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(19) **United States**(12) **Patent Application Publication**
ANDERSON et al.(10) **Pub. No.: US 2015/0132181 A1**(43) **Pub. Date: May 14, 2015**(54) **ALUMINUM WELDING FILLER METAL,
CASTING AND WROUGHT METAL ALLOY**(52) **U.S. Cl.**
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Traverse City, MI (US)(57) **ABSTRACT**(72) Inventors: **Stephen L. ANDERSON**, Traverse City,
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Traverse City, MI (US)(21) Appl. No.: **14/532,431**(22) Filed: **Nov. 4, 2014****Related U.S. Application Data**(60) Provisional application No. 61/902,695, filed on Nov.
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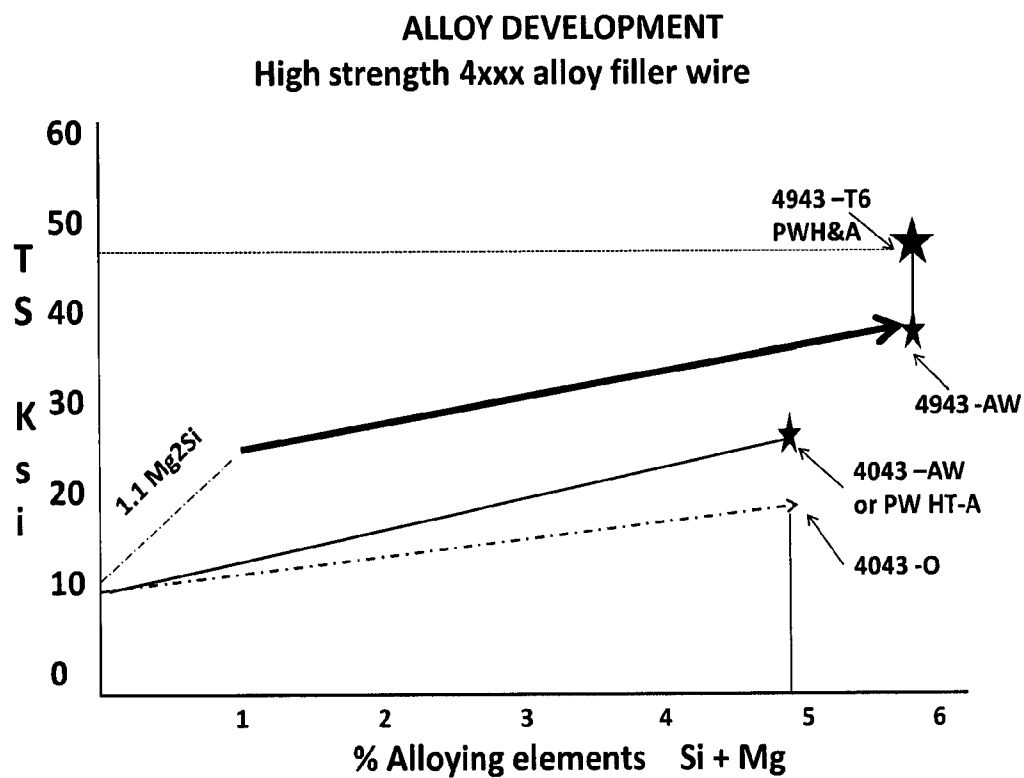
A composition for producing aluminum casting, wrought, and welding filler metal alloys having a chemistry comprising Si varying from approximately 0.1 and 0.9 wt %, Mn varying from approximately 0.05 to 1.2 wt %, Mg varying from approximately 2.0 to 7.0 wt %, Cr varying from approximately 0.05 to 0.30 wt %, Zr varying from approximately 0.05 to 0.30 wt %, Ti varying from approximately 0.003 to 0.20 wt %, and B varying from approximately 0.0010 to 0.030 wt %, and a remainder of aluminum and various trace elements. The alloy is particularly suited to producing high strength structures such as automobiles, truck trailers, rail cars, and ships. It is the first 6xxx series weld filler metal that can be post-weld thermally treated and can weld 3xxx, 5xxx, 6xxx, and 7xxx series base alloys yielding far superior mechanical properties than those attainable from any other aluminum filler metal.

FIGURE 1: Invention alloy approximate chemical analysis

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Be	Zr	Ti	B	Each	Total
Alloy 1	0.50 - 0.70	0.20	0.10	0.05- 0.20	5.7 - 6.1	0.05- 0.20	0.10	0.0003	0.05- 0.15	0.003- 0.10	0.0010- 0.010	0.05	0.15
Alloy 2	0.30 - 0.50	0.20	0.10	0.50- 1.0	3.4 - 3.7	0.05- 0.20	0.10	0.0003	0.05- 0.15	0.003- 0.10	0.0010- 0.010	0.05	0.15
Invention Alloy	0.1 - 0.9	0.50	0.50	0.05- 1.2	2.0 - 7.0	0.05- 0.30	0.30	0.0008	0.05- 0.30	0.003- 0.20	0.0010- 0.030	0.05	0.15

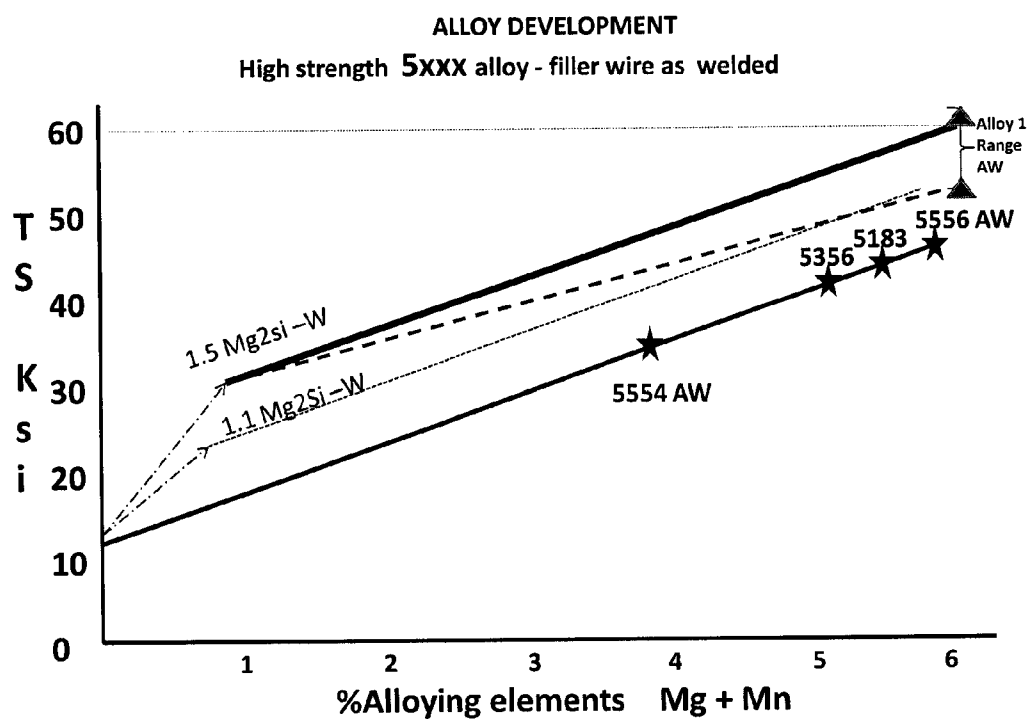
Note: Zr + Ti = 0.20 Max

FIGURE 2:

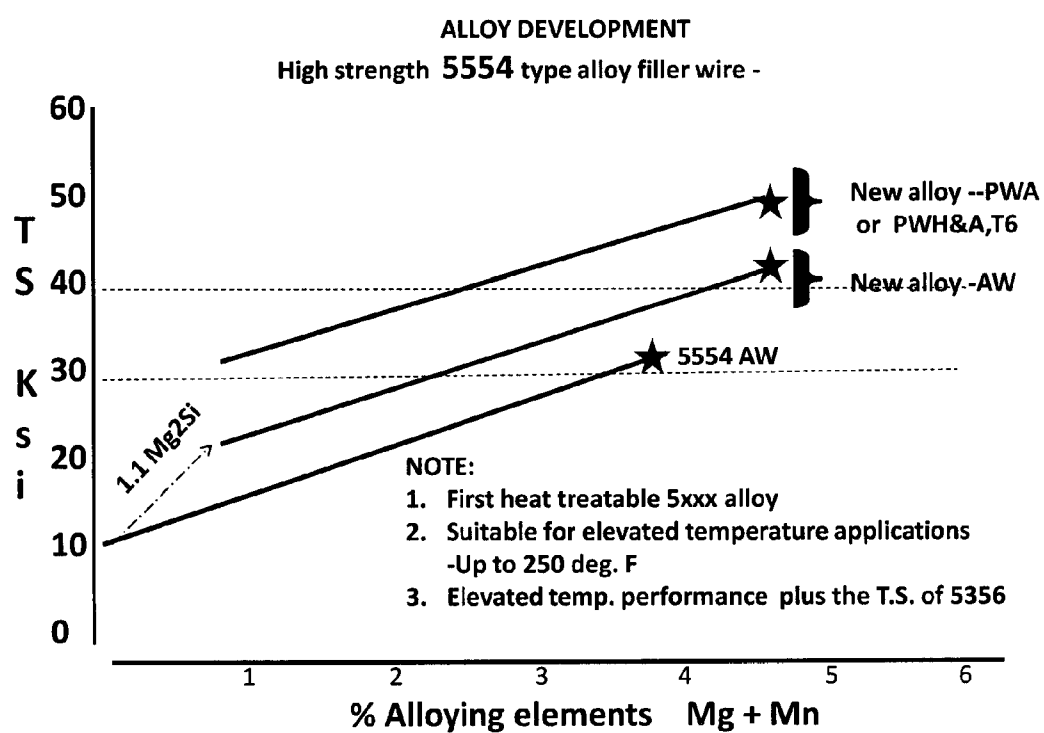


Note: AW - as welded
PWHT-A - post-weld heat treated and aged
O - annealed

FIGURE 3: Properties of pure aluminum vs. aluminum with Mg₂Si plus varying amounts of Mg + Mn alloying elements



