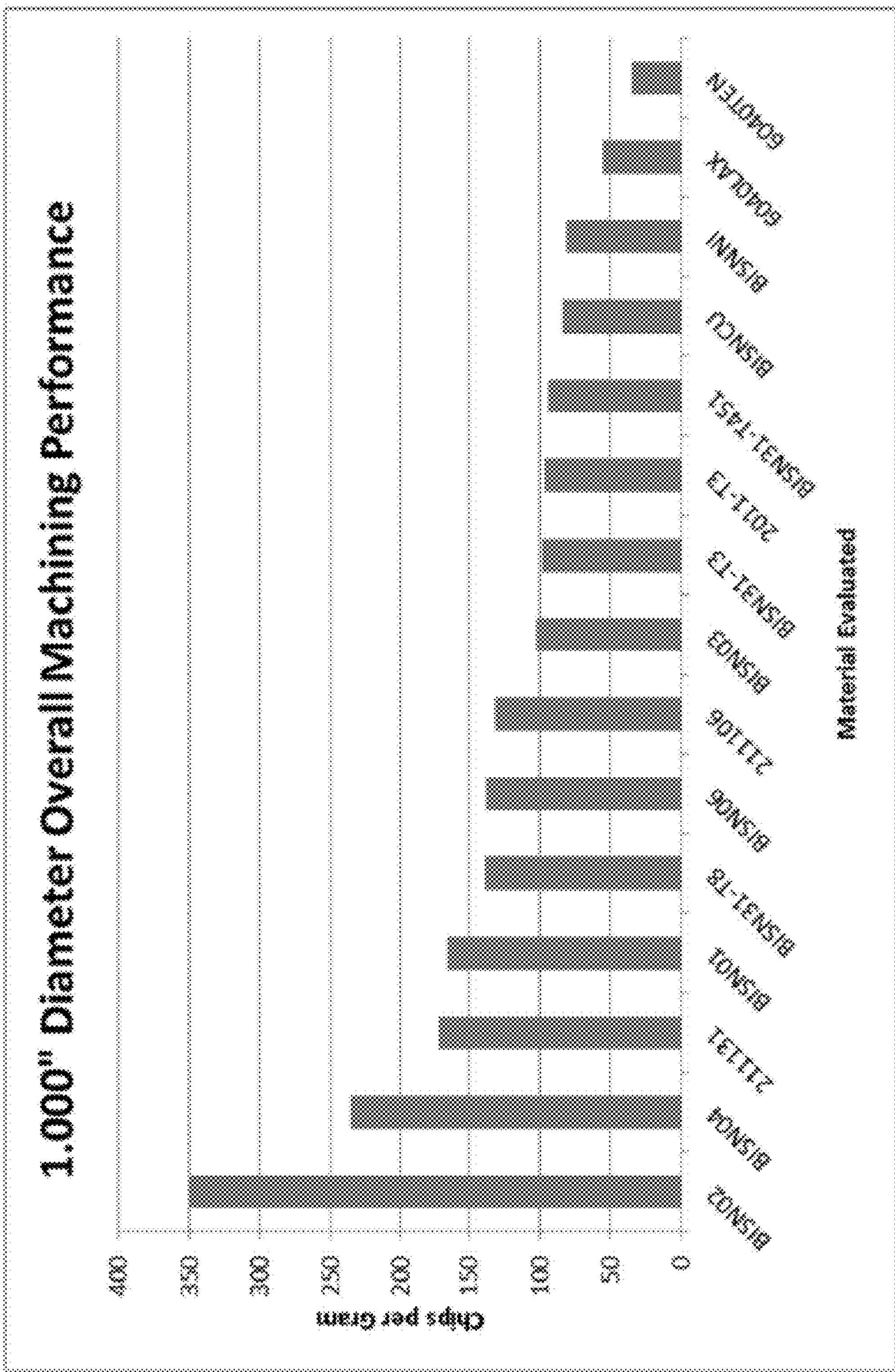
1.000" Diameter Overall Machining Performance
Chips per Gram
400
350
300
250
200
150
100
50
0
Material Evaluated
BISN02
BISN04
211131
BISN01
BISN31-T8
BISN06
211106
BISN03
BISN31-T3
2011-T3
BISN31-T451
BISNCU
BISNNI
6040LAX
6040TEN

