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(54) **7XXX ALLOY COMPONENTS FOR DEFENSE APPLICATION WITH AN IMPROVED SPALL
RESISTANCE**

7XXX-LEGIERUNGSKOMPONENTEN FÜR ABWEHRANWENDUNG MIT VERBESSERTER
SPLITTERBESTÄNDIGKEIT

COMPOSANTS D'ALLIAGE 7XXX TROUVANT UNE APPLICATION DANS LA DÉFENSE ET
PRÉSENTANT UNE RÉSISTANCE AUX ÉCLATS AMÉLIORÉE

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Description**BACKGROUND****Technical Field**

[0001] The present application relates to armor components made of high strength aluminum, such as 7xxx series aluminum alloys, which may be employed in civil or military ballistic protection systems. It relates more particularly to armor components such as armor hull walls and add-on armor appliques in vehicles.

Description of Related Art

[0002] Structures and vehicles are increasingly designed to protect their occupants from penetration of projectiles. These projectiles are typically metal, and may strike the structure at high speed, attempting to perforate the structure, and thereby inflicting damage to the occupants. The aim of an armor shield is to provide ballistic defeat of such projectiles or fragments.

[0003] The demand of ballistic grade aluminum has seen a large increase due to the ballistic advantages of this low density metal when utilized as primary armors on vehicles. Aluminum armors are enablers of lightweight shields, which fit with weight requirements of such vehicles.

[0004] An armor panel has a front face, exposed to impacts and shocks, and a rear face. Upon impact on such armor panel, an armor piercing projectile can be completely stopped in the panel. However, some fragments may be violently ejected from the rear face of the panel, towards the vehicle interior.

[0005] Patent US8206517 B1 discloses 7XXX alloys generally resistant to armor piercing rounds at 2850 fps, resistant to fragment simulated particles at 2950 fps, and resistant to spalling. To achieve the ballistics properties, the alloys are generally overaged so as to obtain a tensile yield strength that is (i) at least about 10 ksi lower than peak strength and/or (ii) no greater than 70 ksi.

[0006] Patent application US2006174980 A1 discloses a Al-Zn alloy wrought product, and a method of manufacturing such a product, with an improved combination of high toughness and high strength by maintaining good corrosion resistance, the alloy including (in weight percent): Zn 6.0-11.0, Cu 1.4-2.2, Mg 1.4-2.4, Zr 0.05-0.15, Ti<0.05, Hf and/or V<0.25, and optionally Sc and/or Ce 0.05-0.25, and Mn 0.05-0.12, other elements each less than 0.05 and less than 0.50 in total, balance aluminium, wherein such alloy has an essentially fully unrecrystallized microstructure at least at the position T/10 of the finished product.

[0007] To characterize their shield effectiveness, armor panels performances must comply with different requirements. Key requirements includes ballistic grade aluminum alloy should achieve a high combination of armor piercing (AP) resistance, fragment simulated particle (FSP) resistance, as well as spall resistance.

[0008] AP resistance means achieving a predetermined armor piercing V50 ballistic limit using a piercing projectile, so called AP round. This characterizes the resistance to perforation. FSP resistance means achieving a predetermined V50 ballistic limit using another kind of projectile: FSP projectile, so-called FSP round, which is defined in MIL-DTL-46593B specification. FSP resistance characterizes the ability to withstand impacts that generate fragmented debris. V50 ballistic limit, which has a speed dimension, is defined in MIL-STD-662F (1997) standard. The V50 ballistic limits shall be calculated by taking the arithmetic mean of an equal number of the highest partial and the lowest complete penetration impact velocities. The specific V50 required at a given thickness, the amount of individual FSP tests to include in the calculation of a V50, and other material requirements can vary between different aluminum alloys. As an example MIL-DTL-46027K enumerates the requirements for 5083, 5456, and 5059 aluminum alloys.

[0009] Spall resistance as indicated within MIL-STD-662F (1997) means that, during ballistic tests conducted in accordance with this standard, no substantial detachment or delamination of a layer of material occurs in the area surrounding the location of the impact, either on the front or the rear surface of the armor. This pass-fail criterion for spalling and the related high-low impact velocity averaging used in a V50 evaluation facilitates the testing method but does not allow for further analysis into the amount of spall damage. Additionally such a testing method can require a sizable volume of metal which can hinder the ability to either rapidly prototype or sweep through a range of alloy chemistry, transformation routes, tempering options, etc... Consequently, in the present application, spall resistance is quantified using a spall resistance score. Spall resistance score is investigated with a FSP test according to MIL-STD-662F (1997) standard. Trials are performed using 20 mm FSP rounds which comply with MIL-DTL-46593B. The dimensions of the FSP rounds are the following :

- diameter: 20 mm - 0. 787 inch ;
- length : 23.0 mm - 0.9 inch ;
- flat: 9.3 mm - 0. 366 inch.