Note: AW - as welded

FIGURE 4: Effect of Mg₂Si on 5554 type filler alloy

Note: AW - as welded
PWA - post-weld aged
PWH&A - post-weld heat treated and aged

FIGURE 5: Effect of alloying elements of conductivity/resistivity

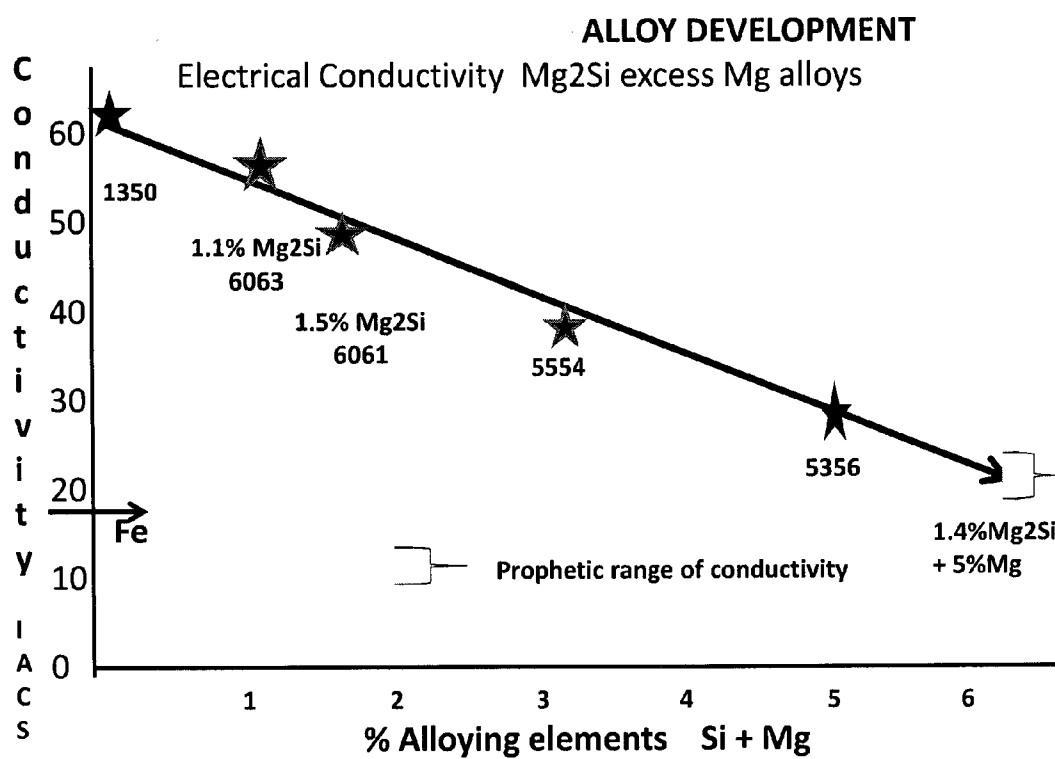
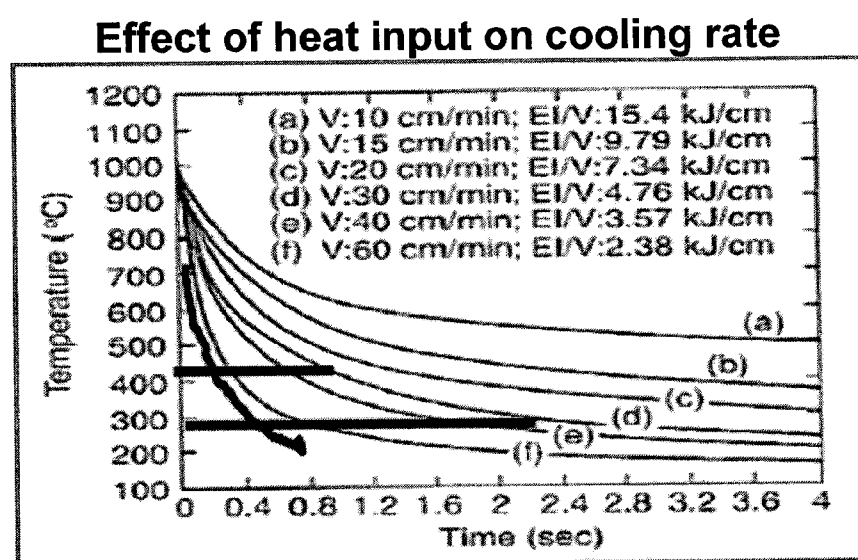


FIGURE 6: Effect of % Mg₂Si on properties of welded aluminum

<u>Alloy Base Metal</u>	<u>T.S. (ksi)</u>	<u>Y.S.(ksi)</u>
Pure aluminum 1350 -O temper	10	4
0.8% Mg ₂ Si (6063) -T1 (wrought)	22	13
-as welded	20	10
1.4% Mg ₂ Si (6061) -T1 (wrought)	35	21
-as welded	30	16

NOTE: The effect of Mg₂Si on base alloys is known. This knowledge gives support for the prophetic values used in providing tensile, yield and shear strength values for the new filler alloys as-welded and in post-welded thermally treated conditions.

FIGURE 7: Weld cooling rates for different heat inputs



Conversion to Aluminum:

Typical Welding Heat inputs for Aluminum

Low 0.580 KJ/CM

Medium 0.750 KJ/CM

High 1.200 KJ/CM

Deg. F 800=C426

500=C260

The bold curve shown is the typical cooling rate for aluminum welds.

FIGURE 8: Effects of Mg plus Mn when combined with Mg₂Si on tensile, yield, and shear strength

			Typical Properties		
<u>Alloy</u>			<u>T.S. ksi</u>	<u>Y.S. ksi</u>	<u>Shear ksi</u>
Pure aluminum 1350	-O		10	4	6
4043 4.5% Si	-AW		27	14	16
5554 3.5%Mg + Mn	-AW		34	15	20
5356 5.2% Mg + Mn	-AW		38	18	23
5183 5.4% Mg + Mn	-AW		42	22	25
5556 5.7% Mg/Mn	-AW		44	24	26.5
5087 5.7% Mg/Mn	-AW		44	24	26.5
Invention Alloy 1 (Prophetic typ.)	-AW		52	34	31
	-PWA		58	40	35
Invention Alloy 2 (Prophetic typ.)	-AW		40	20	24
	- PWA		46	28	28
	-PWHT&A		50	32	30

AW – as welded, PWA – post weld aged, PWHT&A - post weld heat treated and aged

Note 1: It is anticipated that invention alloys 1 and 2 will replace alloys 5356, 5183, 5554, 5556 and 5087. Specifically, alloy 2 will replace 5554 and 4xxx alloys for elevated temperature applications below 250 deg. F.

Note 2: Shear strength for design considerations is based on longitudinal shear direction and is 0.51 x the minimum allowable tensile strength of a filler alloy. The table shown above gives typical shear strength which is based on 0.6 x the typical tensile strength which is also listed.

FIGURE 9: Electro negativity of various solid solutes and individual constituents in aluminum.

<u>Solid Solute or Constituent</u>	<u>Potential Volts</u>
99.95 Al	-0.85*
Al + 1%Mg ₂ Si	-0.83*
Al + 5%Mg	-0.88*
CuAl ₂	-.073
Al + 4%Zn	-1.05

***Considered to have similar potentials and excellent corrosion resistance properties.**

Note: The electronegative potential values affect corrosion properties in welded aluminum alloy structures.