FIG. 3

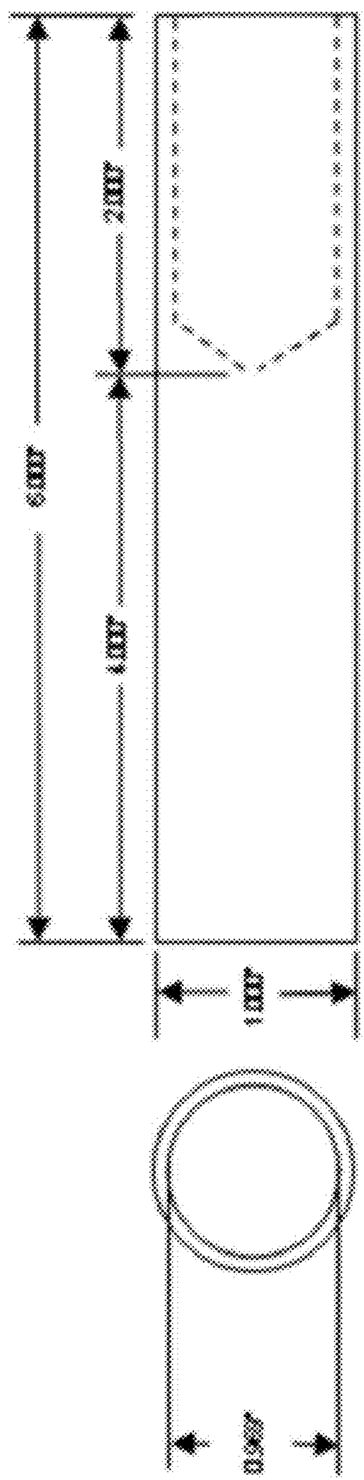

FIG. 4

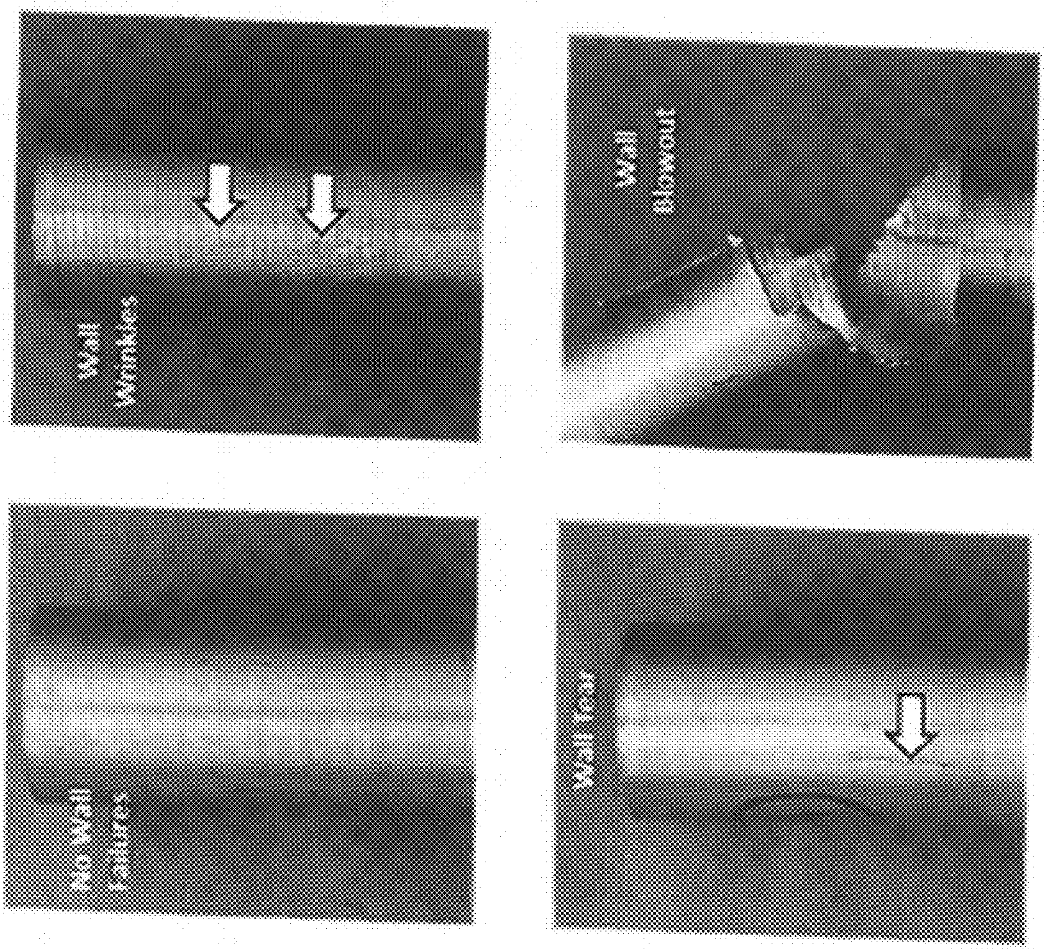

FIG. 5

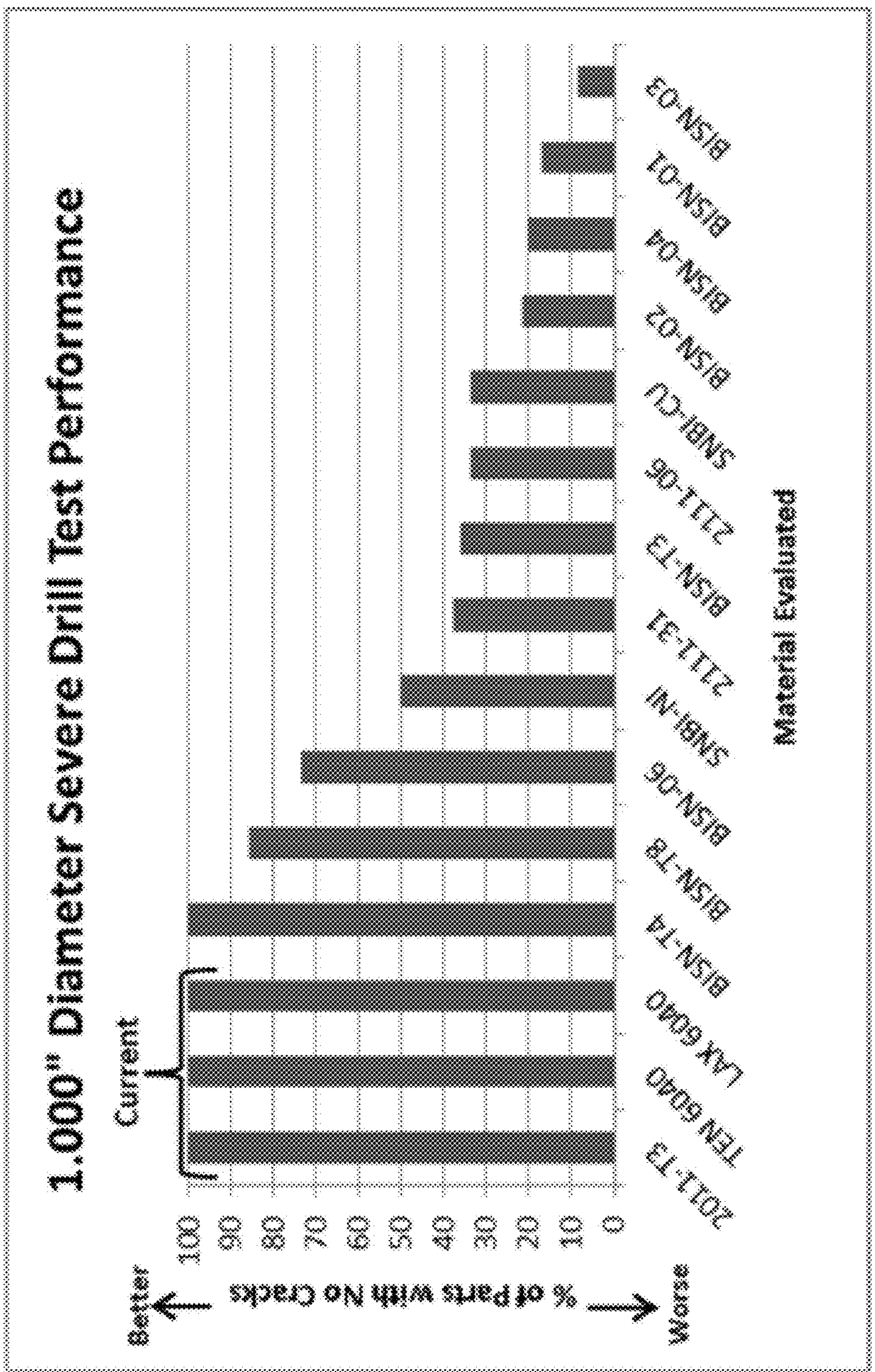
1.000" Diameter Severe Drill Test Performance
Current
Better
% of Parts with No Cracks
Worse
100
90
80
70
60
50
40
30
20
10
0
2011-T3
TEN 6040
LAX 6040
BISN-T4
BISN-T8
BISN-06
SNBI-NI
2111-31
BISN-T3
2111-06
SNBI-CU
BISN-02
BISN-04
BISN-01
BISN-03
Material Evaluated

FIG. 6

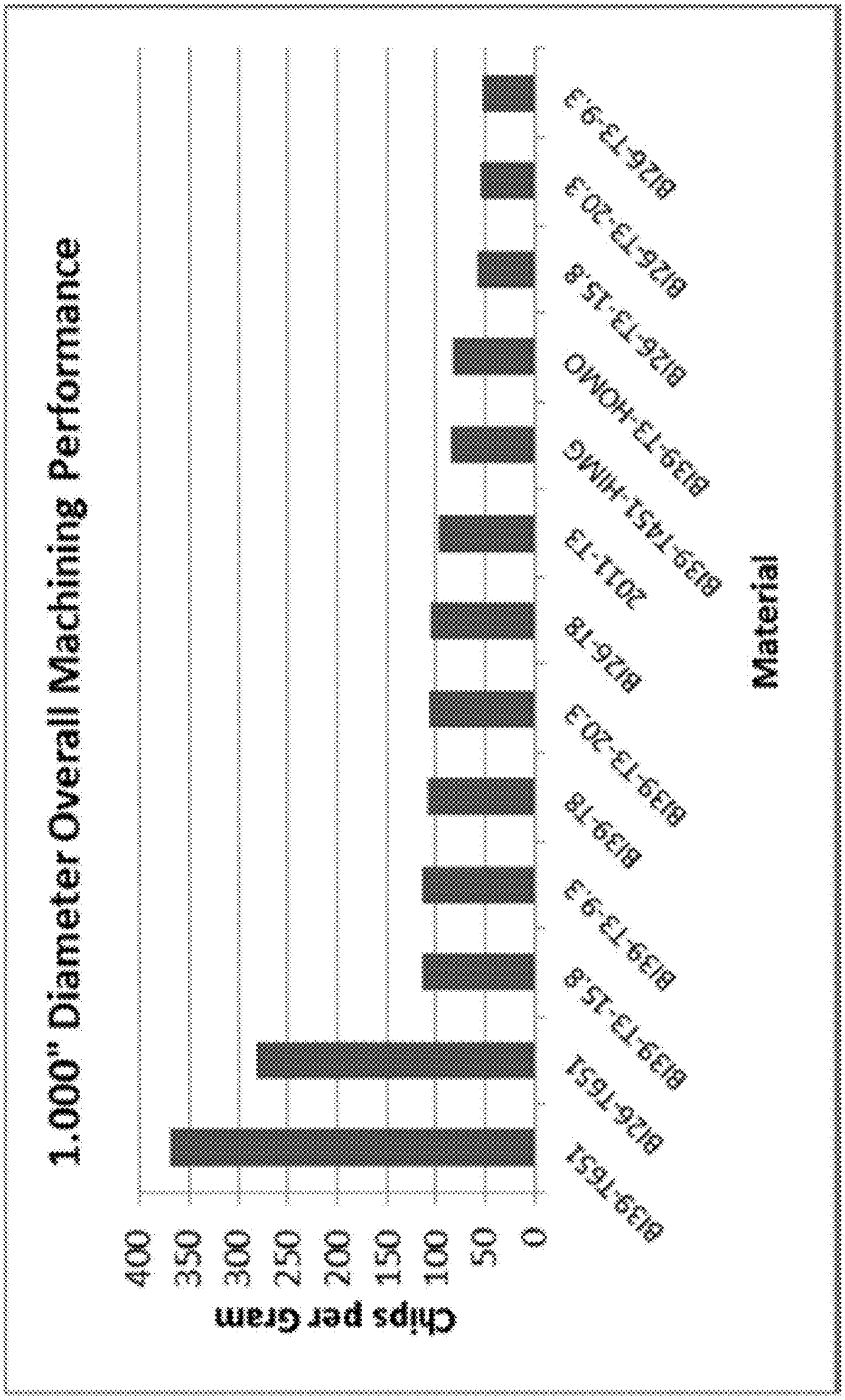
1.000" Diameter Overall Machining Performance
Chips per Gram
400
350
300
250
200
150
100
50
0
BI39-T651
BI26-T651
BI39-T3-15.8
BI39-T3-9.3
BI39-T8
BI39-T3-20.3
BI26-T8
2011-T3
BI39-T451-HIMG
BI39-T3-HOMO
BI26-T3-15.8
BI26-T3-20.3
BI26-T3-9.3
Material

