STRENGTH VARIATION OF PRE-STRAIN ALUMINUM ALLOYS (AXIAL COMPRESSION) DUE TO ISOCHRONAL ANNEALING

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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 attain their strength through work hardening mechanism during press forming process. The strengthening mechanism is due to Mg atoms in solid solutions 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 (softening/thermal recovery). 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. The two factors caused the components made out of Al-Mg alloy sheet to be susceptible to softening during paint bake cycle. This project will scientifically analysis those factors and makes suggestions how to mitigate the problem.

ABSTRAK

Aluminum-Magnesium (Al-Mg) adalah logam aloi yang senang untuk dibentuk dan selalu digunakan di dalam komponen dalaman kenderaan. Semasa proses cetakan, kekuatan aloi ini telah meningkat. Sistem kekuantan aloi ini bergantung kepada kegiatan dan pergerakan zarah magnesium di bawah suhu yang rendah semasa ketegangan berlaku. Walaubagaimanapun, pada suhu yang tinggi, penyebaran ataupun pergerakan yang tinggi oleh zarah magnesium yang menyebabkan campuran atom di dalam aloi tersebut telah bergerak dan menjadi tidak stabil. Ini telah menyebabkan berlakunya pengurangan kekuatan aloi tersebut. Penambahan tenaga tersimpan di dalam struktur yang telah menjadi tidak stabil yang berlaku semasa proses ketegangan juga menjadi penyebab utama kepada proses pemulihan tekanan. Dua faktor ini menyebabkan komponen yang terdiri daripada aluminum-magnersium menjurus kepada pengurangan kekuatan semasa proses pengeringan dan pemanasan. Projek ini akan mengkaji faktor-faktor tersebut dan membuat penyelesaian bagi masalah tersebut.

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CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

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. This group of alloys have been utilised mainly for interior BIW structure where surface quality is not an issue. The alloys are nominally supplied to the BIW press shop in an annealed temper, designated as –O temper.

1.1 PROBLEM STATEMENT

A finished assemble automotive BIW 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 [1]. This set of conditions is adequate to start a thermal recovery that can lead to softening of the material. 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. The softening behaviour is also influenced by heat treatment time [2]. The study carried out by Burger [2] has shown that significant softening could occur under normal paint bake heat treatment.

1.2 OBJECTIVE

The objective of this section is to analyze the softening phenomena sensitivity (compressive stress) to paint bake cycle temperature variations between 150°C to 225°C over a fixed heat treatment time (isochronal annealing) for pre-strain 2.5% and 5%.

1.3 SCOPE OF STUDY

This project will cover on the study about aluminium alloy only. Types of the aluminium alloys are Al 1100, Al-Mg 5052 and Al-Mg 5083. Besides that, analyzing the softening behaviour of the aluminium alloys after the paint bake cycle temperature variation through axial compression test is an important part. The variable in the experiments are the temperature and percentage of pre-strains. This project also carrying the using of the test machines methodologies and software tools.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Aluminium was first produces in 1825 [3]. It is the most abundant metallic element, making up about 8% of the earth's crust. The principal ore for aluminium is bauxite, which is hydrous (water-containing) aluminium oxide and includes various other oxides. After the clay and dirt are washed off, the ore is crushed into powder and then treated with hot caustic soda (sodium hydroxide) to remove impurities. Alumina (aluminium oxide) is extracted from this solution and then dissolved in a molten sodium-fluoride and aluminium-fluoride bath at 1213K to 1253K. This mixture is then subjected to direct-current electrolysis. Aluminium metal forms at the cathode (negative pole), while oxygen is released at the anode (positive pole). Commercially pure aluminium is up to 99.99% aluminium. The production process consumes a great deal of electricity and so contributes significantly to the cost of aluminium.

