DEVELOPMENT OF HIGH STRENGTH ALUMINUM MATRIX COMPOSITE BACKING PLATES FOR BALLISTIC ARMOR

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DEVELOPMENT OF HIGH STRENGTH ALUMINUM MATRIX COMPOSITE BACKING PLATES FOR BALLISTIC ARMOR

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ABSTRACT

DEVELOPMENT OF HIGH STRENGTH ALUMINUM MATRIX COMPOSITE BACKING PLATES FOR BALLISTIC ARMOR

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Recently, aluminum and aluminum alloys have gained great importance in engineering applications by the help of technological developments. Today, it is possible to see aluminum alloys in very different sectors of industry because of their superior properties. Some of these important properties are high specific strength, lightness and ductility. In addition, it has low density, high corrosion resistance and high mechanical properties that make aluminum crucial in transportation, construction, packaging, household items, electrical devices, automobiles, aerospace, sports industries. Moreover, aluminum alloys and aluminum matrix composites are mostly preferred in defense industry and ballistic applications. This study aims to develop aluminum matrix composite backing plates for ballistic armor by using some high strength aluminum alloys such as 7075 and 7085. In order to comprehend the importance of the aluminum matrix composites in the production of ballistic armor backing plate, these two alloys were produced by high pressure casting methods. Then some heat treatments, rolling and forcing processes were applied to obtain the desired mechanical and physical properties of these 7000 series aluminum alloys. By this way, 7075 and 7085 aluminum alloys were investigated for ballistic applications. After that, alumina and boron carbide ceramic preforms and carbon fiber were melt infiltrated with these alloys by squeeze casting. At the end, the composite samples were characterized by microstructural investigations, hardness measurements, mechanical tests and phase analyses for better understanding of the importance of aluminum matrix composites in ballistic applications.

Keywords: Aluminum, 7075, 7085, Casting Methods, Thermo-mechanical Treatment, Metal Matrix Composite, Alumina, Boron Carbide, Carbon Fiber, Metal Infiltration

ÖZ

BALİSTİK ZIRH DESTEK PLAKASI İÇİN DARBE DAYANIKLI YÜKSEK DAYANÇLI ALÜMİNYUM MATRİS KOMPOZİT GELİŞTİRİLMESİ

Durmaz, Tayfun
Yüksek Lisans, Metalurji ve Malzeme Mühendisliği Bölümü
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Şubat 2017, 208 sayfa

Son zamanlarda, teknolojik gelişmelerle birlikte alüminyum ve alüminyum alaşımları mühendislik uygulamalarında büyük önem kazanmıştır. Bugün, bu alaşımları üstün özellikleri nedeniyle endüstrinin çok çeşitli alanlarında görmek mümkündür. Bu özelliklerden bazıları alüminyumun dayanıklı, hafif ve sünek bir malzeme olmasıdır. Buna ek olarak, düşük yoğunluk, yüksek korozyon direnci ve yüksek mekanik özelliklere sahip olması, alüminyumu ulaşım, yapı, paketleme, ev gereçleri, elektronik, otomotiv, havacılık ve spor endüstrileri için önemli kılmaktadır. Ayrıca, alüminyum alaşımları ve alüminyum matrisli kompozitler savunma sanayisi ve balistik uygulamalarda genellikle tercih edilmektedir. Bu çalışma, 7075 ve 7085 gibi yüksek dayançlı alüminyum alaşımlar kullanarak balistik zırh destek plakası üretimi için alüminyum matriksli kompozit üretmeyi amaçlamaktadır. Çalışma kapsamında, alüminyum matriksli kompozitlerin balistik zırh destek plakası üretimindeki önemini kavrayabilmek için, bu iki yüksek dayançlı alüminyum alaşımları yüksek basınçlı döküm yöntemleri ile üretilmiştir. İstenilen mekanik ve fiziksel özelliklerin elde edilmesi için 7000 serisi bu alaşımlara bazı ısıl işlem, haddeleme ve dövme işlemleri uygulanmıştır. Bu sayede 7075 ve 7085 alüminyum alaşımların balistik uygulamalar için kullanımı incelenmiştir. Daha sonra alümina ve bor karbür preformlara karbon fiber sıkıştırmalı döküm yöntemi ile bu alaşımlar emdirilmiştir. Bu çalışmalar sonucunda, alüminyum matrisli kompozitlerin balistik uygulamalardaki önemini daha iyi anlamak için mikro yapı incelemesi, sertlik ölçümleri, bazı mekanik testler ve faz analizleri yapılarak kompozitler karakterize edilmiştir.

Anahtar Kelimeler: Alüminyum, 7075, 7085, Döküm Yöntemleri, Termo-mekanik işlemler, Metal Matris Kompozit, Alümina, Bor Karbür, Karbon Fiber, Metal İnfiltrasyon

To My Dear Family

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TABLE OF CONTENTS

LIST OF TABLES

TABLES:

LIST OF FIGURES

FIGURES:

CHAPTER 1

INTRODUCTION

Ballistic armors are one of the most important components for defense industry. The main purpose of these armors is to protect people or vehicles from threats that come from the environment and terrorists. There are three main groups are highly preferred in this application. The first one is metals. Throughout history, metals are always used as armor material in the battlefields after they were being used by humans. Even today, it is still impossible to stop some threats without any metals. The other group is ceramic materials. Especially after the improvements of technical ceramics, they are widely used as armor materials because of their high hardness, high heat and energy absorbing capacity. The last group of material is composites that enable to combine the properties of different materials at the same time. Fibers and fabric materials were generally used in the armor plates in order to be able to absorb high kinetic energy of the threat.

There are also three main armor types that are used in the defense industry. Reactive armors is the important one and it is used in the vehicles. The idea of reactive armors is to stop treat with small explosion that does not affect the vehicle. With the help of shock waves of small explosion, igniter part of the ammunition is deactivated. This armor type can be seen especially on the tanks. Second armor type is laminate armor. It is the structure of personal armor that is wore by soldiers in the battlefield. It consists of different materials and they come together with the help of ballistic fabrics. The other armor type is composite armors. Nowadays, it is a popular armor type since lots of different kinds of engineering materials can be used in order to produce composite armors. Thus, it can be modified and provides better protection.

In this thesis study, high strength aluminum matrix composite backing plates for ballistic armor were developed. As a metal matrix, 7xxx series aluminum alloys were chosen due to the advantages of aluminum especially in field density. 7075 and 7085 aluminum alloys were chosen and they were produced by squeeze casting, permanent mould casting and high pressure die casting methods. They were all characterized and their mechanical properties were determined by different testing methods. Therefore, it can be said that the production of these armor metals were mainly focused on. Different thermo-mechanical treatments, which include heat treatment, forging and rolling processes, were applied and the best properties were aimed to reach. All specimens were characterized and tested with several methods. After that, aluminum matrix composite plates were produces with alumina, boron carbide preforms and carbon fiber with the help of metal infiltration technique. During this process, squeeze casting was applied in order to provide high pressure under high temperatures. By this way, aluminum matrix ceramic and carbon fiber composites were produced. These composite materials were also characterized and tested same as aluminum specimens.

In the light of this information, this study is aimed to improve both of 7xxx series aluminum alloys and aluminum matrix composite plates for ballistic armor applications. Therefore, 7075 and 7085 aluminum alloys were produced as metallic matrix whereas; alumina, boron carbide and carbon fiber were used in order to create metal matrix composite backing plates.