[0010] The spall resistance score is determined by the following method. As shown on Figure 1, on the rear surface, surrounding the site of impact b, is an area of material which was visibly affected by the ballistic strike and the partial or complete penetration by the FSP round into the plate. The boundary of this affected area is indicated on Figure 1 with the dotted line a. Along with any possible exit hole of the FSP round, any material plug and area of any delaminated material is included within the deformed area. The area also includes bulged or fractured material, which is still connected to the test plate. Radiating perpendicular from the direction of impact (i.e. along the rear surface) a length c is measured which represents the longest distance from the site of impact to the edge or boundary of the deformed area. This maximum length c is then doubled and from the new value 20 mm is subtracted, which corresponds to the diameter of the FSP round. The remaining total is divided by 20 mm, so as to get a dimensionless parameter, so-called Spall Resistance Score. The spall resistance score is 0 when only a plug is formed, and no significant lateral material is affected by the impact. Higher scores represent multiples of the impacting round diameter. A better score is as low as possible.

[0011] Achieving high AP resistance as well as high FSP resistance remains challenging. Provisional US application 61/948870 discloses an armor component produced from a 7XXX aluminum series alloy, having an improved combination of AP resistance and FSP resistance. The aluminum alloys disclosed therein consists essentially of:

- 8.4 wt.% $\leq$ Zn $\leq$ 10.5 wt.% ;
- 1.3 wt.% $\leq$ Mg $\leq$ 2 wt.% ;
- 1.2 wt.% $\leq$ Cu $\leq$ 2 wt.% ;
- 0.04 wt.% $\leq$ Zr $\leq$ 0.08 wt.%;
- ;
- the remainder substantially being aluminum, incidental elements and impurities.

[0012] According to US61/948870, the armor component is in the form of a plate having a thickness ranging from about 0.5 to about 3 inches (about 12.7 to about 76.2 mm) ; it is aged to achieve high AP and FSP V50 ballistic limits. Namely, the FSP V50 ballistic limit is such that:

$$V50 \text{ (FSP 20 mm)} > 1633 T^2 - 1479 T + 1290,$$

where T is the plate thickness (inch) and the unit of V50 is feet/s. "FSP 20 mm" means FSP trials being conducted with 20 mm diameter rounds (1 inch = 25.4 mm, 1 foot = 304.8 mm).

[0013] The AP V50 ballistic limit is such that:

$$V50 \text{ (0.3cal AP mm)} > -282 T^2 + 1850 T + 610,$$

where T is the plate thickness (inch) and the unit of V50 is feet/s. "0.3cal AP V50" means AP trials being conducted with 0.30 caliber rounds (1 inch = 25.4 mm, 1 foot = 304.8 mm).

[0014] The combined targeted ballistic properties can be obtained through a multiple steps aging during the manufacturing process. A typical aging treatment is about 4 - 8 hours at about 110°C - 130°C, followed by about 12 - 20 hours at about 140°C - 160°C.

[0015] Besides FSP and AP ballistic resistance, a high spall resistance is also often required. The present invention provides armor components having high AP and FSP ballistic resistance as well as improved spall resistance.

SUMMARY OF THE INVENTION

[0016] 7xxx series aluminum alloy armor components produced in accordance with the present invention exhibit an improved spall resistance. Processing parameters, as well as the alloy composition, are controlled in order to increase spall resistance, and to have high AP and FSP ballistic resistance.

- The composition of the 7xxx series aluminum alloy comprises Zr as dispersoid forming element, Zr from 0.04 wt.% to 0.08 wt.% which results in a further improvement of the performances.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Figure 1 depicts an embodiment of the method used to determine the spall resistance score according to the present disclosure.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0018] Unless otherwise stated, all compositional percentages are expressed in weight percent (wt.%), based on the total weight of the alloy. Alloy designation is in accordance with the regulations of The Aluminum Association known of those skilled in the art.

[0019] As used herein, the expression "up to" when referring to the amount of an element means that this elemental composition is optional, and includes a zero amount of this element. When the term "between" appears in the present application and claims, it is understood that the upper and lower numbers in the range are included. Similarly, "lower than" or "higher than" and such phrases include the numeral in the recited range.

[0020] The present invention relates to a method of producing an armor component, comprising :

a) casting a 7XXX series aluminum alloy to obtain an ingot, said alloy consisting essentially of

- 8.4 wt.% $\leq$ Zn $\leq$ 10.5 wt.% ;
- 1.3 wt.% $\leq$ Mg $\leq$ 2 wt.% ;
- 1.2 wt.% $\leq$ Cu $\leq$ 2 wt.% ;
- 0.04 wt.% $\leq$ Zr $\leq$ 0.08 wt.%;
- the remainder aluminum, incidental elements, and impurities;

b) homogenizing said ingot;

c) hot working said homogenized ingot to obtain a plate having a first thickness T1 ;

d) cold working the plate having the first thickness to obtain a plate having a second thickness T2, wherein $T2 = T1 - (x_1 * T2)/100$ and $0.5 \leq x_1 \leq 15$;

e) solution heat treating ;

f) quenching; and

g) aging.

[0021] The alloy product according to the invention can be prepared using a conventional melting process and by casting into an ingot form. During casting, the below described grain refiners may be added. After scalping and homogenizing at 460°C - 520°C during 5-60 hours, the ingot is further hot worked, typically hot worked in several steps, to obtain a plate having a first thickness T1. According to an embodiment, hot working is hot rolling or forging, and more preferably hot rolling.