Aluminium alloys have found wide acceptance in engineering design primarily because they are relative lightweight, have a high strength to weight ratio, have superior corrosion resistance, and they are comparatively inexpensive. For some applications they are favoured because of their high thermal and electrical conductivity, ease of fabrication, and ready availability. In fact, aluminium is the fourth most widely distributed of the elements, following oxygen, nitrogen, and silicon. Aluminium alloys density approximately 27679.91 N/m^3, which is one-third the weight of iron (77503.738 N/m^3), and copper (88575.70 kN/m^3). It is just slightly heavier than magnesium (18268.74 N/m^3) and somewhat lighter than titanium (45118.25 N/m^3) [3]. In its commercially pure state, aluminium is a relatively weak metal having a tensile strength of approximately 82.73712 MPa. However, with the addition of such alloying elements as manganese, silicon, copper, magnesium, and/or zinc, and with proper heat treatment or old working, the tensile strength of aluminium can approach 689.476 MPa.

Generally, the strengths of aluminium alloys decrease whereby the toughness increases with increases in temperature and with time at temperature above room temperature [3]. The effect is usually greatest over the temperature range of 373K to 477K (212°F to 400°F). Exceptions to the general trends are tempers developed by solution heat treating without subsequent aging, for which the initial elevated temperature exposure results in some age hardening and reduction in toughness. Further time at temperature beyond that required to achieve peak hardness results in the aforementioned decrease in strength and increase in toughness.

Corrosion resistance of aluminium is attributable to its self-healing nature [3]; a thin, invisible skin of aluminium oxide forms when the metal is exposed to the atmosphere. Pure aluminium will form a continuous protective oxide film, while high strength alloyed forms will sometimes become pitted as a result of localized galvanic corrosion at sites of alloying-constituent concentration. As a conductor of electricity, aluminium compares favourably with copper. Although the conductivity of the electro conductor grade of aluminium is only 62% that of the International Annealed Copper Standard (IACS), on a pound for pound basis the power loss for aluminium is less than half of that of copper – an advantage where weight and space are primarily requirements. As a heat conductor, aluminium ranks high among the metals. It is especially useful in heat exchangers and other applications requiring rapid heat dissipation. As a reflector of radiant energy, aluminium is excellent throughout the entire range of wavelengths – from the ultraviolet end of the spectrum through the visible and infrared bands, to the electromagnetic wave frequencies of radio and radar.

Alclad sheet (sometimes called clad sheet) is a product consisting of an aluminium alloy sheet having on one or both surfaces a layer of aluminium or aluminium alloy integrally bonded to the surface of the base metal [3]. In general, Alclad sheets have mechanical properties slightly lower than those of the bare alloy sheets of the same thickness. However, the corrosion resistant qualities of the aluminium alloy sheet are improved by the cladding.

Aluminium is easily fabricated. It can be cast by any method, rolled to any reasonable thickness, stamped, hammered, forged, or extruded. It is readily turned, milled, bored, or machined. It can be joined by several welding processes. Aluminium can also be coated with a wide variety of surface finishes for decorative and protective purposes.

2.2 ALUMINUM ASSOCIATION ALLOY

The most commonly used alloy designation system in the United States is that of the Aluminium Association. The Aluminium Association Alloy and Temper Designations System are used to identify wrought and casting alloys. The first digit in the alloy designation system identifies the principle alloying constituent of the metal. The second digit notes variations of the initial alloy. The third and fourth digits are chosen to make the designation unique. The four-digit designation system for wrought aluminium alloys is detailed in Table 2.1.

Table 2.1: Alloy Designation System for Wrought Aluminium Alloys [4]

Numerals	Major Alloying Element(s)
1XXX	None($\geq$ 99.00% Al)
2XXX	Cu
3XXX	Mn
4XXX	Si
5XXX	Mg
6XXX	Mg and Si
7XXX	Zn
8XXX	Other elements (Li...etc)

Wrought-aluminium alloys are identified by four digits. The major alloying element is identified by the first digit. Here is the system:

1XXX is commercially pure aluminium. It has excellent corrosion resistance, high electrical and thermal conductivity, good workability, low strength and not heat treatable.
For 2XXX, the major alloying is copper. It is high strength-to-weight ratio, low resistance to corrosion and heat treatable.
For 3XXX, manganese is the major alloying. It has good workability, moderate strength and not generally heat-treatable.
For 4XXX, silicon is the major alloying. It has lower melting point, forms an oxide film of a dark-grey to charcoal colour and not generally heat-treatable.
For 5XXX, magnesium is the major alloying. It has good corrosion resistance and weld ability, moderate to high strength and not heat-treatable.
For 6XXX, magnesium and silicon are the major alloying. It has medium strength, good formability, machinability, weld ability, and corrosion resistance and also heat treatable.
For 7XXX, zinc is the major alloying. It is moderate to very high strength and heat treatable.
For 8XXX, other element would be the major alloying. These alloys contain less frequently used alloying elements such as lead, nickel and lithium. They are heat treatable and have high conductivity, strength and hardness.