CHAPTER 2

LITERATURE REVIEW

2.1 BALLISTIC IMPACT MECHANISM OF MATERIALS

As it is known, there are various kinds of ballistic applications with very different kinds of materials. These materials can be simple armor steels whereas; they can be very high engineering materials as the same time according to their application areas and usage aims. These materials are chosen in order to stop the treat with different design criteria. Therefore, ballistic impact mechanism gains importance for armor materials.

According to the Wadley and his co-workers, all materials have specific ballistic limits. At low impact velocities like a few hundred meters per second, the penetration resistance of a material is governed by the dynamic deformation mechanisms within the projectile and target. On the contrary, as the impact velocity increases into the hypervelocity regime like several thousand meters per second, hydrodynamic effects dominate and the penetration response becomes controlled by only the density of the impacted material and projectile [2].

As it can be seen in the Figure 1, there are three situations, which are impact, penetration and exit, when a projectile hits to the armor material. If initial impact velocity is much smaller that ballistic limit, it produces crater and just stays into the material. It causes panel bulging and material displaces according to the initial position. It is the most desired situation for an armor material because it is able to be stopped the penetration of the projectile. In the second situation, penetration just starts if initial impact velocity is just smaller than ballistic limit. It shows that there is a problem because projectile starts to move throughout the ballistic material. In the last situation, initial impact velocity is bigger than ballistic limit so plugging occurs because of the shear force of the projectile. It produces hole in the material and ballistic material cannot stop the penetration. That is why it causes disaster for a person or vehicle in which armor material is being used. In this point, % perforation vs impact velocity is important graph for ballistic materials. In the safe case, ballistic limit should be smaller than the half of impact velocity v_{50}. After the point of v_{90} fully penetration starts and it can cause some vitals problems for ballistic armor. When this ballistic impact mechanism is taken into consideration, different material groups show different behaviors against to the threats.

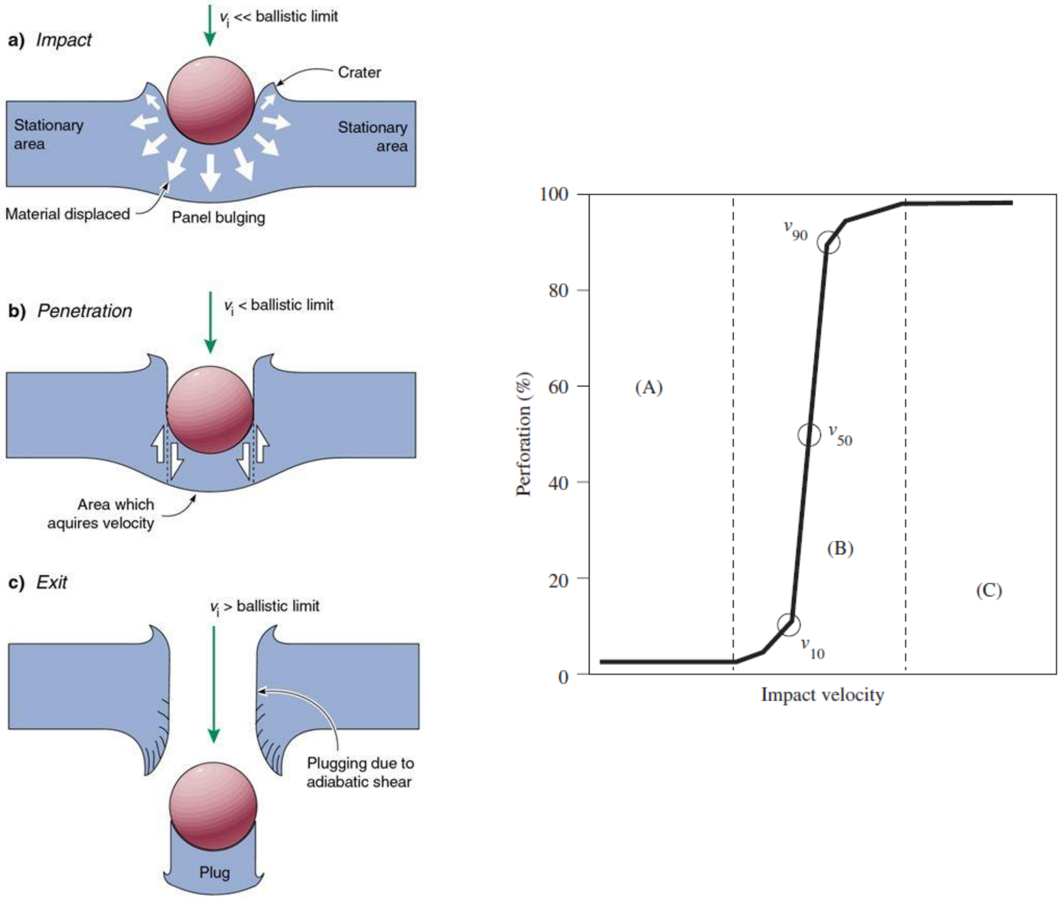


Figure 1. Ballistic impact behaviors of materials and Perforation vs. Impact Velocity Graph [1] [2]

2.1.1 Ballistic Impact Mechanism of Metals

In the defense industry, metals are still the most common materials. According to the literature, metals have some important properties that make them suitable for ballistic applications. Metals are cheaper than other materials and it is very important for mass production. Moreover, it is possible to joint metals to each other by welding and some other processes. Some secondary processes can be applied on the metals in order to be able to get desired mechanical and physical properties. Most importantly, metals can be used more than one time for ballistic applications. Unlike ceramics and fibers, metals can stay together if a projectile hits to the material. On the other hand, metals have a big disadvantage because of their weight. If the importance of weight for ballistic materials is taken into consideration, metals can have some problems in the battlefield because they can have lack of maneuver ability. This situation can make people or vehicle defenseless in some circumstances.

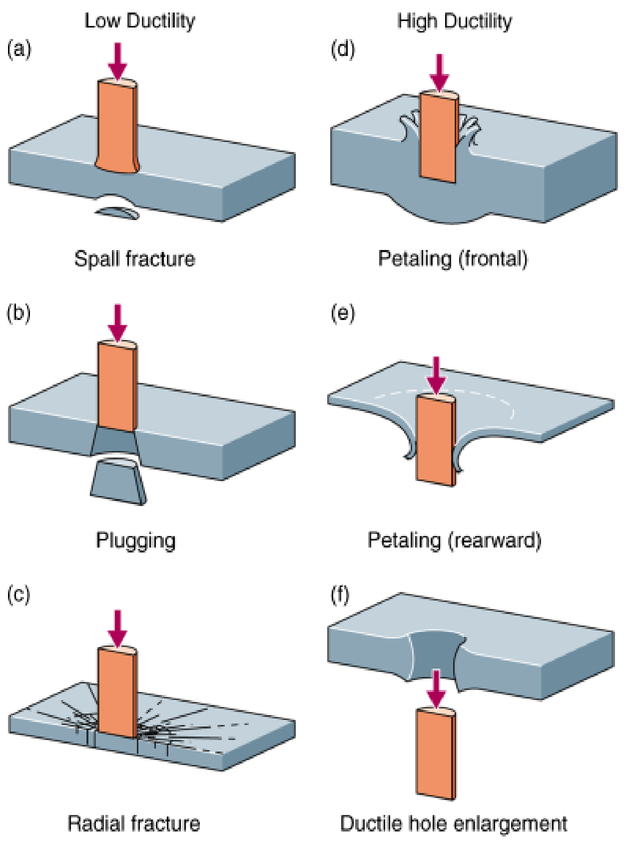


Figure 2. Ballistic impact behaviors of metals [3]

According to Yungwirth and his co-workers, ductility is important parameter for ballistic metals. As it can be seen in the Figure 2, the ductility of metal should be optimized. If metal has low ductility, it can show some behaviors like ceramic sand fracture occurs. On the other hand, if metallic material has high ductility, projectile can penetrate whole material and it can bring about some big problems. Therefore, moderate ductile metals should be chosen if they are going to be used in ballistic application in order to stop the bullet or other threats[3].