FIGURE 10: Alloy design considerations for fatigue strength

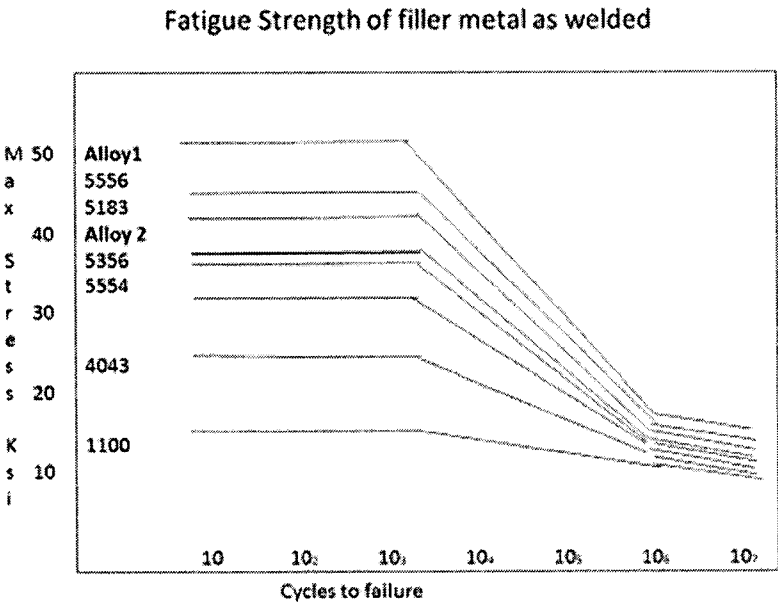


FIGURE 11: Alloy design considerations for toughness

	Tear Resistance	Notch Toughness
<u>Alloy</u>	<u>Unit Propagation Energy</u>	<u>Ratio</u>
5356 AW	1100	2.20
5183 AW	1050	2.05
5554 AW	1050	2.35
4043/4943 AW	350	0.35
4943 PW HT&A	100	0.10
<u>Prophetic toughness values of the new invention alloy 1 as-welded and alloy 2 as welded or post-weld thermally treated.</u>		
ALLOY 1 AW	1050	2.05
ALLOY 1 PWA	1050	2.00
ALLOY 2 AW	1050	2.20
ALLOY 2 PWHT&A	1050	2.05

Terms: Unit propagation energy - energy required to grow a crack in a welded structure.

 Notch toughness - measures the effect of a notch on tensile & yield strengths.

Note: AW – as welded

 PWA – post-weld aged

 PWHT&A – post-weld heat treated and aged

Figure 12: Typical Fillet and Butt weld joints

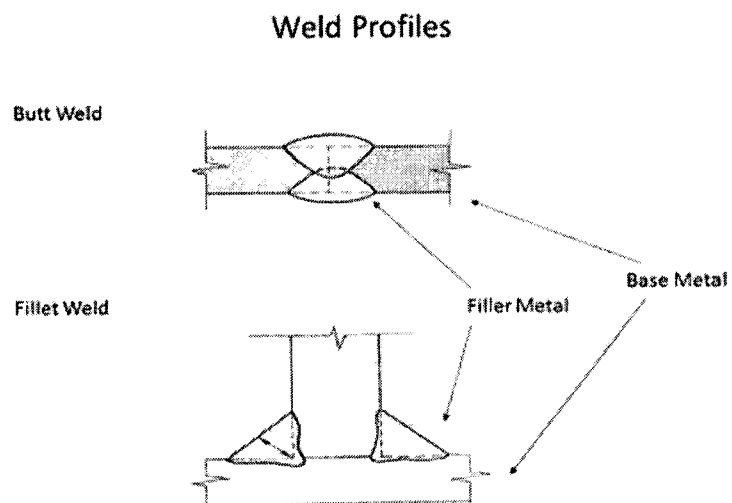


Figure 13: Fluidity in Aluminum Alloys

Internal Friction of Molten Aluminum at 1292 deg. F

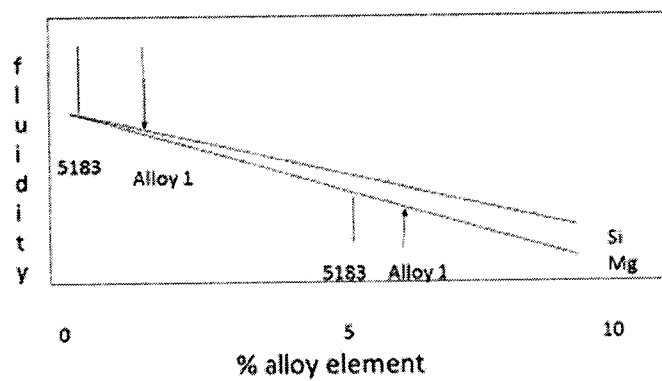
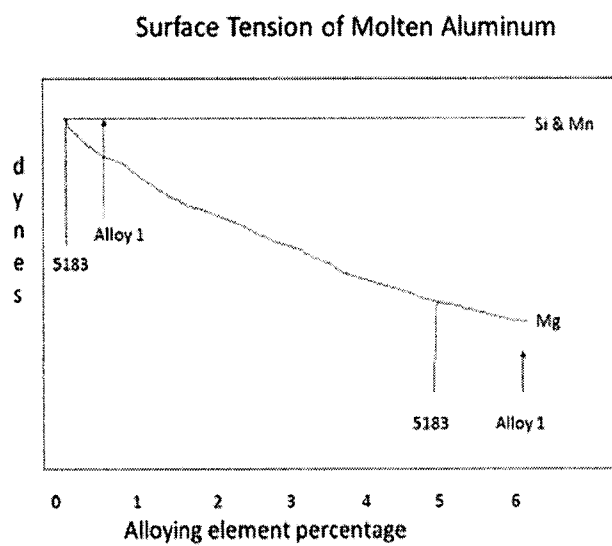


Figure 14: Surface Tension in Aluminum Alloys

ALUMINUM WELDING FILLER METAL, CASTING AND WROUGHT METAL ALLOY

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. provisional patent application Ser. No. 61/902,695 filed Nov. 11, 2013.

FIELD OF THE INVENTION

[0002] This invention relates to the field of welding high strength aluminum structures, and more particularly to the alloy compositions suitable for welding aluminum alloys.

BACKGROUND OF THE INVENTION

[0003] There are currently many types of welding processes used to join metal components. Some of these include Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Plasma Arc Welding (PAW), Electron Beam Welding, Inertia Welding, Friction Stir Welding and others. GMAW, GTAW, and PAW processes use filler metals to accomplish the weld joining process. Electron Beam Welding and the other processes mentioned here do not typically use filler metals to accomplish welding but they may in some instances. The filler metals developed here are applicable to all weld joining processes.

[0004] Arc welding is the most commonly used welding process in use today. It joins metal components by melting a portion of the base metal to be joined and melting a filler metal usually in the form of a wire to create a molten weld pool at the joint. The filler metals currently available for welding aluminum are subject to alteration of their mechanical properties during the welding process. The variables present during welding such as joint design, base metal section size, heat input, and penetration of the weld bead into the base metal with the resultant variation of the amount of base metal dilution into the filler metal puddle all affect the resulting mechanical and physical properties of the finished weld joint. These properties of the currently available filler metals for aluminum result in a severe limitation of the mechanical and physical properties of aluminum structures that can be consistently and reliably produced in modern manufacturing operations.

[0005] Welds in aluminum structures can fail under dynamic or static loading when in service. They can fail from many factors such as impact loading or fatigue. Failure in the weld joint is accelerated by discontinuities or structural defects that are often present in the weld joint. Therefore, it is important that the filler metal used to weld structural components have a higher mechanical strength than the base metals being joined so that failures, if they are to occur, are directed to the base material where there are far fewer discontinuities. The aluminum welding filler metals available today frequently do not provide that mechanical strength advantage and consequently weld joints become the weak links in aluminum welded structures. Welding design engineers are constantly seeking welding filler metals with higher as-welded strength to improve the life of their welded structures and provide additional degrees of safety for their welded products.

[0006] Aluminum filler metals have been developed since the invention of arc-welding processes. The popular aluminum filler metals in use today were developed to weld specific

wrought or cast alloys simply by slightly modifying the composition of the base metals to be joined. For the 5xxx series filler metal alloys, these modifications were mainly done by adjusting base metal chemistries in order to achieve a filler metal chemistry that compensates for burn-off of certain alloying elements, such as Mg, in the welding arc. Most of the 4xxx series filler metal alloys were created by adapting already existing brazing alloys. The resulting filler metals have severe limitations in their ability to provide consistent reliable mechanical and physical properties in welds when subjected to the many variables present in the welding process.

[0007] There is a desire in the aluminum welded structures industry to have weld filler metals that not only produce superior strength but also provide superior corrosion resistance and that match the base metals for anodizing color of the base metal when anodized after welding. It is important to design aluminum welding filler metals that have the corrosion resistance and anodizing characteristics that are desired.

[0008] Heat generated by welding processes and in particular arc welding of aluminum has always been a negative to be dealt with. Heat causes deterioration of the mechanical and sometimes the physical properties of both the weld joint and the heat effected zone of the base metal. This is true for both heat treatable and non-heat treatable aluminum alloys. None of the currently available aluminum filler metal alloys has its metallurgy specifically formulated to develop as-welded mechanical and physical properties that exceed the properties of the base metal in all welding conditions. To achieve this, the metallurgy of the alloy must be designed to take advantage of the unique sequence of thermal events that takes place in the welding process, namely that of melting, rapid solidification, and cooling rate. These cooling rates must be fast enough to meet the time-temperature-transformation limit of the specific filler metal alloy necessary to obtain the microstructure required in the weld to produce the desired mechanical and physical properties on a consistent and reliable basis.

[0009] The chemical composition of filler metals that are to be used in the form of wire or rods must have the mechanical properties that allow it to be fabricated into wire. This has been a limiting factor in developing higher strength 5xxx series filler metal alloys.

[0010] The rapid advancement in the use of aluminum to produce automobiles, trucks, trailers, high-speed trains, rail cars, ships, military vehicles, rockets, missiles, satellites and many other products, demands the development of new filler metals with increased mechanical and superior physical properties to meet the demands of these products.