FIG. 7

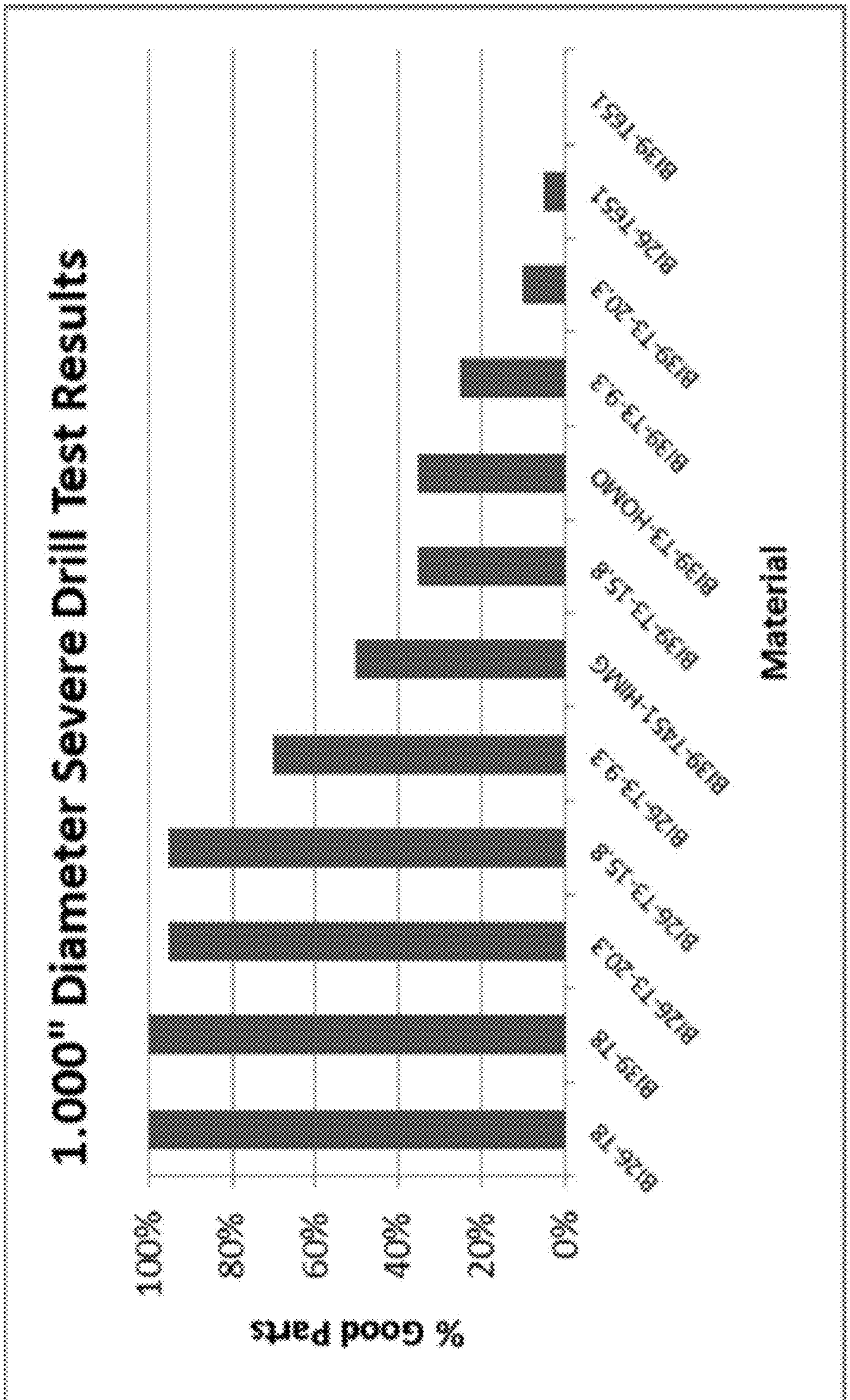
1.000" Diameter Severe Drill Test Results
% Good Parts
100%
80%
60%
40%
20%
0%
8126-T8
8139-T8
8126-T3-20.3
8126-T3-15.8
8126-T3-9.3
8139-T451-HHAG
8139-T3-15.8
8139-T3-9.3
8139-T3-20.3
8126-T651
8139-T651
Material

FIG. 8

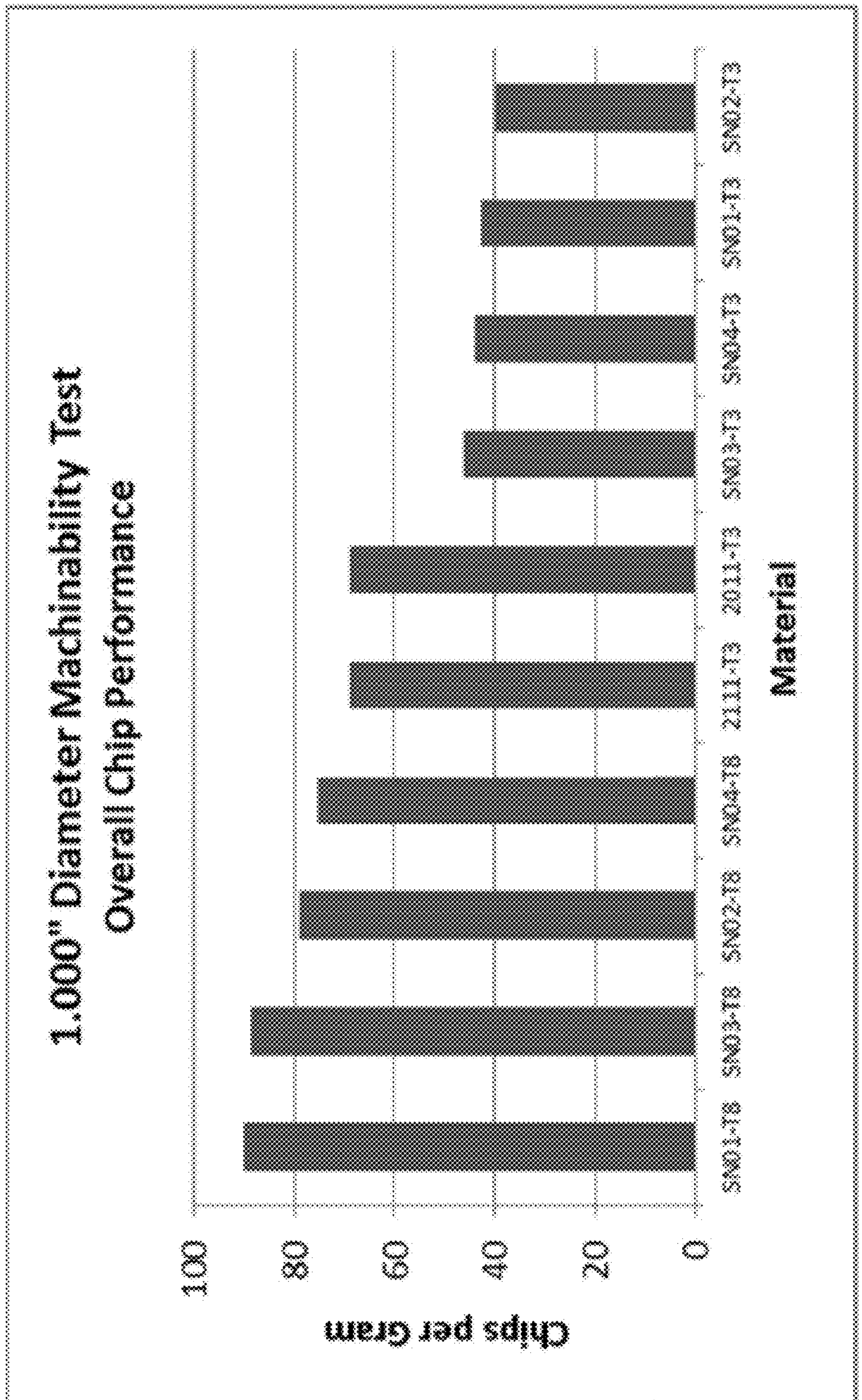
1.000" Diameter Machinability Test
Overall Chip Performance
Chips per Gram
100
80
60
40
20
0
SN01-T8
SN03-T8
SN02-T8
SN04-T8
2111-T3
2011-T3
SN03-T3
SN04-T3
SN01-T3
SN02-T3
Material

