

THE EFFECTS OF ALLOYING ELEMENTS ON THE MICROSTRUCTURE  
AND ANNEALING BEHAVIOR OF THE TWIN-ROLL CAST AA1050 STRIP

by

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## **ABSTRACT**

### **THE EFFECTS OF ALLOYING ELEMENTS ON THE MICROSTRUCTURE AND ANNEALING BEHAVIOR OF THE TWIN-ROLL CAST AA1050 STRIP**

There are two main routes of sheet aluminum production DC casting and hot rolling route and continuous casting and cold rolling route. DC casting and hot milling route is the conventional way of production, the process is well known and controlled to maintain desired properties of the sheet. Continuous casting route includes twin belt casting, twin block casting and twin roll casting. All three processes are important in near net shape production. In twin belt casting and twin block casting, casting thickness is between 10 to 25mm. The produced sheet is not coilable sometimes, to eliminate this disadvantage tandem mills are adapted to the system that helps to produce coilable sheet.

Twin-roll casting is a promising technology for sheet metal production. It was first developed for eliminating preheating and hot rolling operations in conventional sheet production. However it is cost effective and effective way of producing sheet metals, there are some problems in production and material quality such as heterogeneous microstructure. Because of the heterogeneous microstructure we can face problems in further forming operations after heat treatment. Because of heterogeneous microstructure and deformation, surface grains grow much more than the grains in the center.

In this study effect of alloying elements on the microstructure and annealing behavior was investigated. A prototype twin roll caster was built in the Materials laboratory, by modifying the laboratory scale hot rolling machine. Some parts of the hot rolling machine was used; new casting rolls, housings for bearings and a twin roll casting tip was manufactured. Casting trials were utilized by this caster with different alloy content. The cast sheets were cold rolled and annealed to investigate the annealing behavior. Microstructures of as cast and annealed samples were investigated in terms of

optical microscopy. It was observed that however the grain size of samples from unmodified strip were larger than the modified strips, grain size after cold rolling and annealing was smallest and more equiaxed. Strontium was the most effective alloying addition in which the resultant microstructure of both the as cast and annealed samples were equiaxed and uniform through the thickness.

## ÖZET

### **ALAŞIM ELEMENTLERİNİN İKİZ MERDANE SÜREKLİ DÖKÜM YÖNTEMİYLE ÜRETİLMİŞ AA1050 LEVHANIN MİKROYAPISINA VE ISIL İŞLEM DAVRANIŞINA ETKİSİ**

Alüminyum levha üretiminde iki temel yöntem vardır, geleneksel külçe döküm ve sıcak haddeleme yoluyla levha üretimi ve sürekli döküm ve soğuk hadde yöntemiyle levha üretimi. Külçe döküm ve sıcak haddeleme yöntemiyle levha üretimi geleneksel levha üretim tekniğidir, bu nedenle iyi bilinen ve istenen özellikler doğrultusunda kontrol edilebilen bir yöntemdir. Başlıca sürekli döküm yöntemleri ikiz kuşak döküm yöntemi, ikiz blok döküm yöntemi ve ikiz merdane döküm yöntemidir. Her üç döküm yöntem son ürüne yakın kalınlıkta levha üretilmesi bakımından önemlidir. İkiz kuşak ve ikiz blok döküm yöntemlerinde 10-25mm kalınlıkta alüminyum levha üretimi yapılabılır. Bu iki yöntemle üretilen levhalar anında bobinlere sarılacak incelikte olmadıklarından, sıcak hadde tezgâhları döküm makinalarının ardına eklenerek, üretilen levhalar bobine sarılabilecek kalınlığa kadar haddelenmektedir.

İkiz merdane döküm yöntemi diğer döküm yöntemlerine kıyasla daha umut verici bir yöntemdir. Geleneksel külçe döküm ve sıcak hadde yöntemindeki ön tavlama ve sıcak hadde aşamalarından kurtulmak amacıyla geliştirilmiştir. Maliyetler ve üretim açısından etkili olmasına rağmen, üretim sırasında karşılaşılan zorluklar ve heterojen mikroyapı gibi olumsuz yönleri de vardır. Heterojen mikroyapı nedeniyle daha sonra yapılacak şekillendirme uygulamalarında problem yaratabilir.

Bu çalışmada alaşım elementlerinin mikroyapıya ve tav davranışına etkileri araştırıldı. Malzeme laboratuvarında halihazırda bulunan sıcak hadde makinası modifiye edilerek prototip ikiz merdane döküm makinası kuruldu. Sıcak hadde makinasının şasisi, motoru ve aktarma organları kullanıldı, yeni merdaneler, bunların yerleştirileceği yataklar ve sıvı metali merdanelerin arasına vermek için bir tip tasarlandı ve imal edildi. Kurulan

döküm makinası ile AA1050 alüminyum alaşımına farklı alaşım elementleri eklenerek döküm denemeleri yapıldı. Elde edilen levhalardan alınan numuneler, soğuk haddelendi ve 380 °C de tavlandı. Elde edilen numuneler optik mikroskopta incelendi. Alaşım elementi eklenmemiş numuneler döküm sonrasında diğerlerine kıyasla daha büyük taneli olmalarına rağmen, hadde ve tav işlemlerinden sonra eşekslenli ve küçük taneli bir yapıya kavuştular. Stronsiyum eklenen numunelerin döküm ve tav sonrası tanelerin küçük ve eşekslenli oldukları gözlemlendi.

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## LIST OF SYMBOLS/ABBREVIATIONS

$A_x$	Contact area between the rolled material and the roll pass
$F$	Separating force
$F_v$	Particle volume fraction
$T_m$	Melting temperature
$p_z$	Pinning force
$\bar{p}$	The mean unit pressure on the casting rolls
$r$	Second-phase particle radius
rpm	Revolutions per minute
$\varepsilon$	Plastic strain
$\varepsilon'$	Strain rate
$\sigma$	Stress
$\sigma'$	Stress rate
$\bar{\sigma}_{av}$	Average flow stress within the roll gap
$\gamma$	Grain boundary energy
CTRCA	
DC	Direct chill semi-continuous casting
HPTRC	High pressure twin roll casting
HRC	Rockwell Hardness value
MDTRC	Melt-drag twin-roll caster
PSN	Particle stimulated nucleation
TRC	Twin-roll casting

## 1. INTRODUCTION

Aluminum has established itself only recently as a high versatile material on the world market; with little over a hundred years of history, this metal is one of the latest arrivals to reach mass levels of consumption. Unlike steel, aluminum's importance began to grow significantly only in this century not in industrial revolution. Aluminum was first extracted in 1925 by Orsted, and produced in very modest quantities through 1850-1860, and it became truly industrialized after 1880, after Hall Heroult process was invented for production of aluminum in industrial scale [1].

Aluminum is among the most essential materials for transportation, packaging, and construction industries. Only in the U.S. Aluminum Industry employs more than 130,000 people, and produces more than 20 billion pounds of ingot and fabricated mill products, 7 billion of which is secondary recycled metal. That also shows the critical role of aluminum. As a light-weight, high-strength and recyclable structural metal, aluminum has and will continue to play an important role in social progress at the individual and community levels. Aluminum has vital role in areas such as transportation (automobiles, trucks, rail cars, ships, and commercial aircraft), food and beverage packaging (aseptic containers and beverage cans), infrastructure (arenas, bridges, water treatment plants, airports, railroad stations and highway applications), building and construction (windows, doors, siding and curtain wall), rural electrification (electric cable), and aerospace and defense (from all present and future generations of commercial and military aircraft to space vehicles) [2]. The substantial total positive impact of the utilization of aluminum in all of these areas is quite clear when judged on total life-cycle cost and efficiency, when the combined benefits of high design efficiencies, low maintenance, and recyclability are brought out.

Twin-roll casting (TRC) is a continuous sheet metal casting process, which was first invented for production on sheet steel to decrease operating costs and eliminate annealing and hot rolling steps of sheet production. Solidification and hot rolling is combined in the process. Molten metal is delivered through the gap between two counter rotating water cooled rolls with a ceramic nozzle; molten metal solidified and hot rolled to 1-10mm

between the rolls. TRC process is used for ferrous and non-ferrous metals, steel, aluminum, magnesium etc. A commercial twin roll caster can be seen in figure.1.1

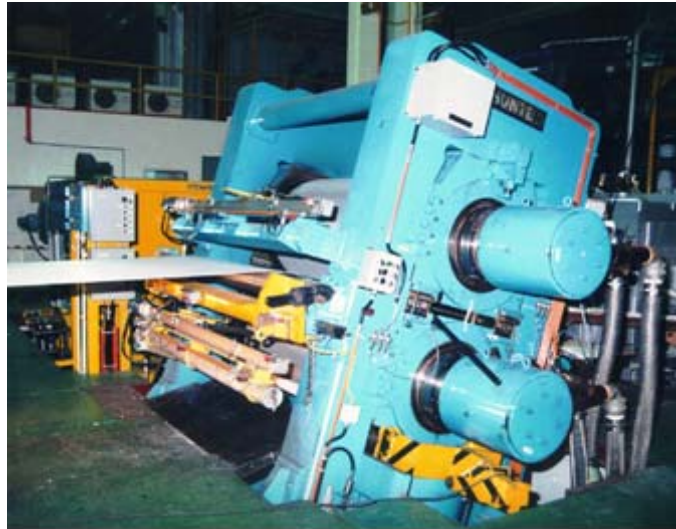


Figure 1.1. A commercial twin roll caster

Twin roll casting for the fabrication of thin metal strips provides a number of advantages over other fabrications methods, including appreciable energy savings. In comparison to direct-chill (DC) casting and subsequent hot-roll milling, twin-roll casting allows metal strip to be produced directly from molten metal at near final gauge without downstream processing, at relatively low running and equipment cost. The higher cooling rate of twin-roll casting also affords improvements in the mechanical properties of some aluminum alloys. However, for other aluminum alloys with wide freezing range, the technique is not suitable because the roll bite is very narrow and the strip cannot be cooled sufficiently. Another drawback of the technique is its low productivity due to the low casting speed of the roll caster. Early twin-roll casters for fabricating aluminum alloy strips of 5–7 mm in thickness operated at speeds of below 1 m/min. Speeds of up to 10 m/min have been realized by employing large-diameter rolls, and recently speeds of up to 15 m/min have been obtained for 1 mm strips. The speed of twin-roll caster can be increased by raising the cooling rate, which is why thinner strips can be cast faster.

The sheets produced by any of the techniques should be heat treated before cold rolling or after cold rolling to achieve desired combination of properties. The sheets are heat treated in order to reduce chemical segregation, improve the workability, soften strain-

hardened and heat treated alloy structures, relieve stresses, stabilize properties dimensions, effect solid solution of alloying constituents and improve mechanical properties of the sheet, provide hardening by precipitation of constituents from solid solution.

The objective of the current work is to study the effects of alloying elements (Mg, Mn, Fe, Sr,) on the microstructure and annealing behavior of AA1050 sheet. Laboratory scale rolling machine is modified and a laboratory scale twin-roll caster is built. Samples containing Mg, Mn, Mg+Mn, Sr, and Fe+Mn+Mg are cast in a thickness of 1.5-2mm and a width of 50mm by the laboratory-scale twin-roll caster. As-cast samples are cold rolled to 0.7-0.9 mm and subsequently annealed at a recrystallization temperature for different periods of time. As-cast and annealed samples are prepared for metallographic examination and the microstructures of as-cast and annealed samples were compared with the samples with no alloying addition.

## 2. LITERATURE SURVEY

### 2.1. Aluminum

Aluminum is the third most abundant element in Earth's crust and is the most heavily consumed non-ferrous metal in the world, with current annual consumption at 24 million tons. About 75% of this total volume, is primary aluminum (aluminum extracted from ore, as opposed to secondary aluminum which derived from scrap metal processing) [2]. The main properties which make aluminum a valuable material are its lightweight, strength, recyclability, corrosion resistance, durability, ductility, formability and conductivity. Due to this unique combination of properties, the variety of applications of aluminum continues to increase. [2]. Its lightweight, strength and corrosion resistance makes it a better choice to use in automobiles in stead of steel. Since reduction of emission in automobiles is vital.

Lightweight, strong and long-lasting; a specific weight of 2.7 g/cm<sup>3</sup>, about a third that of steel which results in reduction in dead-weight and energy consumption while increasing load capacity. Aluminum alloys can exhibit the same strength as many structural steels and the weight is just a third. Unlike steel, aluminum is not embrittled at low temperatures. In fact, the toughness is enhanced at very low temperatures [5]. Highly corrosion resistant; naturally generated protective oxide coating and is highly corrosion resistant. Surface treatments like anodizing, painting or lacquering can further improve this property. Excellent heat and electricity conductor; relation to its weight is almost twice as good a conductor as copper. This has made aluminum the most commonly used material in major power transmission lines [1-4].

Completely impermeable and odorless; aluminum foil, even when it is rolled to only 0.007 mm thickness, is still completely impermeable and lets neither light aroma nor taste substances out. Moreover, the metal itself is non-toxic and releases no aroma or taste substances which make it ideal for packaging sensitive products such as food or pharmaceuticals. Totally recyclable; aluminum is 100 percent recyclable with no downgrading of its qualities. The re-melting of aluminum requires little energy: only about

5 percent of the energy required to produce the primary metal initially is needed in the recycling process [1-4].

### **2.1.1. History**

In nature however it only exists in very stable combinations with other materials (particularly as silicates and oxides) and it was not until 1808 that its existence was first established. It took many years of painstaking research to "unlock" the metal from its ore and many more to produce a viable, commercial production process [4].

In 1808 Sir Humphry Davy (Britain) established the existence of aluminum and named it. It was 1821 when P. Berthier (France) discovers a hard, reddish, clay-like material containing 52 per cent aluminum oxide near the village of Les Baux in southern France. He called it bauxite, the most common ore of aluminum. Four years later in 1825 Hans Christian Oersted (Denmark) produces minute quantities of aluminum metal by using dilute potassium amalgam to react with anhydrous aluminum chloride, and distilling the resulting mercury away to leave a residue of slightly impure aluminum. And in 1827 Friedrich Wöhler (Germany) describes a process for producing aluminum as a powder by reacting potassium with anhydrous aluminum chloride. 1845 Wöhler establishes the specific gravity (density) of aluminum, and one of its unique properties - lightness. 1854 Henri Sainte-Claire Deville (France) improves Wöhler's method to create the first commercial process. The metal's price, initially higher than that of gold and platinum, drops by 90% over the following 10 years. The price is still high enough to inhibit its widespread adoption by industry [4].

In 1855 a bar of aluminum, the new precious metal, is exhibited at the Paris Exhibition. Hamilton Y. Cassner (USA) improves on Deville's process and annual output 15 tones in 1885. In 1886, two unknown young scientists, Paul Louis Toussaint Héroult (France) and Charles Martin Hall (USA), working separately and unaware of each other's work, simultaneously invent a new electrolytic process, the Hall-Héroult process, which is the basis for all aluminum production today. They discovered that if they dissolved aluminum oxide (alumina) in a bath of molten cryolite and passed a powerful electric current through it, then molten aluminum would be deposited at the bottom of the bath [4].

1888 The first aluminum companies founded in France, Switzerland and the USA  
1889 Karl Josef Bayer (Austria), son of the founder of the Bayer chemical company, invented the Bayer Process for the large scale production of alumina from bauxite. From 1900 to 1999 annual output of aluminum increased from 8 thousand tones to 24 million tones.

Aluminum has only been produced commercially for 146 years and is still a very young metal. Mankind has been using copper, lead and tin for thousands of years and yet today more aluminum is produced than all other non-ferrous metals combined. Annual primary production in 1999 was about 24 million tones and secondary - recycled - production to some 7 million tones. The total of some 31 million tones compares with 14.1 million tones of copper, 6.0 million tones of lead and 0.2 million tones of tin.

### **2.1.2. Application**

Aluminum is often called the metal of the future. Aluminum already is, next to steel, the most widely used metallic material in the world. Its use is increasing all the time for more and more products. Aluminum alloys can be given very attractive material properties. Sensitive applications of aluminum often result in reduced energy consumption and thus less environmental impact. This is increasingly valued in our eco-conscious society. Typical applications of aluminum alloys are given in Table 2-1 below.

Even a very thin layer of aluminum gives total protection against light, moisture, oxygen, taste and odor. This is utilized for example by the pharmaceutical and food industries for delicate products where long-term integrity is an absolute requirement. For many types of packaging aluminum is applied in laminates, usually as combinations of aluminum foil, plastic film and paper. The metal usually represents only a few percent of the packaging material weight. Aluminum packaging is light, reducing energy needs both in manufacture and in transport. The weight of a 33cl beverage can is only 5 % of the packaged drink, while a 33cl returnable glass bottle weighs as much as the contents.

Table 2.1. Applications of aluminum alloys

Aluminum Alloy	Typical applications
1XXX	Lightly stressed parts with good corrosion resistance Roofing and cladding, cooking vessels Packaging, small fasteners Special applications in chemical industry
2XXX	Wire for revit                      Heat resistant parts Mechanical parts                  Airplane components Highly stressed parts              Machining parts
3XXX	Hot forged parts, pistons. Applications requiring good heat resistance and low expansion.
5XXX	Welded structures under stresses and resistant to marine corrosion ship building applications, wires for rivets, special nuts and bolts
6XXX	Unstressed anodized structures, door and window frames, furnishing fittings Decorative applications requiring excellent appearance and applicable mechanical strength Moderately stressed structures requiring good corrosion resistance
7XXX	Welded structures with high mechanical resistance Highly stressed structures Very strong paneling
8XXX	Electrical conductors Parts to be deep drawn.

Its good conductivity makes aluminum an important metal for the electrical and electronic industries. Its formability and its low weight make it a preferred material for casings and panels for different types of equipment. Good conductivity in combination with low weight also makes aluminum the best material for high-voltage electrical transmission cables.

Long service life and low maintenance costs, high corrosion resistance, formability, strength and low weight all support the increased use of aluminum for building applications. In modern architecture the application of Aluminum extrusions, often in combination with glass, is well established for roofing, facades, entrances etc.

Aluminum represents an ideal solution for achieving tomorrows' vehicles because it offers auto makers the opportunity to design and manufacture safe, high performance, energy efficient and environmentally friendly vehicles that much lighter than current vehicles. In addition to taking the advantage of the lighter mass of aluminum compared to steel for the body of the vehicle further weight reductions possible though secondary weight savings in engine transmission, brakes, wheels, fuel tank and other systems [5].

Since the Wright Brothers decided to put an aluminum engine in their first plane, which flew in 1903, the rapid adoption and major role of aluminum has made possible the phenomenal growth of the aerospace industries. Today aluminum accounts for approximately 80 percent of the structural weight of modern airplanes. Also in aerospace applications it is necessary to reduce the weight of the vehicle, since the cost of placing 1kg to the low earth orbit is more than \$10000, use of light weight materials is vital.

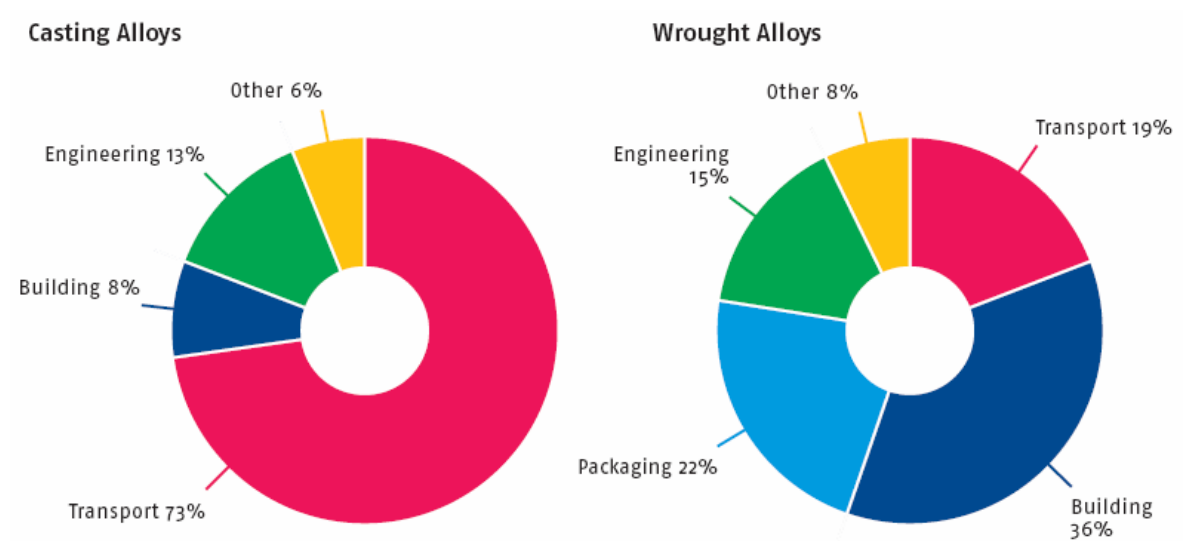


Figure 2.1. Use of aluminum in industry [3]

### 2.1.3. Aluminum Production

Aluminum can be produced via two different routes: primary aluminum production from ore and recycling aluminum from process scrap and used aluminum products. The availability of minerals for aluminum production can be considered unlimited. The main raw material is the oxide known as bauxite, which normally contains 20-30 percent of aluminum. For the annual world demand of aluminum, slightly above 100 million tones of bauxite are mined. Aluminum from used products is an excellent raw material for production of new products. As aluminum scrap has a high monetary value there is an economic driving force for recycling. It is therefore natural that the recycling rate is high. Aluminum can be recycled over and over again with a low energy demand and a low environmental impact. The recycled material has an identical high quality and is as valuable as new metal.

Bauxite has to be processed into pure aluminum oxide (alumina) before it can be converted to aluminum by electrolysis. This is achieved through the use of the Bayer chemical process in alumina refineries. In the high temperature electrolysis process the need for electrical energy is relatively high, 13-14 kWh/kg. The amount of energy used and the environmental impact at this process is often re-gained several times over during the life cycle of aluminum products [3]. The aluminum oxide is released from the other substances in bauxite in a caustic soda solution, which is filtered to remove all insoluble particles. The aluminum hydroxide is then precipitated from the soda solution, washed and dried while the soda solution is recycled. After calcination, the end-product, aluminum oxide ( $\text{Al}_2\text{O}_3$ ), is a fine grained white powder.

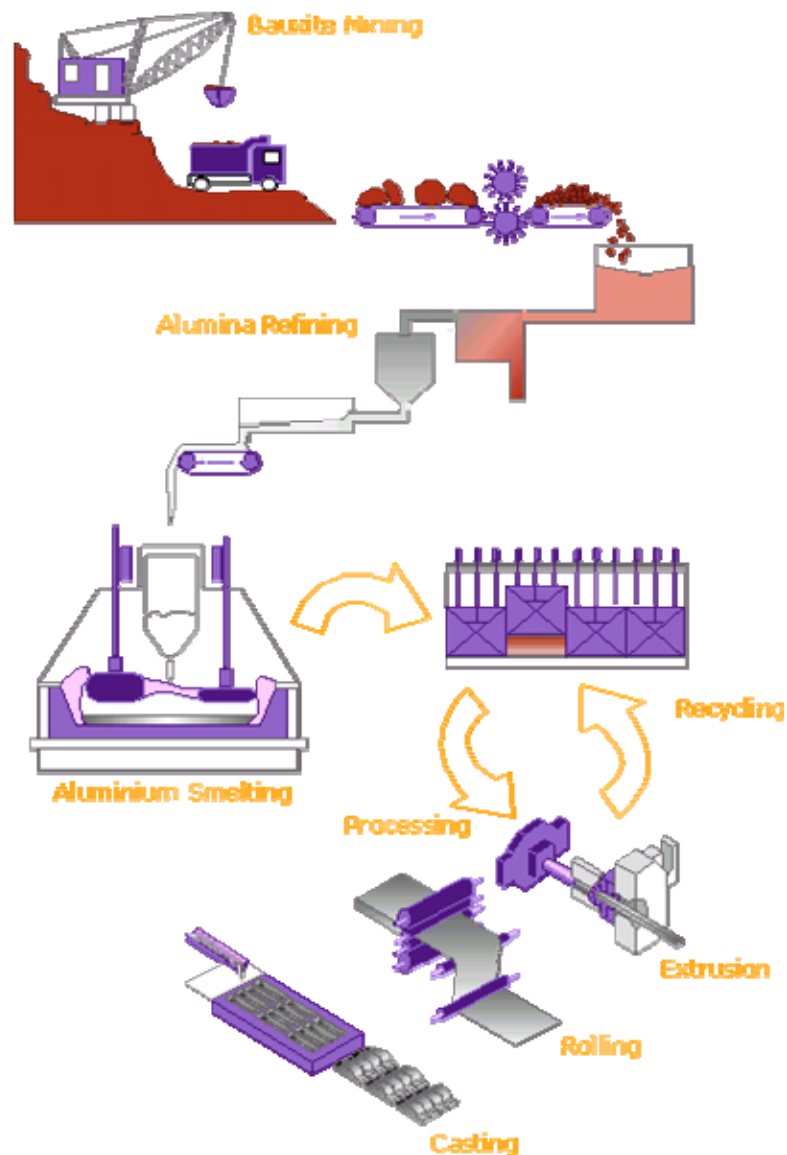


Figure 2.2. Production of aluminum from ore [4]

The basis for all modern primary aluminum smelting plants is the Hall-Héroult Process, invented in 1886. Alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminum fluoride) within a large carbon or graphite lined steel container known as a "pot". An electric current is passed through the electrolyte at low voltage, but very high current, typically 150,000 amperes. The electric current flows between a carbon anodes (positive), made of petroleum coke and pitch, and a cathode (negative), formed by the thick carbon or graphite lining of the pot [4]. Molten aluminum is deposited at the bottom of the pot and is siphoned off periodically, taken to a holding furnace, often but not always blended to an alloy specification, cleaned and then generally cast.

A typical aluminum smelter consists of around 300 pots. These will produce some 125,000 tones of aluminum annually. However, some of the latest generation of smelters is in the 350-400,000 tone range. On average, around the world, it takes some 15.7 kWh of electricity to produce one kilogram of aluminum from alumina. Design and process improvements have progressively reduced this figure from about 21kWh in the 1950's [4].

Aluminum production is an energy intensive process. However less energy is needed for downstream production steps the energy used in metal production make aluminum expensive. Recycling and lifecycle product is very important in that point of view. As long as the metal is recycled energy consumption can be decreased 70-80% of it was before.

#### **2.1.4. Recycling Aluminum**

The recycling rate for aluminum is high and is estimated to be between 70 and 80 percent. The use of aluminum today is five times higher than in the 1950's and the growth continues. Many products from long ago have only just been scrapped. These quantities are enough for only about 30 percent of today's demand for metal. This situation will also be valid in the future as long as the use of aluminum continues to increase. From a technical and economical standpoint aluminum products can be manufactured using a high proportion of recycled material and with high quality. But, as already stated, the necessary quantities of end-of-life products are not yet available [7].

The concept of 'recycled content' in new products is often regarded as environmentally positive. This is however not always the most relevant measure for environmental correctness. A better approach would be to design a product in such a way that it can be easily recycled and also to inform the consumer about this, encouraging an increase in the recycling rate.

Thin gauge aluminum foil is often used as a small but essential part of packaging laminates where the dominant material is often paper and/or plastic. It is comparatively difficult to recycle the materials in laminates, but today aluminum foil from such laminates is recycled on an industrial scale [6].

However, it is often more appropriate and hygienic to direct this type of material to energy recovery. This applies especially to use food packaging. In energy recovery thin gauge aluminum foil is transformed to oxide with a release of heat. The amount of heat released is about 30 MJ/kg, ie as much heat as from coal and twice as much as from bio-fuel such as wood and paper. Remelted metal compared to primary aluminum means: 5% of the energy requirement, 5% of the environmental load and 5% of the investment cost [6].

## **2.2. Type of Products**

Today, casting continues to be the most widely used method of forming. Technical advances, of course, have been made, but the principle remains the same: molten aluminum is poured into a mold to duplicate a desired pattern. Casting is a simple, inexpensive, and versatile way of forming aluminum, so it is not surprising that it was also the first method used. Such historical items as the baby rattle for the French's emperor's son, the cap atop the Washington Monument and the tea kettle were all produced by casting [2].

The three most important methods are die casting, permanent mold casting, and sand casting. Die casting, in which molten metal is forced into a steel die, or mold, under pressure is normally used for high-volume production. Accurate parts, requiring a minimum of machinery can be produced. Permanent mold casting involves molds and

cores of steel or other metal. Molten aluminum is generally poured into the mold, although vacuum is sometimes applied. Permanent mold castings can be made stronger than either die or sand castings. Semi-permanent mold casting, which uses expendable cores of sand or other material, is used when permanent cores would be impossible to remove from the finished part. The most versatile method is sand casting. Virtually any pattern can be pressed into a fine sand mixture to form a mold into which the aluminum is poured. This is a slow process, but usually more economical for small quantities, intricate designs, or when a very large casting is needed [8].

