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Microstructure and Mechanical Properties of Al-Mg-Si Based Alloys Produced by Deformation-Semi-Solid-Forming Process

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In this paper, a relationship between microstructure and mechanical properties of Al-Mg-Si based alloys produced by the deformation-semisolid-forming (D-SSF) process is studied. The Al-Mg-Si based alloys containing Mn, Mn/Cr and high Mg contents are developed as feedstock materials for the thixoforming process. Several intermetallic compounds are formed after the ingots were homogenized. Then, the homogenized specimens were deformed using 60% cold-rolling. The thixoforming process was carried out using the squeeze casting machine. Appearance of thixoformed products shows that complete die-filling is achieved in the specimen heated at 646°C heating time for 17.5min. After T6 treatment, the 0.2% proof. stress and ultimate tensile strength of tensile tested specimens are in the ranges of 300-350MPa and 330-390MPa, respectively. The mechanical properties of the alloy containing Mn and high Mg contents exhibit good strength and elongation compared with other alloys. The fracture of tensile tested specimens generates and propagates along the interface between α-Al grains where the solidified liquid phase is existed. It is found that the mechanical properties of thixoformed specimens in this work are higher than that of the commercially extruded 6082 alloy but the elongation is slightly lower.

Keywords: *Semi-solid process, Thixoforming, Al-Mg-Si based alloys, Deformation-semisolid- forming process*

1. Introduction

Nowadays, thixoforming as ones of the semi-solid process is an attractive forming technology to produce light-weight components with superior mechanical properties, especially in the automotive industry such as the engine or body parts. High quality component is made by this process compared with conventional diecasting process due to gas and shrinkage porosities are reduced [1]. The thixoforming process highly requires an ingot as the feedstock materials in order to produce the refined semi-solid microstructure consisting spherical α-Al phase in the matrix of liquid phase before forming in to the mold. The use of wrought Al-Mg-Si alloys as the light-weight structural materials in automotive industries is becoming increasingly important. Since this alloy has many advantage properties. Al-Mg-Si alloys contain low concentration of alloying elements, especially when compared with aluminum casting alloys and other wrought alloys. During heating and holding in the semi-solid state, grain growth (in solid state) and grain coarsening (in semi-solid state) easily occur. Therefore, several methods have been developed and tried to overcome these problems such as the mechanical stirring, magneto hydrodynamic stirring (MHD), strain induced melt activate (SIMA), grain refinement and low pouring temperature [2-5]. The deformation-semi-solid-forming (D-SSF) process was successfully developed to overcome the grain growth during heating in this alloys [6-9]. The D-SSF process aims to refine semi-solid microstructure of Al-Mg-Si based alloys by control the rerystallization rate and grain growth during heating up to semi-solid state. If finely recrystallized grains can be controlled and kept up to high temperature the α-Al grain size in semi-solid will become small, at the same time. The sequences of the D-SSF process consist of casting, homogenization, heavy deformation, semi-solid heating and forming processes. In this process, the α-$Al_{12}Mn_3Si_2$ compound is precipitated after homogenization. This compound cooperate and heavy cold-deformation are extremely useful to refine recrystallinzed grains and to control the semi-solid microstructures [6,7]. Good favorable semi-solid microstructure with grain size about ~90μm is obtained. The Al_7Cr and mixture of Al_7Cr and α-$Al_{12}Mn_3Si_2$ compounds are formed in the homogenized specimen of the Cr-added and Cr/Mn-added Al-Mg-Si alloys, respectively. These dispersiod particles are also effective to control the semi-solid microstructure [8]. It is reported that the thixoformed steering knuckles of 6061 alloy have high ductility and equal strength as A357 thixoformed steering knuckles [10]. However, mechanical properties of Al-Mg-Si based alloys formed by the D-SSF process are still not clarified. In this work, relationship between microstructure and mechanical properties of Al-Mg-Si based alloys are investigated. The effect of intermeatallic compounds in the alloys containing Mn, Mn/Cr and high Mg contents is explained. investigated.

