THE EFFECT OF β-Mg_5Al_8 GRAIN BOUNDARY PRECIPITATION ON THE PERFORMANCE OF AL-MG-SHEET ALLOY PRODUCTS

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Abstract

Aluminium-Magnesium alloys (AA5XXX type) have been widely used in structural application in view of their good combination of strength, toughness and corrosion resistance. The addition of magnesium also significantly increases the work hardening response of the alloy and this is manifest as an increase in formability. Thus there is currently a great deal of interest in using highly alloyed (4-5wt%Mg) alloys in structural applications including automotive body structures.

Previous attempts to use wrought alloys of these compositions, in hard tempers, realised the problems associated with the precipitation of β (Mg_5Al_8) during low temperature thermal exposure ("sensitisation") which could lead to extensive intergranular corrosion and stress corrosion cracking. This problem could be overcome by "stabilisation" heat treatments designed to develop coarse grain boundary precipitation and reduce the effects of subsequent low temperature precipitation.

For automotive applications, however, formability of the sheet is an important, often vital, property and thus products are frequently supplied in the fully soft (H0) temper. This paper will consider the effect of sensitisation heat treatments on the corrosion behaviour of fully soft Al-4.5wt%Mg alloys and the effect on formability and in-service performance. Specific recommendations concerning the applicability of such alloys for structural components will be discussed.

Introduction

There is currently a rapid increase in the demand for aluminium for automotive applications where the material has the potential to reduce the mass of a vehicle and deliver significant improvements in performance and economy. For some years aluminium sheet has seen limited application for exterior panels and closures but current developments plan to use the material for structural components, presenting new demands on thermal stability, corrosion resistance and impact performance.

Aluminium-magnesium alloys in the soft (H0) temper are attractive for these applications since they offer a combination of high formability and medium strength (stiffness is often the limiting property in a vehicle structure). For these reasons the alloy AA5182, which normally contains about 4.5wt% Mg, has been widely used. Higher magnesium contents are more difficult to process commercially and therefore less attractive to the aluminium industry.

Most of the knowledge of corrosion and stress-corrosion in these alloys is related to thicker gauge, plate products used for marine and general structural applications. In these applications service temperatures are rarely high and the structural and durability requirements for the materials are consequently low. However alloys containing greater than 3.5%Mg are still not recommended for service temperatures above 65°C [1].

The sensitivity to intergranular attack results from precipitation of the equilibrium phase β which nucleates heterogeneously, primarily on grain boundaries. The phase is highly anodic relative to the matrix and, given the high ratio of matrix to grain boundary areas, will give rise to intergranular corrosion susceptibility particularly when the precipitation begins to form a continuous film or network. It is well known [2] that the rate of precipitation is accelerated by cold deformation.

For automotive applications, stability of properties during long service is critical and the service conditions can be severe with prolonged exposure to temperatures above 100°C, high applied loads and a corrosive environment. Under these conditions the corrosive performance and microstructural stability of any candidate alloy must be a consideration.

This work aims to quantify the sensitivity to intergranular attack of high Mg alloy sheet and understanding the mechanisms of precipitation with a view to improving a vehicle's performance and service life.

Experimental

Samples of commercially produced Al-Mg alloys including AA5182 (Al-4.5%Mg) have been subjected to various thermal exposures within the range 100 to 200°C. The effect of cold work was investigated by cold rolling samples of material prior to exposure. The extent of β-phase precipitation was followed using polished sections, etched 2 mins in 10% orthophosphoric acid at 70°C. This etch is very severe but effective in revealing the early stages of β precipitation. Microstructures with extensive precipitation can be studied using conventional etches such as Keller's.

In order to provide a quantitative assessment of the susceptibility of different microstructures to intergranular attack, the nitric acid mass loss test (NAMLT) was used . This was carried out to ASTM G67-86 and involves measuring the reduced mass of a specimen 50mmx6mm following 24h immersion in nitric acid at 30°C. The attack under these conditions is intergranular and the reduction in mass results from the loss of whole grains.