The automotive industry is the largest market for aluminum castings and cast products make up more than half of the aluminum used in cars. Cast aluminum transmission housing and pistons have been virtually universal in cars and trucks throughout the world for years. Many other engine parts are cast aluminum and the applications grow as automakers seek new ways to save weight and gain fuel efficiency and performance. Cast aluminum is also widely used in other forms of transportation, including aircraft and marine engines and structures [5].

Extruded products constitute more than 50 % of the market for aluminum products in Europe of which the building industry consumes the majority. Extruding aluminum is the most innovative forming process for this versatile metal, allowing designers almost unlimited creativity and imagination to specify profiles to meet their exact, specialized needs. Aluminum extrusions are used in commercial and domestic buildings for window and door frame systems, prefabricated houses/building structures, roofing and exterior cladding, curtain walling, shop fronts, etc. Furthermore, extrusions are also used in mass transport for airframes, road and rail vehicles and in marine applications [3].

The process begins with creation of a metal die, which precisely matches the profile of the shape specified by the designer. Aluminum billets or logs, produced from ingots, are heated and forced under pressure through the die. The process is quite similar to squeezing toothpaste from a tube. The variety of shapes is virtually endless, and profiles are produced to exact specifications, with very close tolerances. Once the profile is extruded, it can be further fabricated cut to length, machined, drilled, punched, notched, bent and assembled into a semi-finished product. An extruded tube even can be “stretched” to produce tubing

of exact inside and outside dimensions. Profiles can be painted, anodized, brushed or polished, depending on the desired finish [8].

Forging is a manufacturing process where metal is pressed, pounded or squeezed under great pressure into high strength parts known as forgings. This is usually done by heating the metal, but some forgings are produced without heating. Generally, forged components are shaped by either a hammer or a press. Forging on the hammer is carried out in a succession of die impressions using repeated blows. In a press, the component is usually hit only once in each die impression [2].

As the forging work piece is hammered or pressed, it is repeatedly manipulated between the dies until it reaches final forged dimensions. Because the process is inexact and requires a skilled forging operator, substantial work piece stock allowances are retained to accommodate forging irregularities. The forged part is rough machined and then finished machined to final dimensions.

In automotive applications, forged components are commonly found at points of shock and stress. Forged automobile components include connecting rods, crankshafts, wheel spindles, axle beams, pistons, gears, and steering arms. Forgings are also used in helicopters, piston-engine planes, commercial jets, and supersonic military aircraft. Many aircraft are "designed around" forgings and contain more than 450 structural forgings as well as hundreds of forged engine parts. "Forged" is the mark of quality in hand tools and hardware. Pliers, hammers, sledgers, wrenches, garden implements, and surgical tools are almost always produced through forging [8].

Rolled products, i.e. sheet, plate and foil constitute almost 50 % of all aluminum alloys used. In North America and Western Europe, the packaging industry consumes the majority of the sheet and foil for making beverage cans, foil containers and foil wrapping. When aluminum is passed between rolls under pressure, it becomes thinner, and longer in the direction in which it is moving. This simple process is the basis for aluminum's most widely used forms: plate, sheet, and foil. Aluminum can be flat-rolled and re-rolled until it reaches the desired thickness or gauge. Where the rolling process is stopped determines

whether the final product will be plate (a quarter-inch thick or more), sheet (.249 to .006 inch), or foil (less than .006 inch) [3].

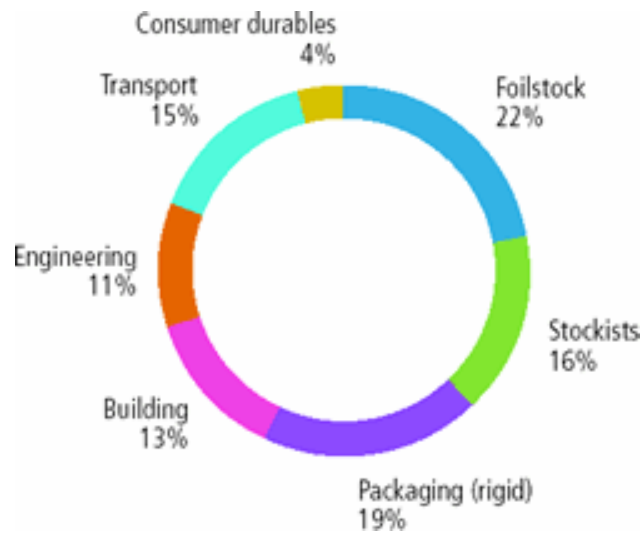


Figure 2.3. Application and use of aluminum [3]

Plate is used in heavy-duty applications in the aerospace, machinery, and transportation markets. Aluminum plate, machined to shape, forms the skins of jumbo jets and spacecraft fuel tanks. It is used for storage tanks and containers in many industries, and because aluminum is actually stronger at super cold temperatures, it is especially useful in holding cryogenic (very low temperature) materials. Plate provides structural sections for rail cars and large ships, and armor protection for military vehicles and the trucks that carry the payroll [8].

Sheet, the most widely used form of aluminum, is found in all of the aluminum industry's major markets. In packaging, sheet is used for cans and closures. In transportation, it provides panels for automobile bodies and for tractor trailer vehicles. Sheet is used in home appliances and cookware. In building and construction, it forms siding and gutters, down-sprouts and roofing, and awnings and carports. License plates and light bulb bases, pleasure boats and printing plates, highway signs and high flying planes are also all made of sheet. Sheet can be color anodized to black or gold, red or blue, or hundreds of other colors. It can be etched to a "matte" finish or polished to a sparkling brightness and it can be textured to resemble wood or painted for lasting beauty [3].

### 2.3. Sheet Production

There are three main production routes of aluminum sheet. The conventional way of production is direct chill casting combined with hot rolling which is mostly used and well known all over the world. The process is well understood and controlled to obtain desired properties of sheet. Strip casting provides direct production of sheet from molten aluminum. Some hot rolling and heat treating steps of production is eliminated by strip casting. Strip casting includes twin roll casting, twin belt casting and twin block casting. The processes are described below.

The semi-continuous direct chill (DC) casting process (Figure 2-4) has been used almost exclusively to produce aluminum sheet ingots during the past 60 years owing to the relative simplicity of the equipment and its ability to produce high quality ingots. In this process, a bottom block is partially inserted into an open rectangular mold at the start of a cast and liquid metal is poured into it. Once the molten metal reaches a prescribed height, the bottom block and cast ingot are lowered into a casting pit while liquid aluminum is continuously added. The aluminum ingot is subjected to cooling by the transfer of heat to the water-cooled mold (primary cooling), and to cooling through the contact of chill water with the solid shell as it emerges from the mold cavity (secondary cooling). Typically, upwards of 80% of total heat is removed by the chill water under steady state conditions, as compared to ~20% of total heat, which is extracted by the mold. The ingot is lowered at a predetermined casting speed, which varies with time and is tailored to suit the alloy. The process is semi-continuous in that, once the ingot has the desired length (usually ~4–10 m), the casting is stopped and the ingot is removed from the casting pit. The process is restarted when the metal and machinery are ready again.

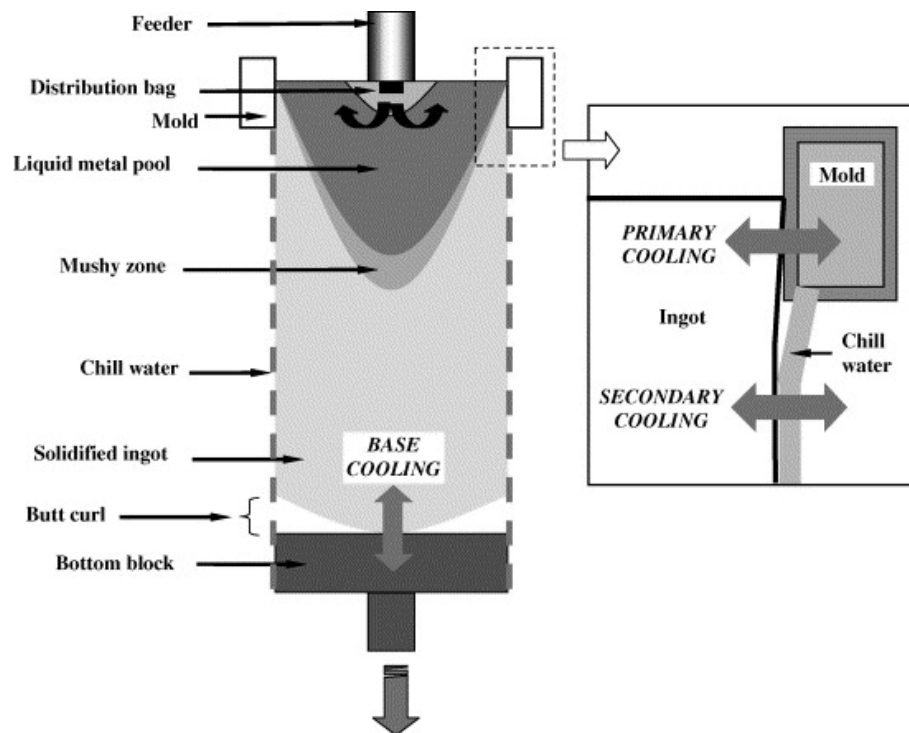


Figure 2.4. Schematic of the DC casting process for aluminum sheet ingots and various cooling phenomena active during the process [10]

The surfaces of aluminum alloy ingots are often scalped to remove segregated or non-uniform surface layers, which vary in thickness and may extend 20mm below the chilled surface. Scalping causes 5% loss in production. Removal of the surface layer is important for further processing. After scalping the ingots are homogenized; to remove particles and segregation gradients that will give films or areas with low melting temperatures, in order to avoid tearing during rolling to round of hard particles with sharp edges, which give poor ductility and holes in thin walled products to form secondary hard particles for grain size control during rolling to obtain uniform distribution of alloying elements in solid solution before rolling. Homogenization is also preheating operation before hot rolling. The homogenized ingots are then hot rolled to thick enough to be coiled. After that they are cold rolled to desired thickness. Figure 2-5 shows the aluminum sheet production steps by DC casting and hot rolling [10].

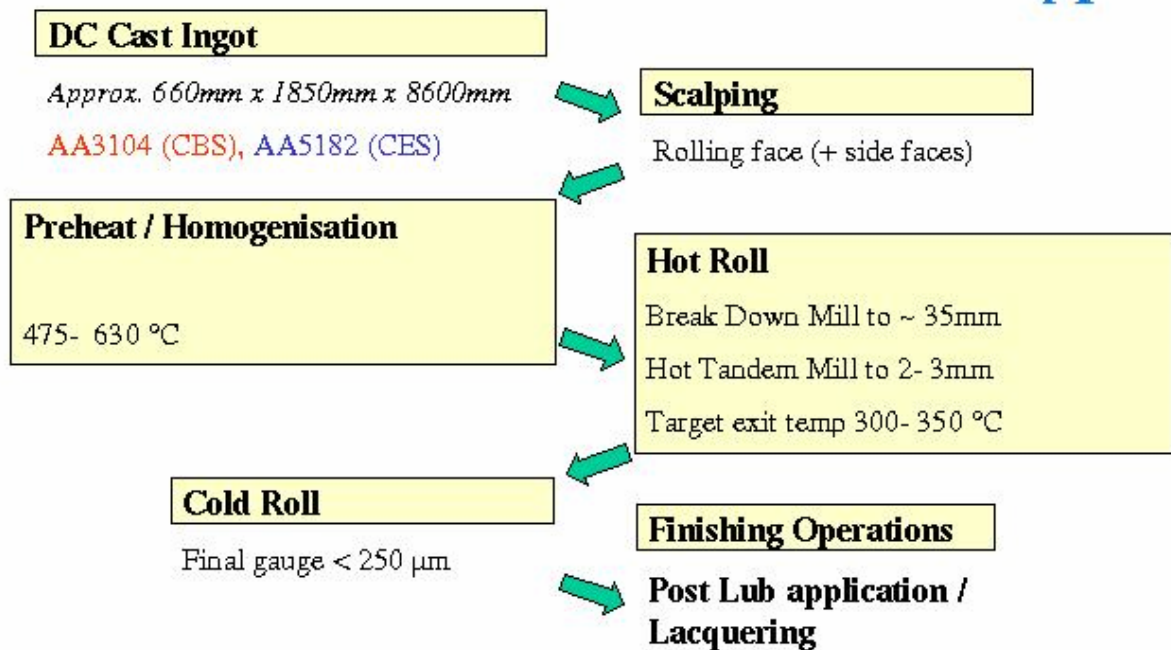


Figure 2.5. Route of hot rolled sheet from ingot to strip

Belt casting is one of the sheet production methods in which molten metal is solidified between counter rotating belts which are cooled by water jets. The sheet produced by this way of production is not thin enough to be directly coiled that it is hot rolled with a tandem mill to a thickness of 1 to 3mm. This production method is suitable for alloys with wide freezing range, because solidification zone in this technique is long enough for them to solidify completely [11].

Twin-belt casting machine is used by metals producers to make aluminum, copper, zinc, lead strip, copper bar and copper anode plate. In the belt caster, molten aluminum is flowed between two almost-horizontal, continuous, thin metal belts in constant motion. Metal side dams moving with the belts contain the aluminum while it solidifies. The belts are usually inclined at an angle of 5 to 9 degrees from horizontal, to minimize turbulence in the pool of molten aluminum, and belt speed is synchronized with the metal flow rate [12].

The caster employs a fully moving mold consisting of parallel carbon-steel belts held in tension as top and bottom surfaces. Chains of rectangular steel or copper blocks moving with the belts and spaced according to the desired cast width form the sides. Cooling of the belts is accomplished by a unique fast-film, highly efficient recirculating water application. Casting thickness for twin belt casting machines ranges from 9mm up to 35mm depending

on the metal and product. Hot rolling of the as-cast slab directly in line produces a finished hot gauge of 1 - 3 mm. Caster designs range up to 2540mm wide [12, 13] .

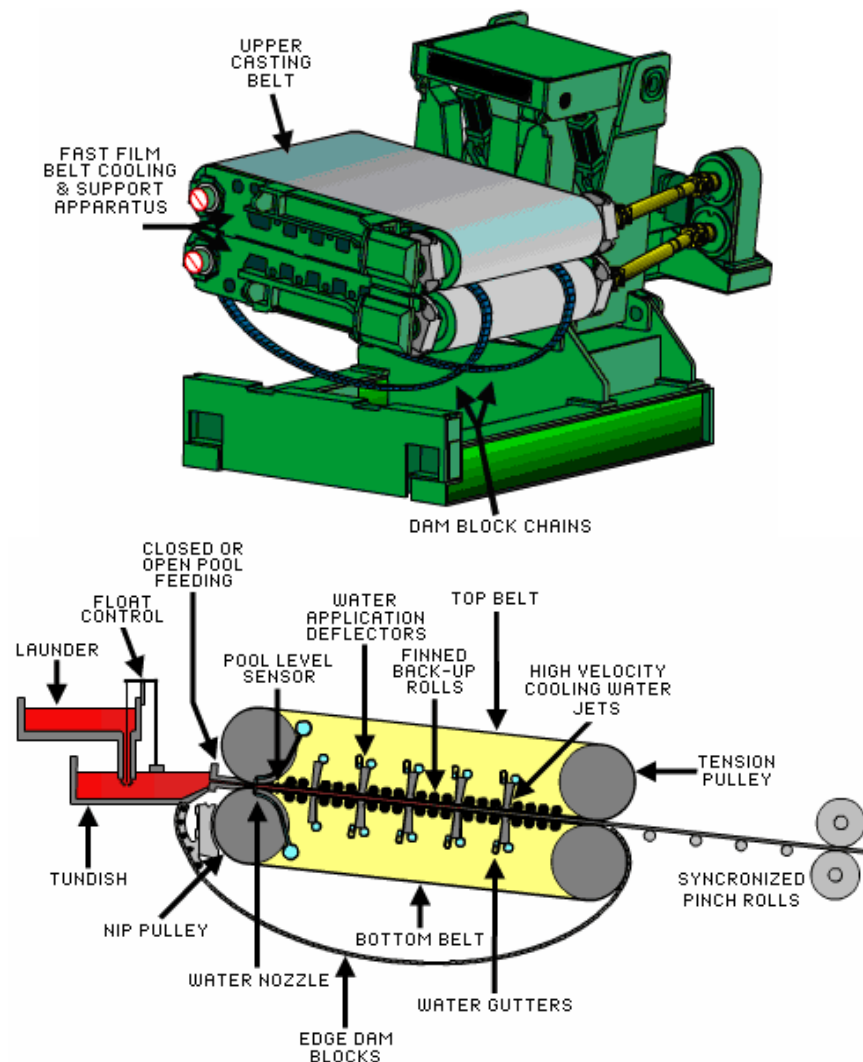


Figure 2.6. Twin-belt casting machine [12]

The hot metal transfers its heat through films of lubricant to the metal belts which are water-cooled on their outer sides, producing slabs typically in the range of 0,5 to 1 inch thick. This continuous slab is usually fed directly into low-speed in-line rolling mills which reduce it to coils of thinner sheet stock for eventual rerolling [13].

The Block caster operates on the same general principle as the belt caster: that is, the aluminum slab is formed between upper and lower traveling walls. In place of continuous flat belts, however, the block caster's traveling walls consist of thick blocks of metal line

up side-by-side so that the exposed surfaces which contact the aluminum form flat walls about six feet long. The sides of the block away from the aluminum are attached to a jointed loop belt, like caterpillar vehicle treads [12].

In the technique, a number of chilling blocks are mounted adjacent to each other on a pair of opposing tracks. Each set of chilling blocks rotates in the opposite direction to form there between a casting cavity into which a molten metal such as an aluminum alloy is introduced. The liquid metal in contact with the chilling blocks is cooled and solidified by the heat capacity of the chilling blocks themselves. Block casting thus differs both in concept and in execution from continuous belt casting. Block casting depends on the heat transfer which can be affected by the chilling blocks. Thus, heat is transferred from the molten metal to the chilling blocks in the casting section of the equipment and then extracted on the return loop. Block casters require precise dimensional control to prevent flash (i.e. transverse metal fins) caused by small gaps between the blocks. Such flash causes sliver defects when the strip is hot rolled. As a result, good surface quality is difficult to maintain [13].

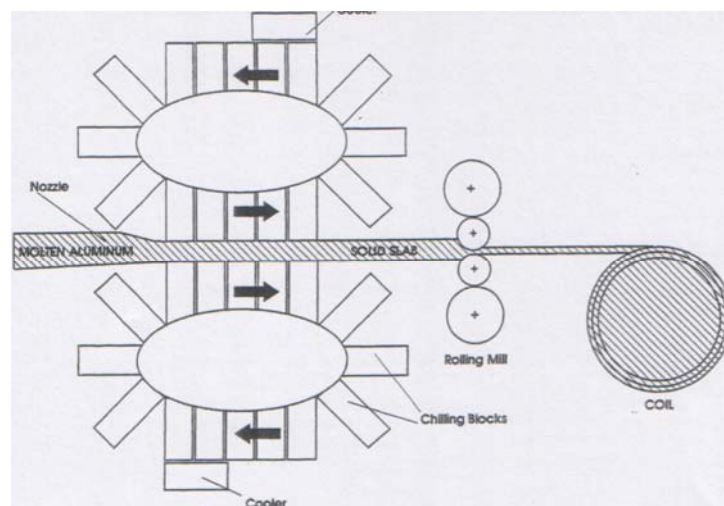


Figure 2.7. Twin block casting machine [11]

As this loop belt rotates around its drive gears, each block takes its turn lining up with its neighbors to contain the flow of molten aluminum from a nozzle. The blocks above and below the aluminum absorb enough heat to solidify the alloy as they travel along with it. Then, as they derive gears, each block lifts away from the aluminum and

moves around to the far side of its loop where a cooling system removes the heat before the block swings back for another turn in the traveling mold wall [12].

As with belt casters, the continuous slab produced by the block caster is usually hot-rolled immediately into thinner sheet stock. Hot mills can also be combined with twin belt casters in order to produce thinner and near net shape production. This combination developed to meet the needs of a growing market for low cost production units. Compared to rival processes, it provides the following striking benefits : short process route, reduced inventory, low conversion cost, low capital cost, hot band down to 1mm, stable process - uniform quality, dynamic gauge and alloy change capability, up to 10 days continuous production.

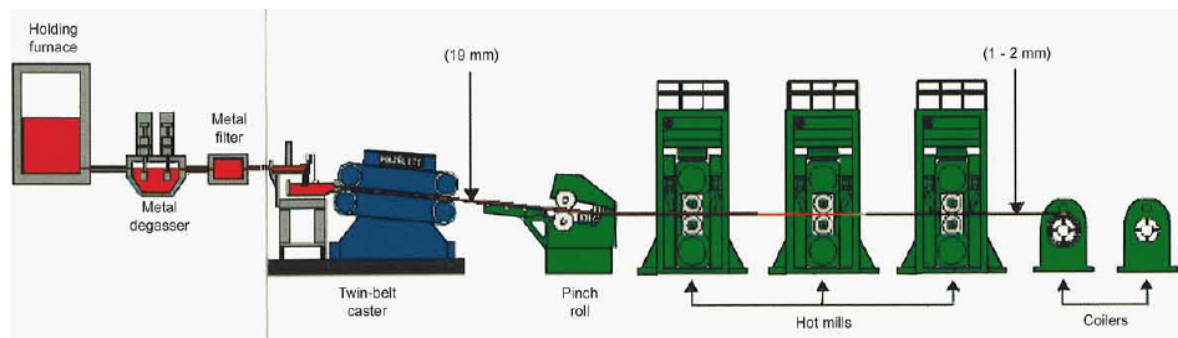


Figure 2.8. Twin belt casting line for production of coilable strip [12]

The most popular type of strip caster is twin roll caster. The term “twin roll” caster itself covers a few different configurations of the rolls. Thus, the rolls may be vertical or horizontal; or may be of different diameters. Some other designs that have been attempted are; cladding roll caster, unequal diameter, gas cushioned caster, and inverted caster. However, horizontal, equal diameter twin roll configuration has been the most successful design used in the aluminum industry [13].

Twin roll casters can produce continuous aluminum sheet thin enough to be coiled immediately after casting, without additional rolling. This coiled sheet may be rerolled later into thinner sheet gauges. Alternatively, the cast sheet may be fed immediately through a hot rolling mill for thickness reduction before the product is coiled. In twin roll casting molten metal is delivered between two counter rotating rolls in with a ceramic tip. The twin roll cast sheet is immediately coiled and stored.

There are few types of twin roll casters depending on the direction of the cast strip. Horizontal, upwards, and tilted twin roll caster are used for production of non-ferrous metals. In downward vertical twin roll casting the molten metal is poured through a ladle to a tundish where a metal pool is originated and from this pool the metal is poured to the gap between rolls by a nozzle where the molten metal solidifies (Figure 2-9). This technique is not appropriate for aluminum and magnesium and mostly used for production of steel sheet because of oxidation problems. Downwards twin roll casters are used for steel strip or slab production (Figure 2-10). Liquid steel from ladle flows through tundish and a refractory core nozzle is positioned between the rolls to distribute molten steel into the melt pool. Side dams are positioned at each end of the rolls to contain the melt pool (also not shown). In non-ferrous metal production the molten metal is separated from the outer atmosphere in order to prevent oxidation, but it is not considered in steel production. Starting at the first point of contact between the rolls and the molten steel, solidification begins and continues as the rolls rotate downwards. Two individual steel shells are formed, one on each roll. The shells form one continuous sheet when they are brought together at the roll nip or kissing point. This steel strip is guided through pinch rolls and a hot rolling stand, where it is reduced to the desired dimensions, typically between 0,7 and 2mm. Water-spray cooling reduces the steel from its rolling temperature to a temperature suitable for coiling.

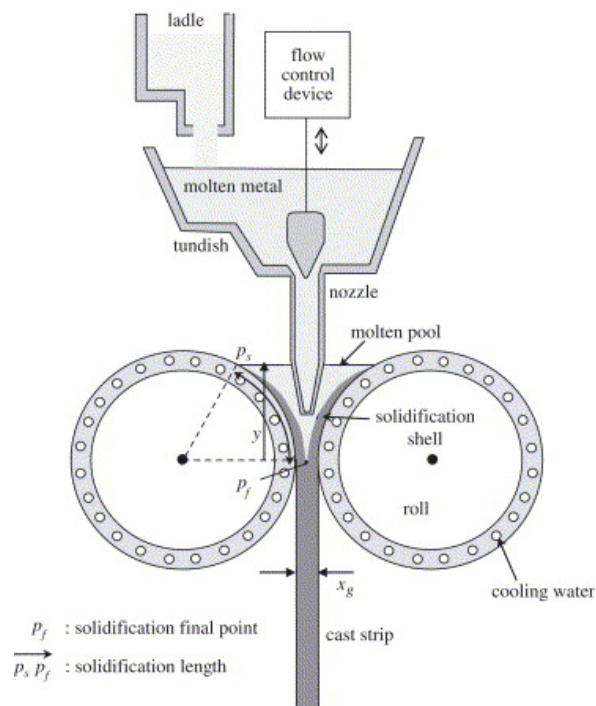


Figure 2.9. Schematic illustration of a downward twin roll caster [14]

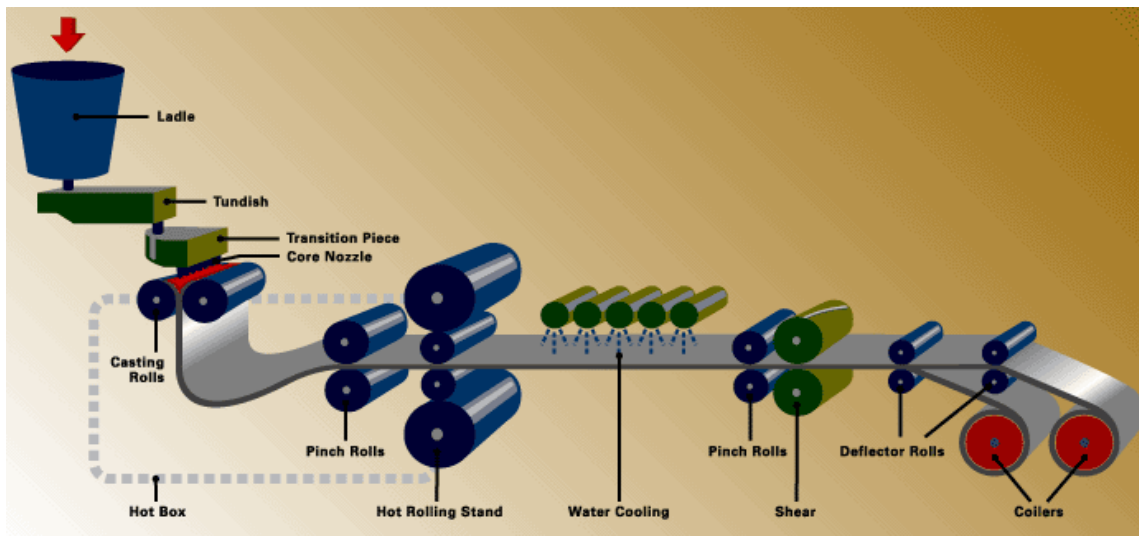


Figure 2.10. Twin roll casting line for steel strip production [15]

Since 1948 the Hunter Engineering machine has become more and more important; the molten metal is fed vertically too, but with one difference; the metal flow is upwards, and the casting nozzle is situated beneath the two rolls (Figure 2-11). By the metallostatic pressure, determined from the level of liquid in the tundish, the molten metal flows through the nozzle and immediately into contact with the rolls. The rolls transport the solidified material in such a way, that the material gets a light deformation. The strip leaves at the top and it is being coiled. The magnesium content is limited to 2.0%. The temperature of the finished strip is 300°C to 350°C. It is possible to cast strip up to 1700mm width with 6mm to 9mm gauge.