2.1.2 Ballistic Impact Mechanism of Ceramics

In the literature, ceramic materials have some important features that make them important candidates for ballistic applications. First of all, ceramics have low density and correspondingly low weight. Moreover, they have very high hardness and high elastic modulus. Beside these properties, ceramics have high compression strength and high energy absorption ability. As it can be seen in the Figure 3; when a projectile hit to the ceramic, cracks will initiate because of its high speed and they will propagate. In the classical fracture mechanism, energy is needed in order to be able to form cracks. In the ceramic materials, there will be so many cracks that the whole energy of the projectile will be absorbed by these cracks. This can be seen as main ballistic impact mechanism of ceramics [4]. In addition, these cracks will help to deformation and fragmentation of the projectile because of high hardness and compressive strength of the ceramic materials.

Unlike the advantages of ceramic materials, they have two important disadvantages. First one is that ceramics have limited elongation. This makes elastic deformation impossible for ceramic ballistic materials. The second and the most important disadvantage is that ceramics materials are able to be used only one time in ballistic applications. However, statistics helps ceramics in this point. It is almost impossible to shot something from same point more than one time. The reason of this situation is that there are lots of variables such as the speed of the wind, the temperature of the weather, the moisture of air and even the breath of the sniper when a riffle is fired. It is almost impossible in even ballistic tests that are proceeded by some special equipment. Moreover, everything moves in the battlefield so it is another factor that makes impossible to shot something from the same region more than one time. That is why ceramic materials are still common materials for ballistic application because these materials may be replaced by new armors just after the combat in the battlefield.

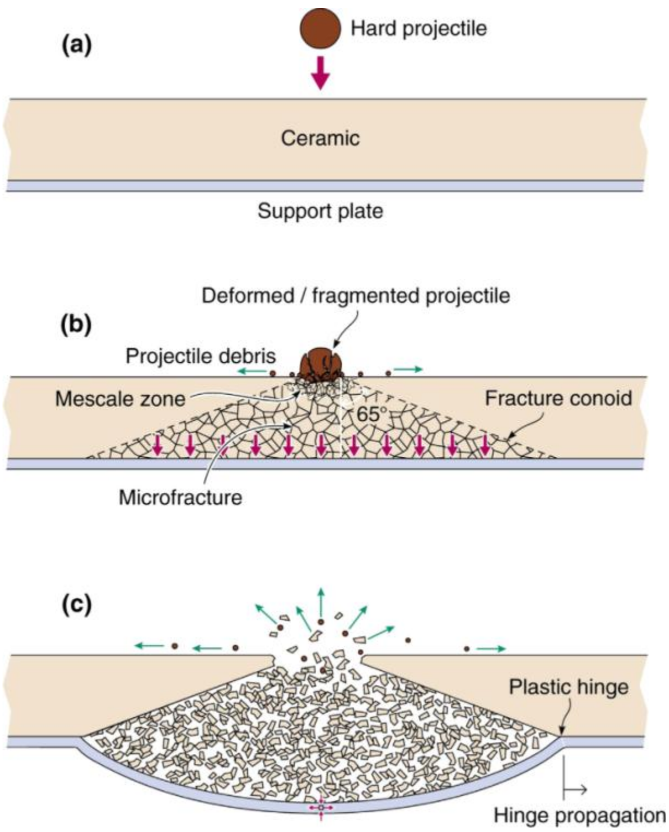


Figure 3. Ballistic impact behavior of ceramic materials [4]

2.1.3 Ballistic Impact Mechanism of Fibers

According to the literature, fibers are another important material group for ballistic applications. Lots of different kinds of fiber materials can be preferred in armor applications. Polymer matrix fibers such as carbon, glass and aramid fibers are generally used as fabric in ballistic applications. However, they can be added into some metallic matrix while ballistic composites are being produced as well. The usage of fibers has some advantages in the ballistic materials. Firstly, they have low density, low weight and high ductility. Secondly, fibers have high energy absorption capability thanks to their high elastic modulus. As it is shown in the Figure 4, there will be high stress in the tip of projectile when it hits to the fiber fabric. After that, this stress will be spread towards whole fiber fabric and the energy of the projectile will be completely absorbed. This is the main ballistic impact mechanism of fabrics. Especially multi-layer fiber fabrics are highly preferred in ballistic applications [5].

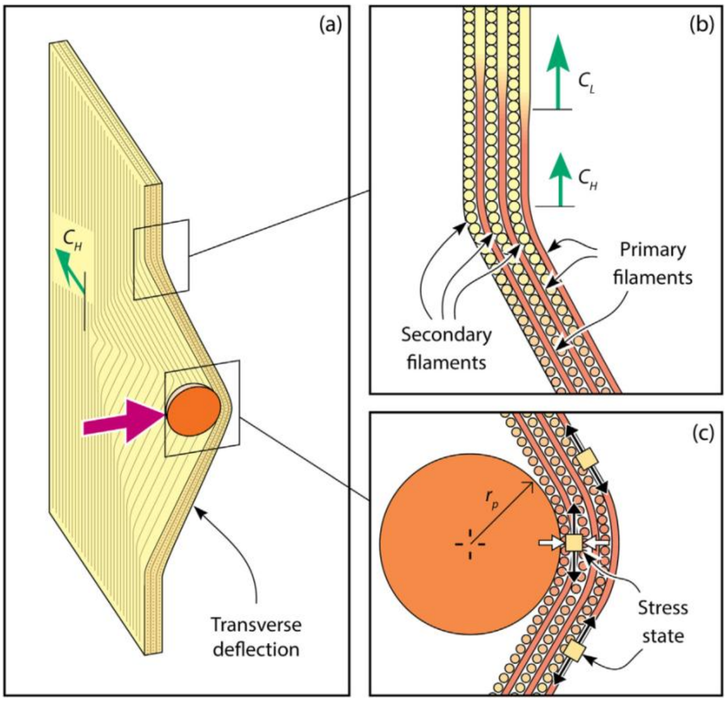


Figure 4. Ballistic impact behavior of fiber materials [4]

On the other hand, there are also some disadvantages in fibers that are used in composite ballistic applications. It would be difficult to produce composite materials with especially polymeric based fiber because wetting problems show up with metals. Moreover, the production roots of fibers are more difficult than other ballistic materials. This means that high engineering fiber fabrics can be very expensive. In addition, especially polymer based fabrics have low melting point. This situation can create some problems if it is intended to produce composites with metal matrix. This situation requires the usage of adhesive bonding and this can create some problems in the interfaces when high stress is applied. If these problems can be solved, fibers are very beneficial materials in order to be able to prevent the penetration of the projectile.