Slow strain rate testing was carried out under dry conditions and when the sample was immersed in a solution containing 3% NaCl and 0.3%H_2O_2. Samples with a gauge length of 25mm and a gauge width of 5mm were strained at an initial rate of $5x10^{-7}s^{-1}$.The elongations of specimens tested in the corrosive environment are then compared with those tested in dry air. The result is an elongation ratio (El_{wet}/El_{dry}) which is 1.0 if the material is insensitive to attack.

Results and Discussion

The extent of precipitation along grain boundaries increases with temperature up to 180°C but is reduced at 200°C, figure 1. This effect is in agreement with both kinetic and thermodynamic considerations. At low temperatures the rate of precipitation is slow whilst at high temperatures (200°C) the β-phase solvus limits the amount of precipitation. The Al-Mg binary phase diagram [3] indicates that a 4.5%Mg alloy would be single phase (α-Al) at approximately 230°C.

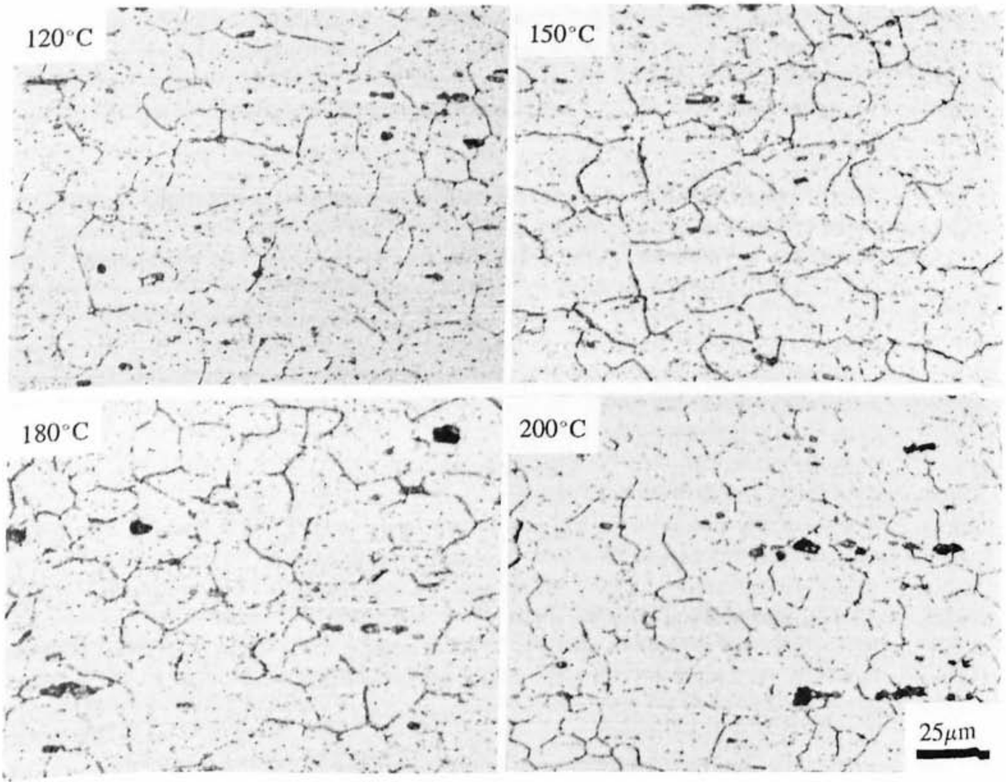
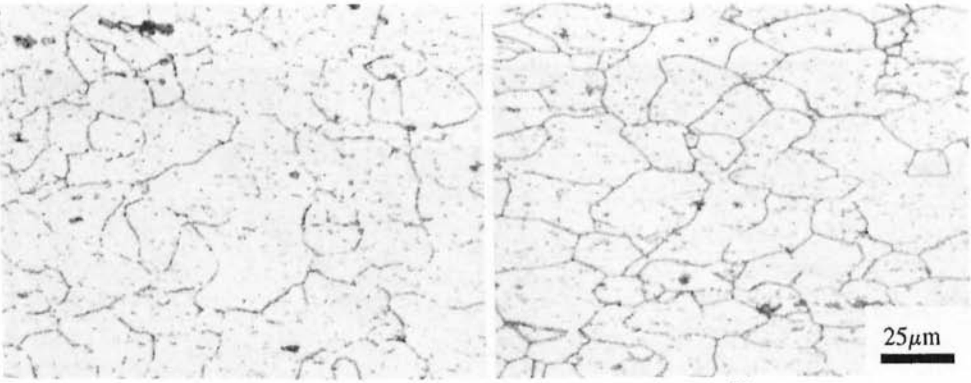