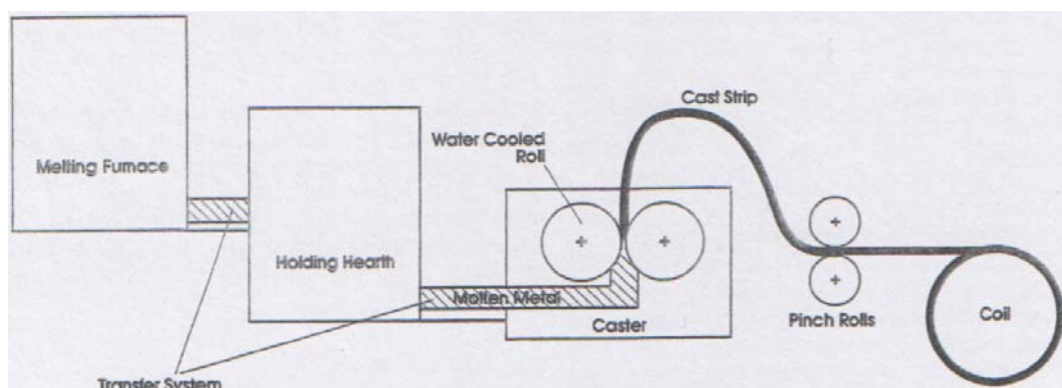


Figure 2.11. Upwards twin roll caster [11]

## 2.4. Twin Roll Casting

Strip casting technology is the most recent innovative casting technology that integrates casting and rolling; thus, re-heating the ingots is avoided. The original roots of strip casting technology go back to the 19th century. Bessemer, one of the classical inventors of the steel industry, applied for a patent in 1857 [16]. Bessemer was one of the important inventors in the steel industry that made the production of cheap steel possible by the invention of the steel converter. With respect to strip casting technology, he started from an existing patent describing twin roll casting of tin foil and lead. After doing some experiments, he was so impressed with the importance of his invention that he immediately applied for a patent in 1857. Bessemer's invention of the steel converter was at that time judged as an absolute failure. One need not, therefore, be greatly surprised that the production of continuous sheets direct from fluid iron did not excite a great amount of enthusiasm in the minds of tin plate manufacturers of that day; in fact, the whole scheme was simply pooh-poohed and laid aside, without any serious consideration of its merits". Bessemer noted that there were difficulties in feeding the liquid steel to the mould, with edge containment and properties of the cast strip. Since he felt his idea was before its time and he was being pressed to make his steel converter work, he did not continue with the development of strip casting technology. A sketch of Bessemer's twin roll caster is shown in Figure 2-12 [16].

The TRC of aluminum was developed into a commercial process by Hunter in the early 1950's since then the process has gained world-wide acceptance in aluminum industry as an economical method for producing wide variety of that rolled products [10]. In the process molten metal solidifies and goes under some hot deformation in the gap between a pair of water cooled rolls. Metal sheet can be produced as thin as that can be coiled. The advantages of this casting technique are numerous. Reduced capital costs, energy consumption, operating costs[2] and less space requirement compared with conventional thin slab casting, the process can save around 70% in respect of production and investment costs[3] Improved process efficiency, reduced scrap rate, better product mechanical properties and reduced need for many machines and space for machines compared with a conventional dc casting route [1,3].

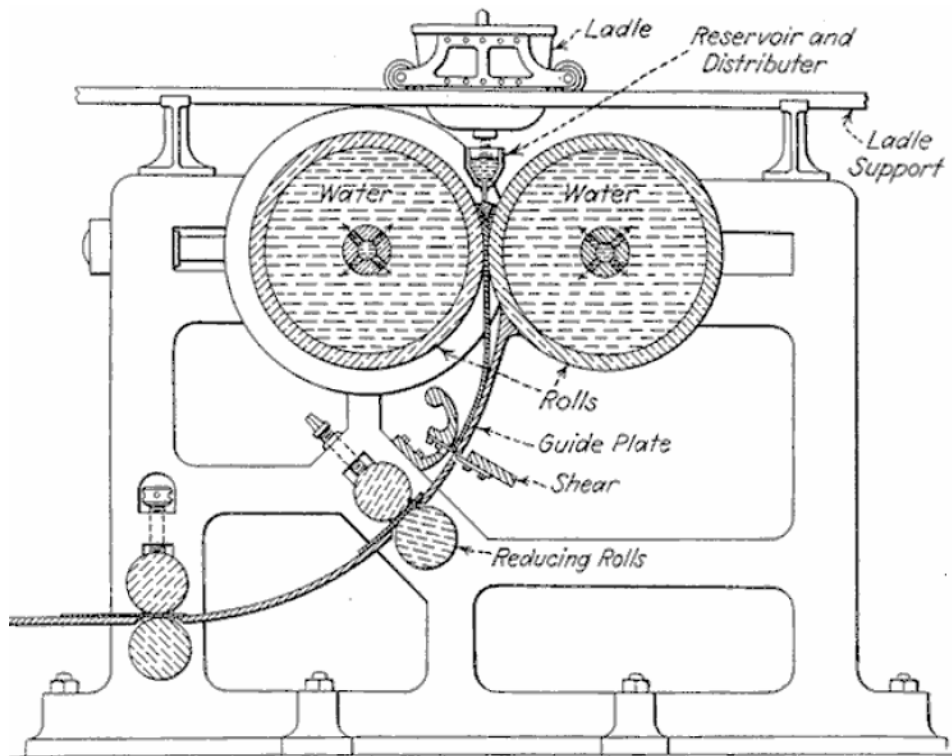


Figure 2.12. Bessemer's twin roll caster for steel sheet production [16]

#### 2.4.1. Advantages and Disadvantages

The advantages of this casting technique are numerous, reduced capital and conversion costs, energy consumption, operating costs and scrap rate compared with a conventional DC casting route. Also faster production and delivery, minimized environmental impact due to less land is required are the advantages of twin roll casting. The drawbacks of twin roll casting are; supersaturated area on the surface, alloys with wide freezing range can not be cast successfully, sticking of the sheet to the rolls, segregation on the surface of the strip.

As previously mentioned, the twin-roll casting process converts molten aluminum directly into thin cast strip suitable for cold rolling; thus effectively eliminating the ingot casting, sawing, scalping, reheating and hot rolling associated with the traditional DC ingot and hot mill method of production. A detailed study performed by the German Metallurgical Institute shows that twin-roll casting not only significantly reduces the capital investments required (Figure 2.13), it also produces considerable savings in energy, consumables and manpower, thus reducing the producers conversion cost (Figure 2.14).

These economic benefits give roll caster based plants a pricing advantage in the increasingly competitive world aluminum market [17].

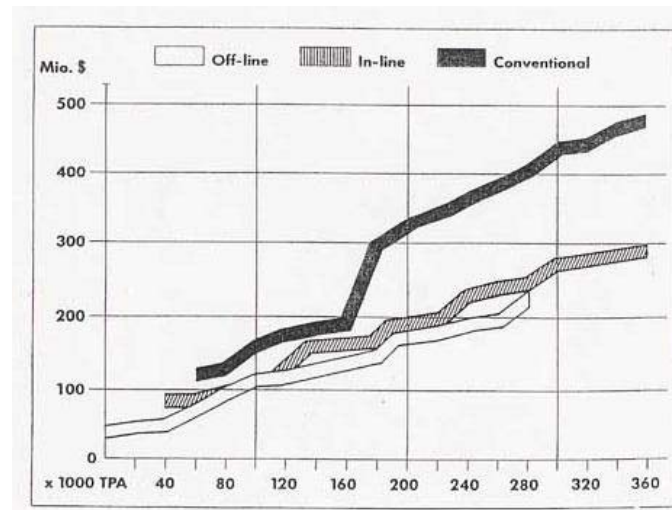


Figure 2.13. Comparison of total investment cost between conventional DC ingot and hot mill (Conventional), thick strip Hazelett/Alusuisse II (in-line) and the TRC (off-line) [17]

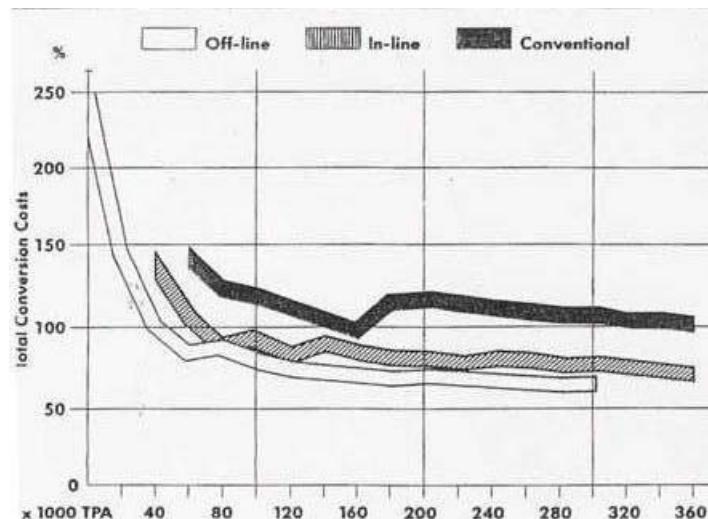


Figure 2.14. Relative conversion cost comparison between conventional DC ingot and hot mill (Conventional), thick strip Hazelett/Alusuisse II (in-line) and the TRC (off-line) [17]

In comparison to direct-chill (DC) casting and subsequent hot-roll milling, twin-roll casting allows metal strip to be produced directly from molten metal at near final gauge without downstream processing, at relatively low running and equipment cost. The higher cooling rate of twin-roll casting also affords improvements in the mechanical properties of

some aluminum alloys. Comparing properties, some of the important differences between twin roll cast and DC cast materials (assuming identical compositions) appear to be; twin roll cast materials have a higher strength, but are less formable; they exhibit a marked increase in recrystallization temperature, but the control of recrystallized grain size is more difficult.

Smaller processing length (around 40m) as compared to direct chill casting of thick and thin slab casting lines (around 300 and 500m) results in less space requirement. The strip is produced very thin which can be coilable so that it is necessary to put tandem mills beyond casting machines. Total energy consumption pickled hot rolled product is estimated to be 60% and 50% less in strip casting as compared to slab casting and thin slab casting respectively. Some production steps such as preheating and hot rolling are eliminated in strip casting which results in reduction in energy consumption. Twin roll casting is also environmental friendly type of production in which greenhouse gas emission are estimated to be 40% and 50% less than that in conventional casting routes [17].

Dimensional control of the strip is much more important in strip casting processes. Because the strip is produced very close to the final thickness that the defects can not be recovered easily. In other processing route the defects can be eliminated in hot and cold rolling steps but it may not be possible in twin roll cast products. The thickness and roughness of the strip is measured during production and preventive action is taken [18]. A problem associated with twin roll casting, which occurs in the absence of any applied parting layer, is strip sticking to the rolls for most commercial aluminum alloys. In general, sticking becomes a greater problem as the thickness of the work piece being cast is reduced. When casting work pieces of a thickness of, say, less than 2.5 mm, sticking of the casting to one or other of the rolls can become very critical [19].

When sticking occurs, the strip adheres to either or both of the rolls somewhere along the arc of contact. The only aluminum alloys that can be cast without the sticking problem are Al-Mg alloys that have Mg concentrations of about 2% by weight or higher. A usual cure for the sticking condition is to apply a parting layer, such as graphite powder, to the roll surface. However, such parting layer application requires a delicate control of the

process, and reduces the high solidification rate, which is one of the inherent advantages of the process [19].

For thick sheet,  $\approx 6$  mm, the sticking of the metal strip to the rolls is not a very serious problem. During commercial use, a layer of metal/metal oxide builds up on the roll and only intermittent application of lubricant is needed. As the thickness of the strip is reduced, sticking becomes much more likely. When the strip thickness becomes less than about 2 mm a uniform, metered quantity of lubricant must be applied for most aluminum alloys. Sticking of the metal to the roll can be so severe that the aluminum has to be ground off the steel roll, and if strip gets attached to both rolls at different points across the width, the strip can be torn into two parts. Partial sticking can lead to the coating on the roll being removed and this then leads to complete sticking after one revolution of the roll. Experience indicates that sticking can always be prevented by the application of a uniform layer of lubricant of sufficient thickness. Too thick a layer leads to a poor heat-transfer coefficient and the lubricant is picked in significant quantities on the strip. Typically the strip exits the caster 4–10% faster than the roll speed because of solid-state rolling [19].

A number of different lubricants and lubrication methods have been investigated. Early trials showed that the uniformity of application was critically important, as was a metered supply rate. It is not very clear whether a parting layer or a lubricant is required. Materials which might be expected to act as a solid lubricant seem to act more efficiently. Most success has been achieved with a water-based graphite emulsion which is sprayed onto the hot rolls. The water must be completely dried off before the roll returns to the tip. A metered computer-controlled pump is used to pump the graphite emulsion. The pump rate is set to vary with strip speed, gauge and alloy type. Alloys which contain Mg are much less likely to stick, and there is practically no sticking problem when more than about 2 wt% Mg is present in the alloy. This observation can possibly be correlated with a mixed spinel forming at low Mg concentrations and magnesia above 2 wt% Mg. A high-magnesium alloy is usually used to condition newly ground rolls or ones where bad sticking has occurred [20].

Because of high solidification rate and deformation a supersaturated area is formed on the surface. The thickness of the supersaturated region changes depending on the

casting parameters; casting thickness and casting speed (Figure 2-15, Figure 2-16). In the supersaturated area the grains are elongated through casting direction or even fragmented because of deformation. The grain size also is much bigger in the center of the strip. The intermetallic particles in this region are too little compared with the ones in the center. They are also too much smaller than the ones produced by direct chill casting and hot rolling [21].

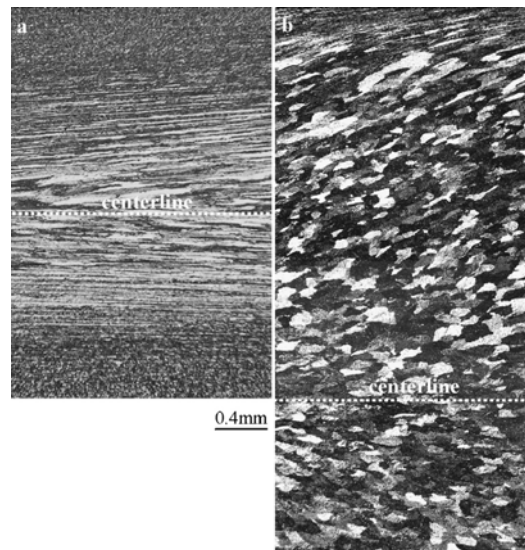


Figure 2.15. The grain structure of the (a) 3 mm-thick and (b) 6 mm-thick strip on the long transverse section[20]

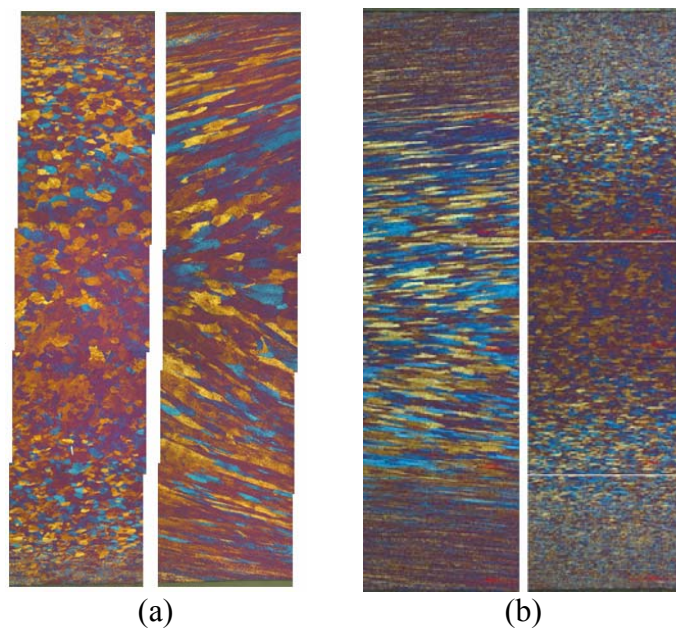


Figure 2.16. Microstructure of twin roll cast (a) AA3003, and (b)AA1235

The supersaturated zone on the surface problematic, because this region recrystallizes faster than the interior part and grain growth causes bigger grains on the surface of the sheet. The large grains on the surface and the little grains in the interior of the sheet acts differently in forming operations. This causes orange peel effect on the surface of the sheet.

The response of the thin strip to an annealing treatment is different at the surface and in the interior as one would expect in view of the cast strip structure. When annealed as-cast, the small surface grains are replaced by very coarse ones starting at approximately 425 °C. Coarse grains are noted first underneath the surface and form a continuous band running in the casting direction (Figure 2-17). This coarse grain band expands towards the surface with increasing temperatures. Having established that the surface layers have already recrystallized during casting, the grain structure at the surface is claimed to be rearranged by an ordinary growth process, driven by the grain boundary energy which is rather substantial due to a very fine grain size in the vicinity of the surface. These structural changes are clearly dictated by the precipitation reactions in the immediate vicinity of the surface where the supersaturation of the aluminum matrix is high and the boundary mobility is severely impaired and is thus retarded. This is essentially why grain growth of the recrystallized surface layer starts not at, but underneath the surface where the boundary pinning is less severe. The growth rate is anisotropic as inferred from the shape of the grains owing to the alignment of the intermetallic particles in the casting direction [21].

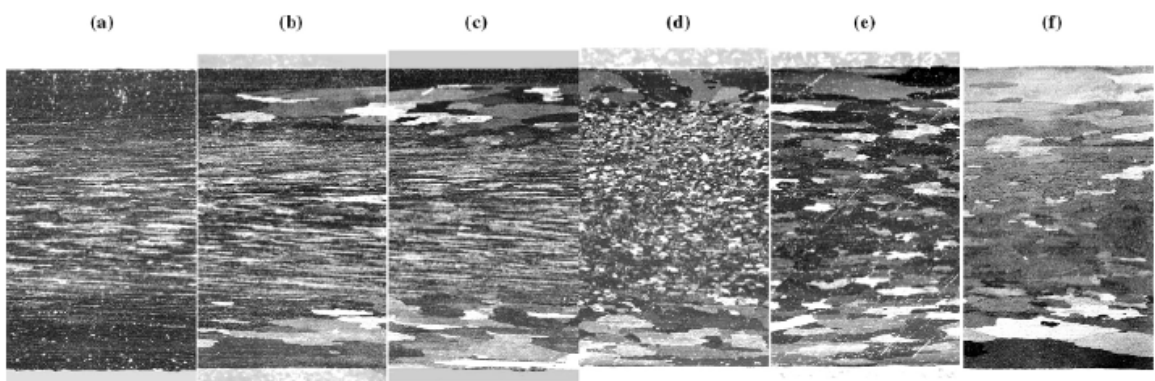


Figure 2.17. Structural changes that take place upon heating a 3 mm-thick strip at a rate of 3 °C /min, at temperatures between 425°C and 560 °C [21]

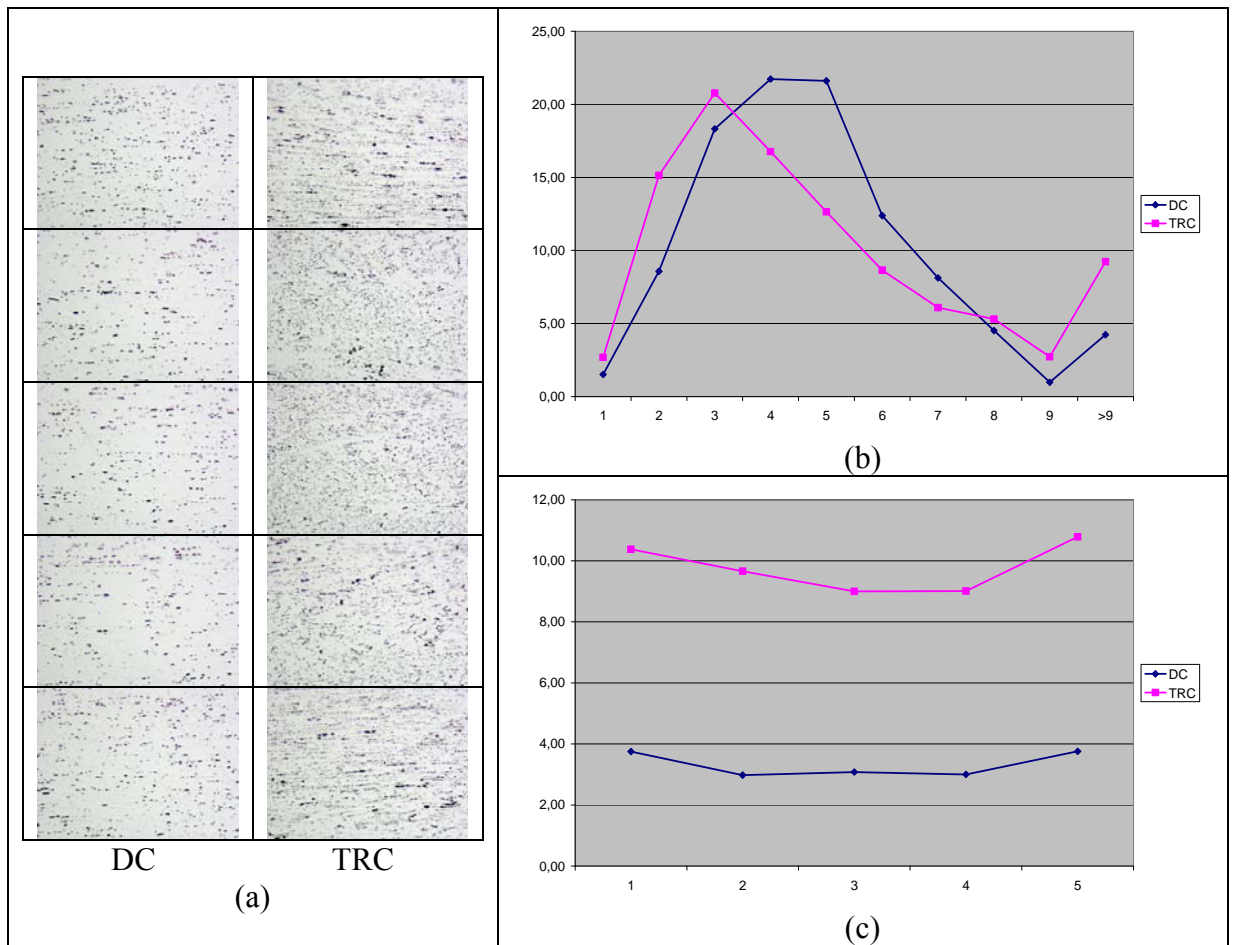


Figure 2.18. (a) Microstructure of DC and TRC aluminum alloy under BW light, (b) the size distribution and (c) volume fraction of intermetallics through

In twin roll cast strips the size of second phase particles of the surface the strips are much smaller than those in the center. Also in the center of the strip the excess alloying elements form centerline segregation. The fraction of the intermetallic particles decreases through the center although the size of the intermetallic particles increases. The fraction of the intermetallic particles are less in DC cast sheets. However the sizes of second phase particles are bigger (Figure 2-18).

#### 2.4.2. Twin Roll Casting Line

The basic components of twin roll casting line are shown in figure 2-19. Molten aluminum of a constant composition, temperature and level is degassed and filtered before being introduced into the head box of the casting machine. Before headbox in the launder

grain refiner is added in order to obtain finer grain size. The head box is connected to a planer pouring nozzle commonly known as tip which distributes the metal between the rolls of the machine; the width of the nozzle determining the width of the cast strip. The exit of the nozzle is slightly ahead of the centerline of the rolls thus the caster rolls solidify and hot roll the aluminum in one process. The metal solidifies between the rolls and the solidified metal is stretched by the pinch rolls and coiled after that.

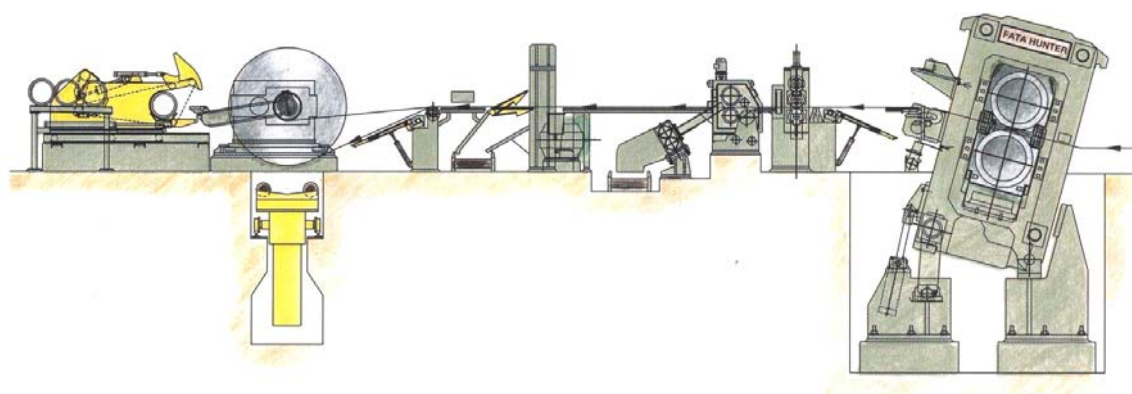


Figure 2.19. Twin roll casting line [27]

Aluminum ingots are melted in the melting furnace and in the required temperature the molten aluminum is transferred to the holding furnace. In holding furnace the alloying elements are added to prepare desired alloy. When the molten metal is ready then it is transferred by a launder system through degassing unit where the dissolved hydrogen is removed from the molten metal.

Hydrogen is the only gas which is able to dissolve to a considerable amount in aluminum and its alloys both above and below their melting temperature. Hydrogen is detrimental since it can cause blisters in heat treated aluminum finished products, especially sheet. Porosity in aluminum castings and pinholes in aluminum foil are also caused by hydrogen. Since most aluminum melting operations can not make a liquid metal free of hydrogen, procedures, the gas is removed from the liquid aluminum by fluxing. Of the gaseous fluxes used, chlorine is the most common. It is cheap and effective but can be dangerous to handle corrosive. Nitrogen, which is another gas for fluxing, will not reduce the hydrogen in liquid aluminum to as low a level as will chlorine. To obtain the combined benefits of both chlorine and nitrogen, some plants are now switching to mixture of 10% chlorine and 90% nitrogen [22].

After degassing unit the molten metal is filtered to remove all the dirt or scrap. After filtering grain refiner is added. The control of grain structure by the deliberate addition of heterogeneous nucleation sites into the melt is a well-established practice. A typical grain refining practice in aluminum foundries involves the continuous addition of a grain refiner rod into molten aluminum on its way to the casting station. The nucleating constituents in the rod are released into the melt upon dissolution of the aluminum matrix and finally act as individual nucleants during solidification. The uniform, fine, equiaxed grain structure thus obtained not only yields superior mechanical properties and surface quality but also provides alloy homogeneity and allows for good castability yielding a high casting output and reduced down stream processing costs [23].

Grain refining is very important in production of aluminum strip by twin roll casting. Addition of grain refiner makes grains smaller if it is added in required amount. The point of addition is very important since if it is added before degassing it does not work. The master alloys from the Al–Ti–B system with soluble  $\text{Al}_3\text{Ti}$  and insoluble  $\text{TiB}_2$  particles dispersed in an aluminum matrix, have been the material of choice. The latter are rather coarse and have a tendency to agglomerate both during the manufacturing process and after being released into the melt, leading to a number of quality problems. Streaking and porosity in thin foils, scratch-like linear surface defects in lithographic and brightened-anodized sheet, internal cracking in extrusion billets, crack initiation in high strength aluminum alloy plate and forgings are often blamed on coarse  $\text{TiB}_2$  clusters. These quality-related problems along with the poisoning effect of Zr in Zr-bearing alloys have prompted the manufacturers of grain refining master alloys to develop AlTiC grain refiners as a replacement for AlTiB master alloys. TiC particles in this new class of grain refiners are smaller than the  $\text{TiB}_2$  particles and are less prone to agglomeration, largely taking care of the problems linked with the  $\text{TiB}_2$  particles [23].

The potential of AlTiC grain refiners has been demonstrated for a number of aluminum alloys, but often in applications dominated by a relatively slow cooling rate as in DC casting. The Al–Ti–C system is claimed to be capable of providing reduced particle agglomeration and chemical segregation, as well as finer grain sizes also at the higher casting speeds employed in twin-roll casting. Apart from a recent report which involves strip casting at a laboratory scale, this new alloy has not been tested in twin-roll casting and

performance data in this rapid solidification process is not available. Commercially available Al–3Ti–0.15C grain refiner was employed in the twin-roll casting of AA8111 foil stock. Its grain refining performance was compared with that of the Al–5Ti–0.2B master alloy, the standard grain refiner in aluminum industry for the manufacture of aluminum foil products, unlike earlier studies which have rated Al–3Ti–0.15C with Al–5Ti–1B, an unlikely grain refiner in the manufacture of foil stock [23].

Continuous casting rolls of the current design type have a cylindrical core, usually made of steel, and a shell connected to it. The core, shell and the assembly of the twin roll casting roll can be seen in figure 20. In the cast-rolling of steel, substances having high heat conductivity, such as copper or copper alloys are usually employed as the material for the shell. In the casting of nonferrous metals, steel shells are normally used [24].