2. Experimental procedures

The Al-Mg-Si based alloys used in this work are listed in Table 1, showing chemical compositions, Mg_2Si content, excess Si content, solidus and liquid temperatures. The alloys were cast and homogenized at 530°C and isothermally held for 24h. The homogenized specimens were deformed by using 60% cold-rolling in order to introduce sufficient strain. Forming sequences of the D-SSF process were carried out using the squeeze casting machine with forming parameters of the plunger speed: 29mm/s, compression force: 26ton and compression time: 10s.. A disk shape specimen (diameter of 80mm x 4mm) was formed as the thixoformed product. In the forming process, the deformed specimens were set on the graphite plate and heated into the semi-solid temperature range of 637-646°C for 14-17.5min using an electric resistance furnace. After solidified, the disk shape specimen was sectioned for the tensile test. The T6 treatment was carried out with solution treatment at 550°C for 6h and aging treatment at 185°C for 4h. After the T6 treatment, mechanical properties were examined by the instron type universal testing machine (cross head speed is 5.0×10^{-2} mm/min). The microstructures near the fracture surface of the tensile test specimens were observed.

Table 1. Chemical compositions of the Al-Mg-Si based alloys (wt. %).

Alloys	Mg	Si	Mn	Cr	Mg_2Si	Excess Si	Solidus(°C)	Liquidus(°C)	Range (°C)
C3	0.89	1.14	-	0.31	1.40	0.63	582	649	67
MC43	0.87	1.17	0.37	0.29	1.39	0.66	584	650	66
M7	0.90	1.06	0.72	-	1.42	0.54	584	650	66
M12	1.37	0.99	0.65	-	2.16	0.20	589	648	58

3. Results and Discussions

3.1 Microstructure of thixoformed specimens

In the homogenized specimens, the Al_7Cr intermetallic compound is precipitated in the C3 alloy. Mixtures of the Al_7Cr and α-$Al_{12}Mn_3Si_2$ intermetallic compounds are found in the MC43 alloy. The α-$Al_{12}Mn_3Si_2$ compound is formed in the M7 and M12 alloys. Fig. 2 shows the comparison of the semi-solid microstructures in same position at point 2 of the thixoformed specimens. It is found that the microstructures of the thixoformed C3 alloy consisting of large (~185μm) and irregular grains in the liquid phase fraction approximately ~45%f_L as shown in Fig. 2(a). The liquid phase inside α-Al grain (as the liquid pool) can be clearly seen. These liquid pools solidify as the shrinkage porosity which is harmful for the mechanical properties. Microstructure of the thixoformed MC43 alloy is shown in Fig. 2(b), consisting of α-Al grains (~128μm) with low fraction of the liquid phases inside grain. Fig. 2(c) and Fig. 2(d) show microstructure of the thixoformed M7 and M12 alloys which consist of smaller α-Al grain size approximately 115μm and 102μm, respectively. More spherical grains and a few numbers of liquid pool inside the α-Al grain are achieved.

3.2 Effect of liquid fraction on appearances and Fluidity

Fig. 3 shows relationship between the appearances and anodized microstructures of the M12 alloy with two different heating conditions in the D-SSF process. Fig. 3(a) shows non-complete die-filling of the specimen heated at 637°C for 14min. The surface defects are included in the edge of specimen. In this specimen, very fine grains about 53μm are achieved but contains low liquid fraction about 23%. The complete die-filling is achieved in the specimen heated at 646°C for 17.5min. Grain size of this specimen is approximately 99μm with the liquid fraction about 33%. From these appearances and semi-solid microstructures, it can conclude that if the liquid fraction is low, the complete die-filling could not be achieved. Because when the liquid fraction decreases, at the same time, fluidity of the slurry during forming is decreased. Thus, the surface defects are formed in the edge of the thixoformed specimen. From these results, it is necessary to ensure that the slurry should be contained sufficient liquid fraction (>30%f_L) before squeeze casting to avoid surface defects and produce more complex component. In these experimental results, the best heating condition is 646°C within 20min in order to achieve the complete die-filling without any surface defects.

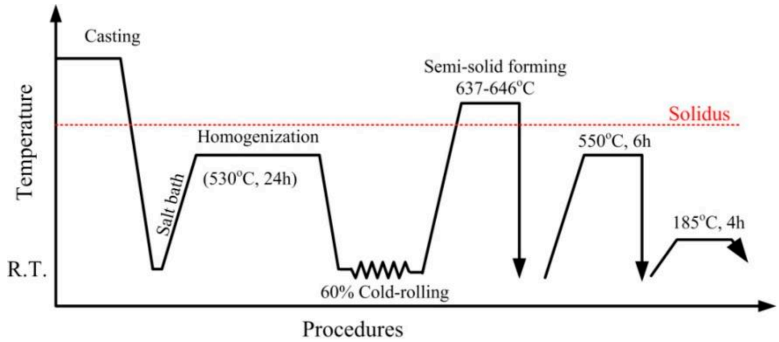

Fig. 1 Schematic illustration of the D-SSF process for Al-Mg-Si based alloys, showing casting, homogenization, semi-solid forming, solution treatment and aging processes.

