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(54) A HIGH-STRENGTH AL-MG-SI ALUMINIUM ALLOY AND ITS MANUFACTURING PROCESS

(57) The subject of the invention is a high-strength Al-Mg-Si aluminium alloy and its manufacturing process. The alloy contains 1.3-1.7 wt. % of Si, 0.14-0.25 wt. % of Fe, up to 0.75 wt. % of Cu, 0.7-0.8 wt. % of Mn, 0.85-1.1 wt. % of Mg, 0.15-0.25 wt. % of Cr, up to 0.2 wt. % of Zn, up to 0.1 wt. % of Ti, 0.15-0.25 wt. % of Zr, and other elements up to 0.15 wt. % (single element up to 0.05 wt. %), and the rest being Al. The manufacturing process includes the charge preparing, melting, melt holding, semi-continuous billet casting or continuous bar casting, homogenizing, cutting of the billets, extruding, forming, and heat treatment. The alloy is produced with high mechanical properties, good formability and corrosion resistance, lower energy consumption, and environmental protection during production and application.

EP 3 214 191 A1

Description

[0001] The invention is in the field of metallurgy and materials and refers to a high-strength Al-Mg-Si aluminium alloy and its manufacturing process. The invented alloy is used in the automotive, aircraft, transport, and construction industries.

[0002] Trends in the modern vehicle-producing industry include the manufacturing of so-called green transportation vehicles. These vehicles have lower fuel consumptions and CO_2 emissions through a reduction in their weight. However, the user's safety must also be considered. In practice this means that the heavy steel parts must be exchanged for lighter materials, such as high-strength Al-Mg-Si aluminium alloys (the 6xxx series).

[0003] Magnesium and silicon are the main alloying elements in the 6xxx aluminium alloys. Together they form the Mg_2Si phase, which allows precipitation hardening of the alloy during ageing. The Al-Mg-Si alloys have good workability, machinability, weldability, corrosion resistance, and strength between 230 and 450 MPa, depending on the heat treatment. A strength above 450 MPa was achieved with addition of 0.8-1.5 wt. % of Cu and 0.05-0.3 wt. % of Zr in the EP 2548983 patent, but this alloy has poor corrosion resistance on account of the higher content of copper. On the other hand, the Al-Zn alloys (the 7xxx series) can achieve a strength higher than 500 MPa, but the use of these alloys is limited by their workability and corrosion resistance.

[0004] The Al-Mg-Si alloys are manufactured in the following sequence: charge preparing and melting, melt holding, semi-continuous billet casting, homogenizing, extruding of the bars or other final forms, forming (e.g. forging), and heat treatment. A recent manufacturing process, i.e., the continuous casting of bars, enables the forming of cast bars directly. In this case there is no homogenizing and extrusion.

[0005] Besides magnesium and silicon, the Al-Mg-Si alloys contain iron, copper, manganese, chromium, zinc, titanium, and zirconium. The addition of zirconium improves the corrosion resistance, inhibits the recrystallization, refines the as-cast grains, and consequently improves the mechanical properties. The content of zirconium in the Al-Mg-Si alloys is to 0.3 wt. % [EP 1458898, EP 2554698, EP 2799564, EP 2644725, EP 2811042, EP 2003219, EP 0987344, EP 1737994, EP 0173632, EP 0787217, EP 1802782, JP 2004043907, JP 2001107168, JP 2003277868, US 2004062946, JP 2007177308, US 2010089503, US 5240519]. The process parameters also depend on the content of zirconium in Al-Mg-Si alloys.

[0006] Until now the chemical compositions of Al-Mg-Si alloys do not contain 1.3-1.7 wt. % of Si, 0.14-0.25 wt. % of Fe, up to 0.75 wt. % of Cu, 0.7-0.8 wt. % of Mn, 0.85-1.1 wt. % of Mg, 0.15-0.25 wt. % of Cr, up to 0.2 wt. % of Zn, up to 0.1 wt. % of Ti, 0.15-0.25 wt. % of Zr, other elements up to 0.15 wt. % (single element up to 0.05 wt. %), with the rest being Al.