SUMMARY OF THE INVENTION

[0011] This invention consists of an aluminum alloy composition comprising Si in a weight percentage of between approximately 0.1 and 0.9 inclusive, Mn in a weight percentage of between approximately 0.05 and 1.2 inclusive, Mg in a weight percentage of between approximately 2.0 and 7.0 inclusive, Cr in a weight percentage of between approximately 0.05 and 0.30 inclusive, Zr in a weight percentage of between approximately 0.05 and 0.30 inclusive, Ti in a weight percentage of between approximately 0.003 and 0.20 inclusive and B in a weight percentage of between approximately 0.0010 and 0.030 inclusive with a remainder of aluminum and trace elements. Except for the trace elements which are noted in FIG. 1 with a single maximum allowable percentage, the balance of the elements present in this new alloy composition

have been intentionally added and controlled with specific percentage ranges in order to achieve the desired properties of this alloy. The reason for the presence and percentage content of each of the intentionally added alloying elements is as follows:

- [0012]** A. Silicon—The approximate Si range of the alloy composition of between 0.1% and 0.9% by weight, allows for the formation of Mg₂Si in amounts that will remain in solid solution at the quench rates present during typical welding operations. The alloy is designed to prevent Mg₂Si that is out of solution in solidified weldments or castings.
- [0013]** B. Manganese—The approximate Mn range of the alloy composition of between 0.05% and 1.2% by weight, enhances mechanical properties through elemental solid-solution strengthening and is controlled to prevent reduced ductility and toughness. The addition of Mn increases mechanical properties when controlled to below its maximum solubility limit in aluminum. It provides added strength without reduction of corrosion resistance in salt water applications.
- [0014]** C. Magnesium—The approximate Mg range of the alloy composition of between 2.0% and 7.0% by weight, allows the formation of Mg₂Si in the amount that remains in solid solution at the quench rates present during typical welding operations. Further, the excess Mg then stays in elemental solid solution to provide the desired mechanical and physical properties. The maximum free Mg is controlled to prevent reduced corrosion characteristics in salt water exposure applications.
- [0015]** D. Chromium—The approximate Cr range of the alloy composition of between 0.05% and 0.30% by weight, is added to control grain structure and to prevent recrystallization. This range improves corrosion resistance and toughness. Above 0.35% Cr forms coarse constituents with other impurities or additions such as Mn, Fe, Zr or Ti.
- [0016]** E. Zirconium—The approximate Zr range of the alloy composition of between 0.05% and 0.30% by weight is controlled to improve the resistance to solidification cracking in weldments and castings.
- [0017]** F. Titanium and Boron—The approximate Ti and B ranges of the alloy composition with the approximate Ti range of between 0.003% and 0.20% by weight and the approximate B range of between 0.0010% and 0.030% by weight are used in combination to control grain structure size and shape in weldments and castings. This cast structure improves stress corrosion cracking, toughness, and ductility. However, Ti tends to form coarse constituents with Cr. With the addition of very small amounts of B, the Ti addition can be minimized without the loss of its grain refinement effects.
- [0018]** G. Zirconium+Titanium—Zr plus Ti has a limit set in the alloy composition of 0.20% maximum. Zr, Ti, B, and Mn form coarse constituents with Cr. In coarse Cr constituent calculations, Zr and Ti are the greatest negative contributors in constituent formation that takes place with Cr. Therefore, Zr plus Ti has been controlled with a combined maximum amount.

[0019] Within the chemical range of the alloy composition, many specific alloys can be formulated which have the basic metallurgical properties of the invention alloy but can be tailored to meet specific properties. For example, when the alloy is used to produce welding filler metal, a chemistry can

be selected to be used for elevated temperature service, or for matching of corrosion resistance properties of the cast or wrought alloys being joined, or for giving good anodizing color matching with the alloys being welded. In accordance with one aspect of the invention, an alloy composition is provided for welding the 5xx, & 7xx casting alloys and all of the 5xxx series of non-heat treatable wrought alloys except for alloy 5454 or other alloys intended for elevated temperature service. This is an alloy for the production of both castings and welding filler metal comprising Si in a weight percent of between approximately 0.50 and 0.70 inclusive, Mn in a weight percentage of between approximately 0.05 and 0.20 inclusive, Mg in a weight percent of between approximately 5.7 and 6.1 inclusive, Cr in a weight percent of between approximately 0.05 and 0.20 inclusive, Zr in a weight percent of between approximately 0.05 and 0.15 inclusive, Ti in a weight percent of between approximately 0.003 and 0.10, B in a weight percent of between approximately 0.0010 and 0.010 with a remainder of aluminum and trace elements (see FIG. 1 for the full chemical analysis). This new alloy will be referred to as alloy 1 and will replace the currently available welding filler metal alloys 5356, 5183, and 5556 for all applications. It will provide welds that have significantly higher as-welded mechanical properties. Higher tensile, yield, shear, and fatigue strengths will allow aluminum to be used in new higher strength applications. It will allow currently designed welded structures to result in fewer structural failures in service.

[0020] In accordance with another aspect of the invention, an alloy composition is provided for welding the corresponding Cu free 3xx, 5xx, & 7xx casting alloys and alloy 5454 as well as other 3xxx, 5xxx or 6xxx series alloys intended for use at elevated temperatures up to 250 degrees F. This is an alloy comprising Si in a weight percent of between approximately 0.30 and 0.50 inclusive, Mn in a weight percent of between approximately 0.50 and 1.0 inclusive, Mg in a weight percent of between approximately 3.4 and 3.7 inclusive, Cr in a weight percent of between approximately 0.05 and 0.20 inclusive, Zr in a weight percent of between approximately 0.05 and 0.15 inclusive, Ti in a weight percent of between approximately 0.003 and 0.10 inclusive, B in a weight percent of between approximately 0.0010 and 0.010 inclusive with a remainder of aluminum and trace elements (see FIG. 1 for the full chemical analysis). This alloy composition will be referred to as alloy 2 and provides higher tensile, yield, shear, and fatigue strengths for elevated temperature applications. It allows currently designed welded structures, used at elevated temperatures, to experience fewer structural failures in service. Further, this alloy is the only 6xxx series filler metal alloy that is heat treatable. The heat treatability of this 6xxx series filler metal alloy allows for post-weld aging or solution heat treatment and aging of both 6xxx and 7xxx alloy structures to fully recover their pre-welded strengths. This alloy is capable of welding silicon based casting alloys to wrought alloys with less than 3% Mg. In complex designs such as automobile or truck structures, where silicon based castings are welded to wrought alloys with less than 3% Mg, there are currently only two choices of filler metal available. The choices are the use of a low strength 4xxx series filler metal alloy or 5554 filler metal. Alloy 2 will allow welding of silicon based aluminum casting to wrought 6xxx and 5xxx series alloys with significantly higher mechanical properties in the weld joint.

[0021] Alloys 1 and 2 can both be used to weld the 3xxx, 5xxx, 6xxx, and 7xxx series aluminum alloy components. Both alloys provide weldments with higher as-welded tensile, yield, shear, and fatigue strengths than any filler metal available in the AWS filler metal specifications. Specifically designed into alloy 2, is the ability to post-weld thermally treat weldments. It can be post-weld aged or post-weld solution heat treated and aged. Historically, only some 4xxx series filler metals would respond to post-weld thermal treatments when welding 6xxx series alloys. The resultant welds have very low fracture toughness with high crack growth sensitivity. This loss of toughness has precluded the use of 6xxx series alloys in many welded applications where toughness and fracture characteristics are important design criteria. Both alloys 1 and 2 selected from the invention have significantly higher toughness than any 4xxx filler alloy as welded and alloy 2 can be post-weld aged or solution heat treated and aged with full retention of toughness. All 4xxx alloys experience a significant loss of toughness with post-weld thermal treatments. This invention addresses this limitation of the currently available families of aluminum welding alloys. If mechanical properties and fracture toughness can be greatly increased, the size of weld beads in existing structures can potentially be reduced to achieve a cost savings in welding filler material and increased welding speeds.

[0022] Alloys 1 & 2 are only a couple of the compositions which can be formulated from the broader range of chemistries included in the composition of this invention alloy. There are any number of alloy compositions that can be formulated within the limits of the broader composition to achieve maximum performance of mechanical properties, and other properties such as corrosion resistance or color matching to the aluminum alloys being welded when post-weld anodizing is performed, or to adjust metallurgical properties to provide superior elevated temperature performance up to 250 degrees F.

[0023] In addition to this, chemistries can be adjusted to provide other advantageous welding performance properties such as electrode burn-off rate, cold metal short-arc transfer, bead droplet performance in the welding arc, improved weld bead penetration, or improved fluidity of the weld filler metal etc. The ability to adjust these welding parameter characteristics of the filler metal affects the shielding gas that is required to achieve desired end results and can result in substantial cost savings.

[0024] The invention alloy composition provides an aluminum welding filler metal comprised of a spooled or a linear wire cut to length, or any other electrode or filler metal shape that is to be melted and fused to aluminum alloy components that are to be joined together by welding. This invention is intended to cover all new methods of weld joining where a filler metal is utilized or where a layer of bonding metal is used between aluminum alloy components and is subsequently melted to join them.