[0022] It has been shown that performing a cold working step prior to solution heat treatment (SHT), and more specifically between hot working step and solution heat treatment, resulted in an improvement of the spall resistance. After the cold working step, the cold worked plate has a second thickness T2, wherein $T2 = T1 - (x_1 * T2)/100$ and $0.5 \leq x_1 \leq 15$. According to an embodiment, the cold worked plate has a second thickness T2, wherein $T2 = T1 - (x_1 * T2)/100$ and $2 \leq x_1 \leq 10$, preferably $4 \leq x_1 \leq 8$. According to an embodiment, said cold working step prior to solution heat treatment is a cold rolling step.

[0023] The cold worked plate having a second thickness T2 is then solution heat treated and quenched. In a preferred embodiment, the solution heat treatment is performed between 1 to 5 hours at 460°C - 480°C and quenched typically to a temperature lower than 95°C.

[0024] Optionally, another cold working step is performed after SHT and quench to obtain a plate having a third thickness T3. This other cold working step can be a stretching. Said other cold working step gives rise to a plastic deformation for example up to 3%, typically between 1 and 3 %. When no second cold working step is applied, the second thickness T2 is the final thickness of the armor component. When the method according to the invention involves two cold working steps, the final thickness is the third thickness T3 of the plate obtained after the second cold working step and the final thickness of the armor component is lower than the second thickness T2.

[0025] According to an embodiment, step g) includes at least a two step aging. Preferably, this two-step aging includes :

- a first aging step of about 4-8 hours, and more preferably of about 5-7 hours, at about 110°C to 130°C, and more preferably at about 115°C to 125 °C ; and
- a second aging step of about 12-20 hours, and more preferably about 14-18 hours, at about 130°C to 180 °C and more preferably at about 145°C to 165 °C.

[0026] According to another embodiment, aging is performed so that the total equivalent time at 150°C ranges between about 5h to about 50h, and more preferably from about 10h to about 40h. The total equivalent time $t(eq)$ at 150°C is given by the expression :

$$t(eq) = \frac{\int e^{\frac{-15683}{T}} dt}{e^{\frac{-15683}{T_{ref}}}}$$

where :

- T is the instantaneous temperature in Kelvin of treatment ;
- t denotes the time, including heating and cooling steps ;
- T_{ref} is a reference temperature, whose value is 423 K (i.e 150°C) ;
- $t(eq)$ is expressed in hours ;
- 15683 is a temperature derived from the diffusion activation energy of Mg, $Q = 130400$ J/mol.

[0027] Aging step, particularly according to the preceding embodiments, is assumed to improve both AP and FSP resistance.

[0028] According to a preferred embodiment, the armor component provided is a plate having a final thickness ranging between 0.5 inch and 3 inches (between 12.7 and 76.2 mm).

[0029] The alloy generally comprises, and in some instances consists essentially of, zinc (Zn), copper (Cu) and magnesium (Mg) as main alloying ingredients, with at least one dispersoid forming elements, the total content of dispersoid forming elements being at least 0.04 wt. %, and the remainder substantially including aluminum, incidental elements, and impurities.

[0030] The Zn content ranges between about 8.4 wt.% and about 10.5 wt.%, preferably between 8.5 wt.% and 9.5 wt.% and more preferably between 8.5 wt.% to 9 wt.%. Trials have shown that such content resulted in the highest results in both AP and FSP ballistic tests and/or in an improvement of spall resistance score.

[0031] The magnesium content ranges between about 1.3 wt.% and about 2 wt.%, preferably between 1.5 wt.% to about 2 wt.%, and more preferably from about 1.6 wt.% to 1.9 wt.%.

[0032] In a preferred embodiment, the Mg/Zn ratio is lower than or equal to 0.25, and preferably lower than or equal to 0.20, where Mg and Zn denote weight percentages of magnesium and zinc respectively.

[0033] The copper content ranges between about 1.2 wt.% and about 2 wt.%. Preferably, Cu content lies between 1.5 wt.% and 1.9 wt.%. High AP and FSP resistances were obtained when copper and magnesium contents were approximately the same, i.e typically when $0.9 \leq \text{Cu/Mg} \leq 1.1$.

[0034] Zr is added as dispersoid forming element. As used herein, dispersoid forming elements means elements that are deliberately added so as to control the grain structure. The total content of dispersoid forming elements is at least 0.04 wt.%. The optimum levels of dispersoid forming elements depend on the processing.

[0035] Zr content is from 0.04 to 0.08 wt. %, and more preferably from 0.05 to 0.08 wt.%. The best AP and FSP resistance compromise and/or the highest spall resistance score is observed when $0.05 \text{ wt.} \% \leq \text{Zr} \leq 0.08 \text{ wt.} \%$. The inventors have shown that, in comparison with the 7XXX alloy series described in US61/948870, lowering the Zr content as well as introducing a cold working before SHT improved spall resistance and maintained a high AP and FSP compromise so that

(i) $V50 \text{ (FSP 20mm)} > 1633 T^2 - 1479 T + 1290$ where T is the thickness plate (unit: inch) and the unit of V50 is feet/s; and

(ii) $V50 \text{ (0.30cal AP M2)} > -282 T^2 + 1850 T + 610$ where T is the thickness plate (unit: inch) and the unit of V50 is feet/s (1 inch = 2.54 mm, 1 foot = 304.8 mm).

[0036] It is assumed that such Zr content, as well as performing a cold working before SHT and quench, results in an increase of the grain size, as well as more equiaxed grain shapes.