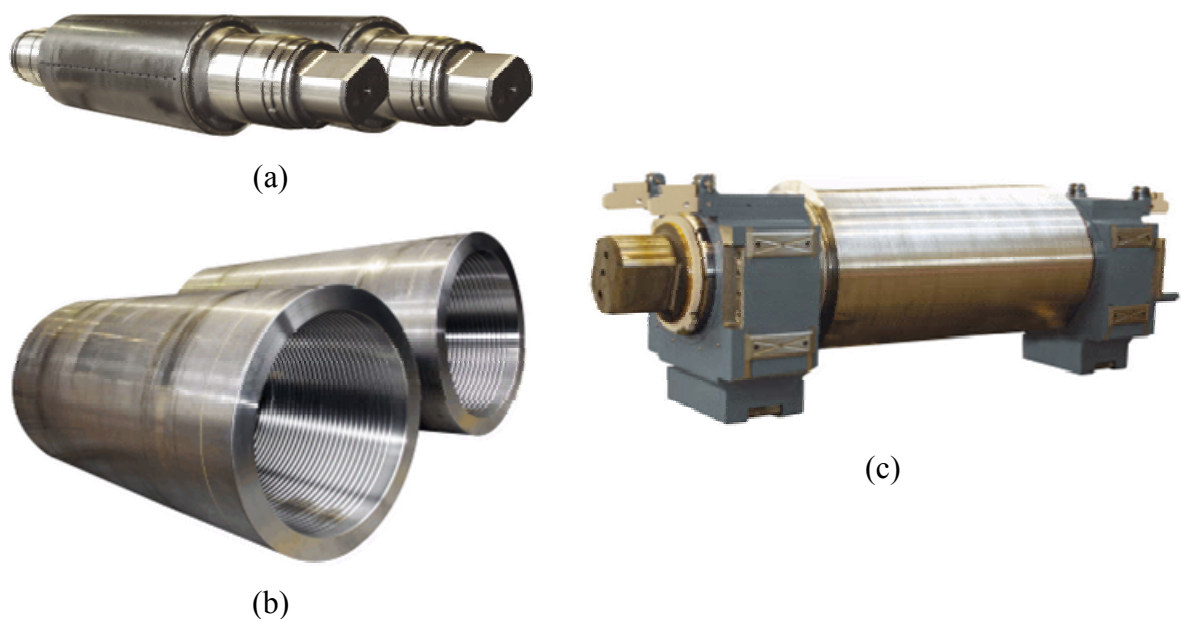


Figure 2.20. The core(a), the shell(b) and the assembly of a twin roll casting roll [24]

Two current methods of making the connection between the core and the shell of the continuous casting roll include hot isostatic pressing and a shrinking technique for the pressing connection between shell and core. In hot isostatic pressing the shell and core are joined to each other under high pressure and temperature. In the shrinking technique for the pressing connection between shell and core, which is the most widespread method, before

joining, the shell is heated and then pushed over the core. Upon cooling, the pressing connection forms by the shrinking of the shell [23].

Because of the shrinking procedure, the shell experiences tensile stresses. When used in operation during a casting procedure, a deformation or swelling of the roll may occur as a function of the rigidity of the construction and the acting forces. As a result, in the edge zones of the continuous casting roll, load stresses may arise which overlap with the acting stresses from the shrinking procedure. These stresses, under load, may lead to the formation of cracks in response to the acting fatigue stress [24].

The rolls are one of the most expensive components in twin-roll casters, thus strongly influencing the price of the as-cast strip. The potential for reducing operational cost may be achieved through a reduction in the wear of the roll surface and hence a reduction requirement for reconditioning. Production of this as-cast strip drastically increases the demands on cast quality. The surface topography of the roll is the most important factor in formation of the strip quality insofar as it influences heat transfer at metal-roll interface, the metallographic structure of the as-cast strip, its surface roughness and inhomogeneous cooling and surface crack formation on the strip surface [25].



Figure 2.21. Twin roll casting roll with copper shell [25]

The as-cast strip is a semi-product which requires some post treatment. The surface roughness of as-cast strip, determined by the topography of the roll surface in the casting process, is important in post treatment operations of the strip insofar as it influences the

cold rolling process, the stamping process, annealing operation, surface coating and painting. To be able to ensure the required quality of the as-cast strip, it is necessary to control the topography of the roll surface [25].

One of the most important drawbacks of the twin-roll method of aluminum strip casting as compared with other casting processes has been low productivity, especially when casting aluminum with high alloying element content. Due to the wide freezing range of these alloys they have to be cast with a lower casting rate. The cause of these productivity limits has been mainly in the difficulty of removing the process heat from the zone of melt/strip-roll contact. Substitution of the steel alloys used today by high-conductivity engineering materials opens up very interesting possibilities of improving the productive capacity of such casting systems [26].

The substitution of the steel alloy shells used today by high conductivity engineering materials opens up very interesting potentials of improving the production capacity of such casting systems. The use of copper shells makes it possible for the user to achieve a significant increase in casting speed and thus in productivity of the machine. It moreover offers possibilities of optimizing cast product quality and can allow the substitution of heat treatment/annealing steps in the processing of the aluminum alloy [26].

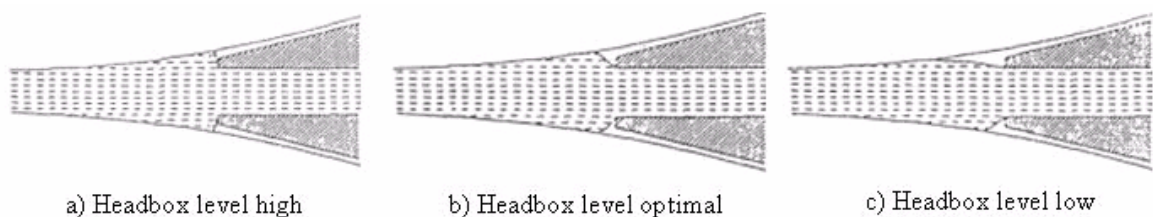


Figure 2.22. Position of the meniscus corresponding to different headbox levels [27]

The molten metal from the holding furnace comes through degasser and filter to the head box. Figure 2-22 shows the effect of head box level on the position of the meniscus. Even the casting speed is the same in each case, thus for a high head box level, the casting region is filled more, whereas with a low headbox level, substantial empty spaces between the nozzle tip and the casting roll are detected [27]. The position of the meniscus changes the contact area and the amount of heat extracted from molten metal. Thus the head box

level should remain constant. The fluctuation in headbox level influences the properties of the metal and metal surface quality.

Molten metal in the head box is distributed to the gap in between the counter rotating rolls by the help of ceramic tip. The tip material should provide dimensional stability, do not experience thermal shock and produce no out-gassing. The ceramic tip comprises a sintered blend of aluminosilicate fibers, silica powder and a boron constituent, preferably boron nitride [28]. The ceramic tip is assembled from two flat. The width of the ceramic tip determines the width of the cast strip. The casting tip provides uniform distribution of velocity and temperature across the width and eliminates difference in solidification behavior, defects on the surface of the cast strip, like segregations and bleed-outs. Romanowski et.al patented a distribution box, which is connected to the tip after headbox for uniform distribution of metal Figure21 and variable width adjustment system having movable end dams located inside the tip nozzle of a roll caster [29]. Optiflow™ system (Figure 2-23), is the unique design which facilitates the changes in width and alloy with minimal component alterations. It allows for finer control of metal distribution, velocity and temperature uniformity across the width, which ultimately means more productivity. However both of the systems seem to improve productivity, it is not possible to use such devices in industrial practices.

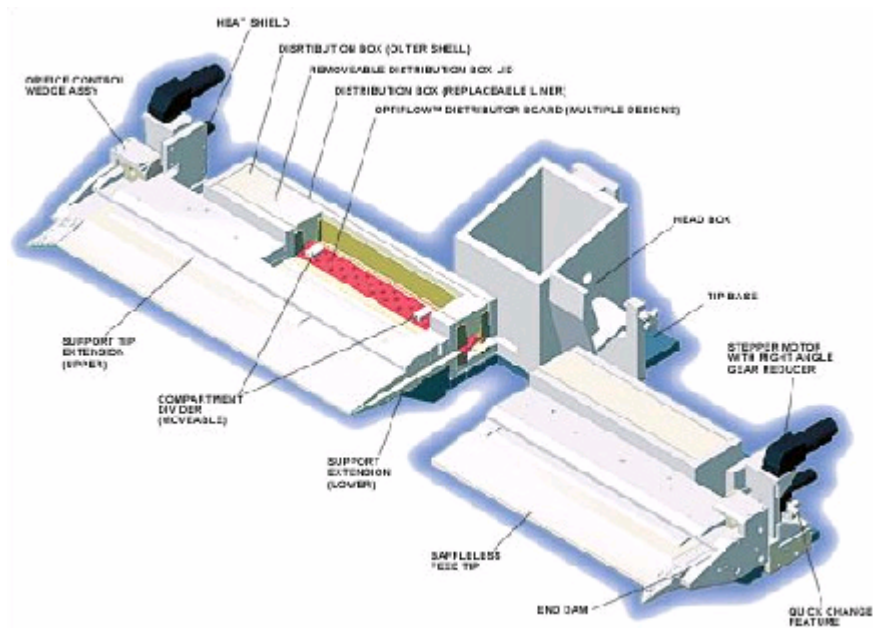


Figure 2.23. Twin roll casting tip with distribution box and Optiflow system [28]

## 2.5. Heat Treatment of Aluminum Alloys

Heat treatment is a process in which products made of metals and alloys are acted upon thermally so as to change their structure and properties in desired direction. The principal purpose for heat treating aluminum alloys is to develop the best combination of mechanical properties that will meet the critical needs required for the specific application. The benefits of heat treatment are; homogenization, stress relief, improved stability and machinability and mechanical property improvement [30].

The heat treatment of aluminum and aluminum alloys are precision process, which must be carried out in furnaces and ovens properly designed to provide very precise thermal conditions and equipped with adequate control instruments to ensure required uniformity and repeatability of temperature-time cycles. Heat-treat process details must be carefully established, controlled and documented for each type of product to ensure that required properties are achieved [30]. The general types of heat treatments applied to aluminum and its alloys are:

- Preheating or homogenizing, to reduce chemical segregation of cast structures and to improve their workability
- Solution heat treatments, to effect solid solution of alloying constituents and improve mechanical properties
- Precipitation heat treatments, to provide hardening by precipitation of constituents from solid solution.
- Annealing, to soften strain-hardened (work-hardened) and heat treated alloy structures, to relieve stresses, and to stabilize properties and dimensions [30]

Casting, plastic forming, welding and other manufacturing processes may cause some non equilibrium changes in structure of metals and alloys. These changes can be eliminated partially or fully by homogenization that brings the metals and alloys into a state close to equilibrium [30]. Wrought aluminum alloys are often given a homogenization heat treatment before extrusion or rolling. The purpose is;

- to remove particles and segregation gradients that will give films or areas with low melting temperatures, in order to avoid tearing during extrusion and rolling;

- to round off hard particles with sharp edges, which give poor ductility and holes in thin walled products;
- to form secondary particles (dispersoids) for grain size control during extrusion and rolling;
- to obtain a uniform distribution of alloying elements in solid solution before rolling, extrusion or age hardening [31].

Aluminum alloys are strengthened mostly by two ways, precipitation hardening and work hardening. Those aluminum alloys which are heat treated for formation of precipitates to increase the strength are called heat treatable aluminum alloys. When they are heat treated stable precipitate phases are formed. The precipitates help to maintain tight dimensional tolerances during and after machining, and also increase mechanical properties. The aluminum alloys which are strengthened by work hardening are called non-heat treatable aluminum alloys. These alloys are softened when they are heated. They are first strengthened, and after that they are softened to maintain desired mechanical properties [31].

Solution heat treating is the process in which the aluminum is heated to a suitable temperature, is held at that temperature long enough to allow a certain constituent to enter into solid solution, and is then cooled rapidly to hold that constituent in solution. Most solution heat treatments soften or anneal. In extrusions of 6000-alloys one is so fortunate that the alloys can be extruded at a temperature above the solution temperature for  $Mg_2Si$ , so that the extruder need only to extrude with a suitable combination of billet temperature and extrusion speed to get a proper exit temperature on the material [31].

### **2.5.1. Annealing Aluminum**

Cold rolling elongates the alloy grains and sets up internal stresses and strain (Figure 2-24). These changes create resistance to further deformation; the cold-rolled plate or sheet is said to become work-hardened. Unwanted precipitation hardening or work hardening is removed before further rolling or product finishing by annealing. Aluminum alloys may be hardened by hot or cold rolling procedures to a degree that is not desired in the finished product or that would interfere with further rolling and the achievement of a desired

temper. Plastic deformation causes certain structural changes in metal, which can be conditionally classed into three groups as follows: change in the shape and size of crystallites; change in space orientation of crystals; and change in the internal structure of the crystallites. Before, after or between cold rolling operations, the sheet may be fully or partially annealed for various reasons by heating and slow cooling, to soften it and counteract the tempering that has already taken place. Also full or partial annealing maybe used to prepare the sheet for later mechanical forming in product fabrication [32].

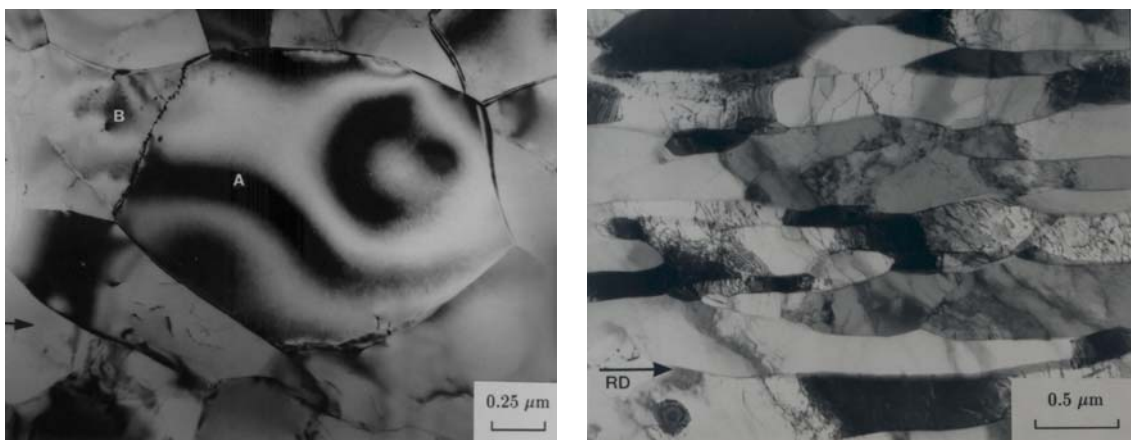


Figure 2.24. Microstructure of aluminum cell before and after rolling [34]

Stored energy of plastic deformation can be released by heating the metal to elevated temperature. The metal softens due to release of stored internal energy.

Recovery is the earliest onset of re-arrangement of crystal defects within the cold worked microstructure at elevated temperature, where some restoration of the original structure and properties may occur through annihilation of point defects and dislocations and, spatial re-arrangement of dislocations. The stored energy of the deformed material is consequently lowered. Recovery is so called as it describes the processes that lead to the recovery of mechanical properties on heating (annealing) a deformed metal. The driving force for recovery is the reduction of total dislocation energy either by re-arrangement into lower energy configuration or annihilation. Recovery typically starts around  $0.3 T_m$  (where  $T_m$  is the melting temperature in Kelvin) depending on the solute content.

Recovery is a multistage process that includes all the elementary processes which take place prior to recrystallization. Recovery should be understood as the process of

structural perfection of a work-hardened metal by redistribution and annihilation of point defects and besides, by redistribution and partial annihilation of dislocations either without the formation of new boundaries (point defect annihilation proper) or with the formation and migration of low-angle boundaries only (polygonization) [32].

In point-defect annihilation process, point defects are redistributed and their concentration is diminished due to their annihilation and dislocations are re distributed by conservative movement without forming new boundaries. Some elementary processes of point defect annihilation require very low activation energy and can occur at quite low temperatures, hundredths of the melting temperature ( $T_m$ ). For instance Molenaar and Aarts studied the recovery in wire specimens of copper, silver and aluminum deformed at 90K. Annealing at 293K diminished the deformation induced gain in resistivity roughly by 30%, but had practically no effect on yield strength. Consequently the whole loss in resistivity was due mainly to a reduction in point defect concentration. Studies of recovery should be done on specimens deformed at lowest possible temperature and then heated gradually. Otherwise, there is a risk to miss the part of the stage of deformation or after it but before measurements [32].

Recrystallization, by contrast to recovery, which occurs uniformly throughout the microstructure recrystallization involves the nucleation and growth of strain free grains in certain areas of the material, which grow to consume the deformed or recovered microstructure.

When primary recrystallization is complete the structure is not yet stable and further growth of recrystallized grains may occur. On further annealing the recrystallized microstructure, smaller grains are eliminated, the large grains grow and the grain boundaries assume a lower energy configuration.

Grain growth is much slower than primary recrystallization and is influenced by

- Microstructural features such as
  - Distribution of grain sizes following primary recrystallization
  - Solute atoms
  - Presence of intermetallic particles

- Crystallographic texture
- Process parameters such as temperature
- Specimen size (grains can only grow up to the specimen surface)

### 2.5.2. Recrystallization

Recrystallization involves a wide spectrum of structural changes which occur in heating of a metal or alloy and result in the replacement of grains of the same phase having a lower energy. Some authors erroneously regard recrystallization only as the process that changes the microstructure of plastically deformed materials during heating. Actually recrystallization is a much more common process and generally occurs when a metal or alloy is heated to a temperature at which migration of high angle boundaries is possible. The process of recrystallization almost always goes with polymorphous transformations and often with some other phase transformations that take place under heat [33].

Plastic deformation of a metal (rolling, extrusion etc) may be necessary to achieve the required shape and properties. The greater part of the work (up to 95%) done in deforming a metal is converted into heat, while the remainder of the energy is accumulated in the metal in the form of increased potential energy of the atoms which have been displaced from their equilibrium. Sheet metal is hot/cold rolled to desired thickness. It is also useful in changing the microstructure obtained after solidification to obtain better properties. During deformation at low temperatures i.e. during cold work (typically less than 150 °C, for Al alloys), work expended on the crystal lattice distorts the lattice by introduction of defects and consequently microstructural changes occur. These include elongated grains, with accompanying increase in grain surface per unit volume, increase in dislocation density, increase in entanglement of dislocations, re-orientation of grains relative to the direction of applied stress (Figure 2-25)[34].

For alloys which do not strain harden, the stored energy per unit volume due to plastic strain  $\epsilon$  for deformation at a stress  $\sigma$  is  $\epsilon'\sigma' 0.05$  because only about 5% of the work done in deformation is actually stored in the metal. The rest is dissipated as heat [34].

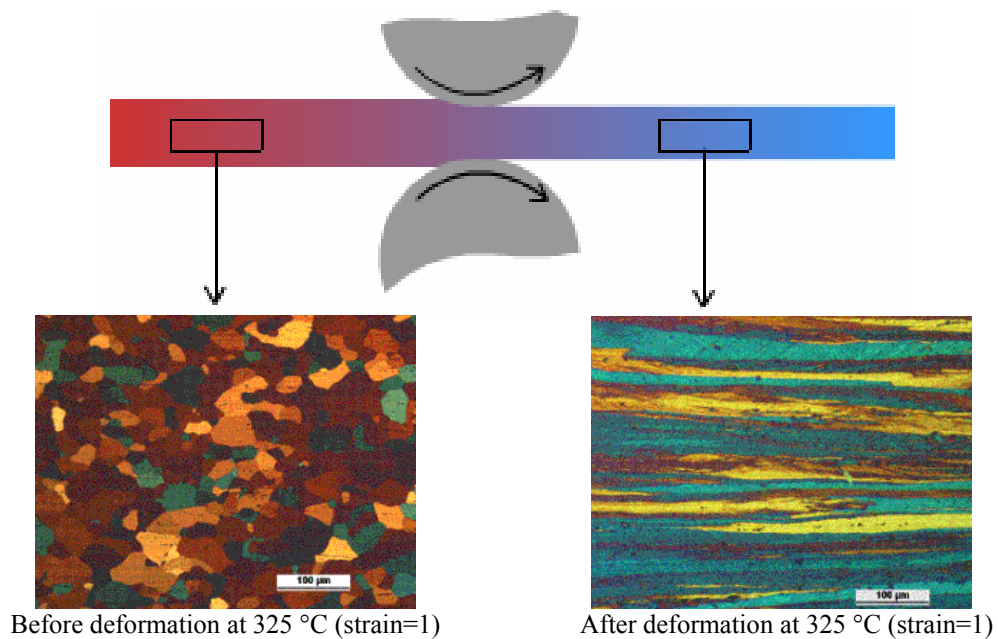


Figure 2.25. Microstructure of aluminum alloy before and after hot rolling [34]

The structure of a deformed (strain hardened) material change on recrystallization within very wide limits: from a partially recrystallized structure that retains to a certain extent to the original deformed structure to a fully recrystallized structure. Recrystallization is not, however, finished on disappearance of the deformed structure. Prolonged heating or especially heating at a higher temperature may lead to further structural changes associated with the growth of some grains at the expense of others. At the final stage of this process which only very rarely be attained in practice, the whole polycrystalline aggregate transforms into a single crystal [33].

Recrystallization diminishes or eliminates fully the additional structural imperfections which have been caused by prior deformation. It is then clear that the nature, density and distribution of these imperfections, i.e. the dislocation structure of the deformed material, should have the decisive effect on the course of recrystallization. The principal mechanism of plastic deformation in metals, and in all crystals in general, is the shear movement of some portions; it is affected through various dislocation movements, including movements along grain boundaries. Under deformation at high temperatures, diffusion movement of dislocations also becomes possible; it contributes somewhat to the shear movement and changes its final result [33].

Finally, at low deformation rates and very high temperatures (above  $0.5 T_m$ ) these types of plastic deformation may be accompanied by a purely diffusion movement of some crystallites relative to others. The dislocation and diffusion mechanisms determine the development of intragranular and intergranular deformation [33].

The types and mechanisms of distribution of crystal structure defects produced by deformation are quite diverse. These defects are eliminated on heating by the way of various elementary processes which occur in different rates, in various temperature intervals, and with different activation energy. If a number of elementary processes are superimposed on one another,  $Q$  usually increases and becomes the effective, rather than the actual activation energy of the process. The elementary processes which can occur on heating of a deformed metal and decrease the activation energy are as follows (in the order of the development of each during heating):

1. Diffusion of point defects and their disappearance in dislocation and boundaries, accompanied by partial annihilation of vacancies with interstitial atoms and by the formation of complexes and groups of point defects;
2. Redistribution of dislocations by simple and cross slip, accompanied by partial dissociation of unlike dislocations and by narrowing of dislocation loops.
3. Redistribution of dislocations by climb, which, in combination with dislocation slip, results in flattening or, sometimes, on the contrary, unraveling of dislocation arrays and their crystallographic reorientations.
4. Formation of low-angle boundaries associated with the processes indicated under (2) and (3)
5. Migration of low-angle boundaries and large-angle boundaries into the deformed matrix accompanied by annihilation (sweeping-out) of defects.
6. Migration of grain boundaries between recrystallized grains and coarsening of these grains.

The above mentioned elementary processes can occur either successively or superpose on one another, depending on the amount and nature of deformation, the rate and the time of heating, the nature and purity of the material and some other factors. As a

result, the effects of cold work on the structure and properties of a metal (alloy) can be eliminated in different ways and to a different extent [33].

There are several, largely empirical laws of recrystallization:

- Thermally activated: The rate of the microscopic mechanisms controlling the nucleation and growth of recrystallised grains depend on the annealing temperature. Arrhenius type equations indicate an exponential relationship.
- Critical temperature: Following from the previous rule it is found that recrystallization requires a minimum temperature for the necessary atomic mechanisms to occur. This recrystallization temperature decreases with annealing time.
- Critical deformation: The prior deformation applied to the material must be adequate to provide nuclei and sufficient stored energy to drive their growth. Deformation affects the critical temperature. Increasing the magnitude of prior deformation, or reducing the deformation temperature, will increase the stored energy and the number of potential nuclei. As a result the recrystallization temperature will decrease with increasing deformation. Effect of cold work on recrystallization and recrystallization temperature is shown in Figure 2-26.

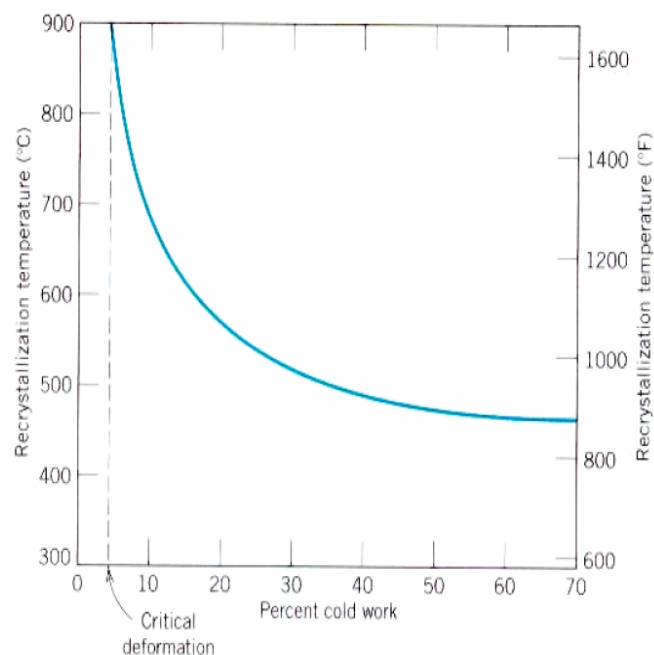


Figure 2.26. Relation between deformation and recrystallization temperature [33]

- Initial grain size affects the critical temperature: Grain boundaries are good sites for nuclei to form. Since an increase in grain size results in fewer boundaries this results in a decrease in the nucleation rate and hence an increase in the recrystallization temperature
- Deformation affects the final grain size: Increasing the deformation, or reducing the deformation temperature, increases the rate of nucleation faster than it increases the rate of growth. As a result the final grain size is reduced by increased deformation.

### **2.5.3. Controlling Recrystallization**

Controlling recrystallization is very important to achieve desired properties of the sheet. Alloying elements and different heat treatment procedures are used to control recrystallization behavior of aluminum sheet. Both heat treating and alloying aims to form intermetallic particles to inhibit recrystallization. All commercial Al alloys contain at least 2 phases. The second phase may be in the form of dispersed particles which are present during deformation or which precipitate during subsequent annealing and, may affect recrystallization as follows:

1. Particles may increase the stored energy by creating an extra particle-matrix interface, and/or by trapping dislocations and/or by increasing coherency strain;
2. Large particles may act as nucleation sites for recrystallization (Particle Stimulated Nucleation - PSN);
3. Particles may exert a significant pinning effect on grain boundaries.

Points 1 and 2 above promote recrystallization where as point 3 retards recrystallization. The overall effect depends on which of these factors dominates [34].

The rate of recrystallization is dependent on both the size and spacing of the particles. This may be related to the effects of the particles on the development of the deformation microstructure.

A dispersion of particles may retard the motion of a grain boundary by a process called Zener Drag. Large ( $> 0.1 \mu\text{m}$ ) incoherent precipitates have large particle-interface

energy. If present at a grain boundary, they will lower their interface energy and the boundary energy. To move the boundary past a particle a force has to be exerted which is related to the size of the particle and the energy of the boundary. For a random distribution of particles, the pinning force ( $p_z$ ) exerted on the boundary is given by:

$$p_x = \frac{3\gamma F_v}{2r} \quad (2.1)$$

where  $\gamma$  is the grain boundary energy,  $F_v$  is the particle volume fraction and  $r$  is the particle radius [34].

The two theories are relevant with our problem. The size of the second phase particles should be big enough to form enough nucleation sites and as small as to stop grain boundary motion. In twin roll cast strips the intermetallic particle size and distribution is heterogeneous. Microstructure and intermetallic particle size and distribution of DC cast and hot rolled sheets are homogeneous through thickness. Scalping of heterogeneous outer layer, homogenization, hot rolling stages make the difference between twin roll cast and DC cast sheets. However the fraction of intermetallic particles is lower in DC cast strip, the size of them are appropriate to achieve the desired effect (Figure 2-27).

