Grain Size Effect on Softening Behaviour of Al-Mg Alloy due to Paint Bake Heat Treatment

HEMALATHA NADARAJAH

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Universiti Malaysia Pahang

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ABSTRACT

Aluminium- Magnesium (Al-Mg) alloys have very good formability properties and have been used extensively for interior structural components of automotive Body in White (BIW). The alloys in an annealed temper achieve their strength through work hardening mechanism during press forming process. The strengthening mechanism is due to Mg atoms in solid solution exerting dislocation drag during low temperature plastic straining. However at elevated temperatures, high diffusivity of Mg atoms allows easy dislocations rearrangements which lead to reduction of mechanical strength. This phenomenon is called softening. Furthermore, accumulation of stored energy in the dislocations substructures due plastic straining during press forming process also serves as a large driving force for thermal recovery. These two factors contribute Al-Mg alloy sheet to be susceptible to softening during paint bake cycle. Al-Mg sheets for automotive Body in White (BIW) applications are normally supplied in an annealed condition known as "-O-" temper. The microstructure of an annealed sheet is characterized by equiaxed recrystallized grains. Average size of grains depends on actual rolling schedule and heat treatment stages on those particular sheets. This project investigates the effect of varying grain size on softening characteristics of pre-strained sheets after paint bake cycle. This is done by annealing Al-Mg H32 sheets in different temperatures to obtain different grain size. Smaller grain size would have more softening than larger grain size.

ABSTRAK

Aloi Aluminium-Magnesium mempunyai ciri-ciri pembentukkan yang baik dan telah digunakan untuk komponen struktur dalaman untuk rangka putih automotif (BIW). Aloi dalam keadaaan 'anneal' mencapai kekuatan melalui proses pengerasan ketika pemampatan berlaku. Mekanisem penguatan berlaku disebabkan atom Mg yang berada dalam keadaan cecair pejal menghasilkan penolakan liang jetika ketegangan plastic pada suhu yang rendah. Walau bagaimanapun, pada suhu berbeza, kehilangan atom Mg mengakibatkan aturan atom bertaburan dan seterusnya menyebabkan kekuatan mekanikal aloi itu menurun. Fenomena inilah yang dipanggil pelembutan('softening'). Tambahan pula, akumulasi tenaga simapanan dalam substruktur hasil daripada ketegangan plastic ketika pemampatan berlaku juga menjadi sebab untuk penyembuhan termal. Kedua-dua factor ini menyumbang kepada pelembutan Al-Mg ketika kala pengeringan cat('paint bake cycle'). Kepingan Al-Mg di hantar dalam keadaan 'anneal' yang juga dikenali sebagai –O-. Mikrostruktur kepingan ini mempunyai butiran yang seragam. Saiz butiran bergantung kepada kepada pemprosesan dan haba. Projek ini menyiasat kesan saiz butiran berbeza terhadap ciri pelembutan untuk Al-Mg yang telah ditegangkan apabila melalui proses pengeringan cat. Ini dilakukan dengan mambakar Al-Mg dalam pelbagai suhu untuk menghasilkan saiz butiran berbeza. Butiran yang bersaiz kecil akan menghasilkan nilai pelembutan yang lebih banyak daripada butiran yang besar.

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LIST OF SYMBOLS

σ_y	-	Yield strength of metal
$\sigma_{o,}k$	-	Hall Patch constants
d	-	Grain diameter
n	-	Number of grain
N	-	Size of grain
F	-	Force
σ	-	Stress
ε	-	Strain

CHAPTER 1

INTRODUCTION

Aluminium is well known for its high strength to weight ratio. Aluminium is a nonferrous metal whereby it has important properties such as corrosion resistance, high thermal and electrical conductivity. Aluminium and aluminium alloys posses a unique combination of properties, making them versatile materials of construction for many applications, from wrapping foil to aerospace components.

Like other metals, aluminium is identified by various designation systems. The principle alloying elements in aluminium are copper, manganese, silicon, magnesium, and zinc. Aluminium alloys are wrought or cast and can be strengthened by cold working or precipitation hardening. Aluminium alloys are formed machined and joined using variety of processes.