[0037] As used herein, impurities mean elements that may be found in the alloy in minor amounts, but that are not intentionally added to the alloy. Those elements result from natural impurities in the individual alloy elements or from the manufacturing process. Fe and Si are the main impurities generally present in aluminum alloys. Fe content is preferably lower than 0.3 wt.%, and more preferably lower than 0.1 wt.%. Si content is preferably lower than 0.2 wt.%, and more preferably lower than 0.1 wt.%. Preferably, each other impurity element is present at up to about 0.05 wt.% with a total impurity (other than Fe or Si) content up to about 0.15 wt.%, based upon the total weight of the alloy taken as wt.%.

[0038] As used herein, incidental elements mean elements that may be optionally added to the alloy during the manufacturing process. Addition of such elements results from casting aids and deoxidizers. Titanium, Titanium boride (TiB_2) or titanium carbide (TiC) are usual grain refiners. Deoxidizers may include Ca, Sr and Be. Preferably, the amount of the incidental elements Ca, Sr, Be, Br and C lies below 0.005 wt.%, that of Ti below 0.05 wt. %.

[0039] In a preferred embodiment, the alloy chemistry is :

- $8.5 \text{ wt.} \% \leq \text{Zn} \leq 9.5 \text{ wt.} \% ;$
- $1.5 \text{ wt.} \% \leq \text{Mg} \leq 2 \text{ wt.} \% ;$
- $1.5 \text{ wt.} \% \leq \text{Cu} \leq 1.9 \text{ wt.} \% ;$
- $0.04 \text{ wt.} \% \leq \text{Zr} \leq 0.08 \text{ wt.} \% ;$
- the remainder aluminum, incidental elements, and impurities.

[0040] Another aspect of the present invention is an armor component produced from a 7XXX series aluminum alloy consisting essentially of:

- $8.4 \text{ wt.} \% \leq \text{Zn} \leq 10.5 \text{ wt.} \% ;$
- $1.3 \text{ wt.} \% \leq \text{Mg} \leq 2 \text{ wt.} \% ;$
- $1.2 \text{ wt.} \% \leq \text{Cu} \leq 2 \text{ wt.} \% ;$
- $0.04 \text{ wt.} \% \leq \text{Zr} \leq 0.08 \text{ wt.} \% ;$
- the remainder aluminum, incidental elements, and impurities;

wherein said 7xxx series aluminum alloy is cold worked with a thickness reduction from 0.5 to 15% (as defined previously, $0.5 \leq x_1 \leq 15$) before a solution heat treatment and is in the form of a plate having a final thickness of about 0.5 to about 3 inches (about 12.7 to about 76.2 mm) so as to achieve an improved spall resistance compared to an armor component obtained with the same manufacturing process except that said manufacturing process does not comprise a cold working step before the solution heat treatment.

Examples

Example 1 : Spall resistance

[0041] Alloy plate products were made from alloys having the chemical compositions, in weight percent, shown in Table 1. Alloy A is a reference alloy, alloy B is according to the invention.

Table 1 : composition of plate products (wt. %)

Alloy	Zn	Cu	Mg	Zr	Si	Fe
A	9.06	1.85	1.82	0.10	0.01	0.03
B	8.97	1.85	1.85	0.07	0.04	0.07

[0042] Plate products were made using the following process :

- casting an ingot of an alloy whose composition is indicated in table 1;
- homogenizing the ingot;
- hot working the homogenized ingot to arrive at an intermediate gauge T_1 ;
- for plate products B-3 and B-4 solely, cold working the ingot at said intermediate gauge to arrive at a final gauge T_2 , thereby reducing the thickness of the ingot at said intermediate gauge T_1 by respectively 2.9 % and 6.3%;
- solution heat treating the plate;
- quenching;
- for plate product A solely, stretching the plate to obtain a plastic deformation of about 2 %;
- artificially aging the plate.

[0043] All sample plates were aged during a two-stage process. Sample A was aged during 24 hours at 120°C (1st step) followed by 35 hours at 150 °C (second step). Samples B-1, B-2, B-3 and B-4 were aged during 6 hours at 120°C (1st step), followed by 16 hours at 160 °C (second step).

Table 2 : experimental results (1 inch = 2.54 mm, 1 foot = 304.8 mm)

Plate product	Final gauge (inch)	Cold Working	Spall Resistance Score	Velocity (FSP 20 mm) ft/s
A	1.37	No	5.35	3608

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(continued)

Plate product	Final gauge (inch)	Cold Working	Spall Resistance Score	Velocity (FSP 20 mm) ft/s
B-1	1.35	No	3	2318
B-2	1.35	No	3	2346
B-3	1.3	Yes $x_1 = 2.9$	2.5	2299
B-4	1.25	Yes $x_1 = 6.3$	2	2279

[0044] The final thickness of each plate product ranges between 1.25 and 1.37 inches (between 31,75 and 34.8 mm). As can be noticed on the third column of Table 2, samples A, B-1 and B-2 were not submitted to cold working before SHT, whereas cold rolling before SHT was performed on samples B-3 and B-4, thereby reducing the thickness of the so called intermediate sample plate respectively by 2.9 % and 6.3 %. Values given with respect to samples B-3 and B-4, in the third column of table 2, represent the value x_1 such that $T^2 = T_1 - (x_1 * T_2)/100$.