2.2 METAL MATRIX COMPOSITE MATERIALS

Generally composite materials come together with two or more materials that have different physical and chemical properties with suitable methods. It is expected to see that composite materials have superior properties according to their components [6]. As any other composite materials, metal matrix composites include two or more materials in which at least one of them should be metal. Metal matrix composite materials, which provide desired properties with the distribution of solid particles or fibrous in the metallic phase, are seen as superior materials and they are used in different branches of the industry.

Metal matrix composite materials are usually used in structural and thermal applications. Due to the fact that they have better mechanical, thermal and physical properties than their components, they are often preferred in the engineering applications. With the combination of different materials, they are able to increase some properties such as strength, toughness, thermal conductivity, wear resistance, creep strength and fatigue resistance. In order to be able to reach desired properties, ceramic and polymer based reinforcement materials are able to be used in metal matrix. They can be also produced by lots of different production routes. That is why they are important materials which are open to the improvements with the help of technology.

Metal matrix composite materials have some basic advantages. These advantages are:

- ✓ High strength/mass ratio that enables to make design according to minimum design criteria
- ✓ Dimensional stability

- ✓ High thermal stability
- ✓ High fatigue resistance [6]

They also have some superior properties according to polymer matrix composite materials as it can be seen in below:

- ✓ Better strength and toughness
- ✓ Higher hardness values
- ✓ Higher electrical conductivity
- ✓ Higher thermal conductivity and operation temperatures
- ✓ Lower contamination[6]

Nowadays, different metals can be chosen as matrix materials for metal matrix composites. It can be said that aluminum and aluminum alloys are important metals for these composite materials because of low lightness and high stability under the environmental conditions. Moreover, the mechanical properties of aluminum can be improved by alloying elements additions. Moreover, the low melting point of aluminum enables to use different production techniques. This means that fibers, filaments and solid particles can be used in aluminum matrix without losing their properties thanks to the low melting point of aluminum and aluminum alloys. Thus, it is suitable material to use for metal matrix composite materials. Aluminum matrix composite materials are used in automotive industry, sport goods, aviation, electric industry and defense industry that requires high engineering point of view.

2.3 PRODUCTION PROBLEMS OF METAL MATRIX COMPOSITES

As all other material types, some problems can appear during the production of metal matrix composite materials. Especially high operation temperatures during the production bring about some problems and defects. Furthermore, some other problems are able to show up because of the physical and chemical properties of reinforcement materials. According to the literature, these problems are basically chemical reactions between interfaces and wetting problems in between metal matrix and reinforcement materials [7].

2.3.1 Chemical Reactions Between Interfaces

During the production of composite materials, some chemical reactions can happen in between metal matrix and reinforcement materials. These chemical reactions can depend on process temperatures, process pressure, metal matrix composition and surface chemistry of reinforcement materials. These chemical reactions decrease the wetting ability of interfaces and this situation deteriorate mechanical properties of composites. Therefore, these problems should be eliminated in order not to face with some defects by controlling chemical reactions.

In this point, some operating temperatures can be important in this thesis study. Especially polymer based fiber reinforcement materials can start to react with aluminum matrix during production processes. For example, carbon fiber can react with aluminum after 1000^{o}C and it forms aluminum carbides [7]. Moreover, carbon fiber starts to deteriorate after 1000^{o}C. That is why production temperatures should be lower than 1000^{o}C. Because of the low melting point of aluminum and aluminum alloys, there is no problem in terms of interface.

2.3.2 Wetting Problem

The other problem that can appear in between metal matrix and reinforcement materials is wetting problem. The reason of this situation is strong chemical bonds in between metal matrix and reinforcement materials. However, it is possible to eliminate this problem by chancing physical properties of the surface of reinforcement materials. Some coating processes with nickel and copper are suggested in the literature to improve the wetting properties of reinforcements [7].

As it can be seen in the Figure 5, wetting conditions can be changed by changing physical properties of material surfaces. In order to be able to provide wetting condition, the angle θ should be kept smaller than 90^o. There are three ways to achieve that goal:

- ✓ Solid surface energy γ_{sv} should be increased
- ✓ Solid-liquid interface energy γ_{sl} should be decreased
- ✓ Surface tension of the liquid γ_{lv} should be decreased [7]

In addition to these, some metals that have low surface tension such as tin contributes to wetting ability of the materials according to the literature. The reason of this situation is that these metals have big atomic number and they are surface-active elements [8].

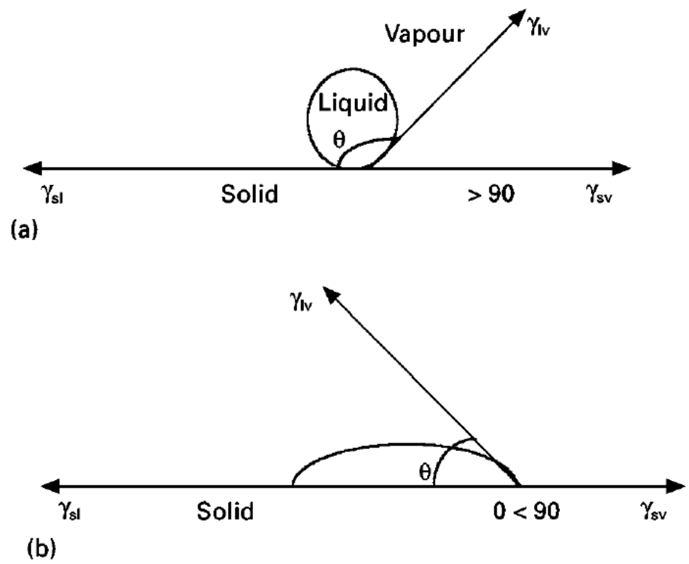


Figure 5. Schematically view of wetting (a) and non-wetting (b) conditions

2.4 ALUMINUM ALLOYS FOR BALLISTIC APPLICATIONS

With technological developments, lightweight materials gain importance in these days. Aluminum and aluminum alloys has decreased the usage of steel in ballistic applications whereas, composite and ceramic materials have already started to take the place of steel in these applications. The main reason of this situation is that these materials give people or vehicles better maneuver ability in the battlefield. Moreover, it is so important that the fuel consumptions of war machines can be decreased with the usage of these materials.

As it is known, aluminum and aluminum alloys can be considered as lightweight metals due to their relatively low density. Some aluminum alloys can be as strong as iron and steels. In addition, it is easy to form and machine these metals and this makes them a good candidate for ballistic armors. Therefore, aluminum and aluminum alloys are pretty important for defense industry in these days. Aluminum alloy series and their main alloying elements can be seen in the Table 1 as below.

Table 1. Series of cast aluminum alloys and their main alloying elements [9]

Serie	Main Alloying Element
1xx.x	Aluminum, 99.00% minimum and greater
2xx.x	Copper
3xx.x	Silicon, with added copper and/or magnesium
4xx.x	Silicon
5xx.x	Magnesium
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other element

At the first sight; 7075, 7085 and FVS812 (AA8009) aluminum alloys can be good candidate for ballistic applications because of their high mechanical properties. The chemical compositions of these aluminum alloys can be seen in the Table 2. Moreover, it is possible to compare the alloying elements of these alloys according to this table. When this table is investigated, it can be seen that zinc is the main alloying element for 7075 and 7085 whereas, main alloying element is iron for FVS 812 aluminum alloy. Moreover, it should be noted that FVS 812 aluminum alloy has important amount of rare earth metal vanadium.