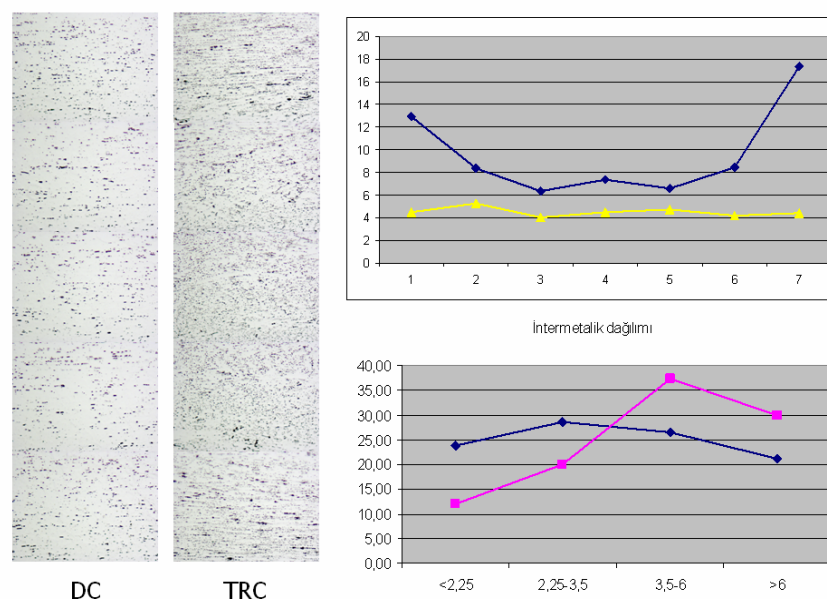


Figure 2.27. Fraction and size distribution of intermetallic particles through thickness

Surface changes created during the plastic co-deformation of coating and substrate metal often entails also a change in color type and color intensity of the polymer and oxide coatings. Such changes are due to the displacements of the pigments and colorants in the polymer. The change in surface roughness also affects optical scattering and, therefore, the reflection of light. More severe surface defects are the formation of orange peel or ridging. These effects exceed in relevance the above mentioned small scale roughening issues since they affect not only the decorative appearance of materials but also their forming limits as well as the frictional conditions during forming. Altogether these various effects are of importance for understanding and optimizing the visual appearance and the micromechanics of surfaces of formed semi-finished parts to eliminate the abnormal grain growth on the surface, control recrystallization kinetics of the aluminum strips is vital. Recrystallization temperature of the material should be increased, to retard or inhibit grain growth. There are few ways to eliminate the problem [34].

When sheets are heated solute atoms diffuse out of grains and precipitate second phase particles on the grain boundaries. Higher heating rate during annealing lead to precipitation of intermetallic particles, before the start of recrystallization. The energy is used for precipitation that less energy is used for recrystallization and grain growth. Also these precipitates pins the grain boundaries and dislocations that grain growth [34].

As the sub-grain grows in a region containing an orientation gradient, it increases its mis-orientation with neighboring sub-grains. When this mis-orientation has reached that of a high angle grain boundary (eg: 10-15°) a potential recrystallization nucleus is formed. The size to which a sub-grain grows is inversely proportional to the orientation gradient where as the time for nucleus formation is inversely proportional to the square of the orientation gradient. The grain boundary stops moving when the deformation zone is consumed.

In Al alloys, the formation of deformation zones occurs at particles larger than  $\sim 2\mu\text{m}$ . These zones can act as nucleation sites for recrystallization because they have a high dislocation density and fine sub-grains (Fig 2-28). This mechanism of creation of recrystallization nuclei is termed particle stimulated nucleation (PSN) of recrystallization [34].

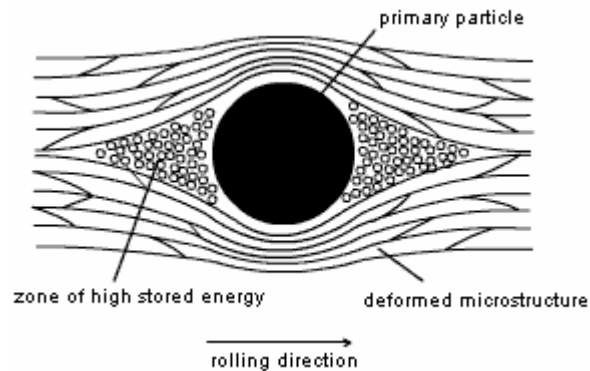


Figure 2.28. Schematic presentation of deformation zone [34]

PSN need not start at the location of highest mis-orientation, which is at the interface. It can occur anywhere in the deformation zone. During deformation, the dislocation density at the particle-matrix interface increases with strain. Therefore, there will be a critical particle diameter (which is a function of strain) below which PSN will not occur.

Homogenization, remove particles and segregation gradients, round off hard particles with sharp edges, form secondary particles, obtain a uniform distribution of alloying elements. Lots of work is done on homogenization and recrystallization. Fig.2-29 shows the recrystallized grain structures for both non-homogenized and homogenized TRC AA3105 after 90% cold roll and annealing. In Fig.2-29(a), for non-homogenized material, most grains are very coarse and elongated in the rolling direction. Although this material contains many large constituent particles, there are apparently few effective nucleation sites. Constituent tends to form a continuous network along grain boundaries during casting. The subsequent cold rolling process does not completely break up the as-cast second phase network into widely spaced discrete particles as in the case of homogenized material, forming instead colonies of particle clusters, greatly reducing the potential to be nucleation sites. Moreover, concurrent precipitation of dispersoid from the supersaturated matrix further hinders nuclei forming near large particles, which makes it even more difficult for a large constituent particle to act as a PSN site in the non-homogenized material [35].

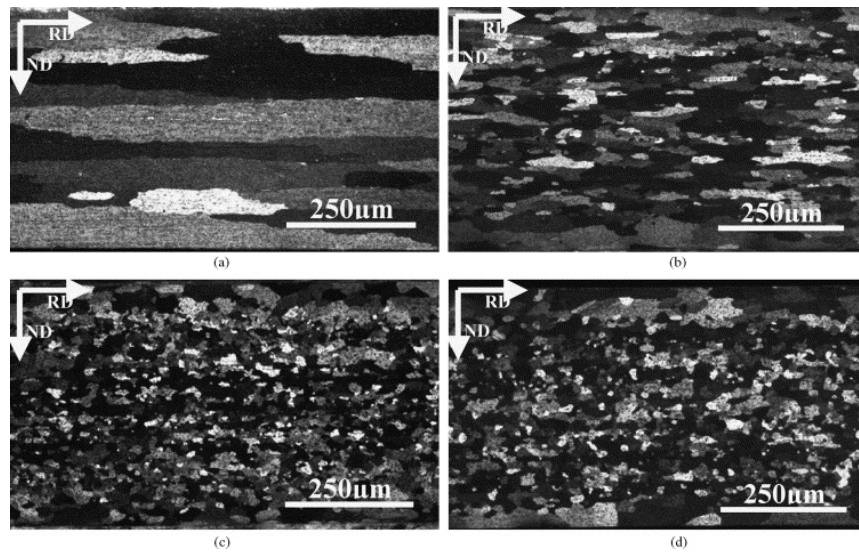


Figure 2.29. Micrographs of cold rolled and recrystallized TRC AA3105: (a) Non-homogenized, and homogenized 5h at (b) 500°C, (c) 550°C, (d) 600°C [35]

Cold rolling tends to align grain boundaries longitudinally, compressed closer together in the normal direction forming a denser barrier to growth of recrystallizing grains than in the rolling direction. As a result, the boundaries of newly recrystallized grains and/or nuclei encounter less inhibition when growing in the rolling direction than in the normal direction, resulting in elongated recrystallized grains. In addition to the resulting very coarse and elongated grain structure, the recrystallization kinetics for non-homogenized material is much slower compared to homogenized material [35].

Fig.2-29(b–d) are optical micrographs of the recrystallized grain structures resulting from the different homogenization treatments prior to cold rolling and annealing. Compared with non-homogenized material, recrystallized grain structures are much finer and more equiaxed after homogenization. Higher homogenization temperature results in a finer recrystallized grain structure, comparing Fig.2-29 (b and c). Note that these homogenized materials contain a grain size gradient, with a larger grain size at the strip surface and finer grains in the center. The structure in Fig.2-29 (d) has a mean linear grain intercept of approximately 70  $\mu\text{m}$  at the surface and 20  $\mu\text{m}$  at the center along the rolling direction [35].

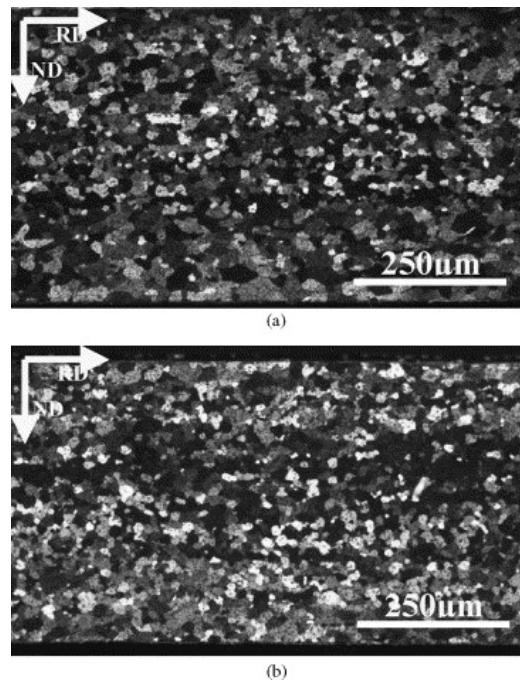


Figure 2.30. Micrographs of cold rolled and recrystallized material after (a) 600°C 120h and (b) 620/450 °C 5h 10 cycles homogenization [35]

It is well established that finely dispersed small particles inhibit recrystallization by pinning moving boundaries while large particles promote recrystallization by acting as nucleation sites. According to Humphreys et al., PSN is usually found to occur only at particles of diameter greater than approximately 1  $\mu\text{m}$ . These factors all contribute the fine and uniform recrystallized grain structure in this material [35].

Alloying additions, Mg, Mn Cr, Ti, Zn are typical additions of aluminum alloys. But they can just be used in a range of limits. Other wise their mechanical, corrosion or other properties. Other than that typical additions rare earth elements like Sc, Zr, Hf are more effective in grain refinement and recrystallization control. In Figure 2-3, addition of different amounts of Sc and Zr to Al-Mg alloy can be seen. Both of the elements are useful for grain refining. But using less amounts of both elements is more effective [36].

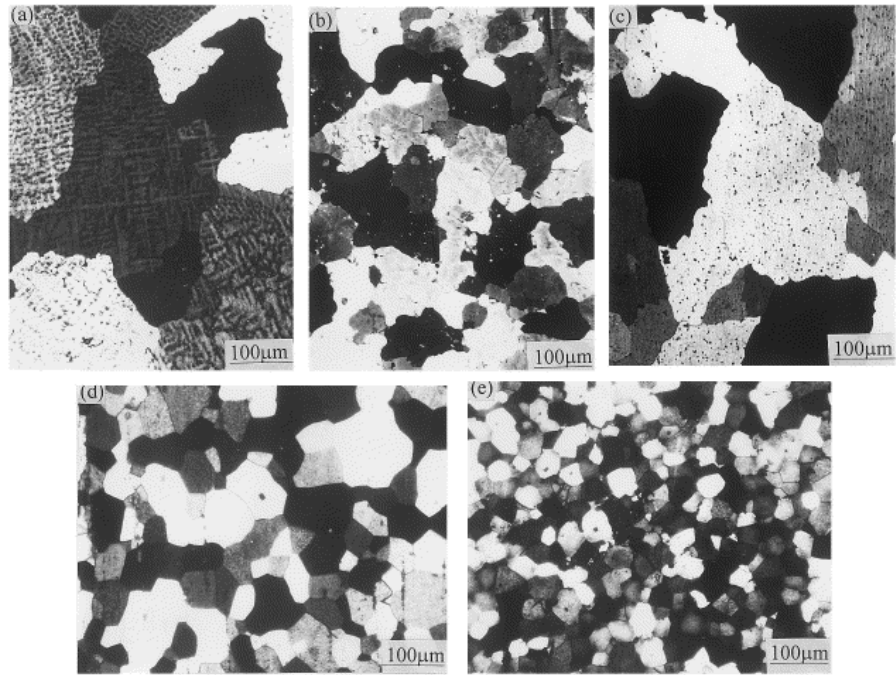


Figure 2.31. Microstructure of (a)Al-5Mg; (b)0,1Zr; (c)0,2Sc; (d)0,6Sc; (e)0,2Sc-0,1Zr  
[36]

### 3. EXPERIMENTAL WORK

#### 3.1. Prototype twin-roll caster

The scope of the present work is to investigate the recrystallization behavior of the twin-roll cast aluminum strip produced in the Material Science laboratory. In order to produce twin-roll cast aluminum strip the existing hot rolling machine (Figure 3-1) in the Material Science laboratory is modified to build a prototype twin-roll caster. The chassis, motor, transmission system, locking system of the hot rolling machine remained unchanged, new rolls are designed, bearings are changed, and new housings suitable for bearings are produced by the help of ASSAN Aluminum.

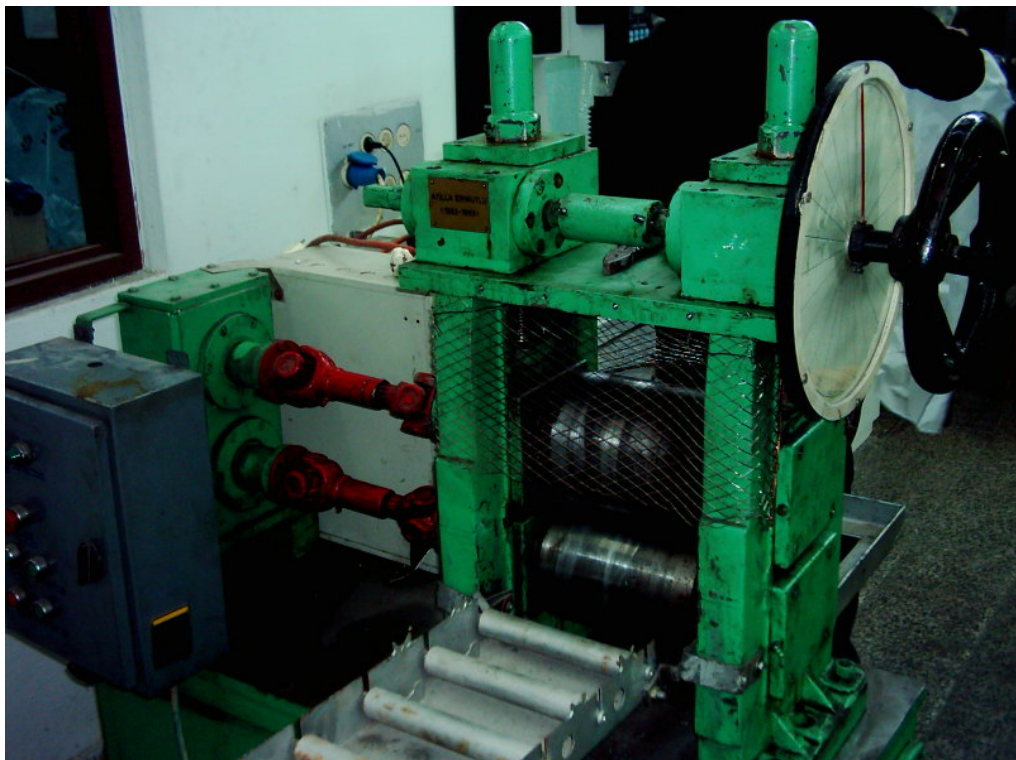


Figure 3.1. Hot rolling machine in the Material Science laboratory

The chassis consists of two main parts lower and the upper frame. The lower frame is one of the main parts of the mill, in which the reduction unit is fixed. It is a reduction unit with a 4kW motor having 1420 rpm output. This output is reduced to 30 rpm by its 1/46 gear box. Via using a chain-wheel system the 30rpm is further reduced to 20 rpm. On top

of the lower frame stand housings, a 1/1 gear box is mounted. The reduced 20 rpm output is distributed to the rolls through the drive shafts by means of this gear box. The stand housings are screwed to the frame and the rolls are mounted into the housing caps by means of double-row ball bearings. The lower caps are fixed to the housing and the upper ones are free to move up and down in a 20mm course to allow the rolling material to pass through the gap.

The roll gap adjusting mechanism is actuated by a handle and its worm. The worm drives the worm gears, in which the power screws are actuated to provide the up and down motion of the upper roll. The maximum roll gap is about 20mm. There is also an electrical cabinet, adapted to the system to control the forward and backward motion of the mill.

A chain-wheel system is used to transmit the motor output in a reduced form to the 1/1 gear box. The system consists of a double strand sprocket with  $D_{t1}=104,2\text{mm}$  and a double strand wheel with  $D_{t2}=106,6\text{mm}$ , having number of teeth 19 and 30 respectively. The pitch  $t$ , which is the linear distance between the roller centers of the chain, is 15.88mm. The gears are changed with the ones, having number of teeth 15 and 45 respectively in order to reduce the casting speed for complete solidification.

There are two drive shafts for transmitting the power from gearbox shaft, to the rolls. These are telescopic shafts with normal extension. The flange diameter is 90mm and the minimum length is 320mm.

In the machine there exists a top roll adjusting mechanism, with power screws actuating by hand. There are two worm gears connected to each other by means of a flange and set screws. They are driven by a handle which is mounted on the worm shaft. During the adjustment, the set screwed connection allows the stands to move separately, if required. The worms drive the worm gears and since there are power screws in the center to move up or down. This motion is responsible for roll gap adjustment, since the power screws are fixed by nuts to the upper housing caps and the moving up or down cause the roll gap to open or close.

New rolls were manufactured consisting two parts the core and the shell as the original twin-roll caster rolls. The shell was manufactured from AISI 1040 carbon steel billet by turning on a Universal lathe. The shell is a 250mm long hollow cylinder with an inner diameter of 160mm and an outer diameter of 200mm. the hardness of the shell was 40 HRC. The core of the roll is also manufactured from AISI 1040 carbon steel billet by turning on a Universal lathe. It is necessary to remove the heat from the surface of the rolls. Water enters the roll through the hole in the center, circulates in the spiral groove on the core then leaves the role from the same hole where a rotary joint (Figure 3-2) arranges the water inlet and outlet. In industrial twin roll casters the grooves are on the shell to eliminate the possibility of weakening the core. Because the core is up against high separating forces and any notch on the core may cause cracks owing to fatigue. But in the prototype twin roll caster the grooves are on the cores because the shell is too thin to open grooves in it.

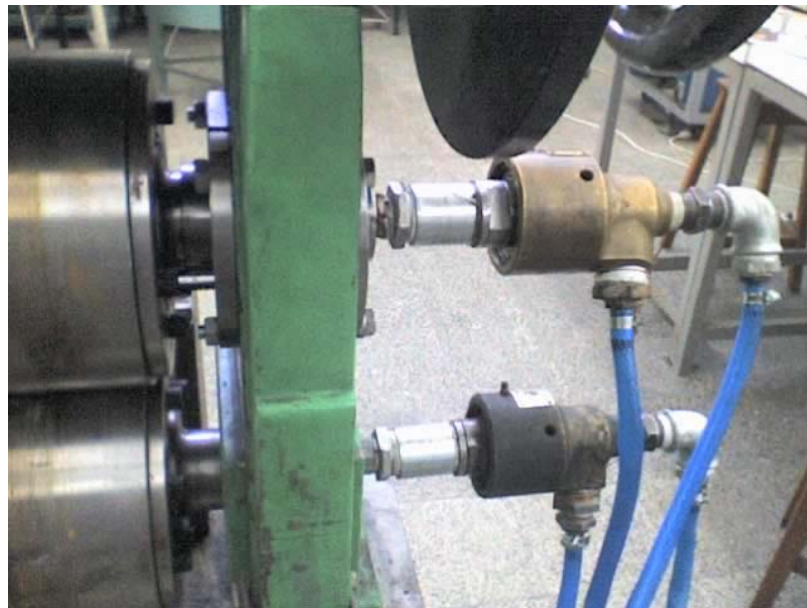


Figure 3.2. The rotary joints

A Rotary Union or rotating joint is a machine element, making it possible to feed a medium from a stationary line into a rotating machine section or drum and/or return it. They are usually made of brass, bronze, plastic, steel, or stainless steel and include one or more ports which range in size from 1/8 in. to 6 in. Straight ports direct media flow straight through the union. Elbow ports cause the media to exit at an angle from the inlet direction. Seals are made from a variety of materials and feature o-ring and bellows-type designs.

Rotating unions connect via flanges or threads and may use dual radial ball bearings to prevent side loading to seals.

Specifications for rotating unions include pressure range, speed range, operating temperature, number of ports, seal type, dimensions, and special features. Pressure is usually measured in pounds per square inch (psi). Speed is usually measured in revolutions per minute (rpm). Operating temperature is a full-required range. Seals are made from nitrile, fluoropolymer elastomers, ethylene propylene (EPDM), polyurethane, or silicone. Length and diameter are important physical dimensions to consider when selecting rotating unions. In terms of features, some devices include an integral slip ring for electrical power or data transfer. Others include a thru-bore for mounting and wiring. Rotating unions with a slowing motion are used to regulate media speed. Devices with dry running protection can operate without lubrication.

Rotating unions are used in the production of textiles, clutches and brakes, automobiles, chemicals, paper, rubber and plastics, and food and pharmaceuticals. They move media such as compressed or vacuum air, hydraulic fluid, steam, pressurized water, chemicals, gases, and slurries or solid materials. Rotating unions are also used to move petroleum products, gasoline, diesel, natural gas, and aviation fuel. Devices that move hot oil, steam, pressurized water, and heated air are often made of stainless steel to provide increased corrosion resistance. Fluorocarbon o-rings and bearing seals allow rotating unions to operate at higher temperatures and pressures. In applications where equipment misalignment is common, bellows-type seals provide added flexibility.

In the conventional rolling process, the roll separating forces are approximately calculated using the formula

$$F = \left( \frac{\bar{p}}{\bar{\sigma}_{av}} \right) \bar{\sigma}_{av} A_x \quad (3.1)$$

Basically, separating force is equal to the product of the contact area between the rolled material and the roll pass,  $A_x$  the mean unit pressure,  $\bar{p}$  on the roll and the average flow

stress,  $\bar{\sigma}_{av}$  within the roll gap. However, for TRC, there is not an established formula for the calculation of the roll separating forces in the literature. The separating forces are directly dependent on the solidification mechanism in the casting region, i.e. the position of the solidification front, the temperature and the type of the alloy being cast, casting speed, etc. From the cast-shop experiences of Assan Alüminyum A.Ş., it was seen that for a specific alloy at a specific temperature, the separating forces change only with the casting gauge and casting width. The roll diameter has no significant effect on the separating forces. In this manner, separating forces for the prototype caster's 250 mm long rolls were calculated from simple direct proportioning. It was known that, a twin-roll caster with 2000 mm wide rolls generated about 1200 tons of separating forces at a casting gauge of 5 mm. Thus, the prototype model had to withstand approximately 150 tons.

Single housing would thus be carrying 75 tons of force. The bearings for this amount of force were selected from SKF. Spherical roller bearings were selected to resist any possible horizontal forces. Bearing housings are designed and manufactured through the changes in the bearing dimensions.

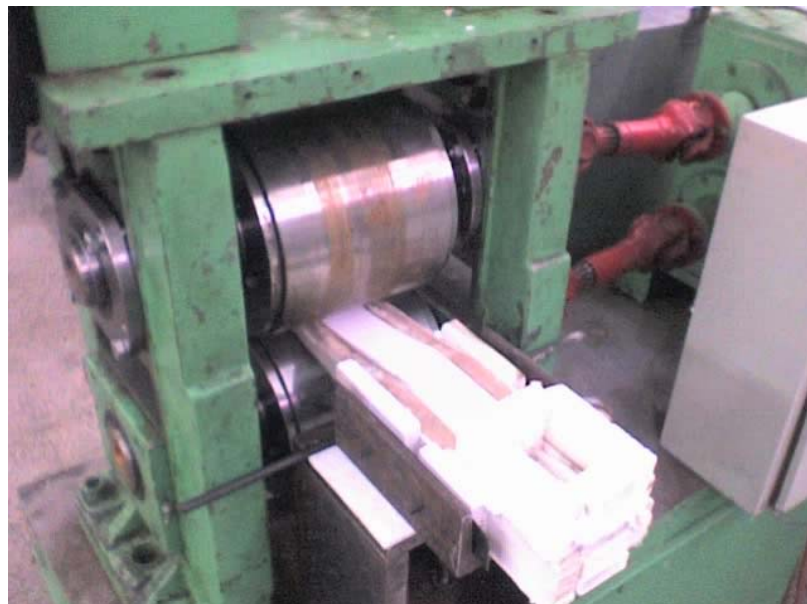


Figure 3.3. The ceramic tip

A ceramic tip is designed and manufactured to deliver the molten metal through the gap between the rolls (Figure 3-3). The tip is 50mm wide and made of the commercial tip

material which consists of  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . Annealing furnace in the Materials laboratory is used for preparation of molten aluminum. While casting trials were performed molten metal is poured manually to the hole on the tip from the graphite crucible.

The casting speed was 20 rpm  $\sim$  12.5 m/s in first casting trials. Molten aluminum could not completely solidify in this casting speed. To reduce the casting speed the gears and chain between the motor and the gearbox. The gear ratio is changed from 19/30 to 15/45 so the casting speed is reduced to 10 rpm  $\sim$  6.2 m/s to the half of the first casting speed.

### 3.2. Casting Trials

Sheets are cast utilizing laboratory scale twin roll caster in a thickness of 1.5-2mm in the width of 50mm. Lubrication and grain refiner is not used in the trials. The aluminum scraps are melted in the annealing furnace in Materials laboratory in a graphite crucible and poured to the hole on the tip by hand. 7 trials over 15 were successful. The main reasons of the unsuccessful trials were solidification of molten metal in the tip and mis-solidification of metal in casting operation. First casting trials are conducted to ensure the optimum casting parameters such as casting thickness, casting temperature, and casting speed.

The prototype casting machine runs at a constant speed. In first casting trials the casting speed was 20 rpm /  $\sim$ 12.5 m/min. This casting speed was not suitable to obtain fully solidified aluminum strip. Casting temperature should be over 690 °C, because under this temperature molten metal solidifies in the tip. Preheating the tip was not possible in the laboratory, so the casting temperature was set above 690 °C. Also the distance in the outlet of the tip was very important to obtain metal flow through the tip to the roll gap without solidifying in the tip. Some casting trials were not successful because of solidification of molten metal in the tip. The distance between the lips of the tip is set between 1.5-2mm.

In the constant casting speed the casting thickness is reduced to obtain fully solidified sheet. But it is noticed that when the casting thickness is below 1mm, the molten metal overspreads on the roll. And if the casting thickness is over 2 mm, the sheet does not

solidify completely. For casting sheet in constant width, and complete solidification the casting thickness should be between 1.5-2.0mm.

In 690°C the casting speed was too fast to obtain fully solidified sheet. The chain-wheel system with 19/30 gear ratio, is changed with the one with 15/45 gear ratio. And the casting speed is set to 10 rpm /~ 6.2 m/min. This casting speed let us cast completely solidified aluminum strip.

Alloying elements are added 10% of the aluminum weight in order to investigate the effects on the microstructure and annealing behavior. The composition of the alloyed strips can be seen in Table 3-1.

Table 3.1. Alloy content of the samples produced in Materials laboratory

Casting No	Si	Fe	Mn	Mg	Other	Al	Alloying Element
1	0,267	0,328	0,054	0,044	0,067	99,24	-
2	0,317	0,383	0,056	0,044	0,080	99,12	-
3	0,262	0,424	0,201	1,207	0,096	97,81	Mg
4	0,253	0,387	0,565	0,230	0,115	98,45	Mn+Mg
5	0,292	0,490	1,305	0,061	0,102	97,75	Mn
6	0,253	0,409	0,200	0,130	0,208	98,80	Sr
7	0,313	0,550	0,316	0,375	0,136	98,31	Fe+Mn+Mg

Cast strip samples were taken after running the prototype twin roll caster in casting temperature of 690 °C and in casting speed of 12.5 and 6.2 m/min. Small pieces were sectioned from the cast strips for characterization studies in the as-cast state and for annealing treatments. The sheet samples from casting trials are cold rolled to 0.5-0.8mm by the prototype twin roll caster. Homogenization anneals were not performed to the sheet samples. Cold rolled aluminum sheets are annealed in the annealing furnace in Materials laboratory at 350 °C and 380 °C to obtain recrystallized microstructure. As-cast and heat treated strips were sectioned to obtain longitudinal cross-sections for metallographic studies. Heat-treated samples were prepared with conventional metallographic techniques

and were finished with colloidal silica. They were examined after etching with 0.5% HF solution with an optical microscope. Grain structure of strip samples was investigated after anodic oxidation with Barker's solution, using cross-polarizers.

## 4. RESULTS AND DISCUSSIONS

### 4.1. Casting Trials

Casting trials via prototype twin roll caster were conducted in two casting speeds in 12.5m/min and in 6.2m/min. Industrial twin roll casters work the casting speed changes according to the casting thickness and twin roll caster roll material. Casting speed increases with the decreasing thickness. When the thickness is reduced, the heat to be extracted from the molten metal reduces and casting speed can be increased according to the cooling capacity of the rolls.

Early twin-roll casters for fabricating aluminum alloy strips of 5–7 mm in thickness operated at speeds of below 1 m/min. Speeds of up to 10 m/min have been realized by employing large-diameter rolls, and recently speeds of up to 15 m/min have been obtained for 1mm strips. The speed of twin-roll caster can be increased by raising the cooling rate, which is why thinner strips can be cast faster. The authors have already proposed a new roll-casting system called melt-drag twin-roll caster (MDTRC), employing copper rolls without lubricant, and have demonstrated casting speeds of up to 60 m/min for A5182. The microstructure of the strip cast by MDTRC is also finer than that produced by conventional twin-roll casters. However, the casting speed of MDTRC appears limited to 60 m/min for this alloy because of the appearance of surface defects at higher speeds [37].