[0045] Samples B-3 and B-4 combine a low Zr content according to the invention as well as a cold working step before solution heat treatment and quench.

[0046] For all plate products, spall resistance was investigated with a FSP test according to MIL-STD-662F (1997) standard. Trials were performed using 20 mm FSP rounds which comply with MIL-DTL-46593B. The dimensions of the FSP rounds are the following :

- diameter: 20 mm - 0. 787 inch ;
- length : 23.0 mm - 0.9 inch ;
- flat: 9.3 mm - 0. 366 inch.

[0047] The fourth column of table 2 shows the spall resistance score. This score is determined by the following method. As shown on Figure 1, on the rear surface, surrounding the site of impact b, is an area of material which was visibly affected by the ballistic strike and the partial or complete penetration by the FSP round into the plate. The boundary of this affected area is indicated on Figure 1 with the dotted line a. Along with any possible exit hole of the FSP round, any material plug and area of any delaminated material is included within the deformed area. The area also includes bulged or fractured material, which is still connected to the test plate. Radiating perpendicular from the direction of impact (i.e. along the rear surface) a length c is measured which represents the longest distance from the site of impact to the edge or boundary of the deformed area. This maximum length c is than doubled and from the new value 20 mm is subtracted, which corresponds to the diameter of the FSP round. The remaining total is divided by 20 mm, so as to get a dimensionless parameter, so-called Spall Resistance Score. The spall resistance score is 0 when only a plug is formed, and no significant lateral material is affected by the impact. Higher scores represent multiples of the impacting round diameter. A better score is as low as possible.

[0048] The fifth column of Table 2 shows the velocities of the projectile that were measured when performing FSP tests.

[0049] From these results, it can be concluded that

- Plate products B-3 and B-4 exhibit a better spall resistance than Plate products B-1 and B-2;
- Plate product B-4 exhibits a better spall resistance than Plate product B-3.

[0050] This tends to show that a cold working step before SHT results in an improvement of the spall resistance. Moreover, combining such cold working together with a low amount of Zr might significantly improve the spall resistance score, while maintaining a high resistance with respect to both AP and FSP rounds, as will be assessed in example 2.

Example 2: AP and FSP properties

[0051] Alloy plate products were made from alloys having the chemical compositions, in weight percent, shown in Table 3.

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Table 3 : composition of sample plates (wt.%) in example 2

Alloy	Zn	Cu	Mg	Zr	Si	Fe
C	8.88	1.81	1.72	0.09	0.04	0.05
D	8.92	1.83	1.78	0.07	0.04	0.06
E	8.85	1.63	1.61	0.06	0.04	0.06

[0052] Alloys D and E have a chemistry according to the invention.

[0053] Plate products were made using the following process according to the invention:

- casting an ingot of an alloy whose composition is indicated in table 3;
- homogenizing the ingot;
- hot working the homogenized ingot to arrive at an intermediate gauge T_1 ;
- cold working the ingot at said intermediate gauge T_1 to arrive at a final gauge T_2 , thereby reducing the thickness of the ingot, at said intermediate gauge T_1 by 2.9 % ($x_1 = 2,9$);
- solution heat treating the plate;
- quenching;
- stretching the plate to obtain a plastic deformation between 2 % to 3% ;
- artificially aging the stretched plate during 6 hours at 120°C, followed by 16 hours at 160°C.

[0054] Plate products had different thicknesses varying from 1.0" to 1.6" and were tested for their ballistic properties. Two ballistic tests have been carried out pursuant to U.S. military standard MIL-STD-662F (1997), namely the armor piercing test using 0.3 inch (7.62 mm) projectiles and the FSP test using 20 mm fragment simulating projectiles. The AP and FSP results are listed in Table 4 and compared to the minimum required ballistic limits defined in US Military specification MIL-DTL 32375 (respectively, V50 (0.3Cal AP M2) 7085 requirement: MIL-DTL-32375 (MR) Appendix A, page 19-20, column "Required BL(P) - Type B" and V50 (FSP 20 mm) 7085 requirement: MIL-DTL-32375 (MR) Appendix A, page 18, column "Required BL(P) - Type B"). This specification covers 7085 wrought aluminum alloy armor plate for non-fusion welded applications in nominal thickness from 0.500 to 3.000 inch (from 12.7 to 76.2 mm) and defines minimum required ballistic limits with respect to different kinds of projectiles as well as plate thicknesses.

Table 4 : experimental results of example 2 (1 inch = 2.54 mm, 1 foot = 304.8 mm)

Plate product	Final gauge (inch)	V50 (0.3 cal AP M2) ft/s	V50 (0.3 cal AP M2) % greater than 7085 requirement	V50 (FSP 20 mm) ft/s	V50 (FSP 20 mm) % greater than 7085 requirement
C	1.11	2342	+ 2.23	1645	+ 3.98
D	1.61			3350	+ 11.93
E	1.00	2211	+ 2.65	1506	+ 9.69

[0055] Plate products C, D and E have combined high AP and FSP performances. In particular, all the preceding plate products meet the minimum required ballistic limits defined in US Military specification MIL-DTL 32375 for alloy 7085. Moreover, regarding examples 1 and 2 combining cold working before SHT together with a low amount of Zr, namely $Zr \leq 0.08$ wt. %, seems to significantly improve the spall resistance score, while maintaining a high resistance with respect to both AP and FSP rounds.