[0007] The content and effect of each element in the invented Al-Mg-Si alloy are described below:

- Silicon (Si: 1.3 to 1.7 wt. %) is one of the major elements of the alloy in the present invention, along with Mg and Cu, which improves the strength. Si is combined with Mg and forms Mg_2Si, which precipitation hardens the α-Al matrix during the artificial ageing. Although the contribution of the precipitation hardening is increased when the content of Si exceeds 1.7 wt. %, the stress-corrosion cracking resistance and the corrosion resistance are aggravated. Also, coarse β-Si particles are precipitated, which likewise deteriorates the corrosion resistance and toughness. The contribution of the precipitation hardening is decreased when the content of Si is less than 1.3 wt. %.

- Iron (Fe: 0.14 to 0.25 wt. %) forms Al-Fe-Si-(Mn, Cr) phases and Al_7Cu_2Fe, $Al_{12}(Fe, Mn)_3Cu_2$, or $Al_6(Fe, Mn)$ precipitates. The fractions of these phases and precipitates increase when the content of Fe exceeds 0.25 wt. %, and this deteriorates the mechanical properties, corrosion resistance, and machinability.

- Copper (Cu: to 0.75 wt. %) is one of the elements, along with Si and Mg, which improve the strength of the alloy with precipitation hardening of the α-Al matrix during the artificial ageing. The effect of the precipitation hardening is increased in proportion with the content of Cu. When it exceeds 0.75 wt. %, the sensitivity to stress corrosion cracking and intergranular corrosion is increased, which reduces the durability of the aluminium alloy.

- Manganese (Mn: 0.7 to 0.8 wt. %) forms, together with Fe, Si, and Cr, the Al-Fe-Si-(Mn, Cr) phase and Al_6Mn dispersed particles, which are formed during the homogenization and solution heat treatment. These dispersed particles also inhibit the grain growth. The fine crystal grains and sub grains improve the mechanical properties, fracture toughness, and fatigue properties. With a content of Mn under 0.7 wt. % the alloy is liable to recrystallize. On the other hand, when the content of Mn exceeds 0.8 wt. %, the coarse Al_6Mn dispersed particles are formed and deteriorate both the mechanical properties and the formability.

- Magnesium (Mg: 0.85-1.1 wt. %) in combination with Si forms the Mg_2Si phase at the grain boundaries during the solidification. The Mg_2Si phase is partially dissolved in the α-Al matrix during the homogenization and the remainder stays at the grain boundaries. The undissolved Mg_2Si particles inhibit the grain growth during subsequent processes. The dissolved

Mg and Si are precipitated as Mg_2Si during the artificial ageing, which then hardens the α-Al matrix. The precipitation hardening is reduced when the content of Mg is below 0.85 wt. % and increased when the content of Mg exceeds 1.1 wt. %, but the coarse Mg_2Si precipitates decrease the elongation, deteriorate the forgeability and lower the intergranular corrosion resistance.

- Chromium (Cr: 0.15 to 0.25 wt. %) along with Fe, Si, and Mn forms the Al-Fe-Si-(Mn, Cr) phase during solidification and forms Sii_2Mg_2Cr and Al_2Mg_2Cr dispersed precipitates during the homogenization. These precipitates inhibit the grain growth. The coarse Al-Fe-Si-(Mn, Cr) phases are formed above 0.25 wt. % of Cr and represent the initial sites for crack formation.

- Zinc (Zn: to 0.2 wt. %) and Mg form $MgZn_2$ precipitates during the precipitation hardening, which contribute to the strength of the aluminium alloy. On the other hand, when $MgZn_2$ is precipitated, the content of Mg in the alloy is decreased. This leads to a decreasing fraction of Mg_2Si precipitates, which contribute more to the strength than the $MgZn_2$ precipitates. The Zn also deteriorates the corrosion resistance.