As it is known; tensile strength, yield strength, modulus of elasticity and toughness are important parameters for ballistic applications. With these mechanical properties, it is aimed that the material should have the least damage after stress and collusion. This means that with these mechanical properties, it is aimed that ballistic materials should have minimum deformation in ballistic applications during combat since the bullet creates high stress level into the ballistic material when collusion occurs. According to J.R.Kennedy, unit propagation energy (UPE) versus yield strength graph is very important in order to be able to choose suitable alloy for ballistic applications. When the projectile hits to the ballistic material, it creates high stress on the material. This high stress forms cracks and little damages in the beginning. After that, these cracks propagate so fast that they cause big damages, and failure. It means that principally the alloy that has bigger propagation energy in the same stress level is better for ballistic applications. In other words, in the same stress level, more energy should be given to propagate cracks for the materials that have bigger propagation energy.

Table 2. Chemical compositions of 7075, 7085 and FVS812 aluminum alloys (weight percentage) [9]*, [10]**, [11]***

ELEMENTS	ALLOYS		
	7075*	7085**	FVS812 (AA8009)***
Silicon	0.4	0.06	1.7 - 1.9
Iron	0.5	0.08	8.4 - 8.9
Copper	1.2 - 2.0	1.3 - 2.0	---
Manganese	0.3	0.04	0.1
Magnesium	2.1 - 2.9	1.2 - 1.8	---
Chromium	0.18 - 0.28	0.04	0.1
Zinc	5.1 - 6.1	7.0 - 8.0	0.25
Titanium	0.2	0.06	0.1
Zirconium	---	0.08 - 0.15	---
Vanadium	---	---	1.1 - 1.5
Other, max. Each	0.05	0.05	0.05
Other, max. Total	0.15	0.15	0.15

In the Figure 6, comparison of unit propagation energy and yield stress values of aluminum alloys can be seen. According to this figure, it can be said that 7000 series aluminum alloys is the best candidate for ballistic applications. Furthermore, Lot96 and Lot 115 represent FVS812 aluminum alloy with different heat treatment process. This means that FVS812 is also another good aluminum alloy that is suitable for ballistic applications. It can have even better ballistic behavior than 7000 series aluminum alloys with proper heat treatment processes. Therefore, 7075, 7085 and FVS812 (AA8009) aluminum alloys can be used for producing backing plate for ballistic armors according to the literature.

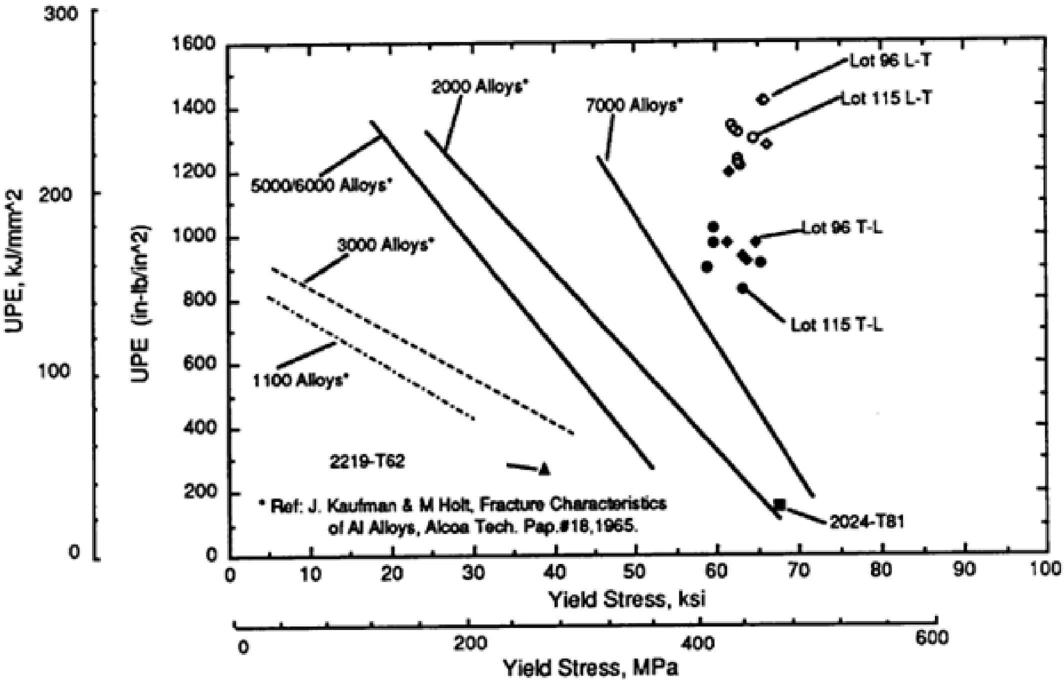


Figure 6. The comparison of aluminum alloys in terms of unit propagation energy (UPE) and yield stress [11]

2.4.1 7075 Aluminum Alloy

When high mechanical properties are taken into consideration, 7075 aluminum alloys can be seen in the first place among aluminum alloys. This aluminum alloy is used in a big variety of the industry branches. One of the most important alloying elements of this alloy, zinc contributes high mechanical properties. Therefore, 7075 aluminum alloy can have as good mechanical properties as some steel types. It is generally preferred in structural parts, which require high mechanical properties whereas high corrosion resistance of aluminum gives important place to this alloy in the industry. The main usage areas of this alloy are aviation industry, gear and shaft applications, rocket industry, bicycle parts, sport goods and defense industry. In addition to these advantages, 7075 aluminum alloy is heat treatable. Especially with T6 and T7 heat treatments, mechanical properties can be improved. Moreover, these heat treatment processes provide stable phases in the microstructure. With the help of high strength/density of this alloy, it is used in the mechanical parts that are designed by minimum weight criteria. Therefore, this alloy can be also used in ballistic applications due to high mechanical properties and other advantages. This is the reason why this alloy was also preferred in this thesis study.

Table 3. Mechanical properties of extruded 7075 aluminum alloys after T6 and T7 heat treatments in different temperatures [9]

Temperature °C	Temperature °F	Tensile strength(a) MPa	Tensile strength(a) ksi	Yield strength (0.2% offset)(a) MPa	Yield strength (0.2% offset)(a) ksi	Elongation(b), %
T6, T651 tempers						
−196	−320	703	102	634	92	9
−80	−112	621	90	545	79	11
−28	−18	593	86	517	75	11
24	75	572	83	503	73	11
100	212	483	70	448	65	14
149	300	214	31	186	27	30
204	400	110	16	87	13	55
260	500	76	11	62	9	65
316	600	55	8	45	6.5	70
271	700	41	6	32	4.6	70
T73, T7351 tempers						
−196	−320	634	92	496	72	14
−80	−112	545	79	462	67	14
−28	−18	524	76	448	65	13
24	75	503	73	434	63	13
100	212	434	63	400	58	15
149	300	214	31	186	27	30
204	400	110	16	90	13	55
260	500	76	11	62	9	65
316	600	55	8	45	6.5	70
371	700	41	6	32	4.6	70

In the Table 3, it can be easily seen that yield and tensile strength values of 7075 aluminum alloy is bigger than 500MPa. Furthermore, %elongation value of this alloy is about 11% and this is also important parameter that makes 7075 suitable for ballistic applications. Especially with age hardening and precipitation hardening mechanisms, these alloys can reach high mechanical properties.