Upper limitation of the roll speed is decided by the continuity of the strip. When the roll speed is too high, the strength of the strip is not enough, and the strip is broken. The continuity of the strip depends on the temperature of the strip. The temperature of the strip becomes higher as the roll speed becomes faster. Contact time between the strip and the roll becomes shorter as the roll speed becomes faster. The strip cannot be cooled enough to get strength for the continuity. The cooling ability of the roll, contact time between the strip and the roll, the strip thickness, and melt temperature affect the cooling of the strip. Use of the roll made by high thermal conductivity material, and no use of the lubricant, increases the cooling ability of the roll. In the HPTRC, the copper roll is used, and the lubricant is not used. The temperature of the strip, especially around the strip surface, can

be kept lower as the contact time becomes longer. The temperature of the strip becomes lower as the strip becomes thinner. The strip becomes thick as contact time becomes long. Usually, when the copper roll is used, the strip can be cast continuously at range of thickness thinner than 3mm. Therefore, it is better that the casting conditions are set as the thickness becomes thinner than 3mm. The melt temperature affects the temperature of the strip. The temperature of the strip becomes high as the temperature of the melt temperature becomes high. Therefore, upper limitation of the roll speed becomes higher as the melt temperature becomes lower. In the CTRCA, the effect of the melt temperature was not investigated at wide range of the melt temperatures. Especially, there was few investigation of low superheat casting. One of the reasons is that the low superheat casting is difficult as the melt may solidify in the tip (nozzle) and a launder in the CTRCA. In the HPTRC, the low superheat casting can be carried out. The mechanism of the nozzle of the HPTRC is different from that of the CTRCA. The effectiveness of the low superheat casting in the field of the roll casting was revealed by the experiment using the HPTRC [37].

Casting AA5182 alloy into strip is difficult using a conventional roll caster, because the freezing zone of A5182 is broad (about 60 °C). Strip casting of AA5182 was attempted using MDTRC. AA5182 can be cast into strip at up to 60 m/min. The effects of the roll material on casting speed, strip surface and microstructure were investigated. Fig. 33 shows the maximum speed of which the strip can be continuously cast. The copper roll is shown to be more suitable for high-speed roll casting than the steel roll. Material having higher thermal conductivity is more suitable as roll material in high-speed roll casting. The use of lubricant is intended to prevent sticking of the strip to the roll. However, the use of lubricant also reduces the roll speed at which strip can be cast. Lubricant reduces the heat transfer between the strip and the rolls, and causes a subsequent reduction in the casting speed at which the strip can be cast continuously, as shown in Fig.4-1 [38].

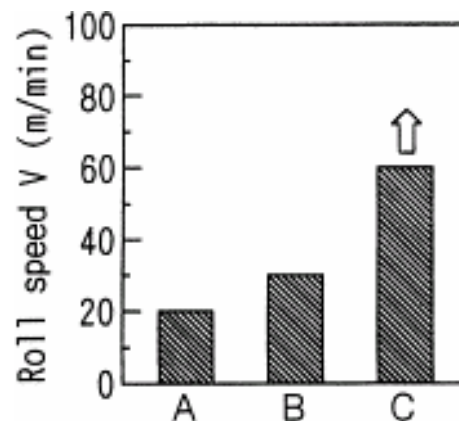


Figure 4.1. (A) Steel roll coated with lubricant; (B) steel roll; (C) copper roll [38]

Figure 4-2 shows effect of the roll material on the defect of the cross-section of the strip. Segregation is observed at the cross-section of the strip cast by steel rolls coated with lubricant. The higher the roll speed, the worse the segregation. Inside of the strip cannot be cooled enough as the cooling time becomes shorter. Fig. 4-3 shows the microstructure near the forming roll of strip cast by steel rolls coated with lubricant under insufficient cooling. In contrast, little segregation is observed at the cross-section of the strip cast by copper rolls using no lubricant. The heat transfer coefficient between the roll and the strip becomes higher when the lubricant is not used. The thermal conductivity of the copper roll is larger than that of the steel roll. Therefore, the copper rolls using no lubricant cooled the strip enough, and prevent the segregation [39].



Figure 4.2. Steel rolls coated with lubricant, (a) 30 m/min, (b) 60 m/min; copper rolls, (c) 30 m/min; (d) 60 m/min [38]

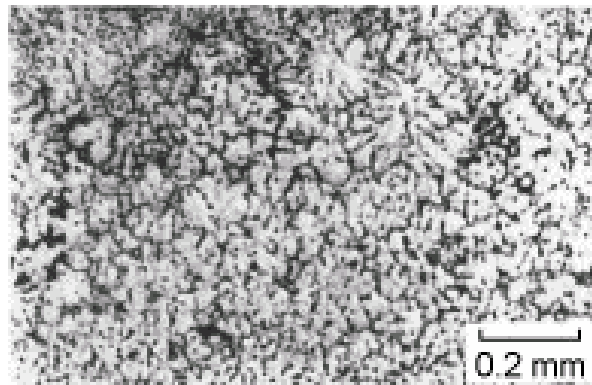


Figure 4.3. Microstructure near the forming roll of the A5182 strip cast at 30 m/min by steel rolls coated with lubricant [43]

As shown in Figure 4-4, in industrial twin roll casters maximum casting speed is between 0.4 m/min and 2.2m/min depending on the casting thickness and roll material [copper shell]. Experimental casting speeds are much faster than industrial casting speeds. In experimental twin roll casting operations casting speed changes from 1m/min to 150m/min [19, 35, 40, 41, 42, 43] depending on the alloy used in casting trial, casting thickness, casting roll material, casting roll diameter and contact length on the roll. Cooling capacity of the rolls directly affects the maximum casting speed of the twin roll caster.

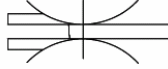
Roll Casting	Strip Thickness	Productivity	Casting Speed
	[mm]	[t / (m · h)]	[m/min]
St / St Shell	10 - 5	0.5 - 1.5	0.4 - 1.1
St / Cu Shell		1.6 - 2.1	1.2 - 1.65
Cu / Cu Shell		1.8 - 2.8	1.3 - 2.2

Figure 4.4. Potential increase in productivity and casting speed depending on roll material [25]

12.5m/min casting speed was not suitable to obtain fully solidified aluminum sheet (Figure 4-5). In order to get complete solidification, the reduction ratio of the chain-wheel system is changed to 1/3 and the casting speed is reduced to 6.2m/min. Casting trials with addition of alloying elements are performed in 6.2m/min casting speed. Even melting temperature of AA1050 is ~650 °C, the casting temperature was set to 690 °C which was

the lowest temperature that the molten metal flows through the tip without solidification in the tip. When the casting temperature was set above 710 °C the molten metal flowed through the tip but the cooling capacity of the strip was not enough to solidify the molten metal.



Figure 4.5. Result of casting trials in casting speed of 12.5m/min

In casting trials it was seen that the distance between the lips of the tip was important to obtain metal flow in the tip. When the distance was below 2mm, molten metal solidified in the tip. Especially when Mg was added the distance was widened more than 3mm, because below 2.5mm the molten metal solidified in the tip several times even the casting temperature was 700-710°C. However the casting thickness, the roll gap, of the strips was set to ~1,5mm, the thickness of the strips vary between 1,5mm to 1,7mm. One of the reasons of the change in the thickness was the deflection of the rolls. The rolls manufactured for the twin roll caster did not have crown. Roll crown was very important in rolling operations in order to compensate the deflection of the work roll and to improve flatness and profile of the rolled sheet. It is also important in twin roll casting operations in order to produce sheet in constant thickness through the width. The other reason was that the rigidity of the roll gap adjustment system was not enough to compensate the separating force generated by the casting operation. The power screws in the top roll adjustment system can be changed with ball screws which are generally preloaded to give zero backlashes. Rigidity of the roll gap adjustment mechanism also determines the change in the thickness of the twin roll cast strip through the width.

In casting trials the metal was melted in a graphite crucible in the annealing furnace. Temperature of the furnace was set well above 720 °C to melt the metal faster, and then it is reduced to 690 °C. Molten metal is kept at 690 °C for about 1h, to ensure that the temperature of the molten metal is stable. Molten metal was poured to the inlet of the tip manually. The beginning of the cast sheet overspreads on the roll because when the metal is poured the molten metal did not fill the tip and it overspreads on the roll with a high flow rate (Figure 4-6). After a while the metal starts to solidify and the width of the metal is fixed to the tip width. When metal was poured by hand, it caused fluctuations in the metal amount that was fed to roll bite. Because of the fluctuations metal sheet produced was discontinuous. It is necessary to prevent fluctuations in metal feeding for continuous metal production. Molten metal should be fed to the tip with a launder system just like industrial use. To build such a system, the annealing furnace should also be adapted to the launder system or rebuilt to make up a melting furnace and launder system like the industrial ones. When molten metal was fed to the roll bite by the help of launder system, the metal flows uniformly through the tip at a constant flow rate.



Figure 4.6. Twin roll cast aluminum strip by the prototype twin roll caster

Addition of magnesium and strontium noticeably influenced the castability of the aluminum alloy used in the trials. In trials with magnesium addition molten metal solidified in the tip, continuous flow could not be obtained because of the interaction of mg with oxygen. To provide continuous flow of metal the distance in the outlet of the tip was expanded up to 2.5mm. Magnesium added aluminum alloy solidified completely when it passed the roll gap but the metal solidified in the tip was more than other trials. In trials with strontium addition it was obvious that molten metal solidified completely. The amount of solidified metal in the tip was the least of all trials.

## 4.2. Microstructures of the Cast Strips

Microstructure of aluminum sheets produced in industrial twin roll casters were discussed in previous chapters. The supersaturated area on the surface of the strip, non-uniform distribution of intermetallic particles, elongated grains in casting direction, like the cold rolled strip, in the surface are the main characteristics of the twin roll cast aluminum strip. When casting thickness is reduced the supersaturated zone becomes wider and the grain size decreases remarkably. In Figure 4-7 the difference in the microstructure of the AA1050 strip produced industrially and experimentally can be seen. Micrographs of the sections longitudinal to the rolling direction were taken via optical microscope under polarized light at 5x magnification.

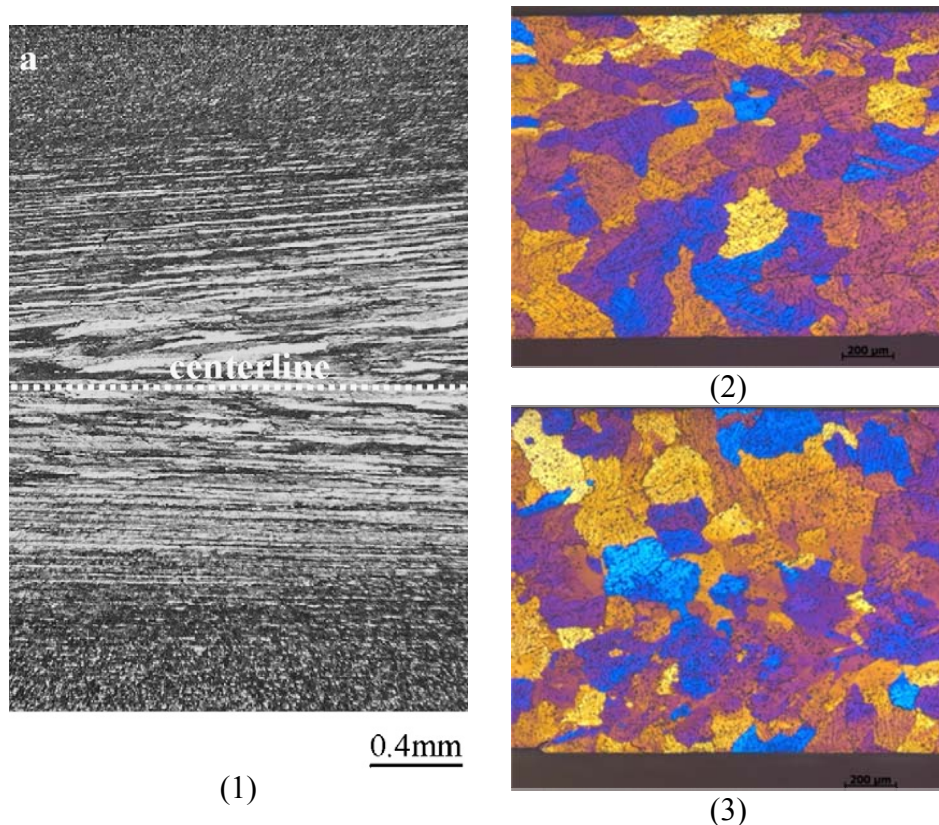


Figure 4.7. Microstructure of (1) 3mm AA1050 produced commercially [20], (2-3) 1.5-1.7mm AA1050 produced in prototype twin roll caster

Supersaturated zone did not exist in the experimentally cast aluminum strip. The supersaturated zone is formed by the high cooling rate of the surface of the strip and the high deformation encountered after solidification of the surface. The prototype twin roll caster only provides solidification of the molten metal. Solidified metal did not deform in

twin roll casting operation. The grain size of the experimentally cast twin roll caster is larger than industrially produced strip. Coarse grain size is because of low cooling rate of the prototype twin roll caster.

In Figure 4-8 the second and the third micrograph show the effect of casting speed on the microstructure of the experimentally cast strips. The casting speeds of the strips were 12.5m/min and 6.2m/min respectively. It is obvious that the decrease in casting speed increased the amount of heat removed from molten metal and that decreased the grain size of the strip. However the grain size is decreased the grain size on the upper and lower surface was different. The amount of heat removed by the upper and lower rolls was different. That was the reason why the grain sizes differ in the upper and lower surfaces. Figure 4-7 shows the distribution of second phase particles. Second phase particles of the first strip were homogeneously distributed and the ones in the second strip were not homogeneous as the first one. The decrease in the casting speed made the difference in cooling rate of the upper and lower roll more visible. Thus the grain size and second phase particle distribution was significantly influenced by the cooling rate and each other.

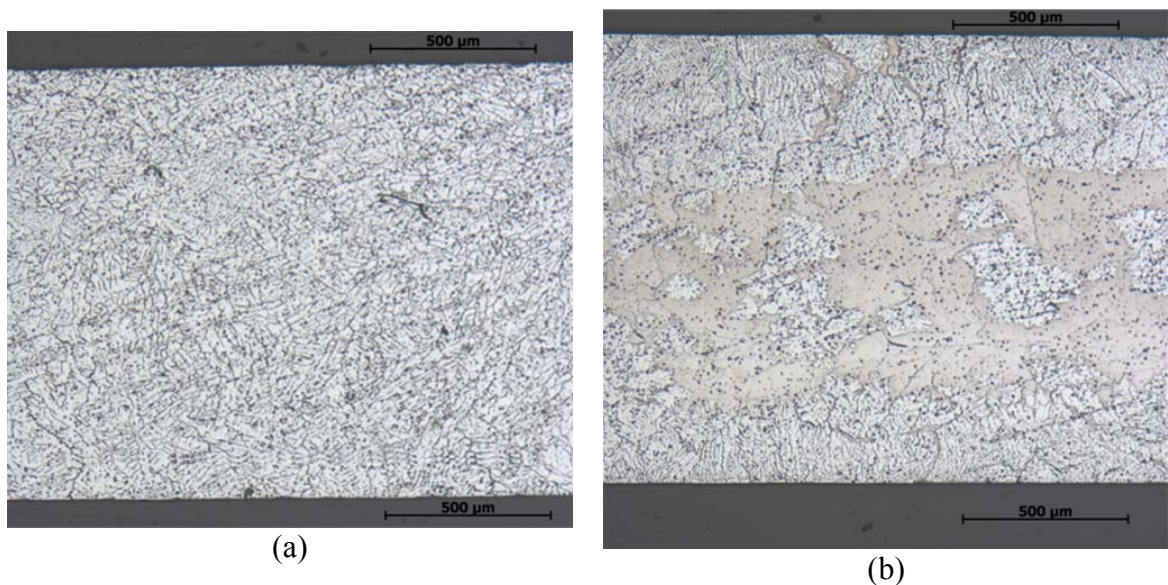


Figure 4.8. Second phase particles of (a)1.5- (b)1.7mm AA1050 produced in prototype twin roll caster

In the last decades, the usage of rare earths, especially La, Ce, Nd, Y, Sc and mischmetall in aluminum alloys has been widely studied. These studies show that the microstructure of these alloys is modified, the mechanical properties and other properties

such as electrical conductivity, optical quality, corrosion and recrystallization resistance are also improved [44]. Rare earth elements in conventional casting aluminum alloys have also shown beneficial effects on melting and solidification. These elements reduce the contents of gases and some impurities and the spacing between secondary dendrite arms [45].

The effects of adding scandium to aluminum have been investigated in great detail both in binary Al-Sc alloys and by Sc-addition to several aluminum alloy types. It seems that the area where Sc has the highest benefit over other alloying elements is as a dispersoid former, and in particular if Sc is added together with zirconium. The effect of Sc or Sc+Zr as a dispersoid former in high strength 7xxx alloys is already reported in several works. For 6xxx alloys there does not seem to have been much work done, most likely due to the expected formation of an  $\text{AlSc}_2\text{Si}_2$  phase on the expense of  $\text{Al}_3\text{Sc}$  for alloys with a significant Si content [46].

The addition of Er to the Al-Zn-Mg alloys has a significant effect on the as-cast microstructure, i.e. grains can be remarkably refined and the dendrite structure almost disappears. This probably can be interpreted that the fine primary particles  $\text{Al}_3\text{Er}$ , formed during solidification, act as nucleation sites. The recrystallization temperature of the Al-Zn-Mg alloy is also increased by about 50 by adding trace rare earth element Er [44]. The addition of the Al-10Sr master alloy was found to increase the volume fraction of the primary  $\alpha$ -Al dendrites. However, it was noted that the results showed an important decrease in the grain size.

The effects of addition of ordinary alloying elements like Mg, Mn, Si, Fe in aluminum alloys has been extensively studied before. Addition of such alloying elements improves the mechanical and microstructural properties of aluminum alloys, by forming second phase intermetallic particles. The second phase intermetallic particles exert drag force on the movement of grain boundaries, dislocations and form nuclei for recrystallization in thermomechanical treatments. There are three reasons why an understanding of the effects of second-phase particles on recrystallization is important: (a) most industrial alloys contain second-phase particles; (b) such particles have strong influences on the recrystallization kinetics, microstructure, and texture; and (c) by a

combination of alloying and materials processing, it is possible to control the distribution of second-phase particles in the microstructure relatively accurately. If the effects of these particles on the annealing behavior are understood, then the metallurgist is able to use second-phase particles as a method of controlling the grain size and texture during thermomechanical processing [47].

Second phase particles may form from melt while casting or precipitate from solid solution while heat treating. Most of the alloying elements exist mainly in aluminum solid solution. And while heat treating the alloying elements diffuse and form second phase particles. It is important to find out best combination of alloying additions in order to obtain desired properties.

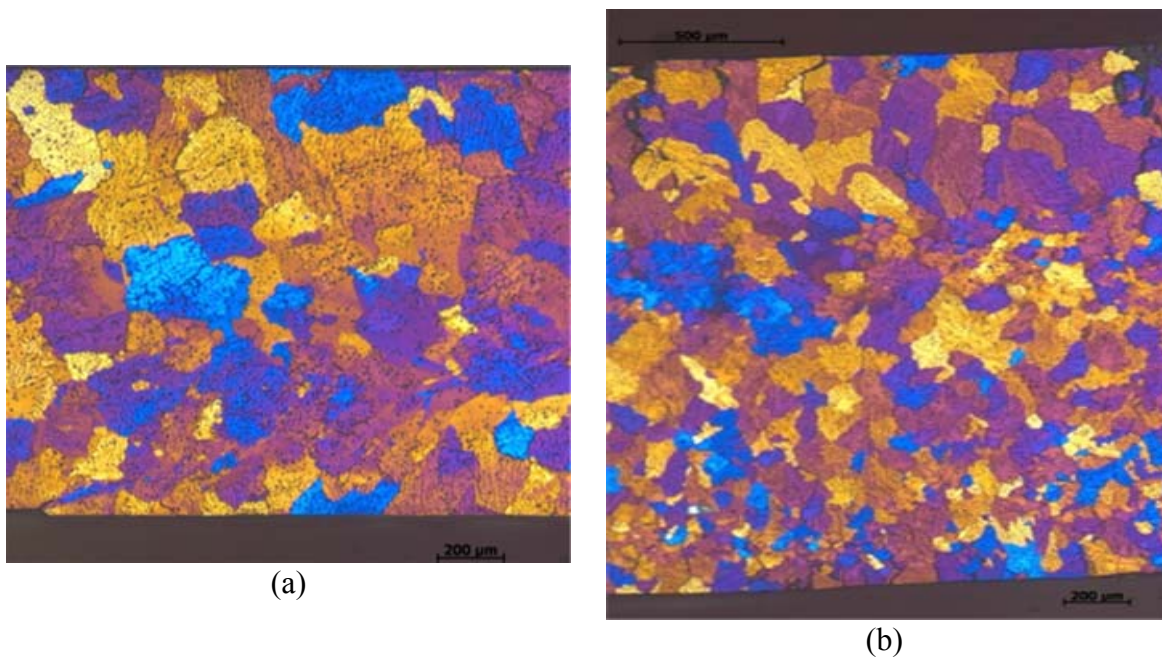


Figure 4.9. Microstructure of AA 1050(a) and Mg added AA1050(b) produced via prototype twin roll caster.

Figure 4-9 shows the effect of magnesium addition on the microstructure of AA1050. Maximum solid solubility of magnesium in aluminum is 17.4%, but the magnesium content in current wrought alloys does not exceed 5.5%. The addition of magnesium markedly increases the strength of aluminum without unduly decreasing the ductility [49]. Addition of magnesium decreased the grain size even the casting thickness is thicker. The

difference in grain size between the upper and the lower half of the strip is distinguishable. However the grain size was smaller, it was not uniform.

The second phase particles were heterogeneously distributed through thickness. The particles on the upper surface are more homogenous than the ones on the lower surface (Figure 4-10). The second phase particles on the lower surface were precipitated on the grain boundaries. That was because of the high cooling rate in the lower surface.

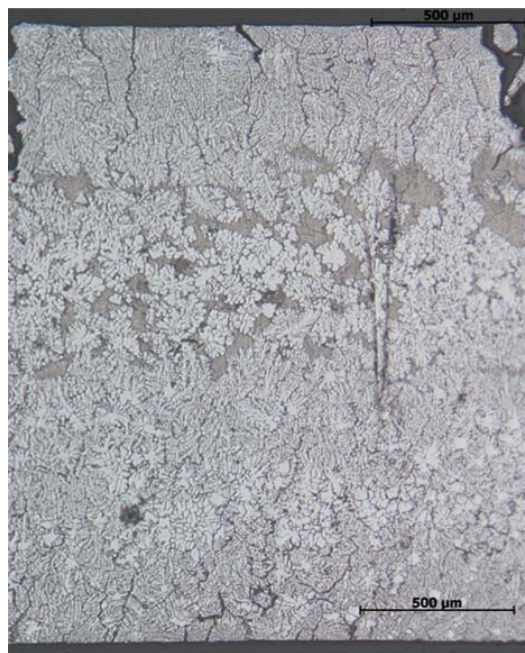


Figure 4.10. Second phase particles of experimentally cast AA1050 modified with Mg

Smallest grain size was obtained by addition of magnesium with manganese (Figure 4-11). However amount of alloying elements were not as much as the other trials the effect was dramatic. The combined effects of few alloying elements were studied before. It was stated that using small amounts of alloying additions of more than one element may be more effective than using a lot of one element. Some of the grains seem to be greater than the others. Non-uniform distribution of the alloying elements and second phase particles (Figure 4-12) or the cooling gradient from surface to the center may have caused formation of the coarse grains.

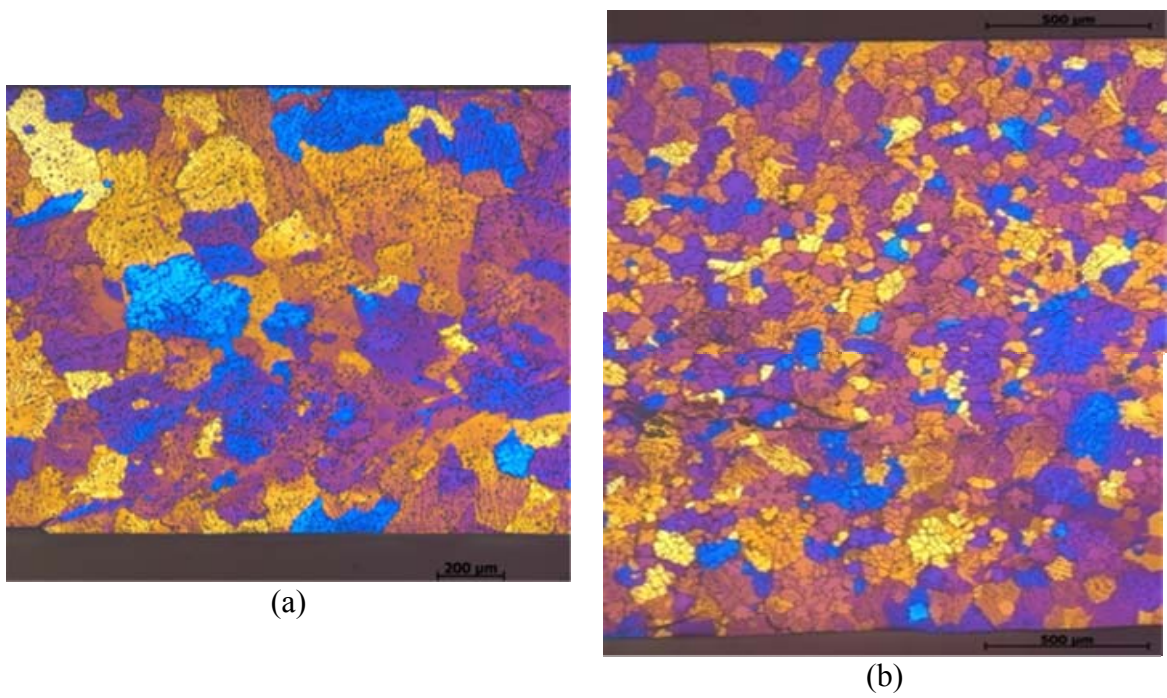


Figure 4.11. Microstructure of AA1050 (a) and Mn+Mg added AA1050 (b) produced via prototype twin roll caster



Figure 4.12. Second phase particles of experimentally cast AA1050 modified with Mg+Mn

Manganese and combination of iron, magnesium and manganese addition did not affect the grain size of the strip. It is obvious from Figure 4-13 that the grain size with or without manganese or iron was nearly the same. The surfaces and the center of the Mn modified aluminum strip solidified differently. The center seems to be solidified after the casting operation ended. The amounts of iron and manganese play important roles in establishing the mechanical properties of aluminum-silicon casting alloys. Iron, as one of the main impurities in aluminum, is always present in alloys made from commercially pure base material. The solid solubility of iron in aluminum is very low with the result that most iron present forms intermetallic compounds, the nature of which depends strongly on other impurities or alloying elements present [49]. Since the solid solubility of iron is low in aluminum, the Fe+Mn+Mg modified aluminum strip contains high amount of the second phase particles probably containing Fe (Figure 4-14). High impurity content may have also resulted the increase in the amount of second phase particles.