Work-hardening wrought Al-Mg alloys which are also known commercially as the 5000 series aluminium-based alloys are currently being used as automotive BIW material. Magnesium is the principal alloying element and is added for solid-solution strengthening. Generally Al-Mg alloys used in BIW applications have very good formability; relatively low yield stress and work harden during cold working.

A finished assemble automotive BIW complete with its exterior closure panel would have to primed, coated and painted; followed by a paint baking cycle. The cycle is nominally being carried out at 175 °C for 30 minutes (Bryant, 1999). This set of conditions is adequate to start the thermal recovery process which leads to softening of the material.

Initial study by Burger *et al.* (Burger *et al.*, 1995) has shown that the softening process is influenced by both heat treatment time and pre-straining. At about 10% pre-strain, the material softens by 50 MPa. This drop can be translated to almost 20% reduction of strength since the material would work harden to about 250 MPa after 10% straining. The softening phenomenon should be considered because in sheet metal forming operations, strain level of between 10%-20% is common in production of stretch-drawn components.

Al-Mg sheets for automotive BIW applications are normally sent in –O-temper whereby the sheet has been annealed and recrystallized. This process is done by heating a number of coils in a large batch furnace. These sheets have equiaxed recrystallized grains. The more heat is supplied the bigger the grain size gets. Grain size affects the softening behaviour of the pre-strained sheets after paint bake cycle.

The softening behaviour is also influenced by heat treatment time. After applying heat treatment at 177 °C for 30 minutes (1800 seconds), the material that has been 15% pre-strain has soften by almost 50 MPa. This study which was carried out by Burger *et al.* (Burger *et al.*, 1995) has shown that significant softening could occur under normal paint bake heat treatment. Therefore a more extensive investigation should be initiated in order to thoroughly understand the softening behaviour of pre-strain Al-Mg alloys subjected to paint bake treatment.

1.1 Objective

i) To study to the effect of varying original material grain size on softening characteristics of pre-strained sheets after paint bake cycle.

1.2 Scopes

i) The research is limited to commercially pure aluminium AA1100, AA5052 (2.3% Mg) and AA5083(4.5% Mg) 5xxx series wrought aluminum alloy.

ii) Heat treatment cycle is limited to ±50°C of the average paint baking temperature which is 175°C- 177 °C for 30 minutes.

iii) Grain size varies from 350 °C to 550 °C.

1.3 Project Background

Al-Mg alloy sheets for automotive BIW applications are normally supplied in an annealed condition known as '-O' temper. The annealing stage for '-O' temper is performed after the final gauge has been achieved in a cold rolling schedule by heating a number of coils in large batch furnace (batch annealing). The microstructure of an annealed sheet is characterised by equiaxed recrystallized grains. Average size of grains of Al-Mg alloy sheet depend on the actual rolling schedule and heat treatment stages of that particular sheet. The size of the grain effects the softening characteristics of pre-strained sheets after paint bake cycle.

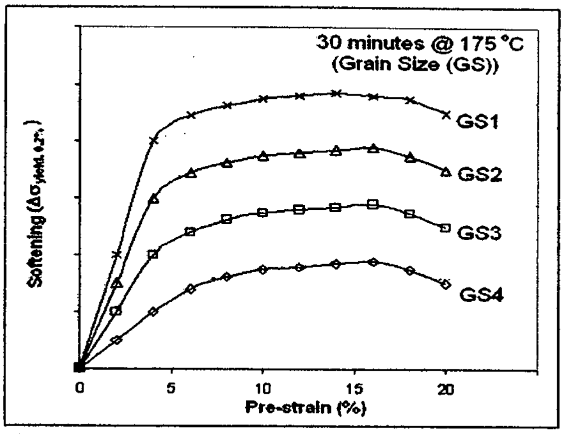

Figure 1.1: Schematic graph showing the effect of varying grain size on softening behavior