[0025] The invention alloy composition provides an aluminum chemistry that can be used to produce cast aluminum products that can be joined to wrought aluminum extrusions, sheet, and plate and will yield similar mechanical properties in either the as-welded or post-weld thermally treated condition. Of critical importance here is that the weld filler metal alloy composition can be matched to the chemistry of the casting.

[0026] The invention alloy composition can also be used to produce wrought products. In one instance this makes it pos-

sible to match castings, wrought shapes, and welding filler metal in welded structures where the entire structure consists of the same chemistry. This allows for the use of one filler metal to be used in modern complex welding cells that will perform all of the welding operations where cast and wrought structures are being welded together. This can result in large cost savings particularly in complex robotic welding operations. The invention alloys are not limited to use in weldments. In another instance, the alloy compositions possible within the limits of this invention can be used to produce forged and cold headed parts. One such application is in the production of aluminum fasteners such as rivets, where the desired fastener can be cold headed to final shape and then solution heat treated, quenched and aged to produce increased tensile and shear strengths while maintaining very high toughness properties. The invention alloy allows for the development of excellent corrosion properties along with the ability to match color when post-fabrication anodizing is performed.

[0027] Other advantages, features and characteristics of the present invention, as well as methods of operation and functions of the related elements of the structure, and the combination of parts and economies of manufacture, will become more apparent upon consideration of the following detailed description and the appended claims with reference to the accompanying photographs, the latter being briefly described hereinafter.

BRIEF SUMMARY OF THE DRAWINGS

[0028] The description herein makes reference to the accompanying drawings wherein like reference numerals refer to like parts throughout the several views and wherein:

[0029] Some of the metallurgical and mechanical aspects of this invention are best illustrated through the use of graphical representations of the principals involved. Several graphs and charts have been included to illustrate the critical elements of this invention.

[0030] FIG. 1 is a table showing the chemical composition of the invention alloy along with alloys 1 & 2 which are two preferred embodiments.

[0031] FIG. 2 is a graph showing the tensile strength of various 5xxx series filler metal alloys as it varies with increasing percentages of the alloying elements Mg and Mn in combination. Included on this graph is a band of prophetic properties that are achievable with the invention alloy composition depending on the chemical compositions chosen within the allowable limits and the properties that are achievable as-welded or in various states of thermal treatment.

[0032] FIG. 3 is a graph showing the tensile strength of various 4xxx series alloy filler metals as it varies with increasing percentages of its alloying elements.

[0033] FIG. 4 is a graph showing the typical tensile strength of as-welded 5554 along with a range of prophetic tensile strengths that the invention alloy 2 is capable of producing as welded and when post-weld thermally treated.

[0034] FIG. 5 is a graph showing the Electrical Conductivity of various aluminum alloys as it is affected by the percentage of alloying elements Si and Mg.

[0035] FIG. 6 is a table showing the typical tensile strength of two aluminum alloys 6063 and 6061 as the content of Mg₂Si is increased. The effects of increasing Mg₂Si on the mechanical properties of a weldment are illustrated.

[0036] FIG. 7 is a chart showing weldment cooling rates for varying welding heat inputs. The critical cooling range for aluminum is illustrated.

[0037] FIG. 8 is a table showing the typical solid-solution strengthening provided by the increasing combination of Mg plus Mn when alloyed into a relatively pure aluminum matrix without Si present. It also shows the impact of including homogenous Mg₂Si into pure aluminum along with free Mg and Mn. The chart shows the typical shear, tensile, and yield strengths of various aluminum filler metal alloys including the prophetic properties of the invention alloys.

[0038] FIG. 9 is a chart showing the electronegative potential of various solid solutes or constituents in aluminum alloys.

[0039] FIG. 10 is a chart showing the as-welded fatigue strength of various aluminum alloys.

[0040] FIG. 11 is a chart showing the toughness of various aluminum alloys welded with various popular aluminum weld filler metal alloys.

[0041] FIG. 12 is a drawing showing a typical fillet weld and butt weld joint.

[0042] FIG. 13 is a chart showing the effect of increasing alloy content on the fluidity of aluminum alloys.

[0043] FIG. 14 is a chart showing the effect of increasing alloy content on the surface tension of aluminum alloys.

DETAILED DESCRIPTION OF THE ILLUSTRATIVE EMBODIMENT

[0044] Historically, welding filler metal alloys for aluminum have been developed by simply adapting the chemistries of already existing brazing alloys or by slightly modifying the chemistries of the cast or wrought alloys to be welded. In the case of the 4xxx series of welding alloys, most were adaptations of pre-existing brazing alloys. In the case of the filler metal alloys for welding cast alloys, they are simply a replication of the chemistry of the cast alloys to be welded with some modifications for elements that will burn off during welding. In the case of the 5xxx series filler metal alloys, they also are a slightly modified chemistry of the 5xxx series wrought alloys to be welded. Consequently, welding engineers struggle to produce welds where the strength of the weld joint significantly exceeds the strength of the base metals being welded. Because of the mechanical defects that are inherently present in all weld joints, it is critical for dynamically and in some cases statically loaded structures to have the strength of the weld joints exceed the strength of the base metals being joined. This becomes particularly critical in fillet welds and in partially penetrated butt-joint welds (See FIG. 12 for pictures of a typical fillet and butt weld joint). It is estimated that in general manufacturing operations, approximately 70% of all welds end up with partial penetration. In these cases, the weld metal bears all of the stress loads when in service. It becomes critical that weld joints have superior strength and toughness if welded structures are to meet their designed service life. This invention addresses this limitation of the currently available families of aluminum welding filler metal alloys.

[0045] Heat generated during the welding process has always been a negative. Heat deteriorates the properties of the base metal in the heat affected zone. Until now, there have not been any alloys registered with the Aluminum Association for welding or listed in the AWS A5.10 filler metal specification for aluminum that have been specifically designed to optimize their mechanical and physical properties by utilizing the

thermal processes that are present in GMA and GTA welding operations. Additionally, when attempts have been made to produce higher strength 5xxx series welding filler metals they have been limited because, as the strength of the alloys was increased through maximizing Mg and Mn additions, the alloys very rapidly reached the point where the ductility of the alloy was lowered such that they could no longer be fabricated into welding wire or rods. The chemistry of the 6xxx series welding filler metal alloy of this invention was designed so that it could be thermally processed in such a way as to allow the alloy to be drawn into welding wire of the popular sizes. Next, the chemistry was designed so as to achieve maximum potential mechanical properties during the melting, rapid solidification, and subsequent cooling to room temperature of the weld joint. In addition to this, the invention alloy composition was designed to be adjustable so as to be able to adjust the corrosion properties and to be able to match the anodizing characteristics of the base metal alloys being welded. It was also a design objective to be able to adjust the Mg content in the alloy so that it could be used to weld 5454 and other base alloys that are used in elevated temperature applications up to 250 degrees F. Finally, this new 6xxx series filler metal alloy can be used to weld the 6xxx series wrought alloys and be responsive to thermal treatments such that after post-weld thermal treatment operations, the strength of the filler metal exceeded that of the 6xxx series base metals being welded without a loss of toughness.

[0046] Aluminum alloys are divided into two categories, heat treatable and non-heat treatable. The 6xxx series alloys are heat treatable. The principal strengthening mechanism in these alloys is achieved through dissolving Si and Mg into solution through a solution heat treatment operation, then quenching to lock them in solution at room temperature. The alloy is then artificially aged at elevated temperatures to precipitate out Mg₂Si as coherent homogeneously dispersed particles that stress and thereby strengthen the microstructure. Non-heat treatable alloys such as the 3xxx, 4xxx and 5xxx series alloys achieve their mechanical properties through solid solution strengthening of the dissolved alloying elements, primarily Mn in the case of 3xxx series alloys, Si in the case of the 4xxx series alloys and Mg plus Mn in the case of the 5xxx series alloys. These alloys achieve additional strength through cold working operations. However, in the as-welded condition the 3xxx, 4xxx, and 5xxx series filler metals obtain their strength solely by solid solution strengthening of their principal alloying elements since no cold working is done after welding.

[0047] In the invention alloy composition, Mn is used in very limited amounts, when in the presence of higher magnesium contents, since it quickly creates a microstructure that results in brittle fracture when the extreme levels of cold work required to fabricate wire is encountered. Cu content is closely controlled in the base metal composition to reduce quench sensitivity during welding.

[0048] The 4xxx series welding filler metals cannot be used to weld the high strength 5xxx series base metal alloys and they have limited use for welding the high strength 6xxx series base metals due to their high Si content and low toughness properties.

[0049] The currently available 5xxx series weld filler metal alloys contain Mg and Mn as the principal alloying elements and contain no intentional additions of Si. FIG. 3 shows the effect of increasing additions of Mg and Mn on the tensile strengths of the 5xxx series welding filler metal alloys. In the

as-welded condition, they rely solely on the solid solution strengthening provided by Mg and Mn. No free silicon is present in the microstructure. FIG. 8 shows the effect of adding Si to form Mg₂Si in combination with Mg and Mn resulting in increased tensile and shear strengths.

[0050] In the 6xxx series of wrought alloys, the alloying elements of Si and Mg are carefully formulated to produce Mg₂Si in the final microstructure with little or no excess Si or Mg present after the final fabrication and heat treatment operations are completed.