In the literature, 7075 aluminum alloy is also known as forgeable aluminum alloy. This means that secondary mechanical properties like forging and rolling processes can be used in order to improve the mechanical properties of this alloy with strain hardening mechanism. Forging and rolling processes cause plastic deformation and it increase dislocation density. This situation decrease the dislocation motion that increase mechanical properties. This can be thought as basic strain hardening mechanism of aluminum alloys.

2.4.2 7085 Aluminum Alloy

Like 7075 aluminum alloy, 7085 is also age hardenable and forgeable aluminum alloy from 7000 series. This aluminum alloy was developed by Alcoa for thick section properties in defense and aerospace industries [12]. This alloy has good fracture toughness and fatigue properties so it is used in structural parts most of the time. 7085 aluminum alloy has high zinc content as it can be seen in the Figure 7 and it is important for precipitation hardening mechanism.

According to the literature, 7085 aluminum alloy can be used with different heat treatments. In the Figure 8, tensile strength and yield strength of extruded 7085 aluminum alloy can be seen. The tensile strength of type A 7085 aluminum alloy can reach up to 80 ksi (550MPa) whereas, yield strength value of this alloy may be 500MPa. In addition, %elongation of 7085 can be about %11 and it means that it is a suitable alloy for ballistic applications. As it was mentioned before, 7085 aluminum alloy is a forgeable alloy so it is also possible to improve its mechanical properties by precipitation hardening mechanism. Hence, some secondary processes like rolling and forging can be applied in order to be able to improve mechanical properties. This properties make 7085 aluminum alloy as suitable matrix material for metal matrix composites.

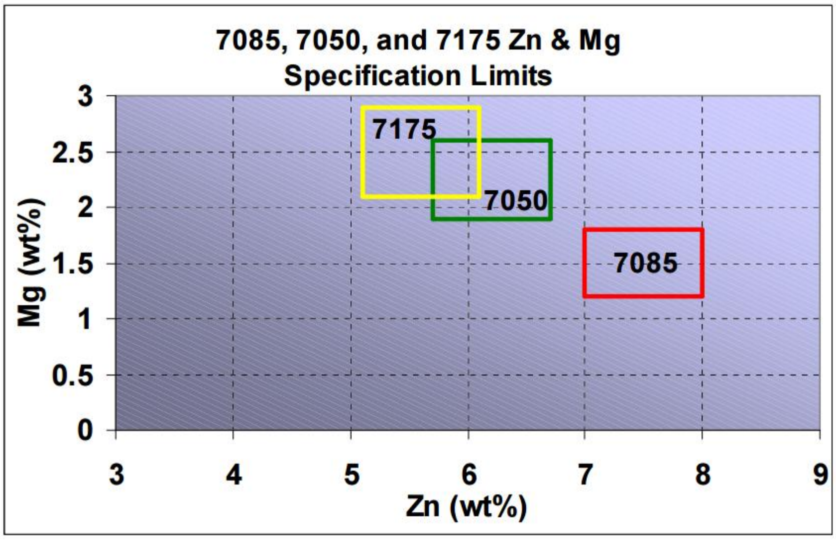
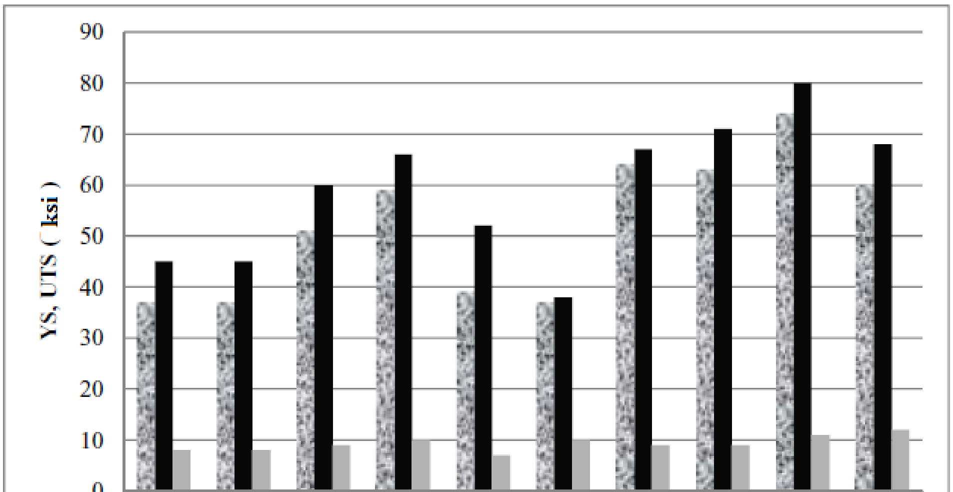


Figure 7. Zinc content comparison of some 7xxx series aluminum alloys [12]



	5083	5456	7039	2519	5059	6061	2139	2195	7085 A	7085 B
YS	37	37	51	59	39	37	64	63	74	60
UTS	45	45	60	66	52	38	67	71	80	68
%EL	8	8	9	10	7	10	9	9	11	12

Figure 8. Mechanical properties of some aluminum alloys that are used in the ballistic applications [10]

2.4.3 FVS812 Aluminum Alloy

According to the literature, FVS812 aluminum is a special aluminum alloy that was improved by NASA. It is especially used for high temperature applications and FVS812 aluminum is preferred in advanced aviation applications. Unlike other aluminum alloys, this alloy has thermal stability until 400^{o}C [11]. FVS812 includes alloying elements iron, vanadium and silicon that produce Al-Fe-V-Si system. Thanks to the dislocation interactions and intermetallic precipitations, this aluminum alloy has high mechanical properties. Moreover, low forming cost and high strength/density ratio, high creep resistance and high service temperature are the reasons why this aluminum alloy can be used in high engineering applications. Therefore, this aluminum alloy can be also good candidate for ballistic applications.

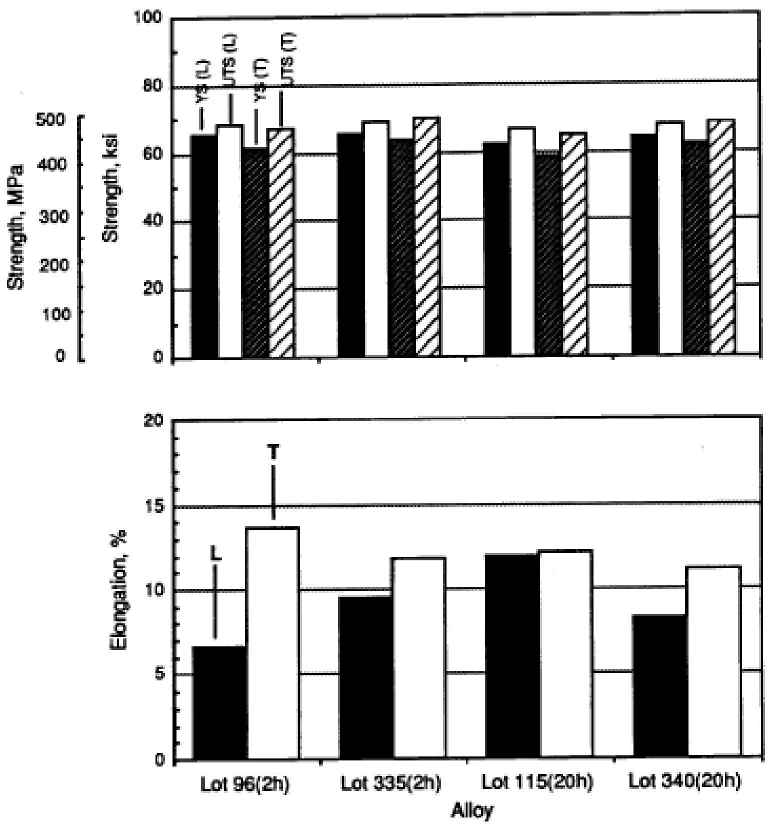


Figure 9. Mechanical properties of FVS812 in the room temperature [11]