Claims

1. A method of producing an armor component having a final thickness ranging between 0.5 inch and 3 inches (between 12.7 and 76.2 mm), comprising :

a) casting a 7XXX series aluminum alloy to obtain an ingot, wherein said alloy comprises or consists essentially of

- $8.4 \text{ wt.} \% \leq \text{Zn} \leq 10.5 \text{ wt.} \%$;
- $1.3 \text{ wt.} \% \leq \text{Mg} \leq 2 \text{ wt.} \%$;

- 1.2 wt.% $\leq$ Cu $\leq$ 2 wt.% ;
- 0.04 wt.% $\leq$ Zr $\leq$ 0.08 wt.%;
- the remainder aluminum, incidental elements, and impurities;

- b) homogenizing said ingot;
 c) hot working said homogenized ingot to obtain a plate having a first thickness T1 ;
 d) cold working the plate having the first thickness to obtain a plate having a second thickness T2, wherein $T2 = T1 - (x_1 \cdot T2)/100$ and $0.5 \leq x_1 \leq 15$;
 e) solution heat treating ;
 f) quenching; and
 g) aging.

2. The method of claim 1, wherein $2 \leq x_1 \leq 10$, preferably $4 \leq x_1 \leq 8$.

3. The method of claim 1, wherein d) is a cold rolling step.

4. The method of claim 1, wherein g) includes at least a two step aging.

5. The method of claim 4, wherein said two-step aging includes :

- a first aging of about 4-8 hours at about 110°C to 130°C ; and
- a second aging of about 12-20 hours at about 130°C to 180 °C.

6. The method of claim 1, wherein g) is performed so that the total equivalent time at 150°C is between about 5h to about 50h, preferably about 10h to about 50h, wherein the total equivalent time $t(eq)$ at 150°C is given by the expression :

$$t(eq) = \frac{\int e^{\frac{-15683}{T}} dt}{e^{\frac{-15683}{T_{ref}}}}$$

where :

- T is the instantaneous temperature in Kelvin of treatment;
- t denotes the time, including heating and cooling steps ;
- T_{ref} is a reference temperature, whose value is 423 K (i-e 150°C) ;
- $t(eq)$ is expressed in hours ;
- 15683 is a temperature derived from the diffusion activation energy of Mg, $Q = 130400$ J/mol.

7. The method of claim 1, including, between f) and g), another cold working to obtain a plate having a third thickness T3.

8. The method of claim 7, wherein said cold working to obtain a plate having a third thickness T3 results in a plastic deformation ranging from 1% to 3%.

9. The method of claim 7, wherein said cold working to obtain a plate having a third thickness T3 comprises or consists of stretching .

10. An armor component produced from a 7XXX series aluminum alloy comprising or consisting essentially of:

- 8.4 wt.% $\leq$ Zn $\leq$ 10.5 wt.% ;
- 1.3 wt.% $\leq$ Mg $\leq$ 2 wt.% ;
- 1.2 wt.% $\leq$ Cu $\leq$ 2 wt.% ;
- 0.04 wt.% $\leq$ Zr $\leq$ 0.08 wt.%.

- the remainder aluminum, incidental elements, and impurities;
 wherein said 7xxx series aluminum alloy is in the form of a plate having a final thickness of about 0.5 to about 3 inches (about 12.7 to about 76.2 mm) and is manufactured by:

- a) casting said 7XXX series aluminum alloy to obtain an ingot,
- b) homogenizing said ingot;
- c) hot working said homogenized ingot to obtain a plate having a first thickness T_1 ;
- d) cold working the plate having the first thickness to obtain a plate having a second thickness T_2 , wherein $T_2 = T_1 - (x_1 \cdot T_2)/100$ and $0.5 \leq x_1 \leq 15$;
- e) solution heat treating;
- f) quenching; and
- g) aging;

so as to achieve an improved spall resistance compared to an armor component obtained with the same manufacturing process except that said manufacturing process does not comprise cold working before the solution heat treatment.

Patentansprüche

1. Verfahren zur Produktion einer Panzerungskomponente mit einer Enddicke, die zwischen 0,5 Zoll und 3 Zoll (zwischen 12,7 und 76,2 mm) liegt, umfassend:

a) Gießen einer Aluminiumlegierung der 7XXX-Serie, um einen Gussblock zu erhalten, wobei die Legierung umfasst oder im Wesentlichen besteht aus:

- 8,4 Gew.-% $\leq$ Zn $\leq$ 10,5 Gew.-%;
- 1,3 Gew.-% $\leq$ Mg $\leq$ 2 Gew.-%;
- 1,2 Gew.-% $\leq$ Cu $\leq$ 2 Gew.-%;
- 0,04 Gew.-% $\leq$ Zr $\leq$ 0,08 Gew.-%;
- wobei es sich bei dem Rest um Aluminium, anfallende Elemente und Verunreinigungen handelt;

b) Homogenisieren des Gussblocks;

c) Warmumformen des homogenisierten Gussblocks, um eine Platte mit einer ersten Dicke T_1 zu erhalten;

d) Kaltumformen der Platte mit der ersten Dicke, um eine Platte mit einer zweiten Dicke T_2 zu erhalten, wobei $T_2 = T_1 - (x_1 \cdot T_2)/100$ und $0,5 \leq x_1 \leq 15$;

e) Lösungsglühen;

f) Abschrecken; und

g) Altern.