The second digit in these designations indicates modifications of the alloy. For 1XXX series, the third and fourth digits stand for the minimum amount of aluminium in the alloy. For example, “1050” indicates a minimum of 99.50% aluminium, “1090” indicates a minimum of 99.90% aluminium. In other series, the third and fourth digits identify the different alloys in the group and have no numerical significance.

For the material that used as automotive BIW components, AA5183 series, weight percent for magnesium (major alloying element) with aluminium as remainder is 4.0% to 4.9%. This is based on Table 2.2. Generally Al-Mg alloys have very good formability; relatively low yield stress in annealed condition and work harden during cold working.

Table 2.2: Composition of commonly used Al-Mg alloys used for automotive BIW components in weight percent with Al as remainder [1]

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

2.3 TABLE OF TEMPER DESIGNATION SYSTEM FOR ALUMINUM ALLOYS

Temper designations indicate mechanical or thermal treatment of the alloy. It follows the alloy number and is always preceded by a dash, as in 2014-T6. Basic designations consist of letters. Subdivisions of the basic designations, where required, are indicated by one or more digits following the letter. These designate specific sequences of basic treatments, but only operations recognized as significantly influencing the characteristics of the product are indicated. Should some other variation of the same sequence of basic operations be applied to the same alloy, resulting in different characteristics, additional digits are added to the designation.

The basic temper designations and subdivisions are as based on Table 2.3:

Table 2.3: Temper Designation System for Aluminium Alloys [5]

Temper	Definition
F	As fabricated. Applies to products that acquire some temper from shaping processes not having special control over the amount of strain hardening or thermal treatment. For wrought products, there are no mechanical property limits.

O	Annealed. Applies to wrought products that are annealed to obtain the lowest strength temper, and to cast products that are annealed to improve ductility and dimensional stability. The O may be followed by the digit other than zero, indicating a product in the annealed condition that has specific characteristics. It should be noted that variations of the –O temper shall not apply to products that are strain hardened after annealing and in which the effect of strain hardening is recognized in the mechanical properties or other characteristics. The following temper designation has been assigned for wrought products that are high temperature annealed to accentuate ultrasonic response and provide dimensional stability.
H	Strain Hardened. Wrought products only. Applies to products that have their strength increased by strain hardening with or without supplemental thermal treatments to produce partial softening. The –H is always followed by two or more digits. The first digit indicates the specific combination of basic operations as follows.
W	Solution Heat Treated. Applies to products whose strength naturally changes at room temperature after solution heat treatment. The change might take place over weeks, or years, and the designation is specific only when the period of natural aging is determined: for example, W 2.5 hours.
T	Thermally Treated to Produce Tempers Other than –F, -O, or –H. Applies to products that are thermally treated with or without supplementary strain hardening to produce stable tempers. The –T is always followed by one or more digits. Numerals 1 to 10 have been assigned to indicate specific sequences of basic treatment.

Table 2.4: Table Explanations for Symbols Hxx [5]

Term	Description
Cold Work	The nomenclature denotes the degree of cold work imposed on the metal by using the letter H followed by numbers. The first number indicates how the temper is achieved.
H1x	Strain-hardened only to obtain the desired strength without supplementary thermal treatment.
H2x	Strain-hardened and partially annealed. These designations apply to products which are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing.
H3x	Strain-hardened and stabilized. These designations apply to products which are strain-hardened and whose mechanical properties are stabilized either by a low temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility. This designation is applicable only to those alloys which, unless stabilized, gradually age soften at room temperature.
H4x	Strain-hardened and lacquered or painted. These designations apply to products which are strain-hardened and which may be subjected to some partial annealing during the thermal curing which follows the painting or lacquering operation.