- Titanium (Ti: to 0.1 wt. %) is added to aluminium alloys with an Al-Ti-B master alloy, where it is precipitated in the form of Al_3Ti and TiB_2 particles. The Al_3Ti particles are dissolved faster in the melt, while the TiB_2 particles coated with a thin Al_3Ti layer act as efficient nuclei for the grain growth of the as-cast α-Al grains. The Ti that is dissolved in the melt also inhibits the grain growth of the α-Al, The fine-grained microstructure improves the workability and mechanical properties of the alloy.

- Zirconium (Zr: 0.15 to 0.25 wt. %) forms fine Al_3Zr and Si_2Zr precipitates at the grain boundaries and sub grains during the homogenization. The precipitates improve the corrosion resistance, inhibit the recrystallization, and consequently improve the mechanical properties.

- Other elements (to 0.15 wt. %; single element to 0.05 wt. %) are presented as trace elements and a small quantity of these elements do not effect to the properties of the aluminium alloy.

[0008] The manufacturing process of the Al-Mg-Si alloy (Figure 1) begins with preparing a charge that consists of the primary aluminium (99.7 wt. % of Al), revert scrap, secondary scrap, and alloying elements. These are added as the pure elements or master alloys. The prepared charge is placed in the melting furnace (gas or induction), where the melting is started. The chemical composition of the melt is checked after the melting. The melting temperature depends on the content of Zr in the melt and is between 700 and 780 °C, while the melting takes up to 5 h. The melt stirring is favourable for the dissolution of Zr, which is implemented naturally in an induction furnace and mechanically in a gas furnace. The melting time is reduced with the use of an Al-Zr master alloy, where the Zr is precipitated in the form of fine Al_3Zr phases. When the chemical composition is achieved, the melt is poured into the holding furnace, where it is cleaned with argon or nitrogen flushing and is held above the liquidus temperature up to 4 h. The liquidus temperature depends on the content of Zr in the melt and is between 700 and 750 °C. If the holding temperature falls below the liquidus temperature, the zirconium begins to precipitate in the form of the Al_3Zr phase, which settles to the bottom of the holding furnace, because its density is 4.1 g/cm^3. The coarse Al_3Zr phases represent the defects in the final products and also decrease the effect of the Zr in the alloy. In the first case, the alloy can be semi-continuously cast with different casting processes (with floats, with a hot top, or in an electromagnetic field at lower frequency) into billets with a diameter of 218-450 mm and a length up to 8 m. The casting temperature is between 680 and 730 °C and the casting rate is 50-85 mm/min. In the second case, the alloy can be continuously cast into bars with a diameter of 30-150 mm. The casting temperature is between 680 and 730 °C and the casting rate is 100-1000 mm/min. The cast bars are subsequently hot or cold formed and heat treated, or only heat treated. The melt temperature in the holding furnace should not fall under the liquidus temperature during the casting. The cast billets are homogenized at a temperature of 400-550 °C for up to 24 h, cooled with fans, water fog, water, or air, and ultrasonically tested. The homogenization is performed below the solidus temperature, because the Mg_2Si phases are melted at higher temperatures and cause the formation of pores within the microstructure. Then the billets are cut into a round length of 600-1600 mm and dressed as necessary. Later, the round is preheated to the homogenous temperature or in the temperature profile (wedge). The temperature of the round is between 470 and 550 °C. The bars, with a diameter of 20-180 mm or other forms to an outlined circle of 270 mm, are directly or indirectly extruded with an extrusion rate of 0.1-25 mm/s. The temperatures of the container and the die are between 360 and 520 °C. The bars are water quenched (spray or wave) immediately after the extrusion (T1 temper). Then the bars in the T1 temper are cold or hot formed and heat treated, or only heat treated according to the required heat treatment. The bars, other forms, or forged parts for the T6 temper are solution heat treated at a temperature of 450-550 °C from 1 to 3 h, water quenched, and artificially aged at a temperature of 120-210 °C for up to 15 h. For the T5 temper they are only artificially aged at a temperature of 120-210 °C for up to 15 h and for the T4 temper they are the solution heat treated at a temperature of 450-550 °C from

1 to 3 h, water quenched, and still naturally aged.

