THE EFFECT OF COPPER AND MANGANESE ON THE STRENGTH AND FORMABILITY OF Al-Mg-Si ALLOYS.

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Abstract

Al-Mg-Si based alloys are finding increased usage in sheet applications where formability is an important requirement e.g. transport applications. The 6000 series have largely been development for extrusion applications where strength, extrudability and press quenchability have been key targets. The use of sheet materials with high formability requires a different criteria for materials design. This paper describes the results of an experimentally designed study into the evaluation of Al-Mg-Si alloys covering a wide range of %Mg_2Si contents (0.6 to 1.4%), excess Si or Mg content (0.4% excess Mg to 0.7% excess Si) with deliberate additions of Cu and Mn. The effect of these elements on T4 strength, n values, natural and artificial aging behaviour and forming behaviour is discussed.

Introduction

Concern for the environment demands that the automotive industry reduces noxious fume emission. Over the past significant gains in automobile fuel efficiency have been achieved through aerodynamic design and drive train improvements. As performance limits are approached in these areas, the recent interest is on alternate materials that would permit lightweight design. Aluminium seems to be increasingly attractive as a candidate for material substitution because of its low density (1,2). One of the limitations for using aluminium alloys in automotive body sheet applications is a lower formability compared to drawing steels, especially in plane strain conditions, where most failures occur (3). Al-Mg-Si based alloys are finding increased usage in outer body panels, where formability and strength are important requirements (4,5). This paper describes the results of an experimentally designed study into the evaluation of Al-Mg-Si alloys covering a wide range of %Mg_2Si contents, excess Si or Mg content, with deliberate additions of Cu and Mn.

Alloy design

When considering the development of aluminium alloys for automotive sheet, the performance criteria which are considered necessary being:-

1. Low to medium 0.2% PS in the T4 temper (110 to 150 MPa)

2. Capability of increasing 0.2% PS to 250 to 300 MPa during a full T6 treatment. This is to ensure a response to bake hardening cycles so that a strength of around 180 MPa can be achieved in the finished part.
3. Improved formability by combinations of alloy design, process control and surface texturing or coating.
4. Good corrosion, fracture and joining performance.
5. Compatibility of the process to existing equipment.
6. Cost minimisation by being fully recyclable.

The 6000 series alloys are considered the one of the better alloy systems to evaluate for long term future potential. Ternary Al-Mg-Si alloys have been extensively evaluated by numerous authors due to their extensive use in the extrusion industry (7,8). From the literature, the effect of the percent Mg_2Si on the T6 yield strength capability for a balanced alloy with an excess of either Mg of Si has been examined and the broad trends clearly be distinguished:

1. Above about 1.5% Mg_2Si the properties flatten out and no longer increase with increasing Mg_2Si. Note that 1.85 Mg_2Si is the solid solubility limit.
2. Below about 0.75% Mg_2Si a high excess Si level is essential to have a strength capability > 250 MPa.
3. Excess of either Mg or Si over that necessary to form Mg_2Si gives higher strength capability compared to the balanced alloy.

In the context of an automotive development programme to develop a comprehensive material solution to the problems facing the introduction of aluminium in body panels, an experimentally designed study into the evaluation of Al-Mg-Si alloys covering a wide range of $\%Mg_2Si$ contents and excess Si or Mg contents with deliberate additions of Cu and Mg was started. A series of alloys based on the following composition range are cast and rolled to sheet: Magnesium (0.40. 0.070 and 0.90 %); Silicon (0.40, 0.75 and 1.00 %); Copper (0.05 or 0.30 %); Manganese (0.05 or 0.50 %); Iron = 0.30 %. This report discusses some preliminary property data.

Experimental details

The ingots were cast using an AluSuisse-type mould. The cross section of the mould was 220 x 520 mm. The molten metal was rotary degassed with argon. The ingots were approximately 2.2 m long.

Table 1 shows the actual alloy chemistries measured by ICP. Also in this table the maximum percentage Mg_2Si that can precipitate in the alloy and the excess Si (or Mg) remaining after all Mg_2Si has precipitated are shown. The excess Si or Mg was taken from the difference between the available Si (Mg) and the amount needed to form Mg_2Si with a correction for the alloys Fe+Mn content.

From metallographic examination of the cast structures, the following observations can be made:

1. The iron rich intermetallics form α-phase when the Mn level is 0.50 weight percent.
2. The iron rich intermetallics form ß-phase when the Mn level is 0.05 weight percent.
3. The Mg and Si form dark particles of Mg_2Si which are usually associated with the iron intermetallics, copper is also associated with Mg_2Si.