2.4 CHARATERISTICS OF ALUMINUM ALLOYS

For this analysis, aluminium alloys series of AA1100, AA5052 and AA5083 as the specimens, have been utilised mainly for interior BIW structure. The alloys are nominally supplied to the BIW press shop in an annealed temper, designated as –O temper.

In the non heat-treatable alloys [6], there are different designations for those alloys which have their mechanical properties adjusted by strain hardening [cold working] rather than thermal treatment. Cold working entails such processes as rolling [stretching], compressing or drawing to change the shape of the material. The letter "H" is followed by 2 or more digits, the first indicates the particular method used to obtain the temper as follows:

Xxxx-H1 — strain hardened
Xxxx-H2 — strain hardened, then partially annealed
Xxxx-H3 — strain hardened, then stabilized

The digit following H1, H2 or H3 indicates the degree of strain hardening. 1 indicates the smallest amount of cold work, and 8 indicate maximum cold work of full-hard condition:

Xxxx-H_2 — quarter hard
Xxxx-H_4 — half hard
Xxxx-H_6 — three quarter hard
Xxxx-H_8 — full hard
Xxxx-H_9 — extra hard

AA1100, H14: This is the commercially pure aluminium alloys. It is non-heat treatable alloy. 1100 means:

1 – Aluminium is the major alloying element
1 – Aluminium is still the modification of the alloy
The third and fourth digits (0) indicate the minimum amount of aluminium in the alloy. That is mean it is indicates a minimum of 99.00% of aluminium.
H14 – (Strain-hardened, half hard). These designations apply to products which are strain-hardened and which may be subjected to some partial annealing during the thermal curing which follows the painting or lacquering operation.

Alloy 5052: The outstanding characteristics for this non-heat treatable alloy are it is moderate mechanical properties, stronger and harder than 1100. It is fairly good formability and also readily weldable and excellent resistance to corrosion by salt water. It is recommended uses because of the general purpose alloy where fairly high strength is required. It is suitable for the marine and outside applications, fuel and hydraulic lines, and tanks. 5052 means:

5 – Magnesium is the major alloying element
0 – no changes to original alloy since it was introduced
52 – identify the chemical composition of this alloy
Thus 5052-H32 indicates the alloy has been strain hardened then stabilized and is quarter hard.

AA5083: This is also the non-heat treatable alloy. It is stronger and harder than AA1100 and AA5052. 5083 means:

5 – Magnesium is the major alloying element
0 – no changes to original alloy since it was introduced
83 – identify the chemical composition of this alloy

2.5 HEAT TREATMENT FOR ALUMINUM ALLOYS

Heat treating processes for aluminium are precision processes. They must be carried out in furnaces properly designed and built to provide the thermal conditions required, and adequately equipped with control instruments to insure the desired continuity and uniformity of temperature-time cycles. To insure the final desired characteristics, process details must be established and controlled carefully for each type of product.

There are general types of heat treatment applied to aluminium and its alloys. One of it is the process of annealing. Annealing is a process that imparts the "softest" or most ductile condition to a heat-treatable aluminium alloy. It's eliminates strain hardening, as well as the changes in structure that are the result of cold working. For annealing, the alloy is heated to above its solution temperature and then slowly cooled to room temperature. During the cooling processes, the alloying elements fall out of solution and form large unevenly distributed crystals, which do not effectively prevent granular slippage. The result is a soft, low strength alloy condition. Heat-treatment temperatures vary for each alloy, and heat treatment cycles should conform closely to handbook recipes [7]. This is based on Figure 2.1. The high thermal conductivity of aluminium allows abrupt heat-up and cooling. An anneal to soften heat-treated alloys is the only heat treatment that requires a very slow cool.