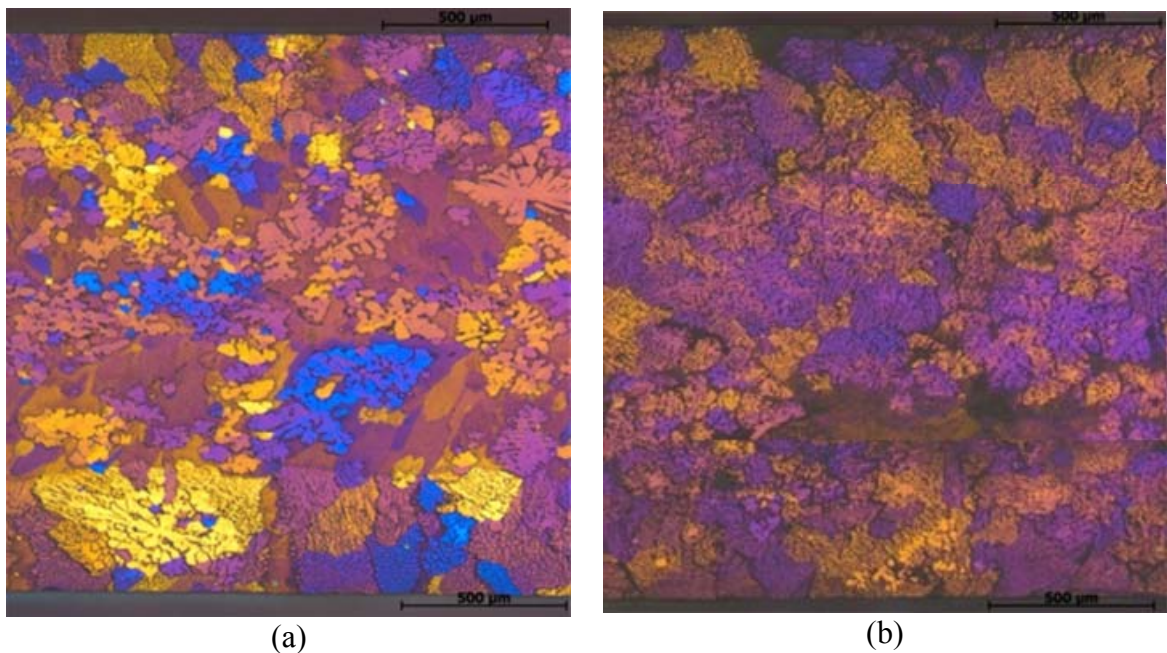


Figure 4.13. Microstructure of Mn added AA 1050(a) and Fe+Mn+Mg added AA1050 (b) produced via prototype twin roll caster

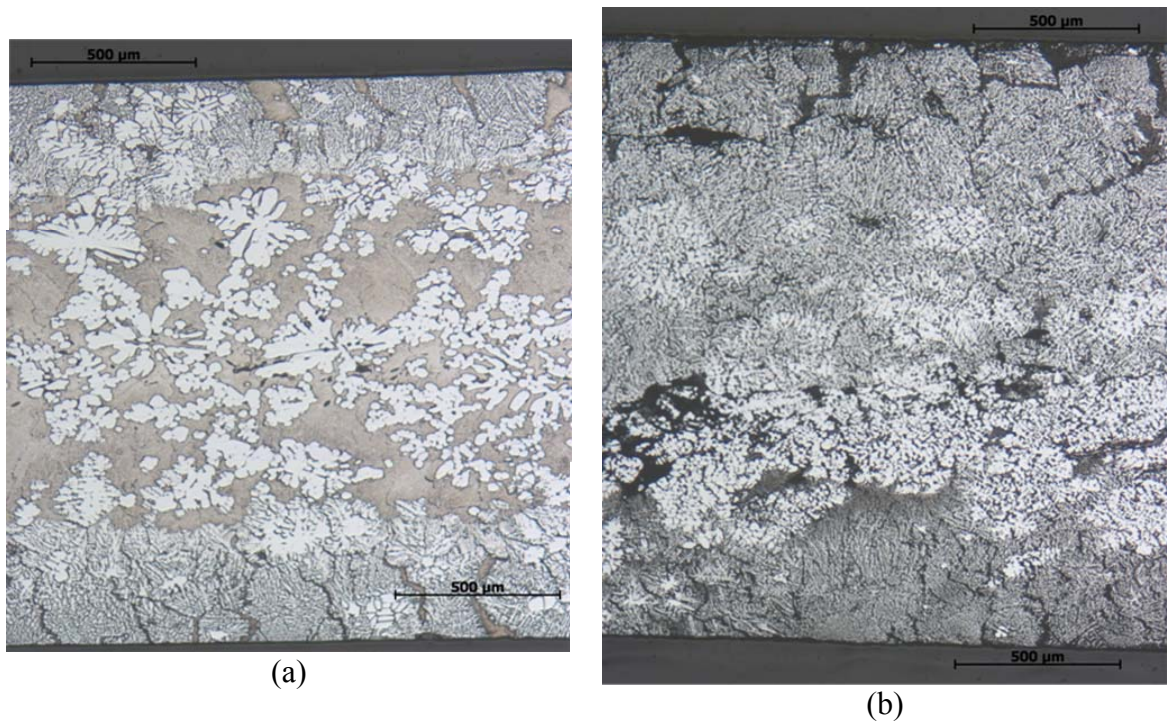


Figure 4.14. Second phase particles of experimentally cast AA1050 modified with Mn (a) and Fe+Mn+Mg (b)

Strontium is used as a modifier and grain refiner in casting aluminum alloys. Strontium added aluminum alloy had homogeneously distributed small equiaxed grains through the thickness. The grains on the upper and lower surfaces are elongated in casting direction like the industrially cast aluminum strips. The elongation of the grains was not as much as the industrially cast ones, but effect of strontium is noticeable (Figure 4-15). The reason why the shape and size of the grains was different was that the cooling rate and amount of deformation was not as much as the industrial casting practices. Cooling rate in casting practices determines the amount of deformation applied on the solidified material. Effect of strontium on castability of molten aluminum was stated in previous section. The distribution of the second phase particles were heterogeneous through the thickness in which the fraction of second phase particles were more close to the surface than in the center (Figure 4-16). If the casting speed could be decreased aluminum modified with strontium could give better results in experimentally casting trials.

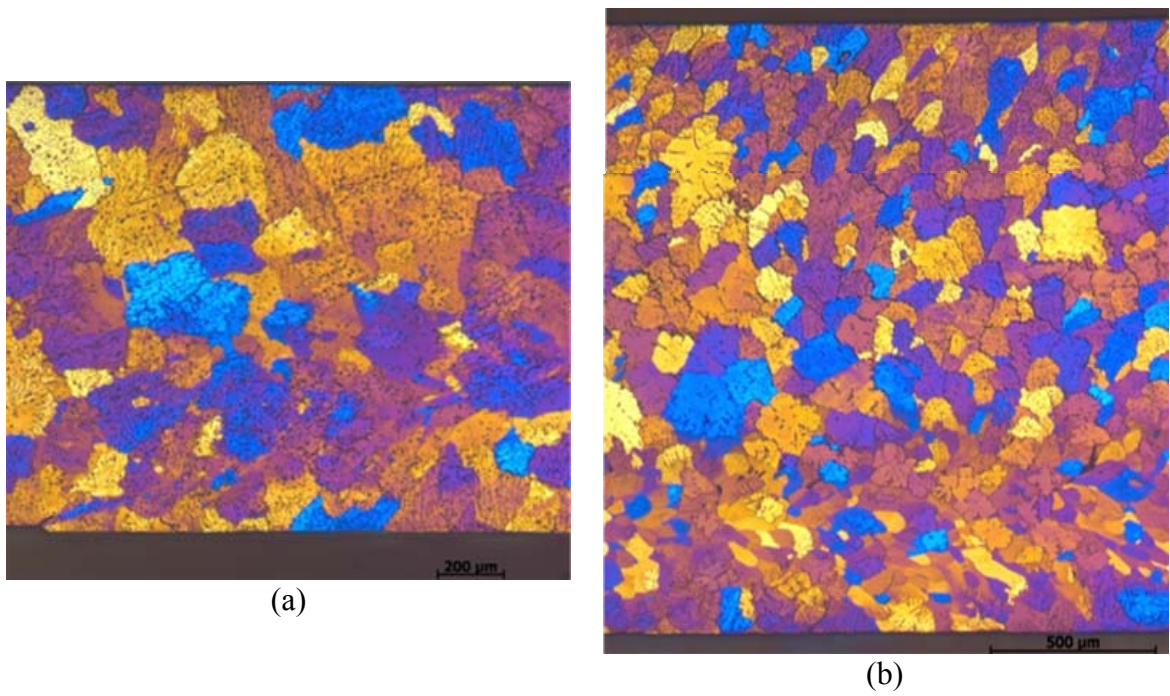


Figure 4.15. Microstructure of AA 1050(a) and Sr added AA1050 (b) produced via prototype twin roll caster

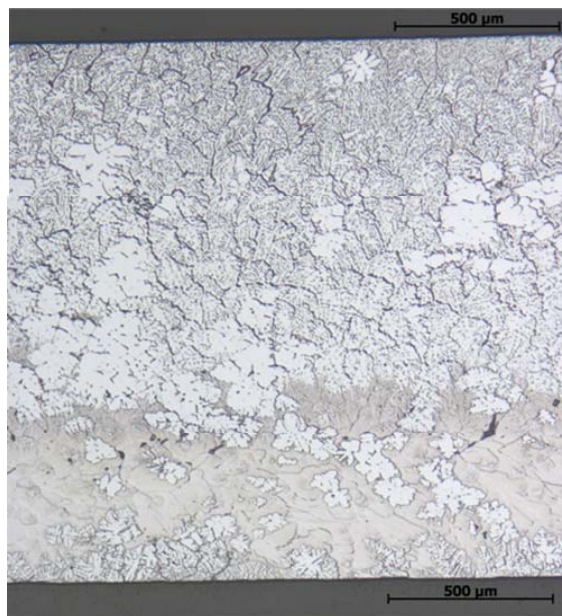


Figure 4.16. Second phase particles of experimentally cast AA1050 modified with Sr

### 4.3. Heat Treatment of Cast Strip

The sheet samples are cold rolled to 0.5-0.8 mm via the prototype twin roll caster and annealed at 350°C and 380°C in order obtain recrystallized microstructure. In order to see whether the strips are recrystallized or not, the strips are etched with HCl, HNO<sub>3</sub> solution after annealing. The samples which are annealed in 350°C were not fully recrystallized. The cold rolled and the annealed strips were the same. Fully recrystallized microstructure was obtained by annealing at 380 °C. Effects of alloying additions were observed via optical microscopy.

Adding alloying element to aluminum alloys decreases the grain size and improves mechanical properties. However some alloying additions increase the grain size of the material, grain refining effect can be observed after rolling and heat treating operations. The alloying additions exist in solid solution and dissolve and precipitate during heat treating. Alloying elements form second phase particles during solidification or heat treatment. The second phase particles formed during solidification may dissolve and form different intermetallic compounds with the dissolving alloying elements from the solid solution during heat treatment. Precipitation and recrystallization interacts with each other during heat treatment. Precipitation lowers the driving force for recrystallization and retards recrystallization. The main function of alloying additions was to form second phase particles while solidification or heat treating and hinder and/or retard recrystallization.

Figure 4-17 and Figure 4-18 show the microstructure and second phase particles through the thickness of the cold rolled and annealed aluminum strips at 380°C for 1h, 2h, 3h and 4h. The aluminum strips in Figure 4-17 and Figure 4-18 were the ones with no alloying additions. Both of the aluminum strips were fully recrystallized, but the grain size of the aluminum strip in figure 4-17 seemed to be bigger than the other one. Grain size of the samples from the 1st casting trial did not change depending on the annealing time. Annealing time should be increased to see grain coarsening of the strip. Two important parameters determining the final grain size of annealed aluminum strips is the size and the fraction of the second phase particles. However the size of the second phase particles seems to be equivalent, the fraction of second phase particles was more in the second strip.

In the 2nd strip grain coarsening was observed after four hours of annealing in the center of the strip.

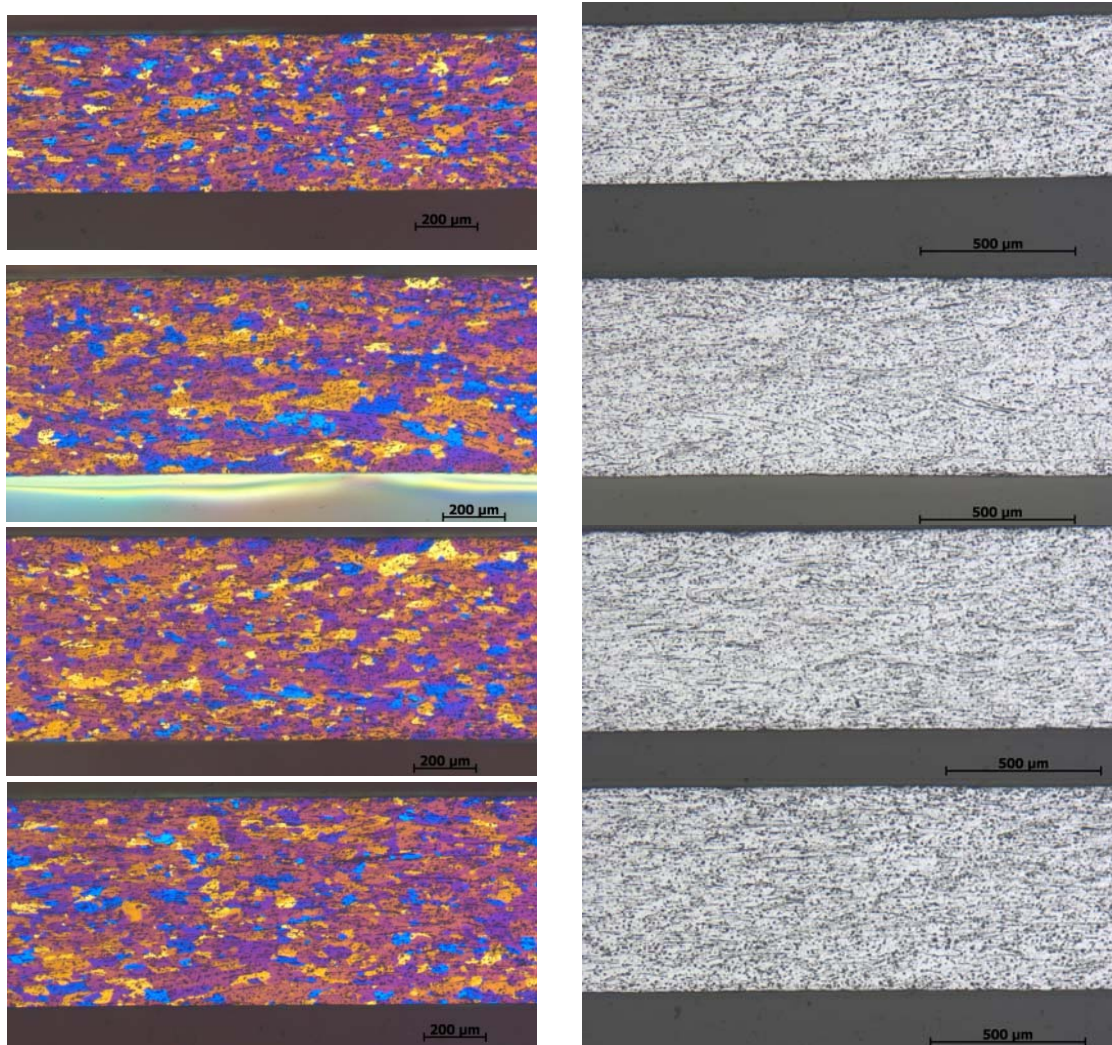


Figure 4.17. Microstructure and second phase particles of cold rolled and annealed samples of 1st casting trial at 380°C for 1, 2, 3 and 4h

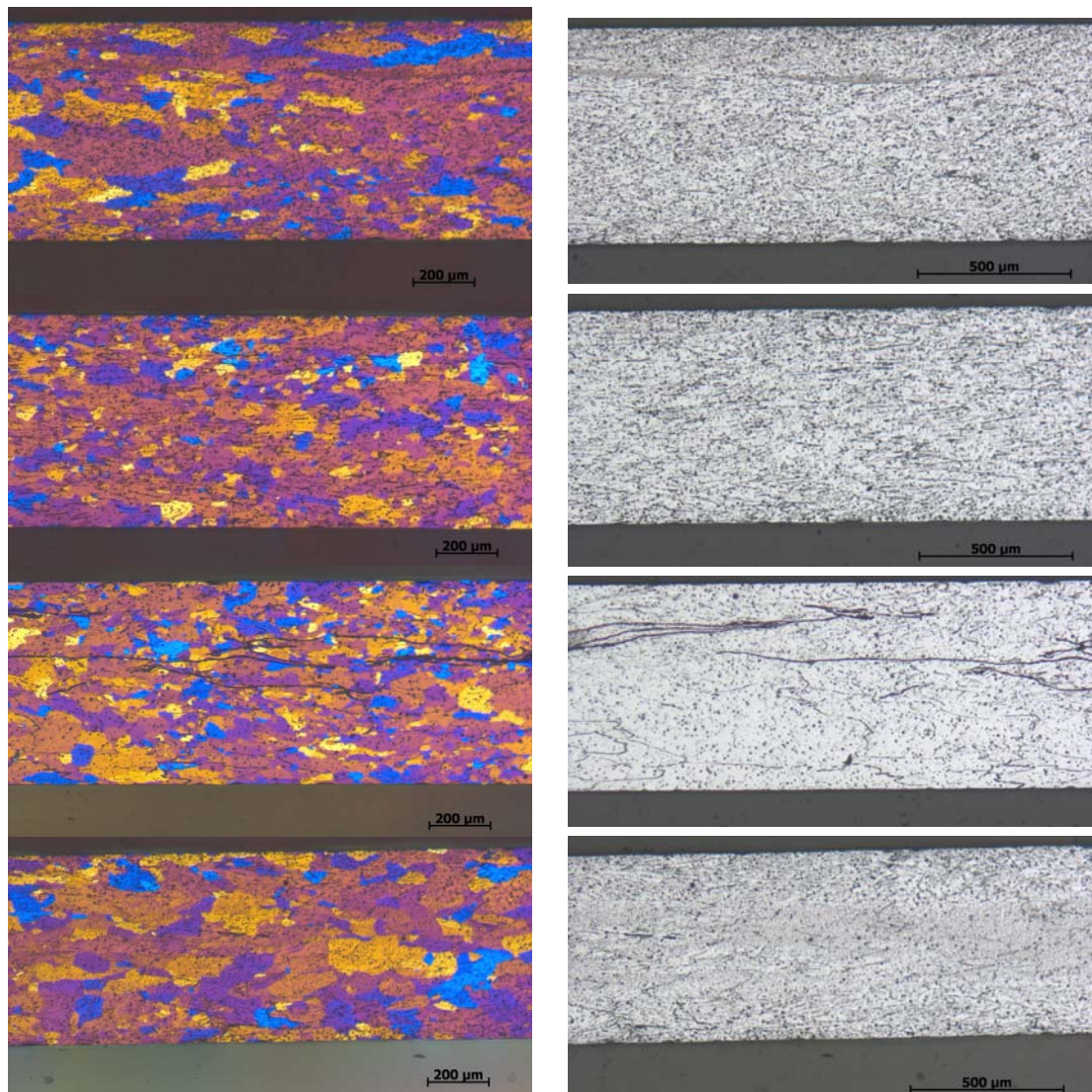


Figure 4.18. Microstructure and second phase particles of cold rolled and annealed samples of 2<sup>nd</sup> casting trial at 380°C for 1, 2, 3 and 4h

Mg modified aluminum strip was fully recrystallized after annealing at 380°C for 4h (Figure 4-19). Grain growth started from the grain on the surfaces of the Mg modified strip. In some parts of the strip the grains were not coarsened that was because of the precipitated second phase particles. Second phase particles generates nucleation sites for recrystallization and that results in few small recrystallized grains in stead of recrystallized one big grain. Mg especially dissolves from solid solution and forms precipitates with Si while annealing.

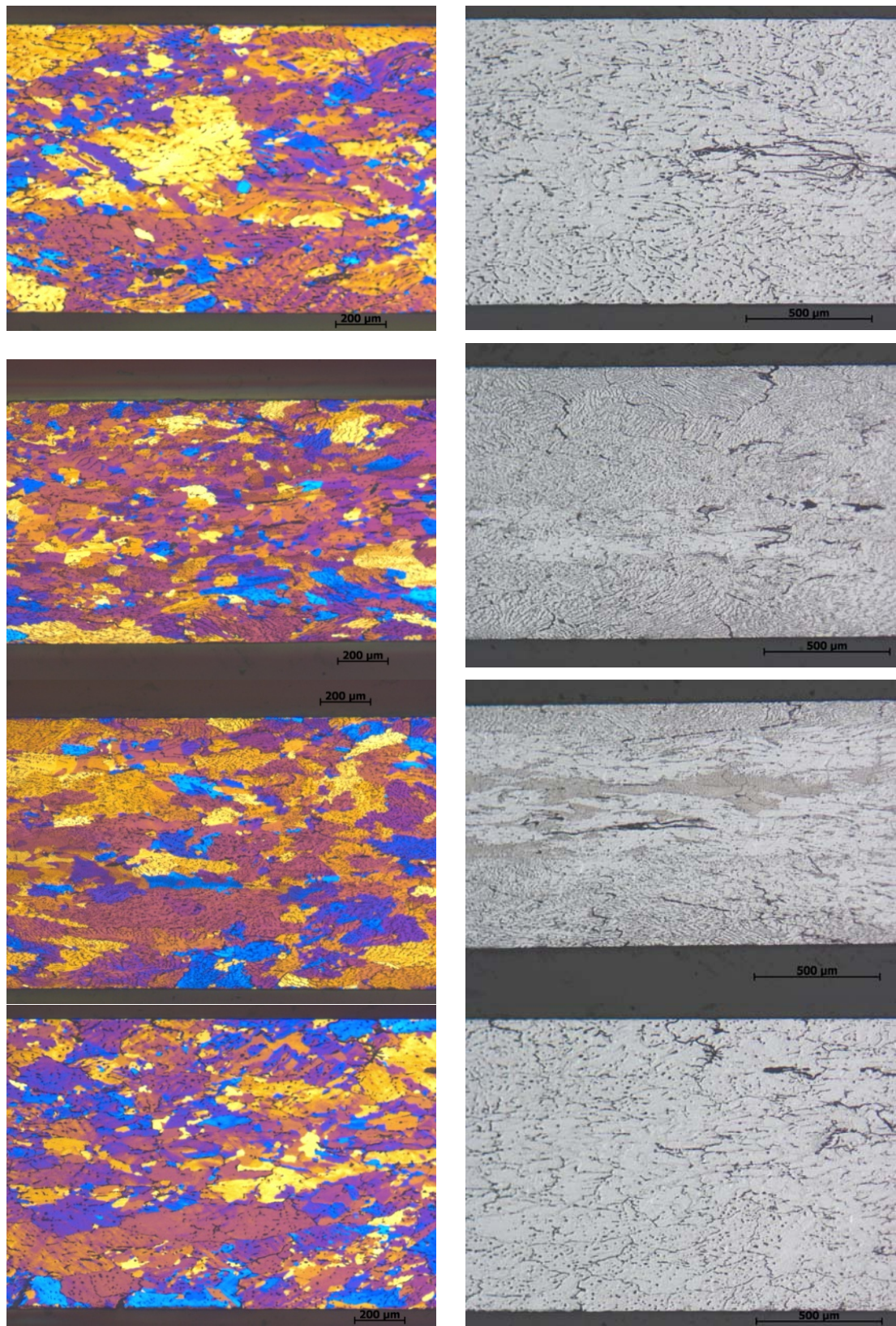


Figure 4.19. Microstructure and second phase particles of cold rolled and annealed Mg modified samples at 380°C for 1, 2, 3 and 4h

Mn modified aluminum strip did not recrystallize after annealing at 380°C for 4 hours (Figure 4-20). 380°C was not appropriate to fully recrystallize Mn modified aluminum strip, to obtain fully recrystallized aluminum strip the annealing temperature should be increased. Effect of Mn on retarding recrystallization was observed in many studies.

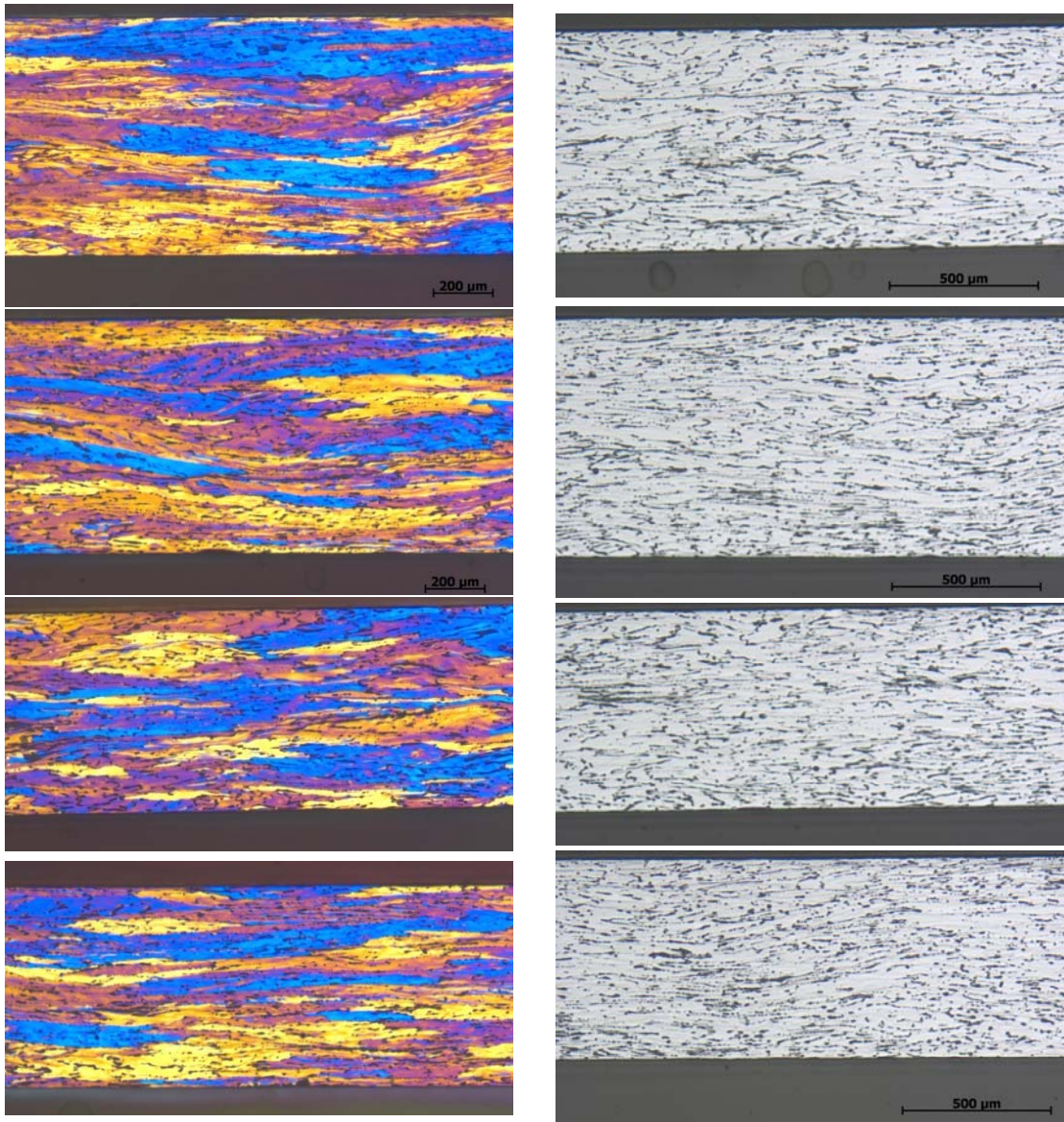


Figure 4.20. Microstructure and second phase particles of cold rolled and annealed Mn modified samples at 380°C for 1, 2, 3 and 4h

Figure 4-21 shows the microstructure of the Mn+Mg modified aluminum strip annealed at 380°C for 1 to 4 hours. However the grains size was the smallest after solidification, after cold rolling and annealing the strip was recrystallized and the grains were coarsened. Addition of Mn+Mg was thought to inhibit recrystallization and grain growth during annealing and refine the grain size just like during solidification.