Figure 1. β-phase precipitation in 1.6mm AA5182 after exposure for 10h at temperatures of 120,150,180 and 200°C

The precipitation is accelerated by cold work, figure 2. In this investigation a 20% reduction was applied by rolling but tensile strains, as would be experienced in the stamping of sheet parts, have the same effect. It can be seen that grain boundary precipitation of β is promoted but additionally a small increase in the level of matrix precipitation is also evident.



(a) (b)

Figure 2 The extent of β-phase precipitation in AA5182 exposed 10h at 150°C.
(a) H0 temper (b) H0 + 20% cold work by rolling.

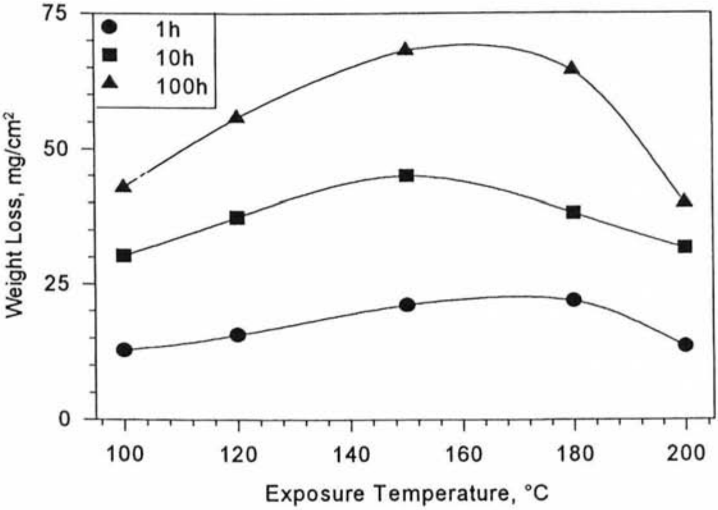


Figure 3. NAMLT data for 5182 H0 + 20% cold work, exposed for various times at temperature in the range 100° to 200°C. The level of susceptibility to

The variation of sensitisation with temperature was followed quantitatively using the NAMLT test. Figure 3 shows the data determined for 1,10 and 100hour exposure to a range of temperatures. The level of susceptibility is peaked in the temperature range 150-180°C for the times chosen, however at all temperatures below 180°C it is unlikely that β-phase precipitation is complete. Conversely at 200°C, β-phase precipitation is largely complete after just 10h and the degree of attack should not become worse after 100h. Intergranular attack increases with time and is peaked around150-180°C.