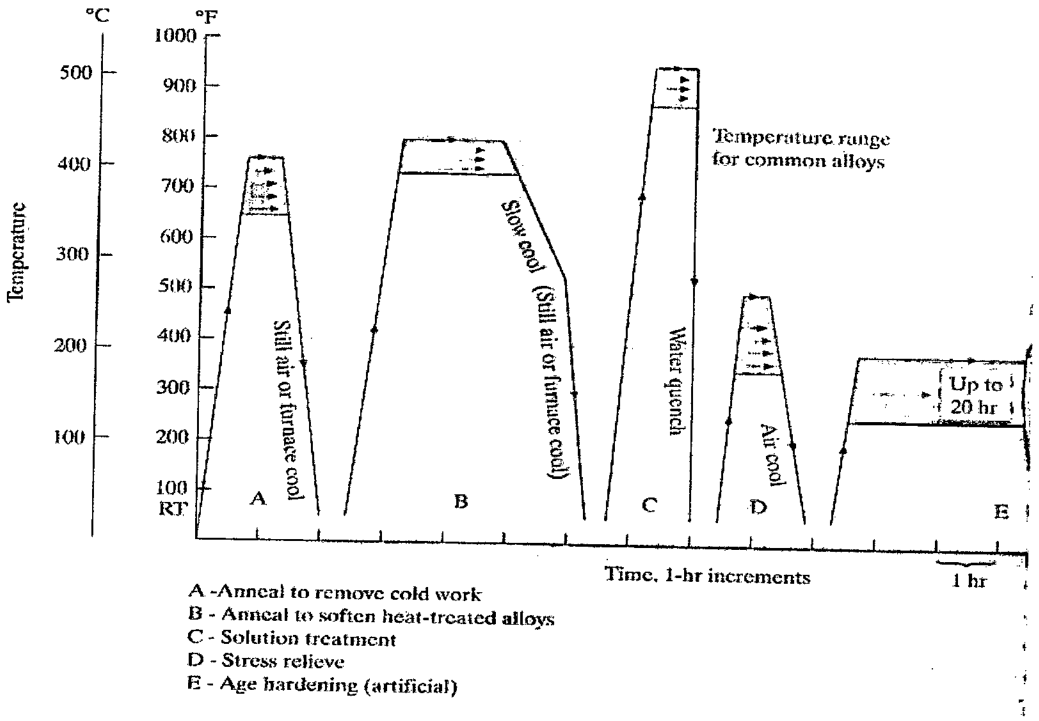

Figure 2.1 - Typical heat-treating cycles for aluminium alloys [8]

Stress relieving is a very important tool for the close dimensional control on aluminium parts. Temperatures are low, and soak times can be as short as 15 minutes. Long, slender parts, weldments, large flats, rings, and complex shapes can be rough machined, stress relieved, and finished. Stress relieving removes residual stresses remaining from mill operations and stresses imparted in machining. Stress relieving can reduce the mechanical properties of age-hardened alloys, so if tensile properties are critical it may be well to avoid stress relieving or measure the strength reduction produced by a particular stress-relieving operation [8].

The first of these, occurring at the lowest temperatures and shortest times of annealing, is known as the recovery process.

2.5.1 RECOVERY

Structural changes occurring during the recovery of polygonization and sub grain formation has been obtained by x-ray diffraction and confirmed with the electron microscope [9]. The electron micrographs may show the change in structure that accompanies advanced recovery. The reduction in the number of dislocations is greatest at the centre of the grain fragments, producing a sub grain structure with groups of dislocations at the sub grain boundaries. With increasing time and temperature of heating, polygonization becomes more nearly perfect and the sub grain size gradually increases. In this stage, many of the sub grains appear to have boundaries that are free of dislocation tangles and concentrations.

The decrease in dislocation density caused by recovery-type annealing produces a decrease in strength and other property changes. The effects on the tensile properties of 1100 alloy are shown in Figure 2.2. At temperatures through 231.7°C (450°F), softening is by a recovery mechanism. It is characterized by an initial rapid decrease in strength and a slow, asymptotic approach to a strength that is lower, the higher the temperature.