1.4 Gantt Chart

The Gantt chart is illustrated in Appendix A

1.5 Flow Chart

The flow chart is illustrated in Appendix B

CHAPTER 2

LITERATURE REVIEW

2.1 Al-Mg Alloy

2.1.1 Aluminium

Metal have played an important role in the development of human civilization. In this development, there has not been a metal, apart from steel as versatile as aluminium because of its unique intrinsic characteristics which are in interest of scientist and engineers (Murakami, 1985). The density of aluminium is only 2.7 g/cm^3, about one third of steel which makes it a useful material for transportation manufactured product (Kalpakjian and Steven, 2001). Since its lighter, it reduces the cost per pound and increases the specific strength of aluminium. 5- 10% fuel savings are realized for every 10% reduction in vehicle weight (Studied by Ford, BMW, Argonne, Ross, EAA, International Aluminium Institute, 2000). An aluminium Body in White (BIW) is typically 40-45% lighter than an equivalent steel structure (R.W.Cahn et al, 2005).

Aluminium has good corrosion resistance, non toxic, and has good electrical properties. Because aluminium has low strength it is alloyed for greater strength. Aluminium offers rapid and economical machinability. Hence, aluminium is very favorable for designing a safer and cleaner car without adding too much weight for various construction part and engines. Moreover with growing environmental pressure to reduce noxious fume emissions and also to achieve maximum recycling of all car materials together with the increasing importance of oil, aluminium seems to attractive as lighter vehicle consume less oil.

2.1.2. Production of Aluminium

Aluminium is the most abundant metallic element, which is 8% of the earths crust (Kalpakjian, 2001). Aluminum is found in earth's crust always combined state with other elements such as iron, oxygen, and silicone. Bauxite, which consists of mainly hydrated aluminum oxides, is the main source of aluminum. This is produced by Bayer process as Figure 2.1.

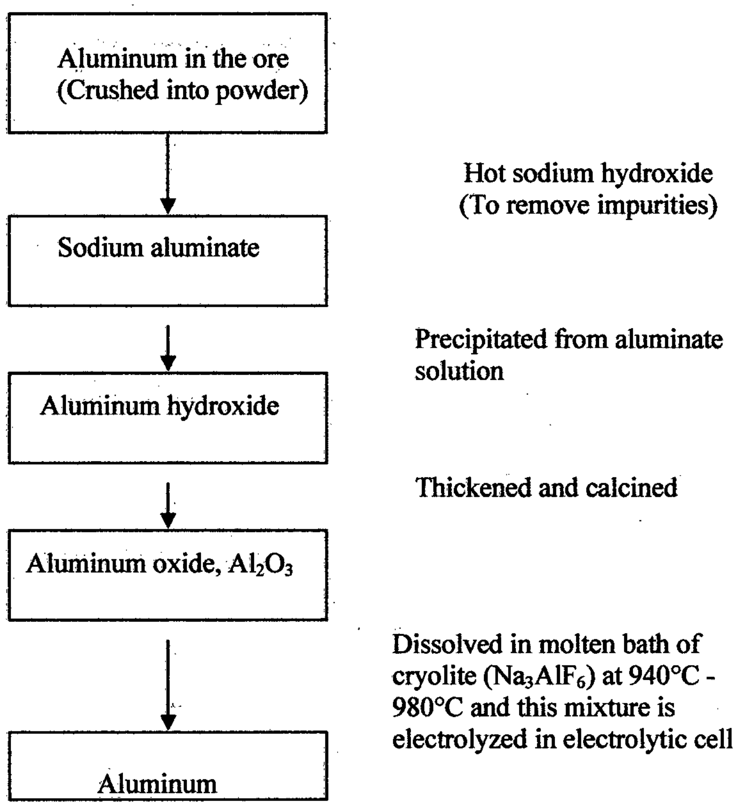

Figure 2.1: Bayer process – Aluminum production

Aluminum metal forms at the cathode (negative pole), while oxygen is released at the anode (positive pole). The production process consumes a great deal of electricity which leads to the high cost of aluminium.

2.1.3 Wrought Aluminum Alloys series

An alloy is composed of two or more chemical elements, at least one of which is metal. Aluminum alloys produced in the wrought form such as sheet, plate, extrusions, rod and wire are classified according to the major alloying element they contain. A four digit numerical designation is used to identify aluminum wrought alloys. The first digit indicates the alloy group that contains specific alloying elements. The second digit indicates modification of the original alloy or impurity limits. The last two digits identify the aluminum alloy or indicate the aluminum purity.