FIG. 9

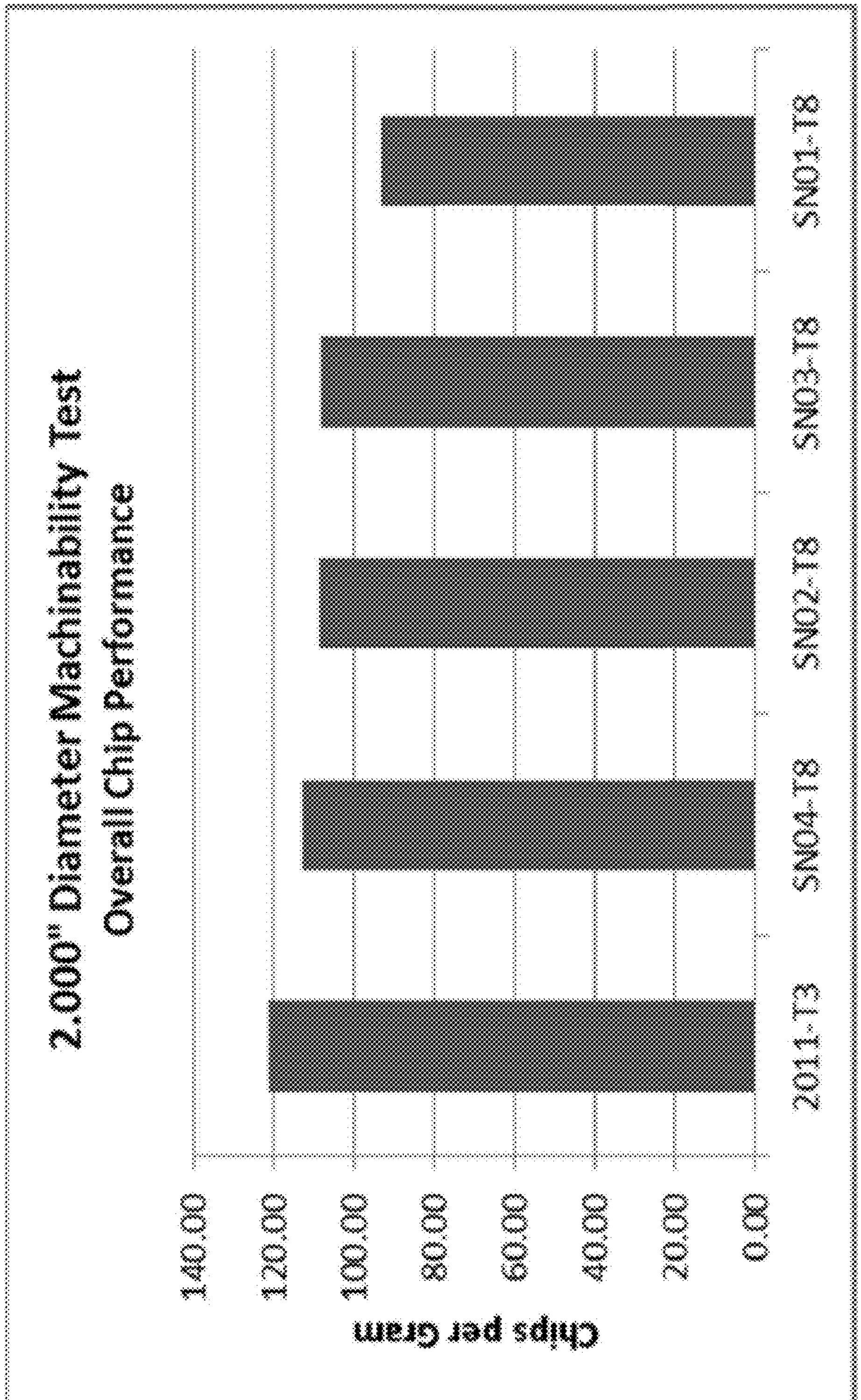
2.000" Diameter Machinability Test
Overall Chip Performance
Chips per Gram
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
2011-T3
SN04-T8
SN02-T8
SN03-T8
SN01-T8

FIG. 10

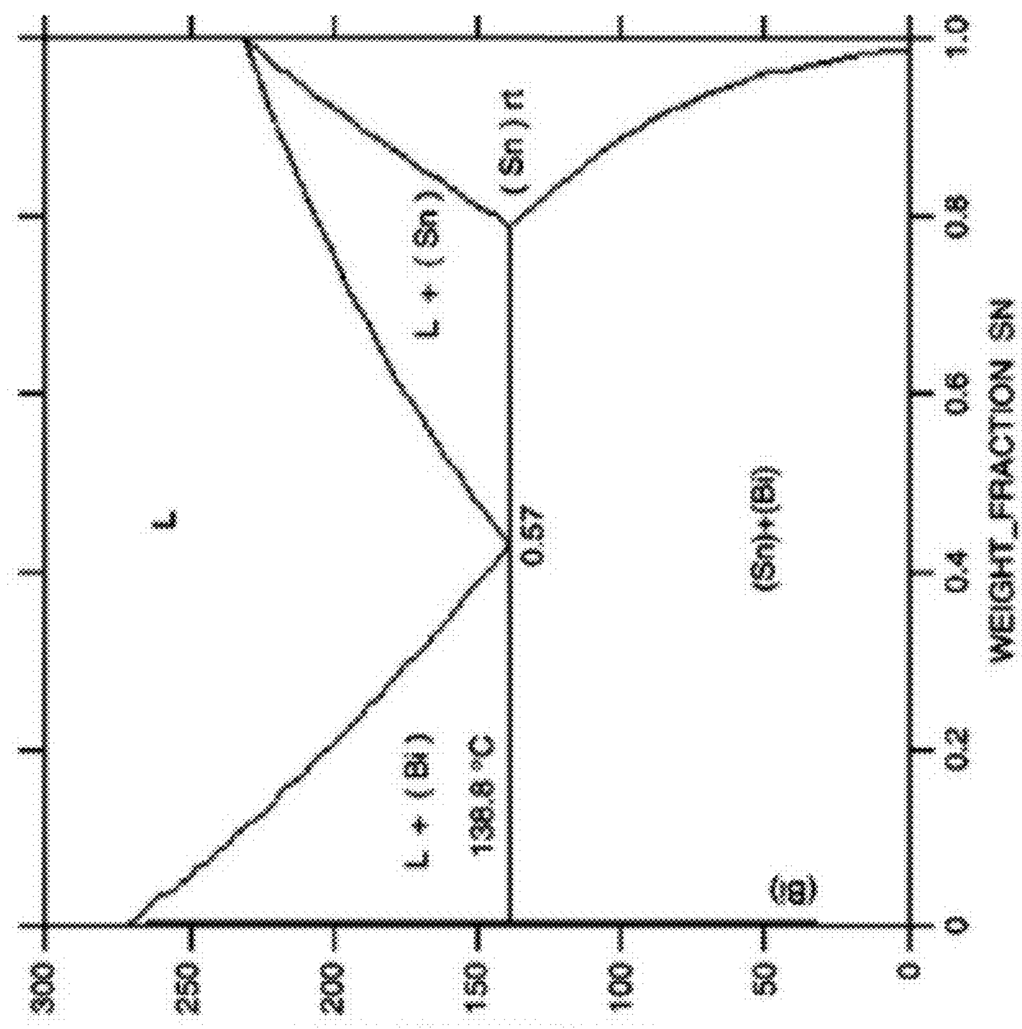
TEMPERATURE_CELSIUS
300
250
200
150
100
50
0
WEIGHT_FRACTION SN
0
0.2
0.4
0.6
0.8
1.0
L
L + (Bi)
138.8 °C
0.57
L + (Sn)
(Sn) rt
(Sn)+(Bi)
(Bi)

FIG. 11

SUBSTANTIALLY PB-FREE ALUMINUM ALLOY COMPOSITION

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application is a divisional application of U.S. Ser. No. 15/640,722 filed Jul. 3, 2017, the entirety of which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0002] The present invention relates to a substantially Pb-free aluminum alloy composition, and method for making said alloy composition, while achieving the machinability characteristics of their Pb-containing counterparts.

2. Description of Related Art

[0003] Historically Pb-containing aluminum alloys such as 2011 and 6262 (registered with the Aluminum Association in 1954 and 1960, respectively) have been used for demanding machinability applications. These applications require an alloy that can be machined at high material removal rates while maintaining good machined surface finishes and producing machine chips that are small and easily removed from the work area to prevent jamming the machine tools. Aluminum alloys containing Pb met this need by providing intermetallic phases that acted as chip breakers in the material which enabled faster material removal rates, small machine chips and good machined surfaces. While Pb does provide an effective solution, it is a heavy metal and considered a hazardous material.

[0004] In an effort to reduce the adverse health effects and environmental risk these alloys may pose, alternative Pb-free aluminum alloys capable of similar machinability performance are desired. There have been several attempts at developing free machining/Pb free alloys over the years including alloys 2012, 2111, 6020 and 6040. These alloys utilized Bi and/or Sn as a substitute for Pb. While many of these alloys were successful from a machining chip size and machined surface finish perspective, many producers of thin wall, complex parts found they could not achieve the material removal rates that were attained with Pb bearing incumbent alloys because the parts had a tendency to crack. Many of these alloys were thus taken off the market or customers were cautioned to limit material removal rates for some applications. This is problematic, considering many of the applications for the Pb bearing aluminum alloys are sold through distribution channels so the end machining application was unknown to the material producer.

[0005] In an effort to avoid potential failures as a result of this crack tendency, the Pb-free alternative alloys that are still available are often restricted in their availability and often have limits placed on the machining parameters that do not achieve the same levels of performance as the Pb-containing alternatives. As a result there is still a market need for a product that meets the machinability characteristics of the Pb-containing alloys, while also meeting the strength requirements. Typically, for example, Pb-containing alloy 2011-T3 has a minimum yield strength of 38 KSI/262 MPa.

BRIEF SUMMARY OF THE INVENTION

[0006] The substantially Pb-free aluminum alloy composition of the present invention provides a free machining product that achieves the same or superior machining performance in terms of high material removal rates, machining chip size and machined surface finish as their incumbent Pb-containing predecessors.

[0007] The substantially Pb-free aluminum alloy composition of the present invention is not susceptible to cracking in thin wall, complex machining under severe material removal conditions. This is a critical distinction that has not been achieved in other inventions attempting to solve the afore-mentioned technical problem. Materials that are susceptible to such cracking conditions render the machining performance irrelevant either by requiring substantially lower material removal rates or disqualifying the material altogether to ensure the integrity of the final part.