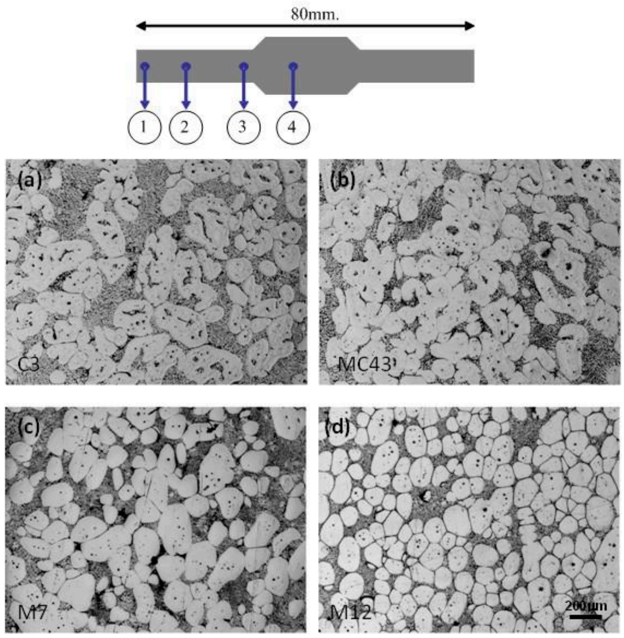

Fig. 2 Semi-solid microstructures of the D-SSF processed Al-Mg-Si based alloys from point No.2, (a) C3, (b) MC43, (c) M7 and (d) M12 alloys.

3.3 Effect of heating rate on mechanical properties

Effect of the heating rate to semi-solid state on mechanical properties of the thixoformed M7 alloys was examined. The rapid heating (~54°C/min) and slow heating rate (~29°C/min) were carried out using an electric resistance furnace in order to heat the deformed specimen into semi-solid state.

However, the rapid heating rate in this work is slower than that of the previous work [11] because the heating equipments are different. Fig. 4 shows the mechanical properties of the thixoformed M7 alloy. It is found that the 0.2% proof stress and U.T.S of the rapid-heated specimen are about 307 and 381MPa, respectively with the elongation about 5.9%. In the slow-heated specimen, the 0.2% proof stress and U.T.S are 140MPa and 257MPa, respectively which is much lower than that of the rapid-heated specimen. Therefore, the rapid heating rate is useful to control the microstructure in order to obtain good mechanical properties.

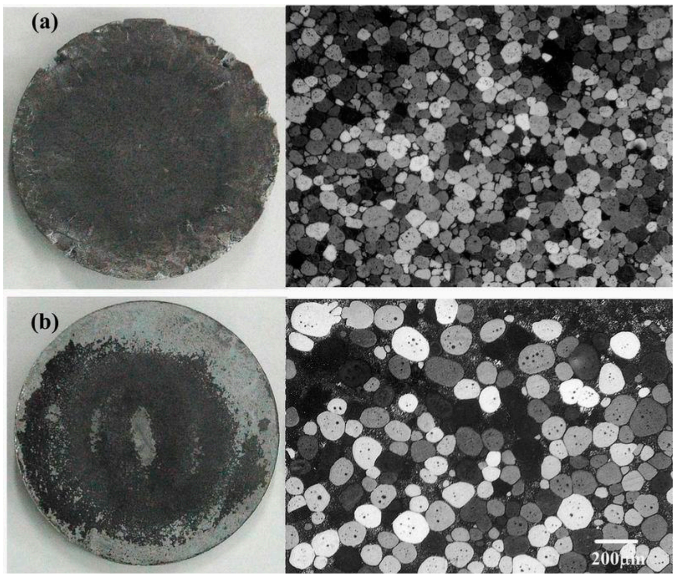

Fig. 3 Appearances and semi-solid microstructures of the D-SSF processed M12 alloy, showing (a) non-complete die-filling (low liquid fraction) of specimen heated of 637°C and (b) complete die-filling (high liquid fraction) of specimen heated of 646°C.