Table 1: Alloy chemistries in weight percent. Measured using ICP.

Alloy	Fe	Si	Mn	Cu	Mg	%Mg_2Si	% Si Excess
601	0.23	0.42	0.05	0.05	0.40	0.63	0.14
602	0.32	0.40	0.52	0.28	0.40	0.63	0.03
603	0.28	0.39	0.50	0.27	0.63	0.73	-0.18
604	0.23	0.40	0.51	0.05	0.86	0.70	-0.38
605	0.30	0.68	0.53	0.06	0.42	0.66	0.30
606	0.19	0.66	0.06	0.26	0.65	1.03	0.24
607	0.27	0.65	0.50	0.05	0.62	0.97	0.16
608	0.30	0.67	0.05	0.34	1.00	1.58	0.03
609	0.28	0.95	0.05	0.26	0.39	0.61	0.67
610	0.26	0.96	0.05	0.05	0.65	1.03	0.53
611	0.28	0.96	0.05	0.06	0.90	1.42	0.38
612	0.28	0.94	0.51	0.27	0.83	1.31	0.33

Three homogenization practices were used. firstly all ingots with ß-phase iron-rich intermetallics (i.e. Mn free) were homogenized for 8 hours at 585°C to ensure spheroidization of the intermetallic particles. Secondly the ingots with α-phase intermetallics and a Mg_2Si concentration of 1.3% or greater are homogenized for 3 hours at 585 °C to ensure dissolution of Mg_2Si and a uniform distribution of Mn containing dispersoids. Finally ingots with α-phase intermetallics and Mg_2Si content less than 1.3% were homogenized for 3 hours at 550 °C to ensure dissolution of Mg_2Si and a uniform distribution of Mn containing dispersoids. After homogenizing the ingots were hot rolled at Hoogovens Aluminium NV to 6 mm from a preheat temperature of ~550 °C. The hot rolled samples were then cold rolled to a gauge of 1.2 mm at the research laboratory.

Alloys with Mg_2Si concentration less then 1.3%, were solution treated at a temperature of 550 °C, whereas alloys with a Mg_2Si concentration of 1.3% or greater were solution treated at temperature 575 °C. Material for ageing studies was solution treated at the research laboratory for 20 minutes. Material for forming studies was solution treated for ~20 seconds using a continuous heat treatment simulator at the University of Gent.

Mechanical properties were determined by duplicate tensile testing in the rolling direction. Test procedures according to EuroNorm 10002 were used, using tensile specimens with a width of 20 mm and a gauge length of 80 mm. The uniform and maximum elongation of the tensile specimen are used to assess the formability of a material. However, the tensile test gives only very limited information on sheet metal formability because firstly, the elongation strain in a tensile test is averaged over a certain measuring length e.g. five times the specimen's width (whereas local limit strains can be twice the maximum elongation), and secondly, a tensile test only gives information on strains resulting from a uniaxial stress state. In an actual pressed part the stress and deformation state can be and, most probably, are different. In practice, during drawing most failures occur in the plane strain direction. Therefore the plane strain direction is considered the most critical deformation mode and instead of a full FLD only the plane strain point was determined to assess formability.

An optimised Nakazima procedure was used on an Erichsen press with a 75 mm diameter punch. Special attention was paid to the lubrication between blank and punch. Blanks were taken out of the sheet so that the largest strain e1 was transverse to the rolling direction.

Results and discussion

Figure 1 shows the effect of magnesium content on the T4 yield strength for the different silicon contents investigated. The data shows that strength increases linearly with increasing magnesium level. For each silicon content there is only a little scatter about the trend line which indicates that the alloy's copper and manganese contents have no significant influence on the naturally aged yield strength.

The trend of work hardening value 'n' is shown in figure 2. The value for 'n' is independent of %Mg_2Si and shows an increase for the copper containing alloys. However the most significant effect is that of the manganese addition; the work hardening value 'n' decreases with the addition of manganese. In addition the alloys with a manganese addition show a dependency of 'n' on the excess silicon. It should be noted that the work hardening exponent 'n' gives an indication of a material's ability to distribute the strains evenly over the product surface during press forming. The 'n' value is not a constant but a function of the uniaxial strain in the tensile test. The listed 'n' values are averaged over the uniform elongation.