[0051] The strengthening mechanism of the combination of Mg₂Si with the addition of excess Mg at varying levels in the invention alloy composition was chosen to achieve the desired properties in the welding filler metal of this invention. The maximum solid solubility of Mg₂Si in aluminum is 1.85%. In the 6xxx series alloys varying amounts of Mg₂Si are used to achieve their mechanical properties (See FIG. 6). For this invention, various levels of Mg₂Si have also been chosen to achieve the desired as-welded properties after welding the 5xxx series alloys and to achieve the desired as-welded and post-weld thermal treated properties desired when welding the 6xxx series alloys. The presence of Mg₂Si that exceeds the solubility limit of 1.85% manifests itself in the as-welded microstructure as large particles of heterogeneous Mg₂Si that do not respond to thermal treatments and have the other undesirable attribute of tying up excess Mg and not allowing it to be available for solid solution strengthening of the matrix. It is also known that Mg present in solid solution lowers the solubility of Mg₂Si from the 1.85% level in pure aluminum. Therefore, the range of levels of Mg₂Si in the new filler metal alloy composition was conservatively chosen in order to avoid producing excess Mg₂Si that would be out of solution in the as-welded or post-weld thermally treated microstructures.

[0052] In the invention alloy composition, the limits of Si content are set at approximately 0.1% to 0.9% by weight, the limits of Mn content are set at approximately 0.05% to 1.2% by weight and the limits of Mg content in the invention alloy are set at approximately 2.0% to 7.0% by weight. For each alloy formulated within the limits of the invention alloy composition, the Mg₂Si content is set at approximately 1.1% to 1.5% by weight. These levels avoid the problems of producing excess Mg₂Si when significant levels of excess Mg are present. The ratio by weight of Mg to Si in Mg₂Si is 1.73 to 1 and this ratio is used to calculate the proper alloy addition levels of Mg and Si. There are a number of other considerations that are designed into the invention alloy composition. Among them is that free Mg must be controlled below 5.2% by weight in order to stay out of corrosion problems that occur when free Mg content gets above that level. The invention alloy composition uses the formation of Mg₂Si to remove Mg from solution thereby controlling the free Mg in solution in the alloy to the proper limit of less than 5.2% by weight. This is important for the weld filler metal alloy and the casting alloy.

[0053] The invention alloy composition was designed specifically to take advantage of the thermal processes present during welding operations. In both GMA and GTA welding processes, the filler metal is melted and solidified very rapidly with the time frame being generally less than two seconds and most commonly less than 1 second. See (FIG. 7). This invention was designed to utilize the rapid liquid-to-solid cooling rate of the welding process which is often as much as one hundred times faster than that of casting operations. This

rapid solidification rate allows a maximum quantity of combined Mg₂Si and free Mg to be put into this alloy and achieve maximum mechanical properties without fear of coarse Mg₂Si particles precipitating during solidification.

[0054] The cooling rate that an aluminum alloy experiences after solidification down to room temperature is also critical for an alloy containing Mg₂Si and excess Mg. Quench sensitivity is a term commonly used to describe the propensity for an aluminum alloy to precipitate alloy constituents such as Mg₂Si as coarse particles in the metal matrix as the alloy cools. The metallurgy of the invention alloy composition was designed so as to create a quench sensitivity that was in concert with the cooling rates experienced in the welding process. Cu, Zn, and Fe increase the quench sensitivity of aluminum alloys and have been controlled to low levels in the invention alloys. The chemistry was further controlled to optimize the effects of thermal energy that is introduced by multiple welding passes. Fe in particular forms negative phases with any solidification and post solidification cooling rate and can only be controlled by chemistry restrictions. Therefore, the invention alloy composition has Fe content controlled below most filler metal alloy specifications.

[0055] For wrought 6xxx series alloys, the critical cooling rates to achieve full design strength specifications are known. For instance, the critical cooling rate to overcome the quench sensitivity of the alloy after solidification, that is the range from 850 to 400 degrees F., depends on the amount of Mg₂Si present in the alloy. For an Mg₂Si content of 0.8 to 1.1% by weight, the critical cooling rate is 100 degrees F. per minute. For an Mg₂Si content of 1.4 to 1.6% by weight, the critical cooling rate increases to 1200 degrees F. per minute. If this cooling rate is not met, Mg₂Si will precipitate into the structure as a relatively coarse phase and the mechanical properties of the alloy will be reduced. Therefore, the invention alloy is carefully designed to contain only 1.1 to 1.5% by weight of Mg₂Si so as to meet the cooling rates experienced during welding operations as shown in FIG. 7. Again, because the invention alloy composition was designed to contain a maximum amount of free Mg without exceeding the limits required to control corrosion resistance, and knowing that the solubility of Mg₂Si is decreased by the presence of free Mg, the control range for Mg₂Si is tightly controlled. Even though the chemistry of the invention alloy composition is carefully controlled, due to the variability of the welding process and subsequent thermal treatment operations, the theoretical maximum mechanical properties may not be met in this alloy. Therefore, in FIG. 2, the tensile strength of the 5xxx series of welding filler metal alloys is compared to the prophetic tensile strengths of Alloy 1 of the invention that are shown as a band of possible post-weld tensile strengths achievable under most welding conditions. What we do know is that the invention alloy will provide mechanical properties far above what is now available. Likewise in FIG. 4 the tensile strength of 5554 filler metal is compared to the prophetic tensile strengths of Alloy 2 of the invention that are shown as a band of possible post-weld tensile strengths achievable under most welding conditions and various levels of post-weld thermal treatments.

[0056] The chemistry of the new alloy contains maximum levels of Mg for another specific reason. The melt-off rate of aluminum electrode is based on the welding parameters set into the welding equipment, the shielding gas, the mechanical stick out of the contact tip and electrode, and the physical properties of the electrode including the electrical resistivity

of the metal in the electrode. Higher electrical resistivity provides increased heating of the wire as electricity is conducted through it. Higher resistivity of the electrode increases the melt-off rate. Further, aluminum is rarely used in the short-arc transfer welding mode. The resistivity is too low to provide a satisfactory burn-off rate during the short-arc portion of the metal transfer process. An objective of this invention is to increase the melt-off rate of the invention alloy composition in all metal transfer modes including globular, spray and short-arc transfer. FIG. 5 shows the effect of alloying elements on conductivity. Resistivity is the reciprocal of conductivity. Consequently, conductivity changes with the addition of alloying elements to aluminum and correlates directly to the electrical resistivity of the resulting alloy. Pure aluminum such as alloy 1350 has a conductivity of 62% IACS (international annealed copper standard). For reference purposes, copper has a conductivity rating of 100% IACS and Iron is down at 18% IACS. A 1.5% Mg2Si alloy has a 49% IACS, a 3% Mg alloy a 40% IACS, and a 5% Mg alloy a 29% IACS value. If a typical 1.4% Mg2Si alloy with an electrical conductivity of 50% IACS has 5% Mg added to it, the resultant conductivity of the new alloy can be estimated. In FIG. 5 we show a prophetic value of between 20% and 25% or a typical value of 23% IACS for the invention alloy composition. A 6 point reduction in conductivity from 29 to 23 represents a 21% relative reduction in conductivity from a straight 5% Mg alloy or conversely, a 21% increase in resistivity. The invention alloy composition is approaching the conductivity of iron which is 18% IACS. Iron has well documented melt-off rates and welding characteristics. Short-arc transfer is commonly used in welding steel, taking advantage of its high electrical resistivity. Specifically designed into this alloy is a conductivity that will facilitate short-arc and globular mode transfer. It should be noted that increased melt-off rate is a desired and intended result of this invention. In all metal transfer modes, including spray transfer, increased melt-off rates facilitate welding with a decreased requirement for heat input from the welding equipment thereby reducing the negative effects of reduced mechanical properties in the heat affected zone. Less structural distortion is produced with less heat input as well. Further, electrodes with higher burn off rates can be welded at higher transfer rates increasing welding speeds and thereby reducing welding costs. By increasing the melting rate of the invention alloy composition through increased resistance heating, the thermal energy needed in the arc plasma has been reduced thereby reducing the amount of Mg burn-off in the welding arc. Reduced heat input from the plasma due to increased resistance heating, allows for a more stable droplet transfer in the spray transfer mode, with less metal vaporization. The invention alloy composition reduces the amount of Mg vapors in the arc plasma and the undesirable condensation of these vapors alongside the weld in the form of vapor condensate, known as smut. It is believed that Mg vapors in the arc plasma affects the ionization potential of the shielding gas which gives a different arc characteristic to high Mg filler alloys as compared to other alloy series such as the silicon series filler metal alloys. Therefore, it is anticipated that the invention alloy will allow the use of reduced levels of shielding gas necessary to achieve quality welds.

[0057] The invention alloy composition was also developed to control its corrosion characteristics. The base metal alloys to be welded with this filler metal are used for automotive, truck trailer, rail car and ship building applications to

name just a few. These structures spend their lives in harsh environmental atmospheres including the very corrosive effects of sea water. The corrosion characteristics of aluminum filler materials are carefully controlled to insure suitability in a variety of service environments. The new alloys 1 and 2 are specifically designed to have controlled and excellent corrosion resistance as welded.