[0009] The high-strength Al-Mg-Si aluminium alloy, in the form of bars, other forms, or forged parts, which is manufactured with the processes and chemical composition described above, achieves a tensile strength of 452-495 MPa, a yield stress of 418-465 MPa, an elongation of 9-12.5 %, and a hardness of 141-145 HB in the T6 temper. Besides the high mechanical properties, the alloy has good corrosion resistance, which is in accordance with automotive standards. The intergranular corrosion test according to the VW PV 1113 standard showed that the depth of the intergranular corrosion of the bars in the T6 temper is less than 200 μm.

Claims

1. The chemical composition of the high-strength Al-Mg-Si aluminium alloy is **characterized in,**
that it contains 1.3-1.7 wt. % of Si, 0.14-0.25 wt. % of Fe, up to 0.75 wt. % of Cu, 0.7-0.8 wt. % of Mn, 0.85-1.1 wt. % of Mg, 0.15-0.25 wt. % of Cr, up to 0.2 wt. % of Zn, up to 0.1 wt. % of Ti, 0.15-0.25 wt. % of Zr, and other elements up to 0.15 wt. % (single element to 0.05 wt. %), and the rest being Al.

2. The manufacturing process of the high-strength Al-Mg-Si aluminium alloy is **characterized in,**
that it includes the charge preparing, melting, melt holding, semi-continuous billet casting or continuous bar casting, homogenizing, cutting of the billets, extruding, forming, and heat treatment.

3. The process according to the claim 2 is **characterized in,**
that the melt temperature in the melting furnace is from 700 to 780 °C and the melting time up to 5 h.

4. The process according to the claim 2 is **characterized in,**
that the melt temperature in the holding furnace is from 700 to 750 °C and the holding time before the casting is up to 4 h, while the melt temperature in the holding furnace should not fall below the liquidus temperature during casting.

5. The process according to the claim 2 is **characterized in,**
that the casting is implemented with a semi-continuous casting process with floats, with a hot top, or in an electromagnetic field at lower frequency into billets with a diameter of 218-450 mm, length up to 8 m, at a casting temperature of 680-730 °C, and a casting rate of 50-85 mm/min or that the casting is implemented with a continuous casting process into bars with a diameter of 30-150 mm, at a casting temperature of 680-730 °C, and at a casting rate of 100-1000 mm/min.

6. The process according to the claim 2 is **characterized in,**
that the cast billets are homogenized at a temperature of 400-550 °C for up to 24 h and cooled with fans, water fog, water, or air.

7. The process according to the claim 2 is **characterized in,**
that the rounds are preheated to a temperature of 470-550 °C before the extrusion.

8. The process according to the claim 2 is **characterized in,**
that the container temperature and the die temperature are between 360 and 520 °C for a direct or indirect extrusion.

9. The process according to the claim 2 is **characterized in,**
that the rounds are directly or indirectly extruded into bars with a diameter of 20-180 mm or other forms to an outlined circle of 270 mm with an extrusion rate of 0.1-25 mm/s, which are still water quenched (spray or wave) immediately after the extrusion.

10. The process according to the claim 2 is **characterized in,**
that the bars, other forms, or forged parts for the T6 temper are solution heat treated at a temperature of 450-550 °C from 1 to 3 h, water quenched, and artificially aged at a temperature of 120-210 °C for up to 15 h.

11. The process according to the claim 2 is **characterized in,**
that the bars, other forms, or forged parts for the T5 temper are artificially aged at a temperature of 120-210 °C for up to 15 h.