The ductility values are summarised in figures 3 and 4 which show uniform and post-uniform elongation respectively. It appears that the uniform elongation is independent of %Mg_2Si and of the excess silicon for the alloys free of manganese. The manganese containing alloys show a dependency of ductility on excess Si, the higher the excess silicon the higher the uniform ductility. This strongly correlates with the work hardening value 'n'. Additions of copper does not seem to effect the uniform ductility. Excess magnesium is detrimental to uniform ductility.

While the uniform elongation is controlled by the relative strain hardening rates up to the maximum load, the extent of post-uniform elongation depends on both strain hardening and strain rate sensitivity. In figure 4 the influence of excess silicon in the post-uniform elongation is shown. Except for alloy 612, it appears that, independent of manganese and/or copper additions, the higher the excess silicon the higher is the post-uniform ductility. This is in contradiction with the work hardening values and therefore implies that the strain rate sensitivity mainly controls the post-uniform elongation. In further work the m-value will be determined.

In figure 5, the plane strain elongation (e1) is plotted as a function of excess silicon. Except for the balanced alloys an effect of the content Mn is observed. The plane strain elongation decreases with Mn addition, but appears to be independent of the %Mg_2Si and the excess silicon. The effect of alloy chemistry on the ageing response of the alloys (data taken from 175 °C) is illustrated in figure 6. The following observations can be made:-

1. All alloys show an incubation time before ageing starts which is independent of alloy chemistry.
2. Once the incubation time is reached ageing kinetics appear enhanced by copper additions and the level of excess Si.
3. Copper additions and excess Si levels also increase the absolute magnitude of the ageing response.

These observations are in addition to the expected trend of higher strength with the alloy's Mg_2Si content.

Conclusions

1. In the T4 temper the 0.2%PS increases linearly with Mg content for the three levels of Si investigated. Additions of 0.3%Cu and/or 0.5%Mn have no significant effect on T4 strength.
2. The work hardening exponent "n" is independent of %Mg_2Si, increases slightly with the addition of 0.3%Cu and decreases with the addition of 0.5%Mn.
3. The uniform ductility in the T4 temper follows the same trend as "n"
4. The post uniform ductility is independent of Mn, Cu or %Mg_2Si, but increases with the % excess Si.
5. The plain strain elongation decreases with Mn and appears independent of the other chemistry variables (%Cu, %Mg_2Si and % excess Si).
6. Copper and excess Si increase the alloy's ageing response in terms of rate of ageing and magnitude of the ageing response.

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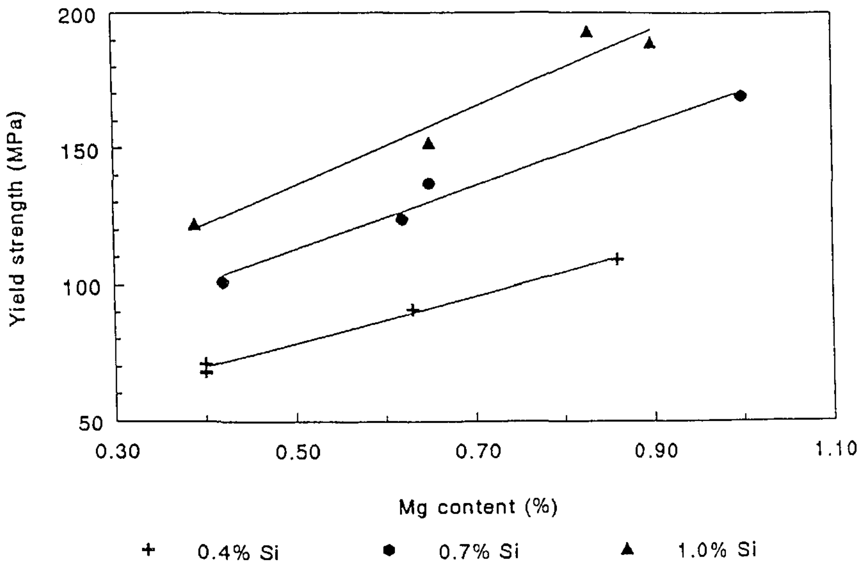

Figure 1. The effect of Mg and Si content on the T4 yield strength (0.2%PS) of alloy investigated. Test carried out after 8 weeks natural ageing. No significant change was found for Cu and Mn variants.