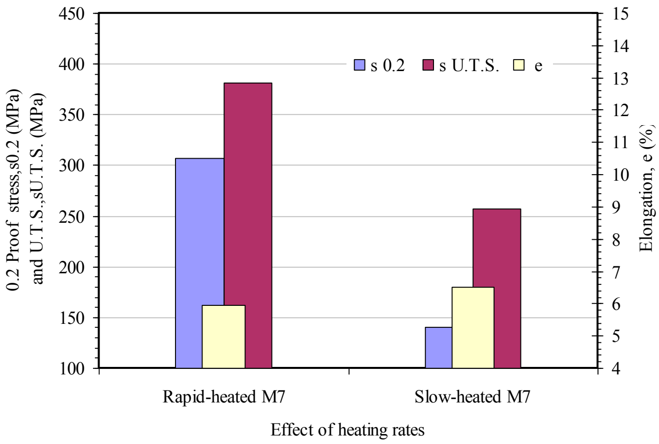

Fig. 4 Comparison of mechanical properties between the rapid-heated and slow-heated specimens of the D-SSF processed M7 alloy, showing higher strength in the rapid-heated specimen.

3.4 Effect of alloying elements on mechanical properties

Effect of alloying elements on mechanical properties of the thixoformed specimens is shown in Fig. 5. It should be noted that each alloy contains different dispersoid particles. The 0.2% proof stress and U.T.S of all alloys are higher than 300MP and 350MPa, respectively. It is found that the 0.2% proof stress and U.T.S of the C3 alloy is the highest about 348 and 387MPa, respectively but slightly lower elongation (about 5.75%) compared with other alloys. Since fine and homogeneously distributed Al_7Cr intermetallic compound is obtained even the solution treatment is carried out using the salt bath furnace, while coarse particles are obtained in the alloys containing Mn [7,8]. The mechanical properties of the thixoformed M12 exhibit good strength and the highest elongation about

6.9% compared with other alloys while the thixoformed MC43 alloy has the lowest mechanical properties.

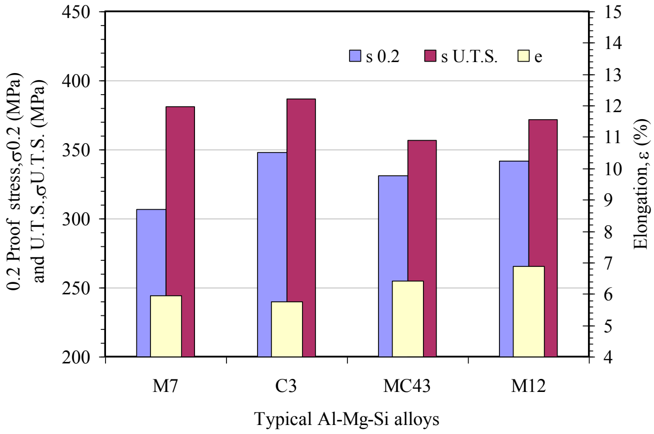

Fig. 5 Mechanical properties of Al-Mg-Si based alloys produced by the D-SSF process.

Fig.6 shows the microstructures near fracture surface of the tensile test specimens. It is found that the fracture occurs along the interface region between α -Al grains where the solidified liquid phase is existed. This interface is consisted of many fine intermetallic compounds such as the crystallized Mg_2Si, $Al_{15}(Fe,Mn)_3Si_2$, $Al_{15}(Fe,Mn,Cr)_3Si_2$ and precipitated α-$Al_{12}Mn_3Si_2$ intermetallic compounds. These compounds initiate the cracks and route of cracks propagation. Smaller and more spherical grains are found in the M12 alloys compared with other alloys. Fig. 10 shows high magnification micrographs near fracture surfaces of the M7 and M12 alloys in T6 treatment. It can be clearly seen that the α-$Al_{12}Mn_3Si_2$ intermetallic compounds is precipitated in the α-Al phase and solidified liquid phase region due to the rapid heating of the solution treatment using the salt bath furnace [7]. Fine particles are located along the grain boundaries and in solidified liquid phase, while rod-like particles are existed in side the grains. These compounds are strongly effective to the mechanical properties of the thixoformed product. Therefore, for the future improvement of the D-SSF process, heating rate of the solution treatment should be considered to produce finer and more homogeneous distribution of the α-$Al_{12}Mn_3Si_2$ intermetallic compounds.