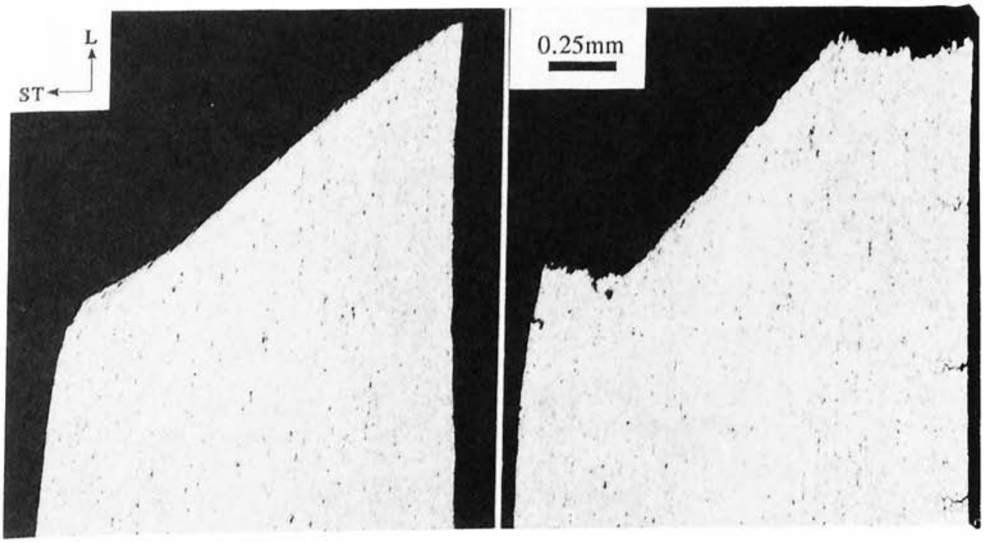


Figure 4. Sections through fractured slow strain rate samples. AA5182 1.6mm (a) tested in dry air, (b) tested in 3%NaCl-0.3%H_2O_2

The performance of these microstructures when subjected to both an applied stress and a corrosive environment has been studied using the slow strain rate test. The failure mode changes dramatically when the test is carried out in the NaCl/H2O2 solution, see Figure 4. A test carried out in dry air produces a highly ductile failure and high elongation to failure data, as is expected for these alloys. The effect of the wet environment is to produce failure by an intergranular mechanism, with a very low elongation figure. This failure can be entirely intergranular or involve the reduction in cross section of the test piece due to intergranular attack followed by failure of the remaining section in a ductile manner.

Figure 5 shows the relative performance of three commercially produced Al-Mg alloys in the slow strain rate test. The Al-3wt%Mg alloy AA5754 has a strain ratio close to 1.0 for exposure up to 2weeks, i.e. the ductility of the material is unchanged by the presence of the corrosive environment. The material can therefore be said to be insensitive to intergranular attack. Increasing the magnesium level to 3.5% and 4.5% produces progressively worse results. The 4.5% alloy, AA5182, after 2weeks exposure at 150°C has zero ductility when tested in the wet environment and must be considered highly sensitive.

The slow strain rate test is unlike other stress corrosion tests which apply a constant stress and record time to failure. In this case the sample is subjected to a constant rate of strain i.e. the applied stress rises continuously until the sample fails. The low ductilities seen for sensitised AA5182 when tested in the wet environment could result from exposure to the environment alone, i.e. intergranular attack and not stress corrosion.