2. Verfahren nach Anspruch 1, wobei $2 \leq x_1 \leq 10$, vorzugsweise $4 \leq x_1 \leq 8$.

3. Verfahren nach Anspruch 1, wobei d) ein Kaltwalzschrift ist.

4. Verfahren nach Anspruch 1, wobei g) mindestens ein zweistufiges Altern beinhaltet.

5. Verfahren nach Anspruch 4, wobei das zweistufige Altern beinhaltet:

- ein erstes Altern von etwa 4-8 Stunden bei etwa 110 °C bis 130 °C; und
- ein zweites Altern von etwa 12-20 Stunden bei etwa 130°C bis 180 °C.

6. Verfahren nach Anspruch 1, wobei g) durchgeführt wird, so dass die gesamte äquivalente Zeit bei 150 °C zwischen etwa 5 h bis etwa 50 h, vorzugsweise etwa 10 h bis etwa 50 h liegt, wobei die gesamte äquivalente Zeit $t(eq)$ bei 150 °C durch den Ausdruck gegeben ist:

$$t(eq) = \frac{\int e^{\frac{-15683}{T}} dt}{e^{\frac{-15683}{T_{ref}}}},$$

wobei:

- T die Momentantemperatur der Behandlung in Kelvin ist;
- t die Zeit bezeichnet, einschließlich Heiz- und Kühschritten;
- T_{ref} eine Referenztemperatur ist, dessen Wert 423 K (d. h. 150 °C) ist;
- $t(eq)$ in Stunden ausgedrückt ist;
- 15.683 eine Temperatur ist, die von der Diffusionsaktivierungsenergie von Mg abgeleitet ist, $Q = 130.400 \text{ J/mol}$.

7. Verfahren nach Anspruch 1, beinhaltend zwischen f) und g) ein weiteres Kaltumformen, um eine Platte mit einer dritten Dicke T_3 zu erhalten.

8. Verfahren nach Anspruch 7, wobei das Kaltumformen zum Erhalten einer Platte mit einer dritten Dicke T_3 zu einer Kunststoffverformung führt, die von 1 % bis 3 % reicht.

9. Verfahren nach Anspruch 7, wobei das Kaltumformen zum Erhalten einer Platte mit einer dritten Dicke T_3 ein Strecken umfasst oder daraus besteht.

10. Panzerungskomponente, die aus einer Aluminiumlegierung der 7XXX-Serie produziert wird, umfassend oder im Wesentlichen bestehend aus:

- $8,4 \text{ Gew.}\% \leq \text{Zn} \leq 10,5 \text{ Gew.}\%$;
- $1,3 \text{ Gew.}\% \leq \text{Mg} \leq 2 \text{ Gew.}\%$;
- $1,2 \text{ Gew.}\% \leq \text{Cu} \leq 2 \text{ Gew.}\%$;
- $0,04 \text{ Gew.}\% \leq \text{Zr} \leq 0,08 \text{ Gew.}\%$;
- wobei es sich bei dem Rest um Aluminium, anfallende Elemente und Verunreinigungen handelt;
- wobei die Aluminiumlegierung der 7XXX-Serie in der Form einer Platte mit einer Enddicke von etwa 0,5 bis etwa 3 Zoll (etwa 12,7 bis etwa 76,2 mm) ist und hergestellt wird durch:

- a) Gießen der Aluminiumlegierung der 7XXX-Serie, um einen Gussblock zu erhalten,
- b) Homogenisieren des Gussblocks;
- c) Warmumformen des homogenisierten Gussblocks, um eine Platte mit einer ersten Dicke T_1 zu erhalten;
- d) Kaltumformen der Platte mit der ersten Dicke, um eine Platte mit einer zweiten Dicke T_2 zu erhalten, wobei $T_2 = T_1 - (x_1 \cdot T_2)/100$ und $0,5 \leq x_1 \leq 15$;
- e) Lösungsglühen;
- f) Abschrecken und
- g) Altern;

um eine verbesserte Temperaturwechselbeständigkeit im Vergleich zu einer Panzerungskomponente, die mit dem gleichen Herstellungsvorgang erhalten wird, mit Ausnahme davon, dass der Herstellungsvorgang kein Kaltumformen vor dem Lösungsglühen umfasst, zu erzielen.

Revendications

1. Procédé de production d'un composant de blindage ayant une épaisseur finale dans la plage entre 0,5 pouce et 3 pouces (entre 12,7 et 76,2 mm), comprenant :

a) la coulée d'un alliage d'aluminium de série 7XXX pour obtenir un lingot, dans lequel ledit alliage comprend ou est essentiellement constitué de

- $8,4 \text{ \% en poids} \leq \text{Zn} \leq 10,5 \text{ \% en poids}$;
- $1,3 \text{ \% en poids} \leq \text{Mg} \leq 2 \text{ \% en poids}$;
- $1,2 \text{ \% en poids} \leq \text{Cu} \leq 2 \text{ \% en poids}$;
- $0,04 \text{ \% en poids} \leq \text{Zr} \leq 0,08 \text{ \% en poids}$;
- le reste étant de l'aluminium, des éléments accidentels, et des impuretés ;

b) l'homogénéisation dudit lingot ;

c) le travail à chaud dudit lingot homogénéisé pour obtenir une plaque ayant une première épaisseur T_1 ;

d) le travail à froid de la plaque ayant la première épaisseur pour obtenir une plaque ayant une deuxième épaisseur T_2 , dans lequel $T_2 = T_1 - (x_1 \cdot T_2)/100$ et $0,5 \leq x_1 \leq 15$;

- e) le traitement thermique en solution ;
- f) la trempe ; et
- g) le vieillissement.