[0008] The substantially Pb-free aluminum alloy composition of the present invention substantially meets or exceeds the material property requirements of the current free machining materials. Specifically, in a preferred embodiment, the substantially Pb-free aluminum alloy composition meets the minimum material properties for AA2011-T3 including Ultimate Tensile Strength ≥45.0 KSI/311 MPa, Yield Strength ≥38.0 KSI/262 MPa, and % Elongation minimum ≥10%.

[0009] The substantially Pb-free aluminum alloy composition comprises, or consists essentially of, the following components (in weight percent): Si<0.40; Fe<0.70; Cu 5.0-6.0; Zn<0.30; Bi 0.20-0.80; Sn 0.10-0.50 with the remainder being aluminum and incidental impurities. In a preferred embodiment, the substantially Pb-free aluminum alloy composition maintains a Bi/Sn ratio of less than 1.32/1 (in terms of weight percent; 1.32/1 being the eutectic ratio for Bi—Sn). In addition to this, producing the material in a T8 temper provides specific advantages for machining applications that are sensitive to machining cracks because of their high material removal rates and thin wall geometries. Conversely, specific machining applications that are not sensitive to machining cracks because of more robust part geometries, but which would benefit from even higher material removal rates can be produced in a T6 temper.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The features and advantages of the present invention will become apparent from the following detailed description of a preferred embodiment thereof, taken in conjunction with the accompanying drawings, in which:

[0011] FIG. **1** is a schematic showing the operational process sequence for the substantially Pb-free aluminum alloy composition produced in the various examples in accordance with the present invention;

[0012] FIG. **2** is a conceptual drawing of the representative part used for evaluating machinability from a chip size perspective of a substantially Pb-free aluminum alloy composition in accordance with the present invention;

[0013] FIG. **3** is a graph showing machinability for alloy/temper combinations evaluated in Example 1, as measured in chips/gram;

[0014] FIG. **4** is a conceptual drawing of the machining crack susceptibility test part;

[0015] FIG. **5** shows pictures of observations made from the Machine Crack Susceptibility Test showing the four classifications used;

[0016] FIG. **6** is a graph showing Machining Crack Susceptibility Test results for Example 1 as measured in % with no tears or blowouts;

[0017] FIG. **7** is a graph showing Machinability results for Example 2 as measured by chips/gram;

[0018] FIG. **8** is a graph showing Machining Crack Susceptibility Test results for Example 2 as measured in % with no wrinkles, tears or blowouts;

[0019] FIG. **9** is a graph showing machinability results for Example 3 as measured by chips/gram;

[0020] FIG. **10** is a graph showing machinability results for Example 3 as measured by chips/gram for 2.000" diameter rod; and

[0021] FIG. **11** is a Bi—Sn Phase Diagram.

DETAILED DESCRIPTION OF THE INVENTION

[0022] The substantially Pb-free aluminum alloy composition comprising, or consists essentially of, the following components (in weight percent): Si<0.40; Fe<0.70; Cu 5.0-6.0; Zn<0.30; Bi 0.20-0.80; Sn 0.10-0.50 with the remainder being aluminum and incidental impurities. In a preferred embodiment, Si, Fe, Cu, Zn, Bi, and Sn are the only components intentionally added to the alloy composition such that any other material exist only as incidental impurities. Said incidental impurities are present in a total amount of less than 1 wt. %, or less than 0.5 wt. %, or less than 0.1 wt. %, or less than 0.05 wt. %. In one embodiment, the substantially Pb-free aluminum alloy composition maintains a Bi/Sn ratio of less than 1.32/1 (in terms of weight percent; 1.32 being the eutectic ratio for Bi—Sn).

[0023] Preferably, the substantially Pb-free aluminum alloy composition of the present invention substantially meets or exceeds the material property requirements of the current free machining materials. Specifically, in a preferred embodiment, the substantially Pb-free aluminum alloy composition meets the minimum material properties for AA2011-T3 including Ultimate Tensile Strength ≥45.0 KSI/311 MPa, Yield Strength ≥38.0 KSI/262 MPa, and % Elongation minimum ≥10%.

[0024] Generally, the phrase "substantially Pb-free" is defined as having no intentional additions of Pb to the aluminum alloy composition as it is being produced. Preferably, any Pb that may be contained in the aluminum alloy composition is the result of tramp contamination. In a preferred embodiment, the aluminum alloy composition of the present invention contains <0.05 wt. % Pb. In another embodiment, the aluminum alloy composition of the present invention contains <0.01 wt. % Pb. In another preferred embodiment, the aluminum alloy composition of the present invention contains <0.005 wt. % Pb. In another preferred embodiment, the aluminum alloy composition of the present invention contains ≤0.003 wt. % Pb.

[0025] It is understood that the ranges identified above for the substantially Pb-free aluminum alloy composition include the upper or lower limits for the element selected and every numerical range and fraction provided within the range may be considered an upper or lower limit. For example, it is understood that within the range of Si<0.40, the upper or lower limit for Si may be selected from 0.30, 0.25, 0.20, 0.15, and 0.10 wt. %. In one embodiment, the amount of Si ranges from <0.20 wt. %. In another embodiment, the amount of Si ranges from <0.16 wt. %. In another embodiment, the amount of Si ranges from 0.10-0.16 wt. %. For example, it is also understood that within the range of Fe<0.70, the upper or lower limit for Fe may be selected from 0.60, 0.50, 0.40, 0.30, 0.20, and 0.10 wt. %. In one embodiment, the amount of Fe ranges from 0.30-0.50 wt. %. In another embodiment, the amount of Fe ranges from 0.33-0.44 wt. %. For example, it is also understood that within the range of Cu 5.0-6.0, the upper or lower limit for Cu may be selected from 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8, and 5.9. In one embodiment, the amount of Cu ranges from 5.1-5.8 wt. %. In another embodiment, the amount of Cu ranges from 5.13-5.63 wt. %. For example, it is also understood that with the range of Zn<0.30, the upper or lower limit for Zn may be selected from 0.20, 0.10, 0.05, 0.01, and 0.005 wt. % In one embodiment, the amount of Zn ranges from 0.002-0.05. In another embodiment, the amount of Zn ranges from 0.002-0.044. For example, it is also understood that within the range of Bi 0.20-0.80, the upper or lower limit for Bi may be selected from 0.30, 0.40, 0.50, 0.60, and 0.70. In one embodiment, the amount of Bi ranges from 0.40-0.80. In another embodiment, the amount of Bi ranges from 0.20-0.40. For example, it is also understood that within the range of Sn 0.10-0.50, the upper or lower limit for Sn may be selected from 0.20, 0.30, and 0.40. In one embodiment, the amount of Sn ranges from 0.20-0.50. Additionally, for example, it is also understood that within the range of Bi/Sn ratio of less than 1.32/1, the upper or lower limit for Bi/Sn ratio may be selected from 1.30/1, 1.25/1, 1.20/1, 1.15/1, 1.10/1, 1.05/1, 1.00/1, and 0.80/1. In one embodiment, the Bi/Sn ration may be between 1.32/1-0.80/1. It is further understood that any and all permutations of the ranges identified above are included within the scope of the present invention. For example, the substantially Pb-free aluminum alloy composition may consist essentially of the following components (in weight percent): Si<0.15; Fe<0.50; Cu 5.1-5.7; Zn<0.05; Bi 0.40-0.80; Sn 0.20-0.50 with the remainder being aluminum and incidental impurities, while maintaining a Bi/Sn ratio of less than 1.32/1 (in terms of weight percent; 1.32/1 being the eutectic ratio for Bi—Sn) or a Bi/Sn ratio from 1.32/1 to 0.80/1, having incidental impurities present in a total amount of less than 1 wt. %, or less than 0.5 wt. %, or less than 0.1 wt. %, or less than 0.05 wt. %.

[0026] In addition to this, producing the material in a T8 temper provides specific advantages for machining applications that are sensitive to machining cracks because of their high material removal rates and thin wall geometries. As such, a free machining, machining crack insensitive aluminum alloy may be produced. The aluminum alloy product has been homogenized to improve the recrystallization for improved grain size control. In a preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) of less than 1.32/1. In yet another preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) ranging from 1.32/1 to 0.8/1. In yet another preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) ranging from 1.20/1 to 1/1.

[0027] Conversely, specific machining applications that are not sensitive to machining cracks because of more robust part geometries, but which would benefit from even higher material removal rates can be produced in a T6 temper. As such, a superior free machining aluminum alloy material for applications that do not require machine crack insensitive properties may be produced. The aluminum alloy product has been homogenized to improve the recrystallization for improved grain size control. In a preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) is less than 1.32/1. In yet another preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) ranging from 1.32/1 to 0.8/1. In yet another preferred embodiment, the alloy has a Bi/Sn ratio (in weight percent) ranging from 1.20/1 to 1/1.

[0028] It is important to note that the preferred process in accordance with the present application does not include any naturally aging beyond that which is inherent in the described processes disclosed herein. Specifically, the present invention does not include any T3 or T4 naturally aging of the alloy composition.