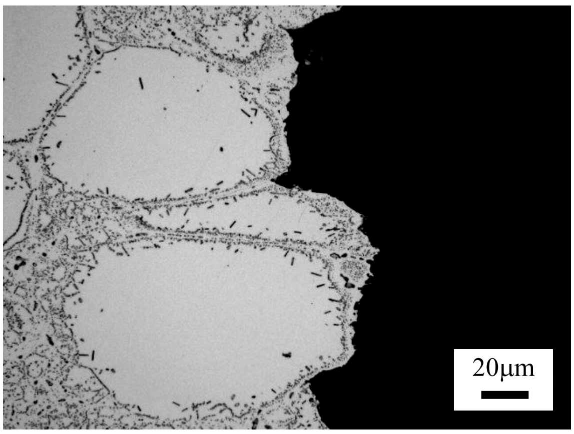

Fig. 6 Optical micrographs near fracture surfaces of M12 D-SSF processed alloys, showing the Mn dispersoid precipitate in α-Al grains and solidified liquid phase regions.

Fig.7 shows the relationship between the 0.2% proof stress/U.T.S. and elongation of all thixoformed specimens compared with the data of references. Several heat-treated specimens of each alloy are shown with the same color. The 0.2 proof stress of as-quenched specimens is in the range of 120-140MPa with high elongation is about 24%. After T6 treatment, the 0.2% proof stress of thixoformed specimens are increased in the range of 290-350MPa but elongation is decreased in the range of 5-12%. The U.T.S. is in the range of 310-390MPa. The relationship between strength and elongation of the specimens is schematically illustrated by a dotted line as the D-SSF zone. It can be seen that mechanical properties of the commercially extruded and standard JIS of 6082 alloy [12] include inside the D-SSF zone. Comparison of mechanical properties, strength of the thixoformed specimens is higher than that of the commercially extruded and standard JIS of 6082 alloy but elongation is lower. Therefore, mechanical properties of the thixoformed specimens may achieve equal or higher by control the T6 treatment such as aging temperature or aging time.

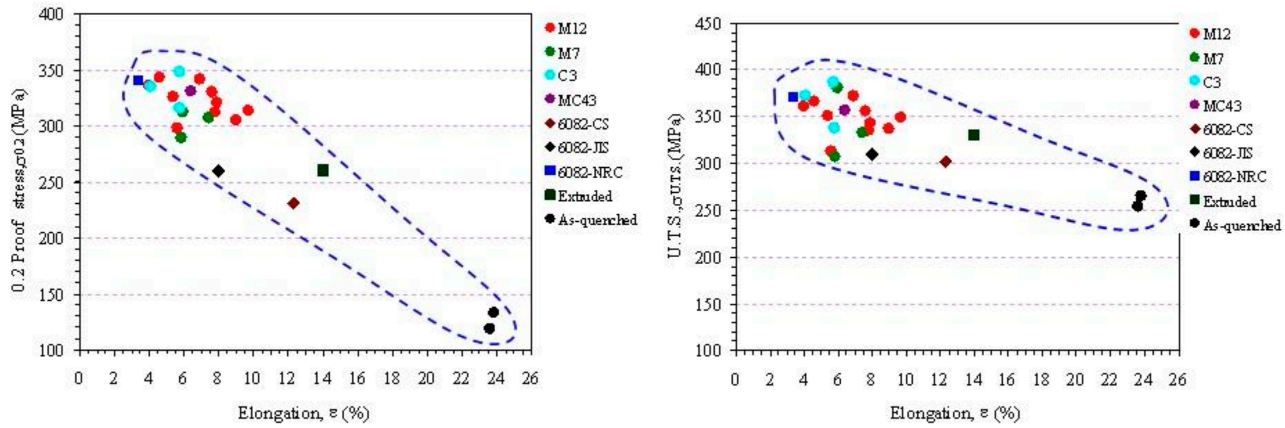

Fig. 11 0.2% proof stress and U.T.S. of the D-SSF processed alloys are shown inside a dotted line.

4. Conclusions

[1] The mechanical properties of D-SSF processed specimens exhibit that the 0.2% proof stress is in the ranges of 300-350MPa and the U.T.S. is in the ranges of 330-390MPa.
[2] The mechanical properties of the M12 exhibit good strength and elongation (~6.9%) compared with other alloys.
[3] The fracture of tensile tested specimen occurs along the interface between α-Al solid grains where the solidified liquid phase is existed. The many crystallized compounds initiate the crack and routes of crack propagation.

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