When the Figure 9 is investigated, tensile strength of FVS812 aluminum alloy can reach 500MPa while, %elongation of this alloy can be in between 10 and 15% after heat treatment. Lot96, Lot335, Lot115 and Lot340 represent different heat treatments for FVS812 aluminum alloy. As it is known, it is possible to improve mechanical and physical properties of aluminum alloys with the help of heat treatments. That is why FVS812 can be considered as another matrix material for ballistic metal matrix composites.

2.5 HEAT TREATMENT OF ALUMINUM AND ALUMINUM ALLOYS

Heat treatment is some heating and cooling processes that follow each other with specific sequences in order to improve mechanical and physical properties of the materials. There are lots of different heat treatment operations for different materials and it is possible to give them new properties with the help of these secondary processes. For aluminum and aluminum alloys, heat treatment is always important for heat treatable series. As it was mentioned before, aluminum alloys are divided into two groups according to their forming techniques as cast and wrought alloys. Wrought aluminum alloys can be produced in the different forms such as sheet, plate, foil, extrusions, bar, rod, wire, forgings, drawn and extruded tubing. On the other hand, cast alloys are produced by sand mold, permanent mold and other processes in which casting is the final form of the product. Similarly, both of cast and wrought aluminum alloys are divided into two groups: heat treatable and non-heat treatable alloys [16].

According to the literature, casting aluminum alloys cannot be work-hardened so they have to be used in the as cast or heat treated conditions. Therefore, heat treatment processes are important for cast alloys. Non-heat treatable wrought aluminum alloys can gain new properties with strain hardening mechanism like solid solution or dispersion hardening. They consist of 1xxx, 3xxx, 4xxx and 5xxx series alloys. Unlike non-heat treatable aluminum alloys, the properties of heat treatable aluminum alloys can be improved by solution heat treatment and controlled aging process. 2xxx, 4xxx, 6xxx and 7xxx series can be strengthened by heat treatments. This heat treatment process has aging step following solutionizing and quenching. With the help of heat treatment processes, materials can have better properties according to their usage areas [16].

Table 4. Wrought alloy designation systems [16]

Alloy Series	Main Alloying Element
1xxx	99.00 minimum and greater
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other elements
9xxx	Unused series

There are different thermal treatments which provide better properties for aluminum alloys. Especially in the automotive and aviation industries, high demands should be provided in terms of mechanical properties, environmental conditions and quality control. These thermal treatments made up of:

- ✓ Homogenization
- ✓ Annealing
- ✓ Solution heat treatment
- ✓ Quenching
- ✓ Natural aging
- ✓ Precipitation hardening (Artificial aging) [16]

2.5.1 Temper Designation System for Aluminum and Aluminum Alloys

Temper designation system is a system that used in United States for wrought and cast aluminum alloys in order to be able to give information about mechanical or thermal treatments, or both. Temper designation consists of capital letters and the major subdivision of the temper. Subdivisions are shown by one more digits following the letter. The basic tempers and their meanings can be seen in the Table 5. Moreover, subdivision of Temper H and T can be also seen in the Table 6 and 7.

Table 5. Basic Temper Designations [16]

Temper Designation	Explanation
"F"	As Fabricated:Applies to products of forming processes in which no special control over thermal and work hardening conditions is employed. Mechanical property limits are not assigned to wrought alloys in this temper, but are assigned to cast alloys in “as cast,” F temper.
"O"	Annealed: Applies to wrought products that have been heated to effect re-crystallization, produce the lowest strength condition, and cast products that are annealed to improve ductility and dimensional stability.
"H"	Strain-Hardened: Applies to wrought products that are strengthened by strain hardening through cold working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The H is always followed by two or more digits (see Table 6).
"W"	Solution Heat-Treated: Applies to an unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat-treatment. This designation is specific only when the period of natural aging is specified. For example, W ½ hour solution heat treatment involves heating the alloy to approximately $1000^{o}F$ to bring the alloying elements into solid solution, followed by rapid quenching to maintain a supersaturated solution to room temperature.
"T"	Thermally Treated: Applies to products to that are hear treated, sometimes with supplementary stain-hardening, to produce a stable temper other than F or O. The T is always followed by one or more digits (see Table 7).

Temper designations for wrought products that are strengthened by strain hardening is shown as H. This designation is followed by two or more digits that are named as subdivisions. First digit indicates basic operations whereas second digit indicates degree of strain hardening. In addition, the third digit indicates variation of two digits temper. For example, HX2 represent quarter-hard whereas HX4, HX8 and HX9 means half-hard, full-hard and extra-hard respectively.

Table 6. Subdivisions of the H Temper [18]

Subdivisions	Explanation
"H1"	Strain-Hardened Only: This applies to products that are strain hardened to obtain the desired strength without supplementary thermal treatment. The digit following the H1 indicates the degree of strain hardening.
"H2"	Strain-Hardened and Partially Annealed: This pertains to products to products that are strain-hardened more than the desired final amount and then reduced in strength to the desired level by partial annealing. The digit following the H2 indicates the degree of strain hardening remaining after the product has been partially annealed.
"H3"	Strain-Hardened and Stabilized: This applies to products that are strain-hardened and whose mechanical properties are stabilized by a low-temperature thermal treatment or as a result of heat introduced during fabrication. Stabilization usually improves ductility. This designation applies only to those alloys that, unless stabilized, gradually age soften at room temperature. The digit following the H3 indicates the degree of strain hardening remaining after stabilization.

The temper designation T represents cast and wrought aluminum alloys that are strengthened by heat treatment in order to get stable tempers other than W, O or H. The T is followed by numbers from 1 to 10 and each number indicates the specific sequence of basic heat treatments. Second digit indicates variation in basic treatment. For instance, T42 or T62 mean heat-treated to tempered by user. Sometimes there can be also some additional digit and they indicate stress relief. For example, TX51 means stress relieved by stretching while, TX52 and TX54 represent stress relieved by compressing and stress relieved by stretching and compressing respectively.

Table 7. Subdivisions of the T Temper [18]

Subdivisions	Explanation
"T1"	Cooled From an Elevated-Temperature Shaping Process and Naturally Aged to Substantially Stable Condition: This designation applies to products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been stabilized by room-temperature aging.
"T2"	Cooled From an Elevated-Temperature Shaping Process, Cold Worked, and Naturally Aged to a Substantially Stable Condition: This variation refers to products that are cold worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which mechanical properties have been stabilized by room-temperature aging.
"T3"	Solution Heat Treated, Cold Worked, and Naturally Aged to a Substantially Stable Condition: T3 applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties have been stabilized by room-temperature aging.
"T4"	Solution Heat Treated and Naturally Aged to a Substantially Stable Condition: This signifies products that are not cold worked after solution heat treatment and for which mechanical properties have been stabilized by room-temperature aging. If the products are flattened or straightened, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.
"T5"	Cooled From an Elevated-Temperature Shaping Process and Artificially Aged: T5 includes products that are not cold worked after an elevated-temperature shaping process such as casting or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment. If the products are flattened or straightened after cooling from the shaping process, the effects of the cold work imparted by flattening or straightening are not accounted for in specified property limits.
"T6"	Solution Heat Treated and Artificially Aged: This group encompasses products that are not cold worked after solution heat treatment and for which mechanical properties or dimensional stability, or both, have been substantially improved by precipitation heat treatment.