[0029] Preferred processes for making the alloy composition of the present invention are similar to the processes described in U.S. Pat. Nos. 5,776,269 and 5,916,385, the contents of which are expressly incorporated herein by reference. In one embodiment, the alloy is initially cast into ingots and the ingots homogenized at a temperature ranging from about 900° to 1170° F. for at least 1 hour but generally not more than 24 hours, optionally followed either by fan or air cooling. In one embodiment, the ingot is soaked at about 1020° F. for about 4 hours and then cooled to room temperature. Next, in one embodiment, the ingots are cut into shorter billets, heated to a temperature ranging from about 500° to 720° F. and then extruded into a desired shape. However, it should be understood that one of ordinary skill in the art may select different times and temperatures and still remain within the scope of the present invention.

[0030] In one embodiment, the extruded alloy shapes are then thermomechanically treated to obtain the desired mechanical and physical properties. For example, to obtain the mechanical and physical properties of a T8 temper, solution heat treatment is conducted at a temperature ranging from about 930° to 1030° F., preferably at about 1000° F., for a time period ranging from about 0.5 to 2 hours, water quenched to room temperature, cold worked, and artificial aged at a temperature ranging from about 250° to 400° F. for about 2 to 12 hours. However, it should be understood that one of ordinary skill in the art may select different times, quenching conditions, and temperatures and still remain within the scope of the present invention.

[0031] In one embodiment, to obtain the properties of a T6 of T6511 temper, prior to extrusion, the billets are homogenized at a temperature ranging from about 950° to 1050° F. and then extruded to a near desired size. The rod or bar is then straightened using any known straightening operation such as stress relieved stretching of about 1 to 3%. To further improve its physical and mechanical properties, the alloy is heat treated by precipitation artificial age hardening. Generally, this may be accomplished at a temperature ranging from about 250° to 400° F. for a time period from about 2 to 12 hours. However, it should be understood that one of ordinary skill in the art may select different times, quenching conditions, and temperatures and still remain within the scope of the present invention.

[0032] The following examples illustrate various aspects of the invention and are not intended to limit the scope of the invention.

Example 1

[0033] Billets were produced in 10 inch (254 mm) diameter with the target compositions found in Table 1. These billets were extruded and processed into T3, T4, T6 and T8 tempers using the process parameters shown in FIG. **1** to produce 1.000 inch (25.4 mm) diameter rod. Casting of the billets was done using conventional direct chill casting techniques. The 6040 alloy variants were produced in both press quenched (T6511 temper) and separate solution heat treatment (T651 temper) processes. Homogenization, extrusion, solution heat treatment, quenching, drawing and artificial aging operations were all completed using typical industry practices. Samples from this material were evaluated for tensile properties and machinability. The tensile property results are shown in Table 2. The mechanical property limits for 2011-T3 were used as a minimum acceptable criteria. These results show that all but BISN-31-T451 materials pass the aluminum association minimum properties for 2011-T3 (Yield Strength 38.0 KSI/262 MPa; Ultimate Strength 45.0 KSI/311 MPa; 10% Elongation).

TABLE 1

Compositions for Example 1 (weight percent)

Alloy	Cast	Si	Fe	Cu	Mn	Mg	Zn	Cr	Pb	Bi	Sn	Ti	Zr	B	Ni
BISN-01	0969	0.11	0.36	5.22	0.00	0.00	0.044	0.020	0.001	0.40	0.35	0.020	0.003	0.001	0.00
BISN-03	0971	0.11	0.38	5.32	0.00	0.00	0.003	0.000	0.002	0.49	0.27	0.025	0.002	0.001	0.00
BISN-31	0973	0.12	0.42	5.40	0.00	0.00	0.004	0.000	0.002	0.63	0.49	0.019	0.002	0.001	0.00
BISN-31	0975	0.12	0.39	5.47	0.00	0.00	0.003	0.000	0.002	0.60	0.42	0.022	0.002	0.001	0.00
BISN-31	0977	0.11	0.40	5.40	0.00	0.00	0.003	0.000	0.002	0.60	0.42	0.021	0.002	0.001	0.00
BISN-04	0978	0.12	0.44	5.63	0.00	0.00	0.003	0.000	0.001	0.85	0.50	0.029	0.002	0.001	0.00
BISN-06	0979	0.13	0.40	5.16	0.00	0.00	0.002	0.000	0.001	0.57	0.45	0.024	0.002	0.000	0.00
2111-06	0981	0.12	0.35	5.37	0.00	0.00	0.003	0.000	0.001	0.64	0.20	0.025	0.002	0.000	0.00
2111-31	0983	0.12	0.33	5.13	0.00	0.00	0.003	0.000	0.001	0.56	0.20	0.023	0.002	0.001	0.00
BISN-02	0985	0.13	0.39	5.34	0.00	0.00	0.009	0.002	0.001	0.67	0.60	0.015	0.002	0.001	0.00
SNBI-CU	0986	0.11	0.36	4.36	0.00	0.00	0.003	0.000	0.001	0.59	0.41	0.023	0.002	0.002	0.00
SNBI-NI	0989	0.13	0.40	5.24	0.00	0.00	0.003	0.000	0.005	0.58	0.42	0.013	0.002	0.001	1.51
TEN6040	40-1	0.60	0.44	0.56	0.11	0.93	0.090	0.055	0.006	0.17	0.89	0.020	0.002	0.000	0.00
LAX6040	0445	0.72	0.29	0.43	0.07	0.95	0.170	0.078	0.025	0.29	0.85	0.036	0.000	0.000	0.00

TABLE 2

Mechanical Properties of Material Evaluated in Example 1

Lot ID	Cast #	Alloy	Temper	Yield (KSI/ MPa)	Ultimate (KSI/ MPa)	% Elongation
299	969	BISN-01	T3	45.9/317	52.3/361	17.2
300	985	BISN-02	T3	46.1/318	52.5/363	15.0

TABLE 2-continued

Mechanical Properties of Material Evaluated in Example 1						
Lot ID	Cast #	Alloy	Temper	Yield (KSI/ MPa)	Ultimate (KSI/ MPa)	% Elonga- tion
301	971	BISN-03	T3	45.3/313	51.5/355	16.5
302	978	BISN-04	T3	46.3/319	52.6/363	15.3
303	975	BISN-31	T3	46.0/317	52.4/362	16.5
304	973	BISN-31	T451	24.5/169	43.9/303	33.8
306	979	BISN-06	T3	44.5/307	50.2/346	16.8
307	983	2111-31	T3	43.8/302	49.6/342	17.3
308	981	2111-06	T3	45.5/314	51.4/355	15.8
310	989	BISN-NI	T3	38.9/268	42.9/296	13.0
311	986	BISN-CU	T3	40.3/278	45.1/311	16.5
305	977	BISN-31	T8	42.1/290	55.9/386	15.2
233	001	2011	T3	46.8/323	51.6/356	15.5
312	822	6040	T651	44.6/308	49.3/340	18.5
000	000	6040	T6511	52.3/361	55.6/384	13.0

[0034] Machinability testing was conducted by producing a representative part that utilizes several machining operations. This part is depicted conceptually in FIG. **2**. Material removal rates were kept constant between materials by keeping the cutting speed and feed rate constant for all machining operations. The chip size is evaluated by determining the number of clean, dry chips per gram. The results from this evaluation are shown in FIG. **3** and are compared with current Pb-containing free machining material, 2011-T3, as a benchmark comparison. This shows that the alloy/temper combinations tested were better or comparable to the incumbent material. Also tested in this matrix were Pb-free 6040 compositions that are currently available in the market. These have historically not performed as well as 2011-T3, and this test validated their inferior performance.

[0035] In order to test that the materials were not susceptible to cracking in thin wall, severe machining applications, a severe machining test was developed. This involves drilling out the center of the 1.000" (25.4 mm) rod using 0.969" (24.6 mm) diameter twist drill, resulting in a 0.015" (0.38 mm) wall thickness, as shown in FIG. **4**. The RPM and feed rate was kept constant at 1500 RPMs and 0.035" (1.27 mm)/revolution feed rate. Once this test was completed, the specimens were examined for conditions as depicted in FIG. **5**. This test was developed for testing the materials susceptibility to cracking under extreme machining conditions with thin walls, high material removal rates and high torque applied. This test was replicated a minimum of 12 times for each material tested that had acceptable performance from a chip size and material property perspective. The percentage of parts with tears (or cracks) and blowouts was recorded and the results are shown in FIG. **6**. The BISN-31 is designated with the different tempers (T3, T4 and T8) in this figure for simplification. This shows that the 2011 (incumbent Pb-containing alloy) consistently passed, as expected, as well as the Pb-free 6040 alloy variants (note these alloy variants did not perform well from a chip size perspective, however). The only experimental alloy that passed was BISN-31-T4, but unfortunately this failed the tensile property requirements.

[0036] Analysis of these results indicates that alloy/temper combinations with lower yield to ultimate strength ratios perform better from a machining crack susceptibility perspective. Closer analysis of BISN-01 through BISN-04 compositions indicates that lower Bi+Sn content and lower Bi/Sn ratios are beneficial from a machining crack susceptibility perspective when taking into account the severity of the failures. The Bi/Sn ratio appears to be the stronger influence relative to the composition related performance input variables. This is illustrated in Table 3. Note that the Bi—Sn eutectic composition from a weight percent basis is at a ratio of 1.32 Bi/Sn (as shown in FIG. **11**).