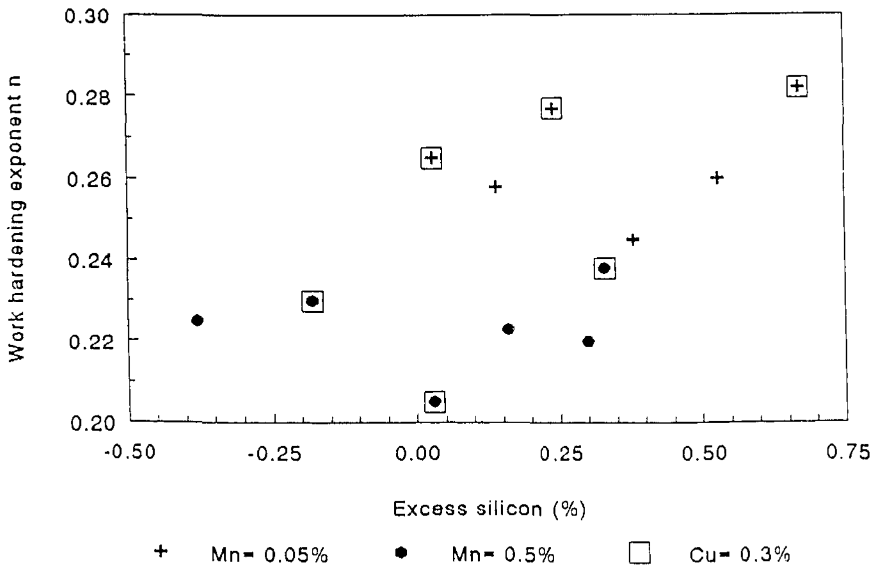

Figure 2. The effect of excess Si content on the work hardening exponent "n" measured in the T4 temper. The effect of Mn and Cu additions are also illustrated.

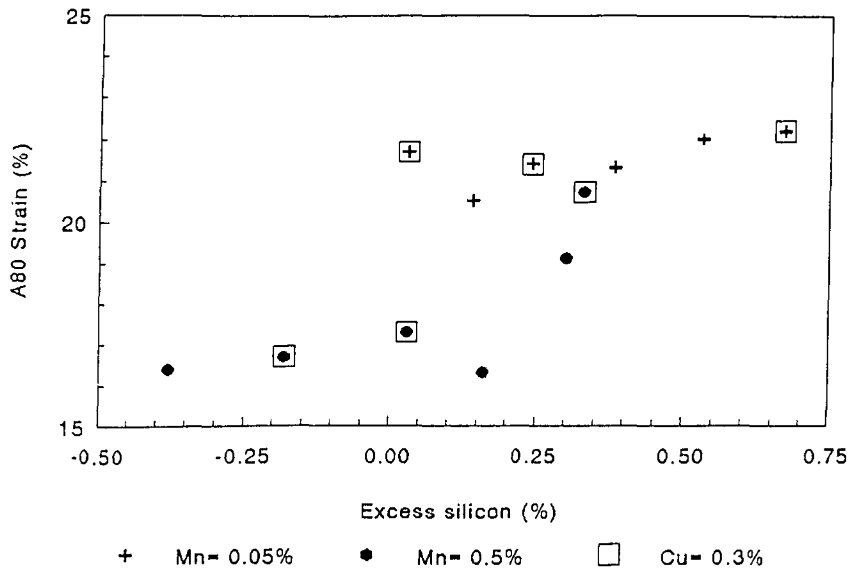

Figure 3. The effect of excess Si content on the uniform elongation measured in the T4 temper. The effect of Mn and Cu additions are also illustrated.