12. The process according to the claim 2 is **characterized in,**
that the bars, other forms, or forged parts for the T4 temper are solution heat treated at a temperature of 450-550 °C from 1 to 3 h, water quenched, and then naturally aged.

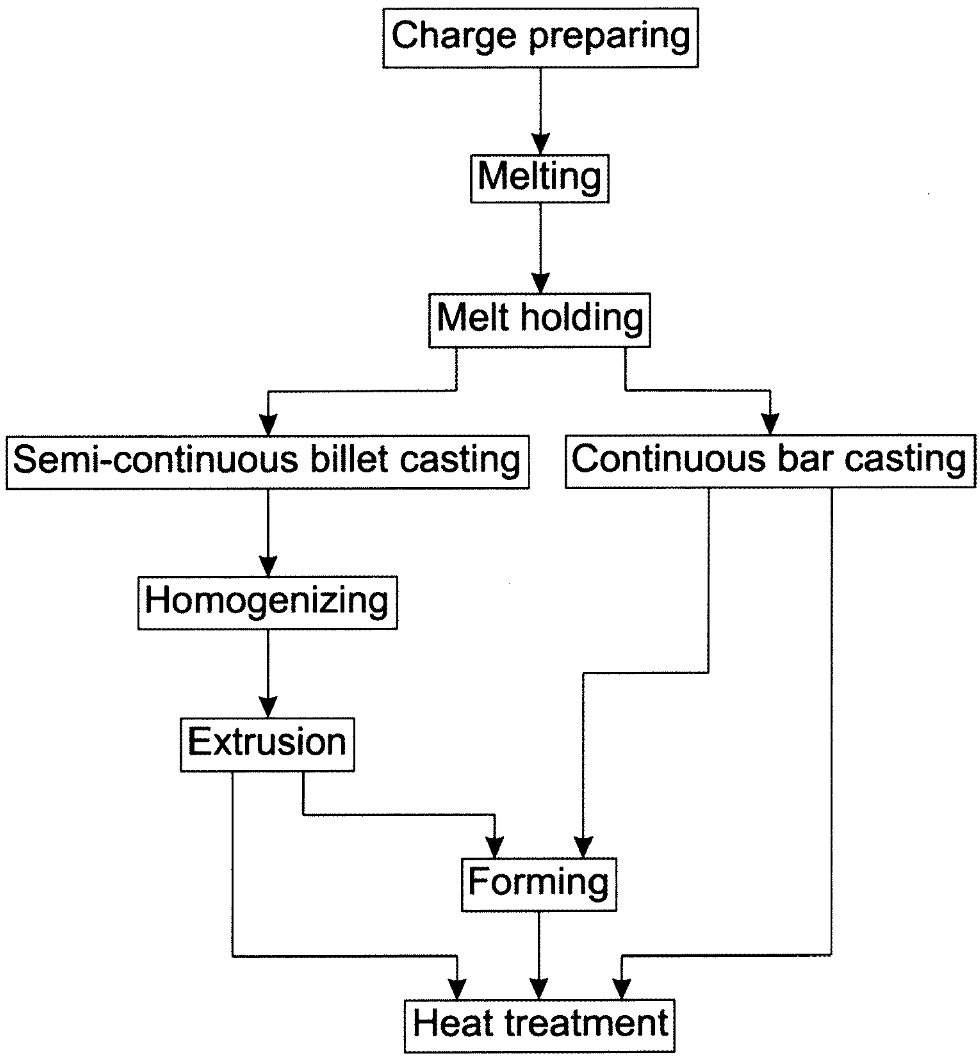
Charge preparing
Melting
Melt holding
Semi-continuous billet casting
Continuous bar casting
Homogenizing
Extrusion
Forming
Heat treatment

Figure 1

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EUROPEAN SEARCH REPORT

Application Number
EP 17 46 8001

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TECHNICAL FIELDS SEARCHED (IPC)
C22C
C22F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	6 July 2017	González Junquera, J

5

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 17 46 8001

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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