TABLE 3

Severity of Machining Crack Susceptibility Results for Alloys BISN-01 through BISN-04					
Alloy	Bi + Sn	Bi/Sn	% Wrinkled	% Torn	% Blowout
BISN-01	0.75	1.14	17%	77%	6%
BISN-02	1.27	1.12	21%	50%	29%
BISN-03	0.76	1.81	7%	13%	80%
BISN-04	1.35	1.70	20%	20%	60%

Example 2

[0037] Billets were cast in 10" (254 mm) diameter and processed into 1" (25.4 mm) rod using the process depicted in FIG. **1** and the compositions listed in Table 4. The % ROA (reduction of area) during the drawing operation was evaluated in this study, particularly in the T3 temper. The effect of homogenization was also evaluated with cast 1110 being homogenized and compared to the unhomogenized cast 1108. The 1" (25.4 mm) rod was evaluated for mechanical properties, machinability, and machining crack susceptibility using the same techniques described in Example 1.

TABLE 4

Compositions and Tempers for Example 2 (weight percent)															
Alloy	Cast	Bi	Sn	Cu	Mg	Fe	Si	Ni	Mn	Pb	Cr	Bi/Sn	Bi + Sn	Temper	% ROA
BI26	1102	0.27	0.24	5.31	0.00	0.42	0.15	0.00	0.00	0.00	0.00	1.13	0.51	T3	20.3
BI26	1103	0.28	0.23	5.40	0.00	0.35	0.13	0.00	0.00	0.00	0.08	1.22	0.51	T3	15.8
BI26	1104	0.27	0.24	5.35	0.00	0.36	0.14	0.00	0.00	0.00	0.00	1.13	0.51	T3	9.3
BI26	1105	0.26	0.24	5.36	0.00	0.38	0.15	0.00	0.00	0.00	0.00	1.08	0.50	T8	15.8
BI26	1106	0.26	0.24	5.34	0.00	0.35	0.14	0.00	0.00	0.00	0.00	1.08	0.50	T651	17.4
BI39	1111	0.39	0.36	5.37	0.00	0.41	0.14	0.00	0.00	0.00	0.00	1.08	0.75	T3	20.3
BI39	1108	0.37	0.35	5.31	0.00	0.39	0.15	0.00	0.00	0.00	0.00	1.06	0.72	T3	15.8
BI39	1109	0.39	0.36	5.41	0.00	0.41	0.14	0.00	0.00	0.00	0.00	1.08	0.75	T3	9.3
BI39	1112	0.40	0.36	5.28	0.00	0.33	0.14	0.00	0.00	0.00	0.00	1.11	0.76	T8	15.8
BI39	1113	0.40	0.36	5.24	0.00	0.40	0.14	0.00	0.00	0.00	0.00	1.11	0.76	T651	17.4
BI39	1110	0.39	0.36	5.32	0.00	0.40	0.14	0.00	0.00	0.00	0.00	1.08	0.75	T3	15.8
BI39MG	1114	0.40	0.37	5.47	0.50	0.42	0.14	0.00	0.00	0.00	0.00	1.08	0.77	T451	17.4

[0038] The mechanical properties are shown in Table 5. This shows that all of the composition and temper combinations were capable of achieving the minimum 2011-T3 target mechanical properties (Yield Strength 38 KSI/262 MPa; Ultimate Strength 45.0 KSI/311 MPa; 10% Elongation). The addition of Mg was successful in achieving these properties as well in the T4 temper.

TABLE 5

Mechanical Properties of Material Evaluated in Example 2							
Lot ID	Cast #	Alloy	% ROA	Temper	Yield (KSI/ MPa)	Ultimate (KSI/ MPa)	% Elongation
338	1102	BI26	20.3	T3	45.3/313	50.5/348	15.0
341	1103	BI26	15.8	T3	43.8/302	49.8/344	18.0
344	1104	BI26	9.3	T3	39.8/275	46.6/322	18.0
345	1105	BI26	15.8	T8	39.2/270	53.8/371	15.0
347	1106	BI26	17.4	T651	40.2/277	58.8/406	23.0
339	1111	BI39	20.3	T3	46.9/324	51.4/355	14.0
342	1108	BI39	15.8	T3	43.8/302	49.7/343	18.5
343	1109	BI39	9.3	T3	38.4/265	47.1/325	12.0
346	1112	BI39	15.8	T8	39.2/270	53.9/372	14.0
348	1113	BI39	17.4	T651	39.9/275	57.5/397	22.0
350	1110	BI39	15.8	T3	43.9/303	50.3/347	17.0
351	1114	BI39	17.4	T451	38.7/267	58.2/402	20.0

[0039] The machinability test, relative to chip size was evaluated with the results depicted in FIG. **7**. These results show that higher Bi+Sn compositions (BI39) perform better from a machinability perspective, as measured by chips/gram, and perform as good or better than the incumbent 2011-T3. The lower Bi+Sn compositions (BI26) generally did not perform as well as the incumbent 2011-T3, but were comparable. It also shows that there is very little difference on the machinability as related to percent reduction area for T3 tempers, regardless of Bi+Sn levels. The addition of homogenization did not improve the machinability, but examination of the grain structure revealed significant improvement relative to peripheral coarse grain (recrystallized grain size on outer periphery of the rod). Therefore the use of homogenization, while not necessary for machinability, may be beneficial for some applications requiring improved surface appearance (such as parts requiring anodizing). The T651 temper material, regardless of alloy composition, performed very well, with small chip size. The T8 tempers generally performed better than the T3 counterparts for a given alloy, particularly the BI26 composition.

[0040] In terms of the machining crack susceptibility test, these results are shown in FIG. **8**, in this case, wrinkles on the surface (per FIG. **5**) were also considered unacceptable. These results show that while composition BI26 performed significantly better than BI39 (confirming that higher Bi+Sn makes the material more susceptible to machining cracks), the temper has a much stronger influence. Note that all of the compositions in this example had less than 1.32 Bi/Sn ratios. The T8 tempers did not crack in this test regardless of composition, while the T6 samples performed very poorly. The T3 tempers all had some failures, with the higher Bi+Sn containing materials having significantly higher failure rates. The BI26-T3 compositions had no failures in terms of tears or blow-outs per FIG. **5**, thus the Bi+Sn has a significant impact on performance.

[0041] These results therefore demonstrate that by producing the material in a T8 temper, higher Bi+Sn levels can be utilized, thus achieving the superior machinability from a chip size perspective as well.

Example 3

[0042] Billets were cast in 10" (254 mm) diameter and processed into 1" (25.4 mm) and 2" (50.8 mm) T3 and T8 rod using the process depicted in FIG. **1** and the compositions listed in Table 6. The rods were evaluated for mechanical properties, machinability, and machining crack susceptibility using the same techniques described in Example 1.

TABLE 6

Compositions and Tempers for Example 3 (weight percent)														
Alloy	Cast	Si	Fe	Cu	Mn	Mg	Zn	Cr	Pb	Bi	Sn	Ti	Bi + Sn	Bi/Sn
SN01	1172	0.16	0.45	5.76	0.03	0.00	0.00	0.00	0.002	0.25	0.21	0.009	0.46	1.21
SN01	1173	0.14	0.36	5.32	0.03	0.02	0.00	0.00	0.000	0.24	0.20	0.010	0.44	1.20
SN02	1175	0.15	0.39	5.55	0.03	0.00	0.01	0.00	0.002	0.35	0.21	0.013	0.56	1.65
SN02	1176	0.15	0.36	5.25	0.03	0.02	0.00	0.06	0.002	0.34	0.19	0.010	0.53	1.83
SN03	1178	0.10	0.38	5.77	0.03	0.02	0.00	0.01	0.000	0.26	0.33	0.005	0.59	0.80
SN03	1182	0.16	0.39	5.37	0.03	0.01	0.00	0.01	0.003	0.24	0.30	0.009	0.55	0.81
SN04	1180	0.15	0.36	5.35	0.03	0.02	0.00	0.00	0.002	0.35	0.35	0.006	0.70	1.00
SN04	1184	0.14	0.37	5.25	0.04	0.02	0.00	0.00	0.002	0.35	0.31	0.011	0.66	1.15

[0043] The mechanical properties are shown in Table 7. This shows that all of the composition and temper combinations were capable of achieving the minimum 2011-T3 target mechanical properties (Yield Strength 38 KSI/262 MPa; Ultimate Strength 45.0 KSI/311 MPa; 10% Elongation).