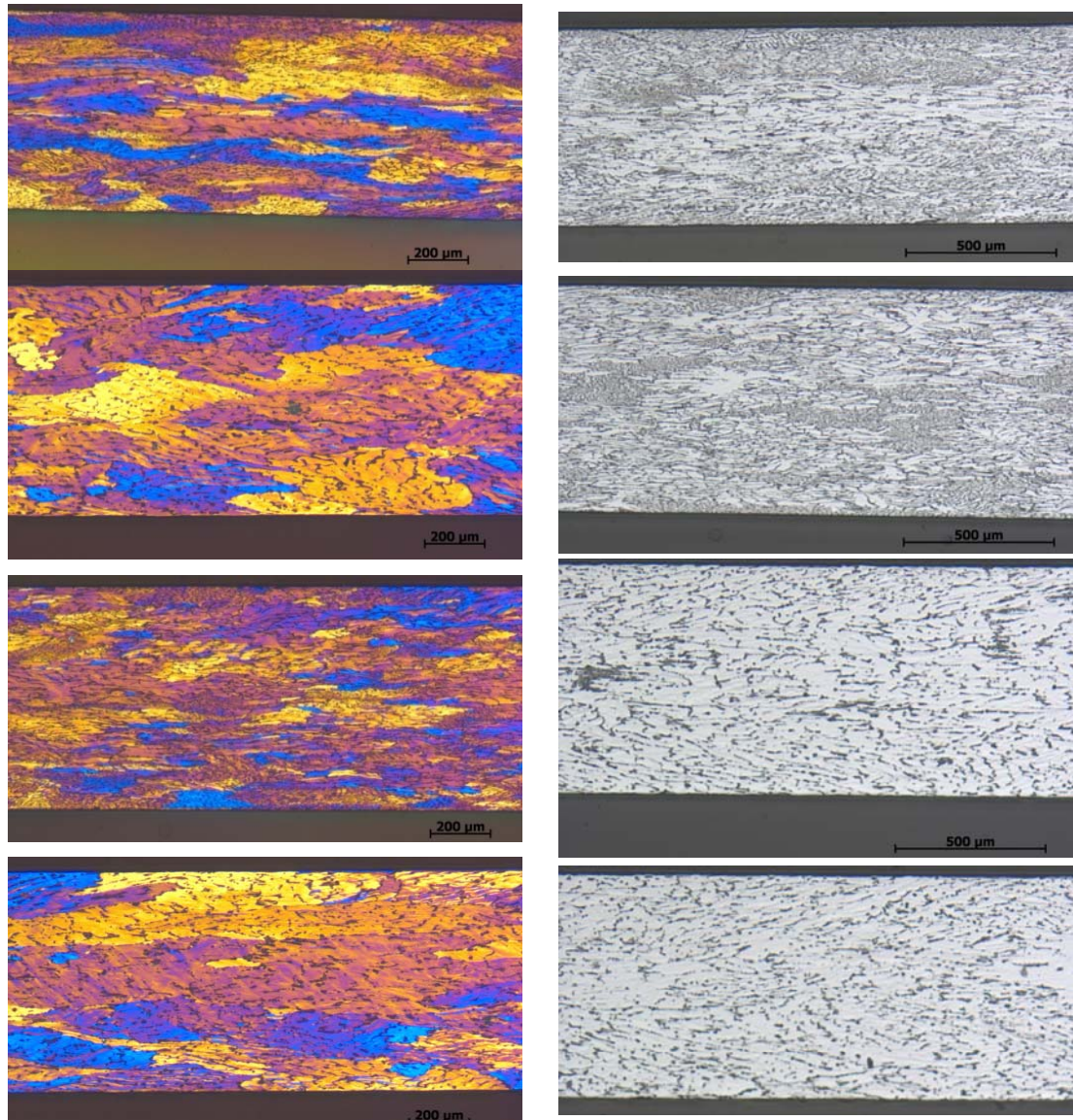


Figure 4.21. Microstructure and second phase particles of cold rolled and annealed Mn+Mg modified samples at 380°C for 1, 2, 3 and 4h

The microstructure of the Sr modified aluminum strip annealed at 380°C for 1 to 4 hours was shown in Figure 4-22. The strip was fully recrystallized but there was no evident of grain coarsening. Addition of strontium had strongly influenced the castability and grain size of the strip after solidification. Strontium also affected the recrystallization behavior and grain size of the strip during heat treatment.

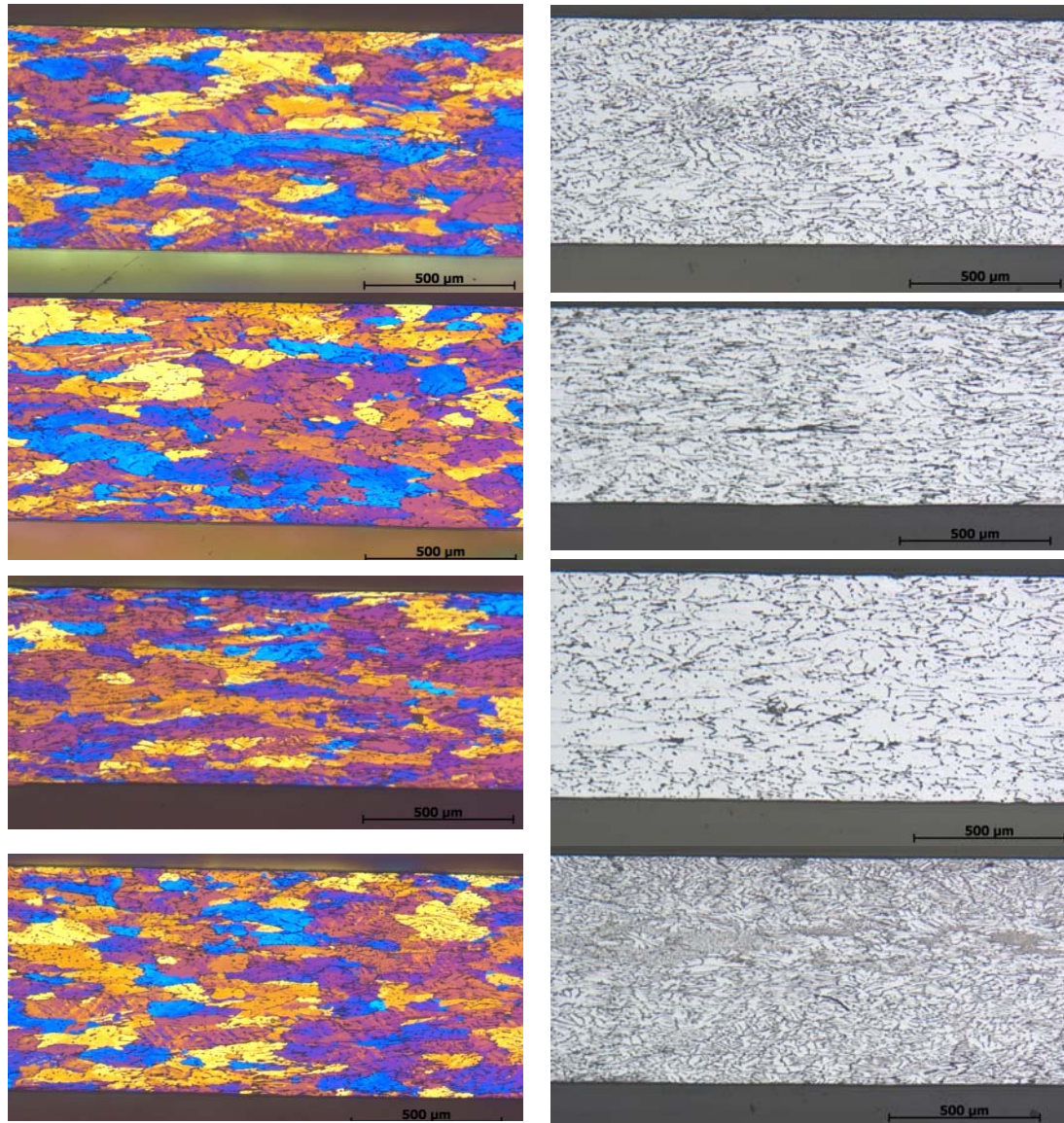


Figure 4.22. Microstructure and second phase particles of cold rolled and annealed Sr modified samples at 380°C for 1, 2, 3 and 4h

Addition of Fe+Mn+Mg had not affected the grain size of the strip after solidification, however the grain size of the strip was small compared with the other samples (Figure 4-23). The Fe modified aluminum strip was completely recrystallized after annealing at 380°C for 1hour. The grains were elongated in the in rolling direction. After annealing at 2 hours and more, the grains coarsened starting from the outer surface to the center of the strip.

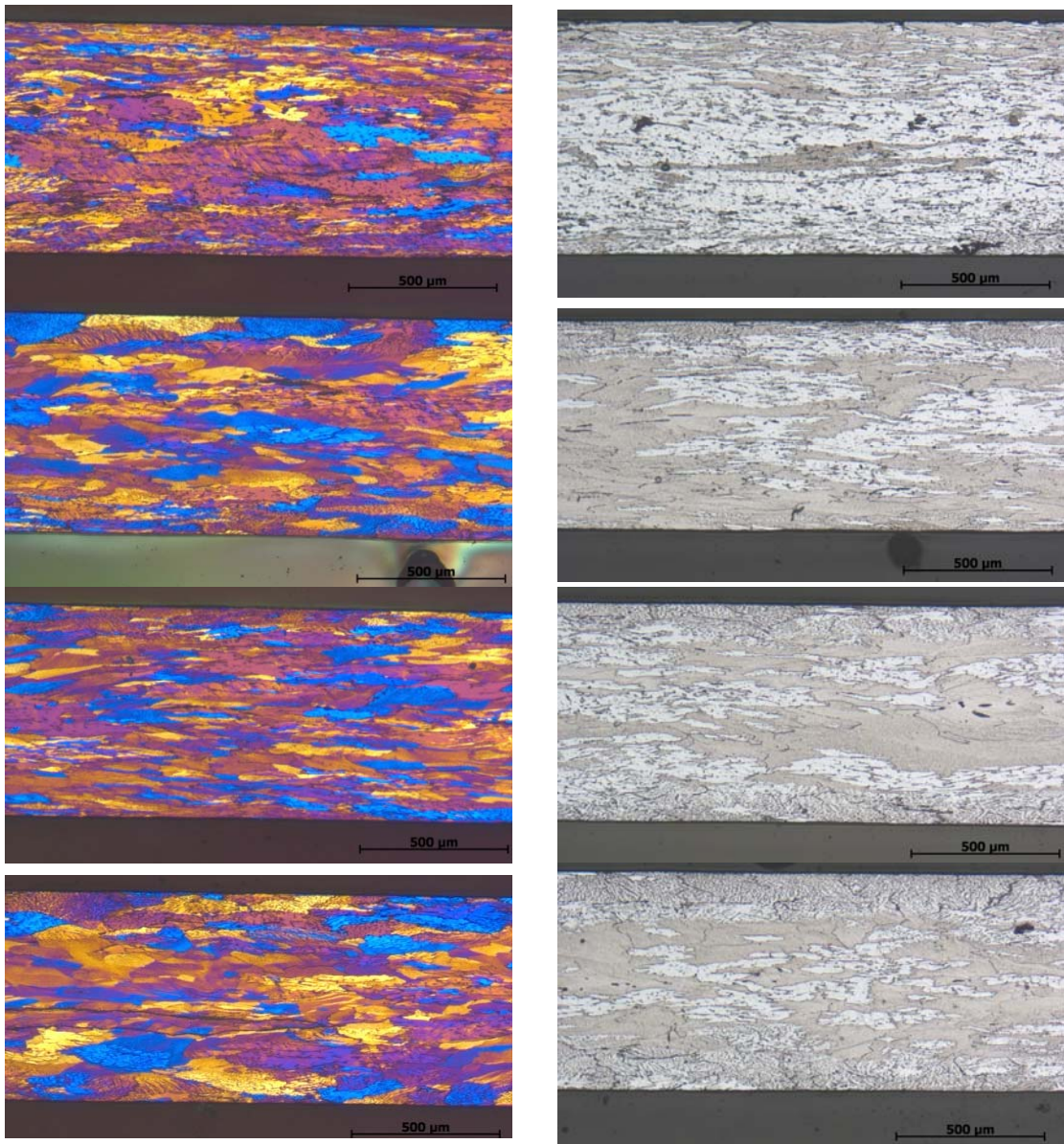


Figure 4.23. Microstructure and second phase particles of cold rolled and annealed Fe+Mn+Mg modified samples at 380°C for 1, 2, 3 and 4h

## 5. SUMMARY and CONCLUSIONS

The objective of the current work was to build a prototype twin roll caster and investigate the effects of alloying elements on the microstructure and annealing behavior on twin roll cast AA1050 sheet.

Prototype twin roll caster was build by modification of existing hot rolling machine in the Materials laboratory. The chassis, motor, transmission system, top roll adjusting system of the hot rolling machine was used. The chain wheel system was used at first casting trials, but the gears were changed in order to change the gear ratio and reduce the casting speed. New twin roll casting rolls and housings were designed and manufactured by the help of ASSAN Aluminum AŞ. Bearings and rotary joints were replaced for circulation of cooling water in the roll. Casting tip was designed and manufactured for casting 50 mm aluminum strip.

Casting trials via the experimental twin roll caster were conducted in two different casting speeds 12,5 m/min and 6.2m /min. However in experimental casting trials casting speed up to 150m/min were used, 12,5 m/min casting speed was suitable to obtain fully solidified aluminum strip in the prototype twin roll caster. The gear ratio of the chain wheel system was changed to reduce the casting speed. To find out proper casting temperature, trials were performed between 710 and 680°C. 690°C was found to be the appropriate casting temperature, in which below this temperature continuous flow could not be obtained and above this temperature molten metal did not completely solidify.

Annealing furnace was used to melt the aluminum scraps for casting trials, grain refiner and lubrication was used. Molten metal was poured in to tip manually which caused fluctuation and irregular feeding of the metal. Launder system should be built in order to overcome misfeeding and obtain continuous flow of molten metal.

Mg, Mn, Mn+Mg, Sr and Fe+Mn+Mg was added in order to investigate the effects on the microstructure and annealing behavior. When Mg was added to the aluminum, molten metal solidified in the tip despite the increase in casting temperature. In order to

obtain metal flow the outlet distance was increased. Grain size of Mg modified aluminum strip was smaller than the non-modified aluminum strip however the casting thickness was thicker. Manganese and iron, manganese, magnesium combination did not affect the grain size of the aluminum strip. Amount of impurities was too much to dissolve in solid solution and formed second phase particles when Fe+Mn+Mg were added. However the grain size reduced after heat treatment. Addition of magnesium with manganese decreased the grain size of the aluminum strip dramatically. The smallest grain size was obtained by addition of Mg and Mn. Strontium improved the castability of aluminum and the microstructure of the strip modified with Sr was the most likely to the industrially cast aluminum strips.

350°C was not suitable to obtain recrystallized microstructure so the annealing temperature was increased to 380°C. Smallest grain size of cold rolled and annealed samples were obtained in the non modified aluminum strips. The grains were small and equiaxed through the thickness of the strip. Addition of Mg increased the grain size of the annealed strip. Mn modified aluminum strip did not recrystallize during annealing. However the smallest grain size was obtained by addition of Mn+Mg, the grain size after annealing was the largest. Sr seemed to be the most effective alloying addition on the microstructure of solidified and annealed samples.



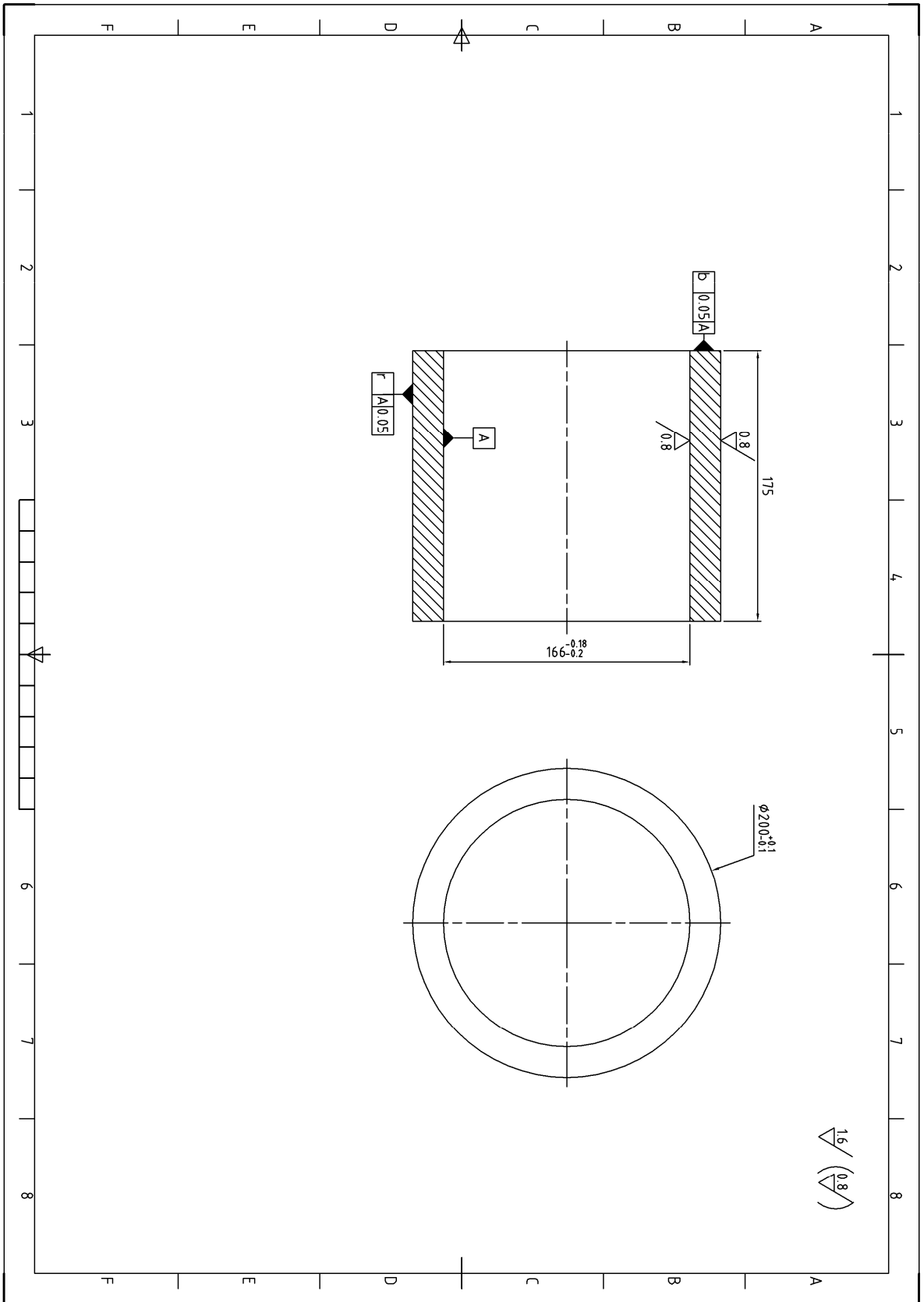


Figure A.2. Shell of the prototype twin-roll caster

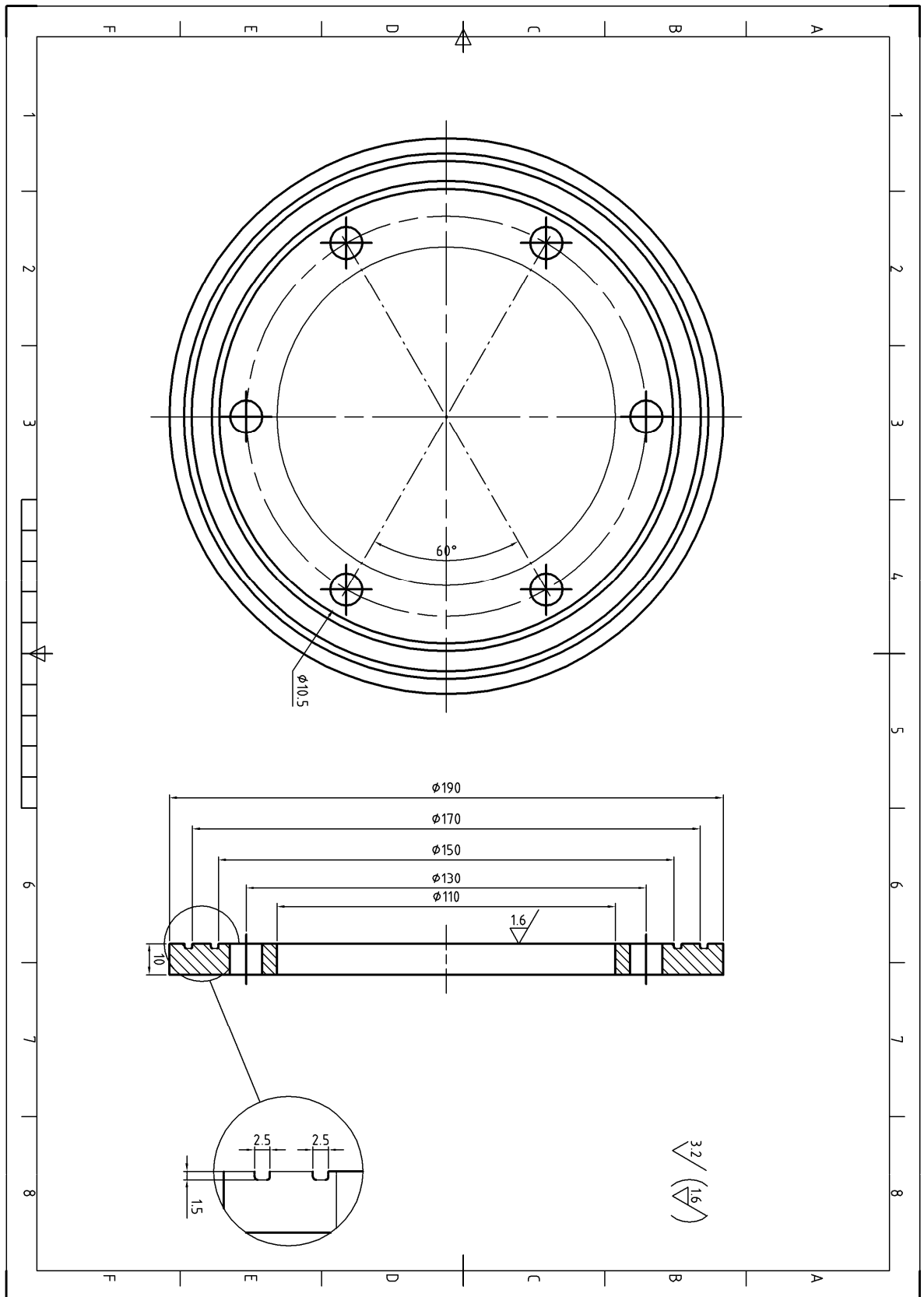


Figure A.3. Flange of the prototype twin-roll caster

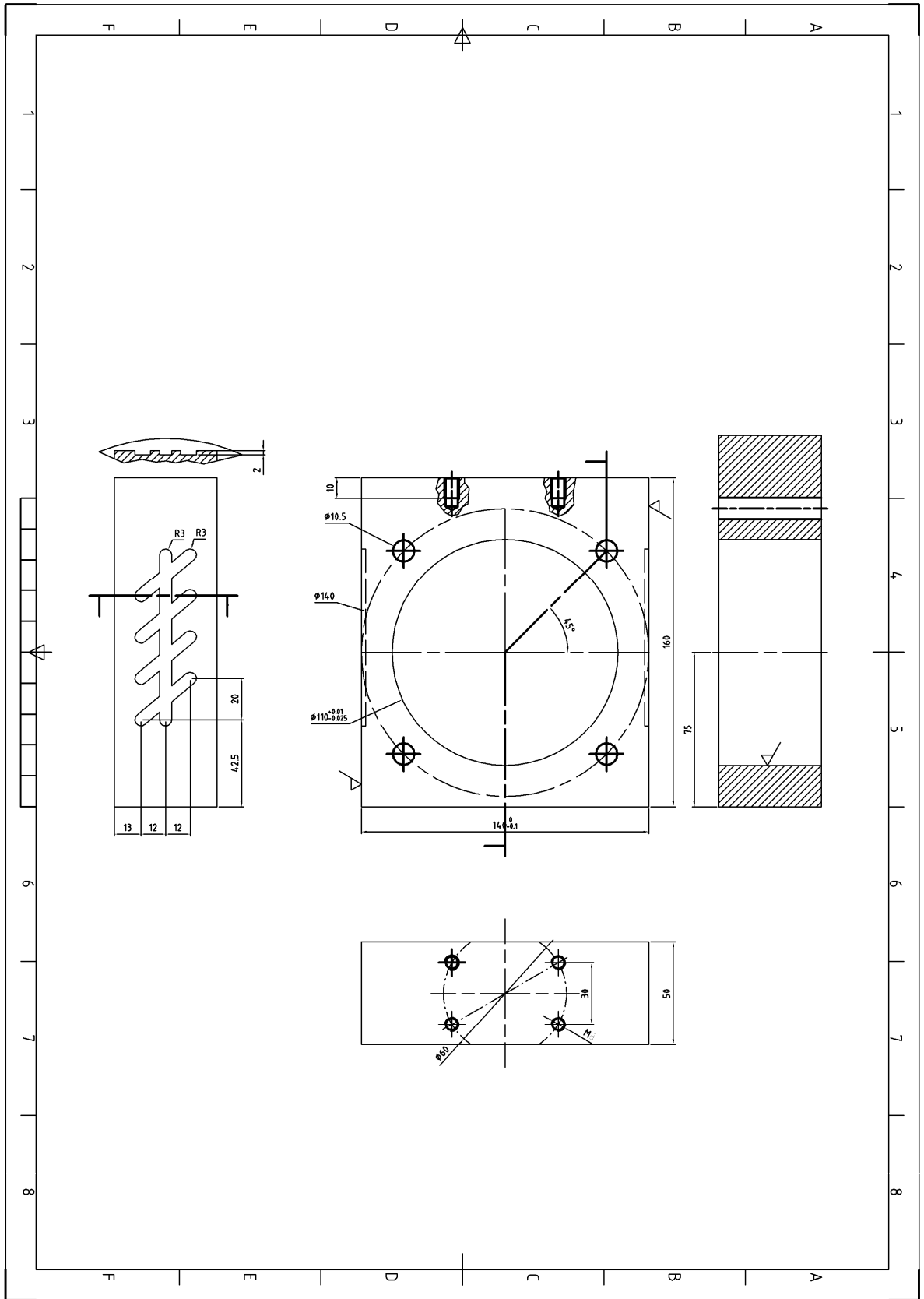


Figure A.4. Housing of the prototype twin-roll caster

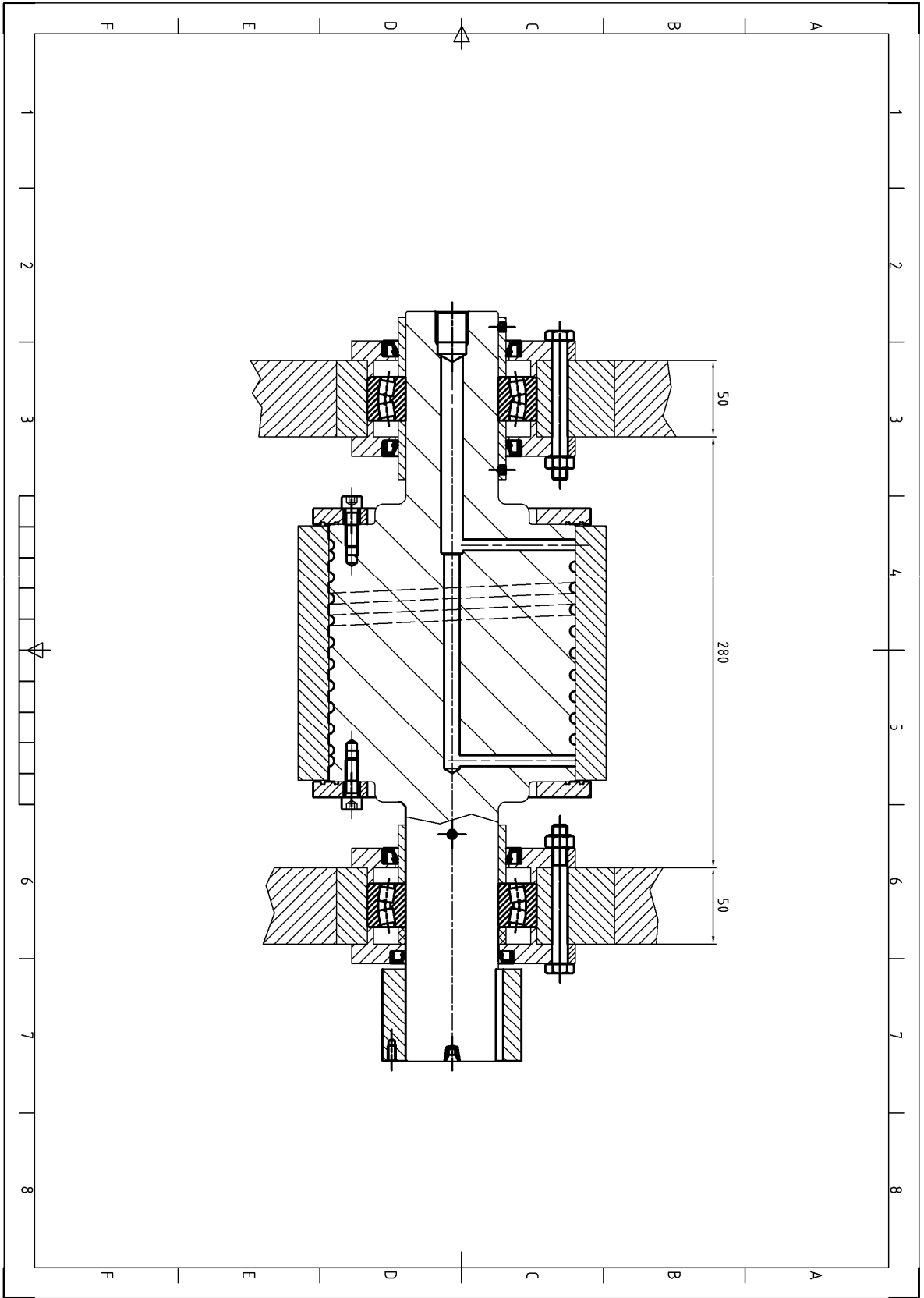


Figure A.5. Core and shell assembly

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