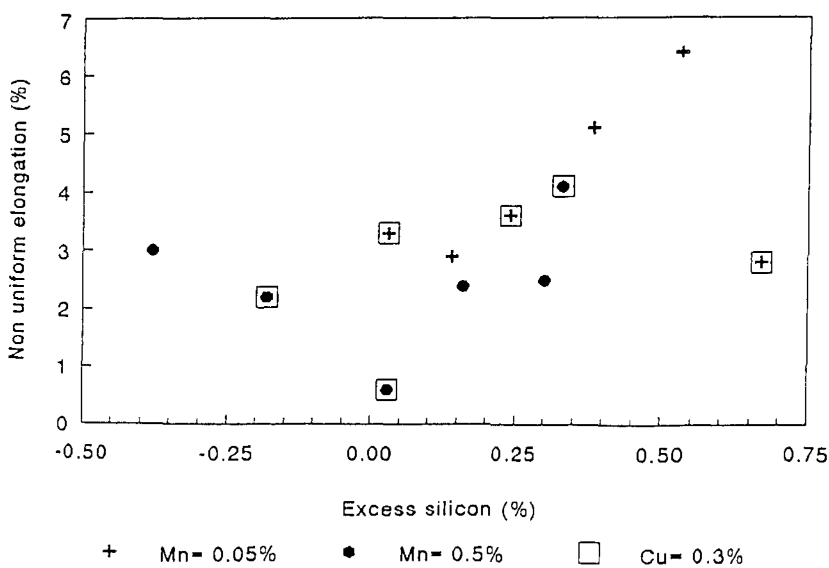

Figure 4. The effect of excess Si content on the post uniform elongation measured in the T4 temper. The effect of Mn and Cu additions are also illustrated.

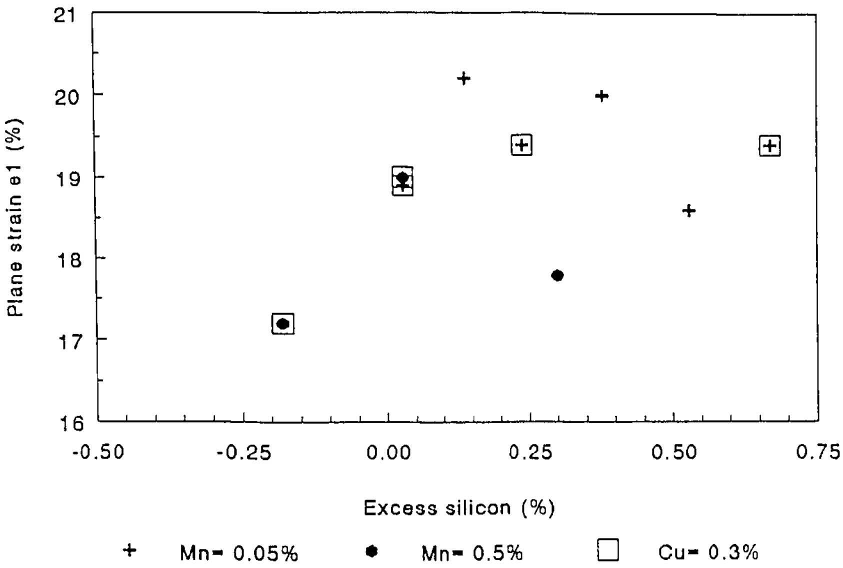

Figure 5. The effect of excess Si content on the plain strain elongation (e1) measured in the T4 temper. The effect of Mn and Cu additions are also illustrated.

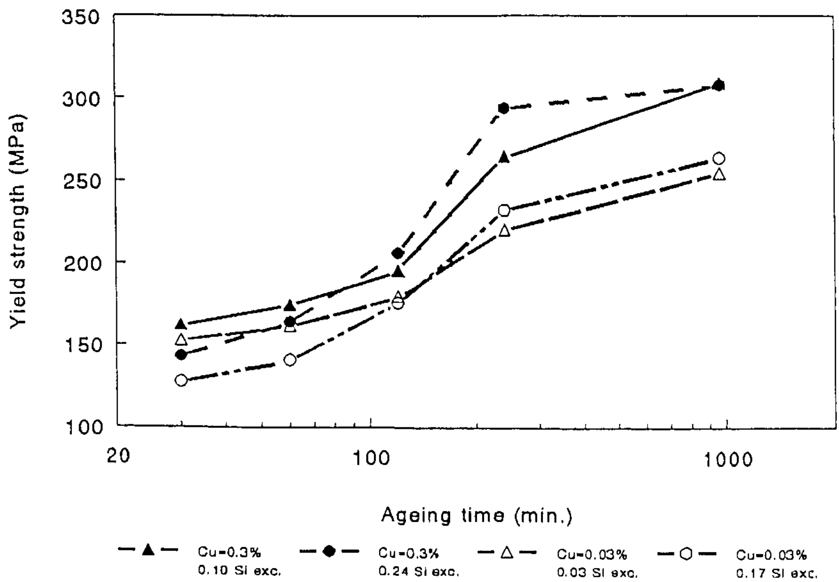

Figure 6. Typical ageing curves at 175°C showing the change in 0.2%PS with time at temperature. The effect of Mn, Cu and excess Si levels are illustrated.