TABLE 7

Mechanical Properties of Material Evaluated in Example 3						
Alloy/ Temper	Cast	Lot ID	Diameter (inch/ mm)	Yield (KSI/ MPa)	Ultimate (KSI/ MPa)	% Elongation
SN01-T3	1172	402	1.000/25.4	45.0/311	50.4/348	14.0
SN02-T3	1175	403	1.000/25.4	44.4/306	50.3/347	16.0
SN03-T3	1182	404	1.000/25.4	44.5/307	50.7/350	15.0
SN04-T3	1184	405	1.000/25.4	43.9/303	49.6/342	16.0
SN01-T8	1173	398	2.000/50.8	44.2/305	56.6/391	13.0
SN02-T8	1175	399	2.000/50.8	42.1/290	56.2/388	14.0
SN03-T8	1182	400	2.000/50.8	43.3/299	56.8/392	14.0
SN04-T8	1184	401	2.000/50.8	44.8/309	57.2/395	14.0
SN01-T8	1172	760	1.000/25.4	42.7/295	55.8/385	14.0
SN02-T8	1176	761	1.000/25.4	45.4/313	57.3/395	15.0

TABLE 7-continued

Mechanical Properties of Material Evaluated in Example 3						
Alloy/ Temper	Cast	Lot ID	Diameter (inch/ mm)	Yield (KSI/ MPa)	Ultimate (KSI/ MPa)	% Elonga- tion
SN03-T8	1178	762	1.000/25.4	41.5/286	55.3/382	15.0
SN04-T8	1180	763	1.000/25.4	42.8/295	55.0/380	15.0

[0044] The machinability test relative to chip size was evaluated with the results depicted in FIG. **9** for the 1.000" (25.4 mm) diameter material. The results show that the T8 performed superior to the Pb-containing 2011 material, while the T3 material, which still performed acceptably, was not as good as the Pb-containing 2011 material. The test was replicated with the 2.000" (50.8 mm) diameter to ensure the material machined well over a wider range of diameters. While the 2.000" (50.8 mm) diameter results were slightly worse than the Pb-containing 2011 incumbent material in this test, it must be noted that from a chips per gram basis, it was better than any of the 1.000" (25.4 mm) diameter test results. Thus it can be concluded that the material performs well throughout these diameter ranges.

[0045] Machining crack susceptibility testing was also performed on the 1.000" (25.4 mm) diameter material considering wrinkles, tears and blow-outs (per FIG. **5**) as failures. The results of this testing are shown in Table 8.

TABLE 8

Summary of Results for the Machining Crack Susceptibility Testing for 1.000" (25.4 mm) Diameter Example 3					
Alloy	Temper	Cast	Lot ID	Bi/Sn	Percent Passing
SN01	T3	1172	402	1.21	5%
SN02	T3	1176	403	1.83	0%
SN03	T3	1178	404	0.80	0%
SN04	T3	1180	405	1.00	0%
SN01	T8	1172	760	1.21	100%
SN02	T8	1176	761	1.83	45%
SN03	T8	1178	762	0.80	100%
SN04	T8	1180	763	1.00	95%

[0046] These results confirm that for applications with severe material removal rates and part geometries with thin walls that are susceptible to tearing, processing the material in a T8 temper and maintaining Bi/Sn ratios less than 1.32 virtually eliminates this failure mechanism.

[0047] Although the present invention has been disclosed in terms of a preferred embodiment, it will be understood that numerous additional modifications and variations could be made thereto without departing from the scope of the invention as defined by the following claims:

1. A method for making a substantially Pb-free aluminum alloy comprising the steps:

a. producing a billet via direct chill casting an aluminum alloy composition comprising the following components (in weight percent of the aluminum alloy composition):

Pb 0-0.10; Si 0-0.40; Fe 0-0.70; Cu 5.0-6.0; Zn 0-0.30; Bi 0.20-0.80; Sn 0.10-0.50;

with the balance being aluminum save for incidental impurities;

said alloy composition having a ratio by weight of Bi/1Sn of less than 1.32/1;

b. optionally homogenizing the cast billet between 900-1020° F. (482-549° C.);

c. extruding the cast billet into a shape for machine stock;

d. solution heat treating the extrusion from step c. by heating to a soak temperature between 900-1020° F. (482-549° C.);

e. drawing the extrusion from step d.; and

f. artificially aging the product of step e. between 275-375° F. (135-191° C.),

wherein said substantially Pb-free aluminum alloy has an Ultimate Tensile Strength ≥45.0 KSI/311 MPa, Yield Strength ≥38.0 KSI/262 MPa, and % Elongation minimum ≥10% and Pb-free aluminum alloy can withstand a 0.015" (0.38 mm) thick machined wall using a 0.969" (24.6 mm) diameter twist drill at 1500 RPM and 0.037" (1.27 mm) per revolution feed rate with <10% failing for wall tearing or cracking.

2. The method of claim **1** wherein said aluminum alloy composition comprises the following components (in wt. % of the aluminum alloy composition):

Si 0-0.16; Fe 0-0.50; Cu 5.1-5.8; Zn 0-0.05; Bi 0.20-0.40; and Sn 0.20-0.50.

3. The method of claim **1** wherein said aluminum alloy composition has a ratio by weight Bi/Sn in the range from 0.8/1 to 1.32/1.

4. The method of claim **1** where the draw reduction is greater than 5% cross sectional area reduction.

5. The method of claim **1** where the step of artificially aging is a two-step cycle with a first cycle within the temperature range of 200-300° F. (93-149° C.) and a second step within the temperature range of 275-375° F. (135-191° C.).

6. The method of claim **1** wherein said the alloy composition has <0.05 wt. % Pb.

7. The method of claim **1** wherein said alloy composition comprises the following components (in wt. % of the aluminum alloy composition):

<0.05 wt. % Pb, 0.10-0.16 wt. % Si, 0.30-0.50 wt. % Fe, 5.1-5.8 wt. % Cu, 0.002-0.05 wt. % Zn, 0.20-0.80 wt. % Bi, and 0.20-0.50 wt. % Sn.

8. The method of claim **1** wherein said alloy composition consists of the following components (in wt. % of the aluminum alloy composition):

<0.05 wt. % Pb, 0.10-0.16 wt. % Si, 0.30-0.50 wt. % Fe, 5.1-5.8 wt. % Cu, 0.002-0.05 wt. % Zn, 0.20-0.80 wt. % Bi, and 0.20-0.50 wt. % Sn with the balance being aluminum and incidental impurities.

9. The method of claim **1** comprising the steps:

homogenizing the cast billet between 900-1020° F. (482-549° C.) for a time period of not less than 1 hour; and

solution heat treating the extrusion from by heating to a soak temperature between 900-1020° F. (482-549° C.) for 0.5 to 2 hours.

10. A method for making a substantially Pb-free aluminum alloy comprising the steps:

a. producing a billet via direct chill casting an aluminum alloy composition comprising the following components (in weight percent of the aluminum alloy composition):

Pb 0-0.10; Si 0-0.40; Fe 0-0.70; Cu 5.0-6.0; Zn 0-0.30; Bi 0.20-0.80; Sn 0.10-0.50 with the balance being aluminum save for incidental impurities;

said alloy composition having a ratio by weight of Bi/Sn of less than 1.32/1;

b. optionally homogenizing the cast billet between 900-1020° F. (482-549° C.);

c. extruding the cast billet into a shape for machine stock;

d. optionally drawing the product of step c.;

e. solution heat treating the extrusion between 900-1020° F. (482-549° C.);

f. optionally stretch stress relieving the product of step e.;

g. artificial aging the extruded cast billet between 275-375° F. (135-191° C.), wherein said substantially Pb-free aluminum alloy has an Ultimate Tensile Strength >/=45.0 KSI/311 MPa, Yield Strength >/=38.0 KSI/262 MPa and Elongation >/=10% and the Pb-free aluminum alloy has superior machinability when compared to a product having the same aluminum alloy composition in a T8 temper as determined by chip size (chips per gram) as measured in the following machining operations:

a) drilling operation at 650 SFPM and 0.075" (1.91 mm) per revolution feed rate

b) cutoff operation at 550 SFPM and 0.0025" (0.06 mm) per revolution feed rate

c) turning operation at 550 SFPM and 0.014" (0.36 mm) per revolution feed rate

d) forming operation at 150 SFPM and 0.003" (0.076 mm) per revolution feed rate

wherein a greater number of chips per gram is considered a superior measure of machinability.

11. The method of claim **10** wherein said aluminum alloy composition comprises the following components (in wt. % of the aluminum alloy composition):

Si 0-0.16; Fe 0-0.50; Cu 5.1-5.8; Zn 0-0.05; Bi 0.20-0.40; and Sn 0.20-0.50.

12. The method of claim **10** wherein said the alloy composition has <0.05 wt. % Pb.

13. The method of claim **10** wherein said alloy composition comprises the following components (in wt. % of the aluminum alloy composition):

<0.05 wt. % Pb, 0.10-0.16 wt. % Si, 0.30-0.50 wt. % Fe, 5.1-5.8 wt. % Cu, 0.002-0.05 wt. % Zn, 0.20-0.80 wt. % Bi, and 0.20-0.50 wt. % Sn.

14. The method of claim **10** wherein said alloy composition consists of the following components (in wt. % of the aluminum alloy composition):

<0.05 wt. % Pb, 0.10-0.16 wt. % Si, 0.30-0.50 wt. % Fe, 5.1-5.8 wt. % Cu, 0.002-0.05 wt. % Zn, 0.20-0.80 wt. % Bi, and 0.20-0.50 wt. % Sn with the balance being aluminum and incidental impurities.

15. The method of claim **10** wherein said aluminum alloy composition has a ratio by weight Bi/Sn in the range from 0.8/1 to 1.32/1.

16. The method of claim **10** where the step of artificially aging is a two-step cycle with a first cycle within the temperature range of 200-300° F. (93-149° C.) and a second step within the temperature range of 275-375° F. (135-191° C.).

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