2. Procédé selon la revendication 1, dans lequel $2 \leq x_1 \leq 10$, de préférence $4 \leq x_1 \leq 8$.
3. Procédé selon la revendication 1, lequel d) est une étape de laminage à froid.
4. Procédé selon la revendication 1, dans lequel g) inclut au moins un vieillissement en deux étapes.
5. Procédé selon la revendication 4, dans lequel ledit vieillissement en deux étapes inclut :

- un premier vieillissement d'environ 4 à 8 heures à environ 110 °C à 130 °C ; et
- un second vieillissement d'environ 12 à 20 heures à environ 130 °C à 180 °C.

6. Procédé selon la revendication 1, dans lequel g) est réalisé de manière à ce que la durée totale équivalente à 150 °C se situe entre environ 5 h et environ 50 h, de préférence d'environ 10 h à environ 50 h, dans lequel la durée totale équivalente $t(eq)$ à 150 °C est obtenue par l'expression :

$$t(eq) = \frac{\int e^{\frac{-15683}{T}} dt}{e^{\frac{-15683}{T_{ref}}}}$$

où :

- T est la température instantanée en Kelvin du traitement ;
- t indique le temps, incluant les étapes de chauffage et de refroidissement ;
- T_{ref} est une température de référence, dont la valeur est de 423 K (en d'autres termes 150 °C) ;
- $t(eq)$ est exprimé en heures ;
- 15 683 est une température dérivée de l'énergie d'activation de diffusion de Mg, $Q = 130\,400$ J/mol.

7. Procédé selon la revendication 1, incluant, entre f) et g), un autre travail à froid pour obtenir une plaque ayant une troisième épaisseur T3.
8. Procédé selon la revendication 7, dans lequel ledit travail à froid pour obtenir une plaque ayant une troisième épaisseur T3 résulte en une déformation plastique dans la plage de 1 % à 3%.
9. Procédé selon la revendication 7, dans lequel ledit travail à froid pour obtenir une plaque ayant une troisième épaisseur T3 comprend ou est constitué d'un étirage.
10. Composant de blindage produit à partir d'un alliage d'aluminium de série 7XXX comprenant ou essentiellement constitué de :

- 8,4 % en poids $\leq Zn \leq 10,5$ % en poids ;
 - 1,3 % en poids $\leq Mg \leq 2$ % en poids ;
 - 1,2 % en poids $\leq Cu \leq 2$ % en poids ;
 - 0,04 % en poids $\leq Zr \leq 0,08$ % en poids ;
 - le reste étant de l'aluminium, des éléments incidents, et des impuretés ;
- dans lequel ledit alliage d'aluminium de série 7XXX est sous la forme d'une plaque ayant une épaisseur finale d'environ 0,5 à environ 3 pouces (d'environ 12,7 à environ 76,2 mm) et est fabriqué par :

- a) la coulée d'un alliage d'aluminium de série 7XXX pour obtenir un lingot,
- b) l'homogénéisation dudit lingot ;
- c) le travail à chaud dudit lingot homogénéisé pour obtenir une plaque ayant une première épaisseur T1 ;
- d) le travail à froid de la plaque ayant la première épaisseur pour obtenir une plaque ayant une deuxième épaisseur T2, dans lequel $T2 = T1 - (x_1 * T2)/100$ et $0,5 \leq x_1 \leq 15$;
- e) le traitement thermique en solution ;

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- f) la trempe ; et
- g) le vieillissement ;

5 pour obtenir une résistance à l'éclatement améliorée comparé à un composant de blindage obtenu avec le même processus de fabrication à l'exception que ledit processus de fabrication ne comprend pas le travail à froid avant le traitement thermique en solution.

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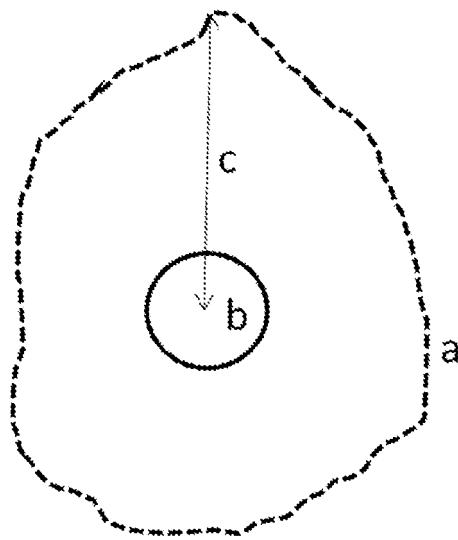


Figure 1

REFERENCES CITED IN THE DESCRIPTION

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