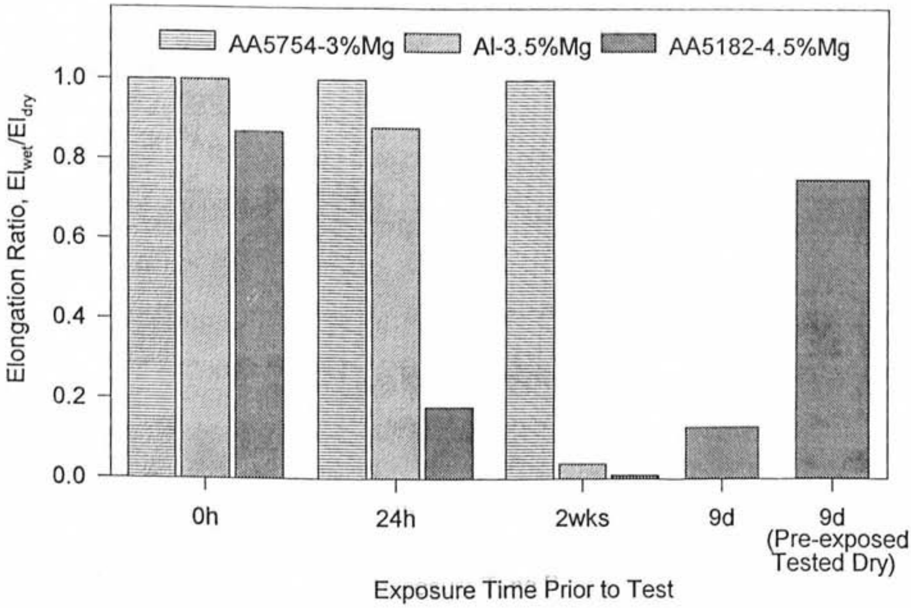


Figure 5. Slow strain rate for 3,3.5 and 4.5% Mg alloys after simulated service exposure at 150°C.

The data on the right hand side of figure 5 shows the strain ratios for samples of AA5182 exposed for 9 days at 150°C. One sample is tested in the same way as described above and results in an elongation ratio of about 0.2; the second sample was exposed to the same wet environment for the same period with no applied strain and then removed and cleaned prior to testing in dry air. The elongation ratio in this case is considerably improved suggesting that the combination of strain/stress and a corrosive environment is required to produce the very low elongation ratios observed. This is clear evidence that stress corrosion cracking is responsible and not simple intergranular attack.

One important consideration in the design of structures subjected to high service temperatures is the effect that the β precipitation at grain boundaries has on the mechanical properties and fracture toughness. The stability of both is important for any structure but especially those that are require to perform as energy absorbing elements in a crash situation. The table below summarises the tensile test and Kahn tear test data for 5182 in the H0 and in a sensitised condition.

It is clear that the tensile strengths are not affected by the precipitation which is easily explained by the very small volume of precipitate that is formed relative to the large volume of matrix and the level of Mg supersaturation within the matrix. The fact that the fracture energies remain unaffected by sensitisation is highly encouraging since it suggests that there should be no loss in fracture performance due to high service temperatures alone. There are, however, other important considerations, such as the effect of intergranular attack of a sensitised microstructure on residual properties, especially fatigue. This is the subject of continuing studies.

Table I. The effect of exposure on mechanical properties of AA5182-H0 1.6mm gauge.

Mechanical Property	AA5182-H0	AA5182 H0 + 1wk120°C
0.2%Proof Stress (MPa)	125.1	124.8
UTS (MPa)	271.6	270.7
Uniform Elongation (%)	23.8	23.6
Total Elongation (%)	27.3	25.5
Kahn Tear Initiation Energy	83.6	82.8
Kahn Tear Propagation energy	147.2	146.6
Kahn Tear Total Energy	230.8	229.4

Clearly β-phase precipitation in high magnesium alloys is only an issue for areas of a structure that will be exposed to a corrosive environment and elevated service temperatures. There remain many components within a vehicle structure that are not safety critical or are not exposed. For these applications high Mg alloys offer some advantages in terms of strength and formability. However if an alloy is to be selected for an entire structure for production or recycling reasons then an alloy containing less than 3.5% Mg provides the best combination of strength, formability and stability of properties with service life

Conclusions

- Alloys containing >3%Mg have been shown to be susceptible to intergranular attack and SCC following exposure to temperatures the range 100-200°C
- The low elongations observed in slow strain rate testing of these materials in the wet environment are the result of stress corrosion and not simply intergranular attack.
- Sensitisation alone i.e. without corrosive attack does not affect tensile and Kahn tear performance.
- Alloys containing <3.5% provide the best compromise for formability, strength and thermal stability.
- The effect of intergranular attack of sensitised high Mg alloys on fracture toughness and fatigue performance should be investigated further.

References

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2. R.Akeret,Metall, August 1989, 824

3. L.F.Mondolfo, Aluminium Alloys: Structure and Properties, (London:Butterworths, 1976),311