[0058] FIG. 9 is a table showing the electro negativity of various aluminum alloy compositions. It shows two compositions, that of Al+1% Mg2Si and Al+5% Mg. They both have an electro negative potential very close to that of pure aluminum. Therefore, we believe that the chemical content we have designed into the invention alloy composition will have excellent as-welded corrosion performance. In particular, alloys 1 and 2 will have excellent salt water corrosion performance when welding the typical ship building sheet and plate alloys, 5052, 5086, 5083, 6061, 6082 and 6351.

[0059] FIG. 8 is a table showing the typical as-welded shear and tensile strengths of various aluminum welding filler metal alloys along with the prophetic shear and tensile properties that the invention alloys have. In industry, the number of partially penetrated fillet type welds far exceeds fully penetrated butt type welds. Shear strength is the primary factor considered in designing weld strengths for all partially penetrated welds. Fillet welds represent 70 percent of all structural welds. The invention alloy composition will provide significant increases in tensile, shear and fatigue strengths when compared to all of the other weld filler metal alloys in use today.

[0060] The invention alloy composition was also carefully engineered to weld the 6xxx series base metal alloys. Currently these alloys are welded with 4xxx or 5xxx series alloys that do not respond to post-weld heat treatment and frequently yield lower mechanical properties in the weld joint than are achieved in the base metal with post-weld heat treatment. One of only two exceptions to this is filler metal 4643 which will respond to post-weld heat treatment but has not been a commercially successful alloy for a number of reasons that limit its use. Alloy 4943 is the other exception and it does respond to post-weld treatment giving significantly improved mechanical properties and has its place where high fluidity, increased ease of welding, and low levels of smut deposit are desired. The invention alloy 2 will weld all of the 6xxx series alloys as well as 5454 and will provide excellent elevated temperature service up to 250 degrees F. It fully responds to post-weld thermal treatment processes and will provide higher mechanical properties, higher toughness and reduced crack propagation sensitivity than all of the Si based welding filler metal alloys (See FIG. 12). Alloy 1 will weld all of the 6xxx and 5xxx series base alloys except if elevated temperature service is desired. Alloy 1 will provide large as-welded increases in tensile, shear, and fatigue strengths compared to all other filler metals now available. Alloy 1 will exceed the as-welded strength of all of the current 5xxx series base metal alloys available.

[0061] Experience with aluminum welded structures in service has shown that 90% of all failures are the result of cyclic loading and the failure of weld joints from fatigue. Because there are higher levels of discontinuities in weld joints than in the parent base material, there are higher levels of stress risers in the weld joints. The majority of welds are partially penetrated joints such as fillet welds. In these joints, the weld root in every weld is in fact a sharp notch. This notch acts as a stress riser during cyclic loading. In a fillet weld, the weld

bead carries the full stress of cyclic loading. Consequently, the fatigue strength of the weld bead filler metal alloy is of prime importance. The fatigue strength of an aluminum alloy is directly proportional to its tensile strength. The tensile properties of the invention alloy composition are higher than that of any currently available aluminum welding filler metal alloy and consequently the fatigue properties are also higher. The prophetic fatigue strength targeted for the invention alloy composition is illustrated in FIG. 10.

[0062] FIG. 11 shows the documented effect of post-weld aging or post-weld heat treatment and aging on the toughness properties of alloy 6061 welded with 4043, 4643, & 4943. To date, there are no aluminum weld filler metal alloys that will respond to post-weld thermal treatments that do not significantly reduce the energy required to propagate a crack or significantly reduce the crack sensitivity to notches. Consequently, when toughness is a design requirement, 6xxx series base metal welded structures which require post-weld thermal treatments to restore pre-welded properties cannot be used when welded with 4xxx series filler metals. The physical structure of welds is controlled by Specification AWS D1.2 including the amount of allowable discontinuities that are permissible in the weld joint. However, for the majority of welds, over 70% of all welds made in structures are partially penetrated joints. When weld joints are partially penetrated, there is a sharp notch at the root of the weld. Sharp notches significantly reduce the toughness of weld joints. The elimination of the significant loss of toughness in post-weld thermally treated 6xxx alloys is a specific objective of invention alloy 2. Alloy 2 can be post-weld aged or post-weld heat treated and aged without loss of toughness. Alloy 2 also increases fatigue life when stress risers are present. FIG. 11 shows the prophetic toughness for alloy 2. Alloy 2, both as welded and post-weld thermally treated, and alloy 1 as welded are both expected to be similar in toughness to the as-welded properties of 6061 with filler alloy 5356. Both alloy 1 and 2 in the as-welded or post-weld thermally treated condition have much higher toughness than the 4xxx series filler metal alloys. Alloy 2 will allow for the full restoration of the strength properties of 6xxx alloys in the heat affected zone after welding, by post-weld thermal treatments with the retention of high toughness in the welds. The toughness of alloy 1 and 2 are retained while the higher ultimate tensile strengths achieved are significantly higher than currently available filler metal alloys. In FIG. 11 it can be seen that alloy 5183 has higher tensile strength than 5356 but lower toughness. This is due to the brittle effect of increasing the Mn to Mg percentage ratio in these Mg/Mn alloys. Replacing the Mg content with Mn in any Mg/Mn alloy reduces the toughness due to the effects of the Mn. Alloy 1 is designed to replace alloys 5183, 5556 and 5087 while having a lower controlled Mn content. The Mn content in alloy 1 is controlled similarly to alloy 5356. With the addition of higher levels of Mg & Si to convert alloy 1 into a 6xxx series alloy, the resultant toughness is expected to be equal to 5183, 5556 and 5087. Alloy 1 will have no loss of toughness while having significantly higher tensile and shear strengths as compared to the alloys being replaced. This toughness design feature cannot be accomplished with the use of any of the currently available filler metal alloys.

[0063] The invention alloy has also been designed to provide an increase in fluidity and a reduction in surface tension of the molten weld bead when used as a welding filler metal. The chart in FIG. 13 shows the effect of increasing alloy

content on the fluidity of molten aluminum alloys. Fluidity of the molten weld bead affects the molten filler metal's wetting action during welding and the weld bead profile after solidification. The chart in FIG. 14 shows the effect of increasing alloy content on the surface tension of molten aluminum alloys. The surface tension on the molten weld bead also affects the weld bead profile after solidification. Higher fluidity and lower surface tension of a molten metal weld bead produces a lower and flatter weld bead profile after solidification. Welding standards control the allowable contour of weld beads. The invention alloy's chemical composition will provide improved wetting action and lower surface tension thereby improving the control over weld bead contour. A weld joint with reduced bead height and a lower angle of incidence of weld metal to base material will have superior fatigue life. The invention alloys will have improved fatigue strength characteristics not only from a material stand point but also from the result of improved physical control over the weld bead contour. This is a specific objective of this invention.

[0064] The invention alloy composition has been designed to reduce hydrogen solubility in molten aluminum weld beads. Increasing alloy content reduces the liquid solubility of hydrogen in aluminum alloys. Silicon reduces the solubility of hydrogen in aluminum to one half that of pure aluminum at the eutectic composition level. Welding specifications limit the amount of allowable hydrogen porosity in welds in order to control mechanical properties. The invention alloys contain substantially greater amounts of alloying elements that the weld filler metal alloys they are intended to replace. Consequently, they will have a lower propensity for hydrogen porosity contamination after welding. This is a specific design objective of this invention.

[0065] Alloys of the invention alloy composition have the ability to be fabricated into wire. In embodiments where the alloys are formed into wire, such wire (i.e. welding filler metal) may be produced on spools for use in GMA welding or it may be cut into straight lengths for GTA welding. These are the two most common forms of aluminum filler metals, but they are not limited to these forms. Typically the linear wire or cut-to-length wire has a diameter of at least 0.010 inches and typically less than 0.30 inches in diameter. In preferred embodiments the wires have one or more diameters, such as 0.023 inches, 0.030 inches, 0.035 inches, 0.040 inches, 0.047 inches, 0.062 inches, 0.094 inches, 0.125 inches, 0.156 inches, 0.187 inches, and 0.250 inches. The invention alloys are specifically designed to be able to be drawn into all of the required wire sizes while the Mg₂Si matrix phase has been deliberately removed from solid solution through annealing. When the excess Mg is limited to approximately 5.2%, Mn limited to approximately 0.20%, and the Mg₂Si phase has been removed from solid solution, the resulting alloy has excellent mechanical cold-working properties.

[0066] The invention alloy composition is designed for use in the production of aluminum castings. The casting chemistries that are available for use in building complex structures such as automobiles, rail cars, truck trailers and many other products require that different weld filler metal alloys be used to weld the structural components together. Because of the large differences between the casting alloys and wrought alloy chemistries being welded together into a single assembly, many compromises have to be made when selecting the appropriate weld filler metal alloys to accomplish the job. The different filler metal alloys that must be used to weld castings to each other and to wrought alloy components prevents

designers from being able to achieve structures with the high mechanical properties or desirable physical properties they would like to achieve. From a manufacturing consideration, the use of several different filler metals on a single welded structure requires that separate welding operations be performed. If a single weld filler metal can be used to produce an entire structural component, the weldment can be produced in a single robotic welding cell with one filler metal. This yields a large cost savings in today's automated manufacturing operations.