Table 2.1: A four digit numerical designation is used to identify aluminum wrought alloys. (Source: Handbook of Aluminium, Marcel Dekker.Inc)

	Alloying elements
1xxx series	Pure aluminum with a minimum 99% aluminum content by weight and can be work hardened
2 xxx series	Copper, high strength to weight ratio; low resistance to corrosion
3 xxx series	Manganese, and can be work hardened
4 xxx series	Silicon, lower melting point
5 xxx series	Magnesium, derives most of their strength from solution hardening.
6 xxx series	Magnesium and silicon, are easy to machine, and can be precipitation hardened, but not to the high strengths that 2000, 5000 and 7000
7 xxx series	Zinc, and can be precipitation hardened to the highest strengths of any aluminum alloy
8 xxx series	Miscellaneous category (other element)

2.1.4 Basic temper designations

Aluminium and aluminium alloy products are identified by various designation systems, standards, and specifications. Aluminium products are covered by standards produced by American Society for Testing and Materials, the Society of Automotive Engineers, and the Aerospace Materials Specification.

Wrought and cast aluminium alloys are identified by various assignation systems, which include the Aluminium Association (AA) numbering system and Unified Numbering System for metals and alloys. Aluminium Association designation for wrought aluminium alloys consist of four digits as indicated in Table 2.1.

Temper designations are letters that indicate the final condition of cold worked (H) or heat treated (T) material. The temperature designation is separated from the alloy with a hyphen. For example, 3003-H2 designates a quarter hard aluminium manganese alloys, and a 2014 –T4 designates an aluminium copper alloy that is solution treated, quenched and allowed to age at room temperature.

The Unified Numbering System for metals and alloys identifies wrought and cast aluminium alloys with the uppercase letter A followed by five numbers that identify a composition range for a specific alloy. For wrought aluminium alloys, the first number is 9 followed by the Aluminium Association number for the alloy. For example, alloy 3003 is equivalent to UNS A93003.

Table 2.2: Temper designations that are used to indicate cold worked or heat treated aluminium alloy (Source: Metallurgy, B.J. Moniz, ATP)

Designation	Condition
F	As fabricated
O	Annealed and recrystallized(from cold worked or cast state)
H1	Strain hardened only
H2	Strain hardened and partially annealed
H3	Strain hardened and thermally stabilized
W	Solution heat treated
T1	Cooled from elevated temperature shaping process, and naturally aged
T2	Cooled from elevated temperature shaping process, cold worked and naturally aged
T3	Solution heat treated, cold worked, and naturally aged
T4	Solution heat treated and naturally aged
T5	Cooled from an elevated temperature shaping process and
T6	then artificially aged
T7	Solution heat treated and then artificially aged
T8	Solution heat treated and stabilized
T9	Solution heat treated, cold worked and artificially aged
T10	Solution heat treated, artificially aged, and then cold worked
	Cooled from elevated temperature shaping process, cold worked and then artificially aged.

2.1.5 Non heat treatable and heat treatable wrought aluminum alloys

Wrought aluminum alloys can be divided into two groups; non heat treatable and heat treatable alloys. Non heat treatable aluminum alloys cannot be precipitation strengthened but only can be cold worked to increase their strength. Three main groups of this type are 1xxx, 3xxx and 5xxx series. Cold work is the plastic deformation which is carried out in a temperature region and over a time interval. In the early stage of plastic deformation, slip is essentially on primary glide planes and the dislocations from coplanar arrays. As deformation proceeds cross slip takes place. this increases the strength of the material. Magnesium is the principal alloying element in 5xxx series aluminum alloy and is added for solid solution strengthening in amounts up to about 5 %(Source: Foundation of Material Science, McGraw Hill). Some aluminum alloy can be precipitation strengthened by heat treatment (heat treatable). These series are 2xxx, 6xxx and 7xxx.