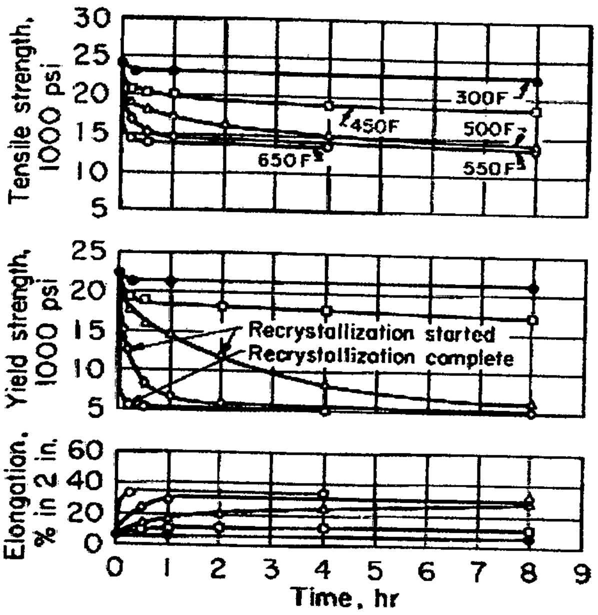

Figure 2.2 – Isothermal annealing curves for 1100-H18 sheet [9]

Recovery annealing is also accompanied by changes in other properties of cold worked aluminium. Generally, some property change can be detected at temperatures as low as 363K to 393K (200°F to 250°F); the change increases in magnitude with increasing temperature. Complete recovery from the effects of cold working is obtained only with recrystallization.

2.5.2 RECRYSTALLIZATION

Recrystallization is characterized by the gradual formation and appearance of a microscopically resolvable grain structure. The new structure is largely strain-free. There are few if any dislocations within the grains and no concentrations at the grain boundaries. Recrystallization decreases the density of dislocations, lowers the strength, and raises the ductility of the metal.

Recrystallization depends on the degree of work hardening; the more cold work, the lower the temperature required for recrystallization to occur. The reason is that, as the amount of cold work increases, the number of dislocations and amount of energy stored in dislocations also increases.

At a temperature range, new equiaxed and strain-free grains are formed, replacing the older grains. The temperature for recrystallization ranges between approximately 0.3Tm and 0.5Tm, where Tm is the melting point of the metal on the absolute scale.

Composition also influences the recrystallization process. This is particularly true when various elements are added to extreme purity aluminium; almost any added impurity or alloying element will raise the recrystallization temperature substantially. For commercial-purity aluminium and commercial alloys, however, normal variations in composition have little effect on recrystallization behaviour. Extensively cold worked commercial alloys usually can be recrystallized by heating for several hours at 650 to 775°F (340°C to 410°C). The recrystallization happens is showed in Figure 2.3.

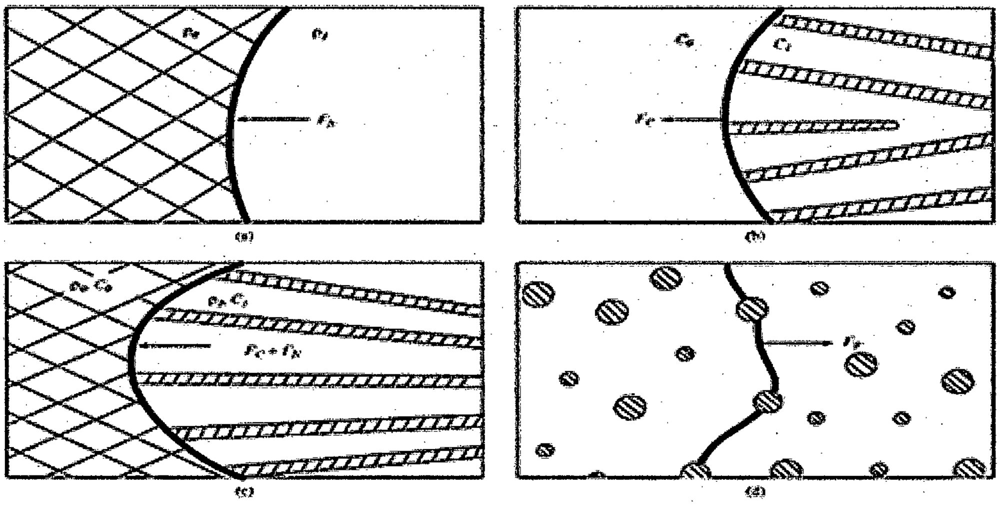

Figure 2.3 – Recrystallization (Forces acting at the reaction front) [16]

2.5.3 GRAIN GROWTH

If we continue to raise the temperature of the metal, the grain begin to grow, their size may eventually exceed the original grain size. Large grains produce a rough surface appearance on sheet metal, when they are stretched to form a part, or when a piece of metal is subjected to compression.