[0067] There are currently no heat treatable 5xxx series casting alloys. This invention, for the first time, creates an alloy for producing castings that is exactly matched to a weld filler metal alloy where they both make use of Mg₂Si and excess Mg to achieve very high as-welded or post-weld thermally treated mechanical properties. The invention alloy composition provides a casting/filler metal alloy combination that can be used to weld castings to 3xxx, 5xxx, 6xxx, and 7xxx series wrought alloys and, for the first time, match the mechanical properties of the three components, both in the as-welded or the post-weld thermally treated condition depending on which chemistry is chosen. For instance, if alloy 1 is chosen, the casting/filler metal pair will yield mechanical strengths in excess of wrought 3xxx and 5xxx series base alloys being welded. If alloy 2 is chosen, the casting/filler metal pair will be suitable for welding 5454 or other base metal alloys intended for high temperature service up to 250 degrees F. This pair can also be used to weld the 6xxx series wrought alloys and will respond to post-weld thermal treatments yielding mechanical properties in excess of the 6xxx series base metal alloys being welded. The invention alloy composition can be used for the production of aluminum structures with mechanical properties that are significantly higher than those possible with currently available casting and welding filler metal alloy combinations. The invention alloy composition casting alloy combined with its matching welding filler metal alloy yields excellent corrosion resistance properties and allows for a good match of corrosion properties between the casting, filler metal, and wrought alloy base metal. The invention alloy composition to be used in various casting/filler metal pairs will yield toughness far beyond that of currently used casting/filler metal combinations. In short, the invention alloy composition allows for the design of welded structures, which combine cast and wrought components with significantly higher strengths and lower fabrication costs.

[0068] It is also anticipated that the invention alloy composition may be used to produce sheet and plate and the many components that can be shaped by roll forming, hydro forming and other shaping processes. By use of the unique combination of Mg₂Si and excess Mg, the invention alloy composition lends itself to high degrees of mechanical deformation in the annealed state. The invention alloy composition has been designed to undergo a high degree of cold work without fracturing. Therefore, in the annealed state this alloy can be drawn into wire, or rolled into sheet and plate and subsequently roll formed, pressed or otherwise formed into myriads of shapes for the construction of welded structures. A principal attribute of this alloy composition is that a single chemistry can be used to produce castings, weld filler metals, and wrought base metal alloys that can be welded together into structures that will have closely matched mechanical and physical properties throughout. Structures can be manufac-

tured that have mechanical properties substantially higher than anything achievable with the present alloys available.

[0069] While only certain features of the invention have been illustrated and described herein, many modifications and changes, including numerous alloy compositions will occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

What is claimed is:

1. A composition for producing aluminum casting, wrought, and filler metal alloys from the same chemistry having a composition comprising silicon in a weight percentage of between approximately 0.01% inclusive and 0.9% inclusive; manganese in a weight percentage of between approximately 0.05% inclusive and 1.2% inclusive; magnesium in a weight percentage of between approximately 2.0% inclusive and 7.0% inclusive; chromium in a weight percentage of between approximately 0.05% inclusive and 0.30% inclusive; zirconium in a weight percentage of between approximately 0.05% inclusive and 0.30% inclusive; titanium in a weight percentage of between approximately 0.003% inclusive and 0.20% inclusive; and boron in a weight percentage of between approximately 0.0010% inclusive and 0.030% inclusive.

2. In accordance with claim 1, a composition comprising silicon in a weight percentage of between approximately 0.50% inclusive and 0.70% inclusive; manganese in a weight percentage of between approximately 0.05% inclusive and 0.20% inclusive; magnesium in a weight percentage of between approximately 5.7% inclusive and 6.1% inclusive; chromium in a weight percentage of between approximately 0.05% inclusive and 0.20% inclusive; zirconium in a weight percentage of between approximately 0.05% inclusive and 0.15% inclusive; titanium in a weight percentage of between approximately 0.003% inclusive and 0.10% inclusive; and boron in a weight percentage of between approximately 0.0010% inclusive and 0.010% inclusive.

3. In accordance with claim 1, a composition comprising silicon in a weight percentage of between approximately 0.30% inclusive and 0.50% inclusive; manganese in a weight percentage of between approximately 0.50% inclusive and 1.0% inclusive; magnesium in a weight percentage of between approximately 3.4% inclusive and 3.7% inclusive; chromium in a weight percentage of between approximately 0.05% inclusive and 0.20% inclusive; zirconium in a weight percentage of between approximately 0.05% inclusive and 0.15% inclusive; titanium in a weight percentage of between approximately 0.003% inclusive and 0.10% inclusive; and boron in a weight percentage of between approximately 0.0010% inclusive and 0.010% inclusive.

4. In accordance with claim 1, a 6xxx series aluminum alloy composition that provides for the use of a single chemistry to produce castings, weld filler metals, and wrought base metal alloys that can be welded together into structures that will have closely matched mechanical and physical properties throughout resulting in welded structures that have mechanical properties substantially higher than anything achievable with the currently available aluminum alloys.

5. In accordance with claim 3, a 6xxx series aluminum alloy filler metal composition that will respond to post-weld thermal treatments thereby allowing the restoration of mechanical properties degraded in the heat affected zone of heat treated alloys during welding operations thus yielding

finished weldments where the resulting weld joint yields mechanical properties that meet or exceed that of both cast and wrought aluminum alloy components.

6. In accordance with claim 2, a 6xxx series aluminum filler metal alloy composition capable of welding 3xxx, 5xxx, 6xxx, and 7xxx series aluminum metal alloys yielding higher mechanical properties and fatigue strength than can be achieved with any 4xxx or 5xxx series aluminum filler metal alloys currently available.

7. In accordance with claim 3, a 6xxx series aluminum filler metal alloy composition capable of welding silicon based aluminum casting alloys to wrought 5xxx and 6xxx series aluminum alloys containing less than 3% Mg, yielding significantly higher mechanical properties than can be achieved with the 4xxx or 5xxx series aluminum filler metal alloys currently available.

8. In accordance with claim 3, a 6xxx series aluminum filler metal alloy composition capable of being post-weld aged or post-weld heat treated and aged with mechanical properties in the as-welded or post-weld thermally treated condition that substantially exceed the post-welded properties of all of the currently available 4xxx and 5xxx series aluminum filler metal alloys while maintaining a high level of toughness.

9. In accordance with claim 3, a 6xxx series aluminum filler metal alloy that can be used for elevated temperature applications up to 250 deg. F with higher mechanical properties than any other suitable filler metal alloy designed for elevated temperature applications that is currently available.

10. In accordance with claim 1, a 6xxx series aluminum filler metal alloy composition that can be adjusted to provide color matching for post-weld anodizing treatments of various welded aluminum alloy components.

11. In accordance with claim 1, a 6xxx series aluminum filler metal alloy composition that can be adjusted to provide corrosion protection properties that match or exceed those of the aluminum alloy components being welded.

12. In accordance with claim 1, a 6xxx series aluminum filler metal alloy composition that will provide a typical electrical conductivity of approximately 23 IACS which will allow this alloy to be arc welded in the globular transfer or short arc mode which is not now possible with any other aluminum filler metal currently available.

13. In accordance with claim 11, a 6xxx series aluminum filler metal alloy composition that creates higher resistance heating of the electrode during arc welding, resulting in reduced thermal energy required in the arc plasma which in

turn produces a more stable droplet transfer with reduced Mg burn off and less undesirable condensation of vaporized Mg (referred to as smut) on the base metal surfaces resulting in lower shielding gas requirements and reduced welding costs.

14. In accordance with claim 11, a 6xxx series aluminum filler metal alloy composition that increases melt-off rate of the electrode during arc welding and consequently a reduction of total heat input resulting in a reduction of the loss of mechanical properties in the heat affected zone and less mechanical distortion of aluminum base metal components being welded.

15. In accordance with claim 11, a 6xxx series aluminum filler metal alloy composition that increases melt-off rate of the electrode during arc welding resulting in higher welding speeds and lower electrode consumption which reduces welding costs.

16. In accordance with claim 6, a 6xxx series aluminum filler metal alloy composition that because of increased tensile strength, shear strength, and fracture toughness, provides the opportunity to reduce weld bead size and increase welding speeds resulting in cost savings in welding operations.

17. In accordance with claim 1, a 6xxx series aluminum welding filler metal alloy composition that has lower molten surface tension than any 5xxx series filler metal alloy thus producing lower and flatter weld beads thereby improving the fatigue strength of the welded joint.

18. In accordance with claim 1, a 6xxx series aluminum filler metal alloy that has higher molten fluidity than any current 5xxx series filler metal alloy thus increasing wettability during welding which improves fusion and flattens the edge of the weld bead thereby improving fatigue strength of the welded joint.

19. In accordance with claim 1, a 6xxx series aluminum welding filler metal alloy that has a lower liquid solubility for hydrogen than any 5xxx series filler metal alloy, thus reducing the volume of hydrogen porosity present in solidified welded joints.

20. In accordance with claim 1, a 6xxx series wrought aluminum alloy for use in producing forged and cold headed products such as rivets, and similar products which can be cold formed, then solution heat treated, quenched and aged to yield substantially higher mechanical properties along with the desired physical properties of corrosion resistance and anodized color matching.

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