2.1.6 Wrought Al - Mg alloys

Work-hardening wrought Al-Mg alloys which are also known commercially as the 5xxx series aluminium-based alloys are currently being used as automotive BIW material. Magnesium is the principal alloying element and is added for solid-solution strengthening. Generally Al-Mg alloys used in BIW applications have very good formability; relatively low yield stress and work harden during cold working. Alloy grades that have been used extensively as automotive BIW material are listed in Table 2.3. Nominal values of their mechanical properties are shown in Table 2.4. The alloys are supplied to the BIW press shop in an annealed temper, designated as – O temper.

Table 2.3.: Composition of commonly used Al-Mg alloys used for automotive BIW components in weight percent with Al as remainder (Source: Handbook of Aluminium; Alloy production and Materials manufacturing)

Alloy	Mg	Si	Cu	Fe	Mn	Zn	Cr	Ti
5251	1.7-2.4	0.40	0.15	0.50	0.10-0.50	0.15	0.15	0.15
5052	2.2-2.8	0.25	0.10	0.40	0.10	0.10	0.15-0.35	-
5754	2.6-3.6	0.40	0.10	0.40	0.50	0.20	0.30	0.15
5182	4.0-5.0	0.20	0.15	0.35	0.20-0.50	0.25	0.10	0.10
5083	4.0-4.9	0.40	0.10	0.40	0.40-1.00	0.25	0.05-0.25	0.15

Table 2.4.: Mechanical properties of commonly used Al-Mg alloys used for automotive BIW components (Source: Handbook of Aluminium; Alloy production and Materials manufacturing)

Alloy	Yield stress, 0.2% (MPa)	Ultimate Tensile Strength (UTS) (MPa)	Maximum Elongation %
5251	80	180	25
5052	90	195	24
5754	100	215	24
5182	135	290	22
5083	145	300	22

2.2. Grain, grain boundaries, and grain size

2.2.1 Structure of metals

Metal structure is the arrangement of atoms within metals. The arrangement influences the behavior and properties of certain metal. Others that influence properties and behavior of metal are composition of the metal, impurities and vacancies, grain size, grain boundaries, and environment.

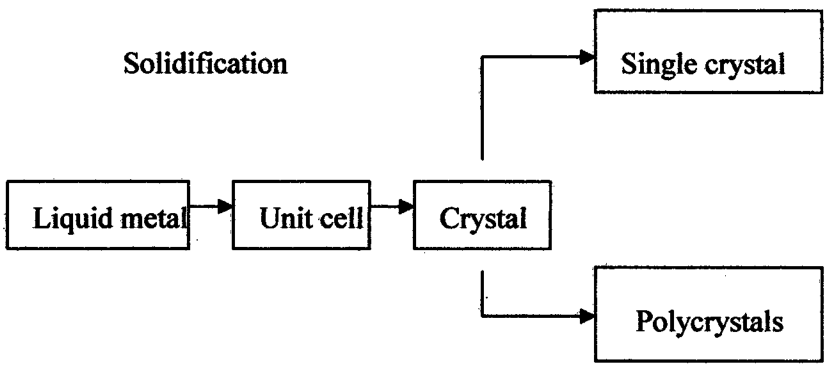

Figure 2.2: The flow of crystal production.

2.2.2 Crystal structure of metals

When metals solidify from a molten state, the atoms arrange themselves into various orderly configurations, called crystals. The arrangement of atoms within the crystal is called crystalline structure. Crystal structure is the configurations of atoms as they add to one another in an orderly and repeating three dimensional pattern. Amorphous solids are solid that do not exhibit a crystal structure. They posses the random arrangement that commonly occur in liquids. Examples of these are nickel-zirconium and molybdenum-rhenium.

Crystal structure may be present with any of the four types of bonding which is metallic, covalent, and ionic or Van de Waals bonding. A space lattice and unit cell help to illustrate crystal structures. A space lattice is a regular array of points produced by lines connected through the points. A unit cell is the smallest arrangement of atoms tat repeats itself through the space lattice. As the number of atoms per lattice increases, the unit cell becomes more complex.

Although 14 types of unit cell types are possible, most metal exhibit one of three types. The three basic atomic arrangements are as shown in Table 2.5.