Table 7. Continued

"T7"	Solution Heat Treated and Overaged or Stabilized: T7 applies to wrought products that have been precipitation heat treated beyond the point of maximum strength to provide some special characteristic, such as enhanced resistance to stress-corrosion cracking or exfoliation corrosion.
"T8"	Solution Heat Treated, Cold Worked, and Artificially Aged: This designation applies to products that are cold worked specifically to improve strength after solution heat treatment and for which mechanical properties or stability, or both, have been substantially improved by precipitation heat treatment.
"T9"	Solution Heat Treated, Artificially Aged, and Cold Worked: This grouping is comprised of products that are cold worked specifically to improve strength after they have been precipitation heat treated.
"T10"	Cooled From an Elevated-Temperature Shaping Process, Cold Worked, and Artificially Aged: T10 identifies products that are cold worked specifically to improve strength after cooling from a hot-working process such as rolling or extrusion and for which mechanical properties have been substantially improved by precipitation heat treatment.

2.5.2 Preheating, Reheating and Homogenization

Preheating, reheating and homogenization are applied to the aluminum alloys that are produced by different processes. Preheating is applied to aluminum logs or billets and they are heated up to intermediate uniform temperatures. It is a fast heating process that should be controlled very well in order not to cause surface melting. It is applied just before some secondary processes. Reheating is a heating process that is applied to slabs just before the rolling process. During the rolling process, the thickness of slab is decreased and it gives big deformation to the material. That is why reheating is used to eliminate cracking in the material. Homogenization is also used for aluminum logs or billets. Unlike preheating and reheating, homogenization process requires long period of time like 15-20 hours [16]. It is also applied just before secondary processes such as rolling or extrusion. All of these thermal treatments are applied below the recrystallization temperature.

2.5.3 Annealing

Annealing process is applied to aluminum alloys in order to soften the material at intermediate temperatures. The important thing is that this process is done above crystallization temperature. However, it is generally used at the lowest temperature that yields the soften state of the aluminum alloys. Cast aluminum alloys are annealed in order to relief residual stressed. Moreover, it is done to increase dimensional stability of the casting parts. It is applied around 340^{o}C during 3-4 hours [16,17]. Non-heat treatable wrought aluminum alloys should be annealed quickly in order to eliminate grain growth that deteriorates mechanical properties. For heat treatable wrought aluminum alloys, annealing should be done for two situations. In the first one, if the material has already gained hardness because of secondary processes like rolling, forging or extrusion, annealing should be done in the lower temperatures around 340^{o}C. It is also done to prevent some problems that are caused by residual stressed. In the second situation, if the material has hardness because of the other heat treatments, annealing is operated at relatively high temperatures like 410^{o}C. Annealing is generally applied in two steps that include first and second situations. Annealing temperatures and required information for some aluminum and aluminum alloys can be seen in the Table 8.

Table 8. Annealing conditions for wrought and cast aluminum and aluminum alloys [16]

Alloy	Annealing Temperature, F	Time at Temperature	Alloy	Annealing Temperature, F	Time at Temperature
1060	650	/ 1	5083	650	/ 1
1100	650	/ 1	5086	650	/ 1
1350	650	/ 1	5154	650	/ 1
2014	760 / 2		5254	650	/ 1
2024	760 / 2		5454	650	/ 1
2036	760 / 2		5456	650	/ 1
2117	760 / 2		5457	650	/ 1
2219	760 / 2		5652	650	
3003	775	/ 1	6005	760 / 2	
3004	650	/ 1	6053	760 / 2	

Table 8. Continued

3105	650	/ 1	6061	760 / 2	
5005	650	/ 1	6063	760 / 2	
5050	650	/ 1	6066	760 / 2	
5052	650	/ 1	7001	760 / 3	
5056	650	/ 1	7075	760 / 3	
A140	600		7178	760 / 3	
214	600		142	650	
364	650		319	650	
/1 Time at temperature should not be any longer than to get the center of the furnace load up to temperature. Rate of cooling from the annealing temperature is not important.					
/2 This annealing practice removes the effect of prior solution heat treatment. Material must be cooled at 50F for hour from the annealing temperature to 500F. Subsequent cooling rate is not important.					
/3 This is a two stage annealing practice that removes the effect of prior solution heat treatment. This is accomplished by air cooling from the annealing temperature to 400F or less. The second stage requires heating the material to 450F for 4 hours and cooling to room temperature in any convinient manner.					

2.5.4 Solution Heat Treatment

Solution heat treatment, that is also named as solutionizing, is a heating process of aluminum and aluminum alloys up the just below the eutectic temperature. The main aim of this treatment is to get maximum solute in the solid solution. Because of that, materials should be hold long enough in that temperature in order to be able to allow the formation of maximum amount of solid solution. Just after solutionizing process, aluminum and aluminum alloys should be quenched to maintain the existence solute in the super saturated solute solution [16].

There are some critical parameters during solution heat treatment. The first one is solutionizing temperature. It should be chosen carefully in order to not to decrease properties of the materials. This is so critical especially in the alloys that have low solutionizing range. If the temperature is chosen higher than the normal, localized melting can occur. This situation is names as incipient melting and it deteriorates the mechanical properties of the aluminum and aluminum alloys. Similarly, if the solutionizing temperature is chosen lower than normal, solute solutes cannot go into the solute solution. Therefore, there will be low amount of solutes during precipitation hardening reactions. Suitable solutionizing temperatures for different aluminum alloys can be seen as below.

Table 9. Solutionizing temperatures for wrought alloys (Extruding Forgings) [16]

Alloy	Product Type	Solution Heat Treating Temperature, ^oF
2011	Wire, Rod and Bar	945-985
2014	Sheet, Plate, Extrusion and Tube	924-945
2017	Wire, Rod and Bar	925-950
2020	Sheet, Plate	950-970
2024	Sheet, Plate, Extrusion and Tube	910-930
2048	Sheet, Plate	910-930
2117	Wire, Rod and Bar	925-950
	Rivets	890-950
2124	Plate	910-930
2219	Sheet, Plate, Extrusion and Tube	985-1005
2618	Extrusion	970-990
6061	Sheet, Plate, Extrusion and Tube	960-1075
6066	Extrusion and Tube	960-1010
6262	Sheet, Plate, Extrusion and Tube	960-1050
6951	Sheet	975-995
7001	Extrusion	860-880
7039	Sheet, Plate	840-860
7049	Extrusion	865-885
7050	Sheet, Plate, Extrusion, Wire and Rod	880-900
7075	Sheet, Plate, Wire, Rod and Bar	860-930
	Extrusion, Drawn Tube	860-880
7178	Sheet	860-930
	Plate	860-910
	Extrusion	860-880

Table 10. Solutionizing temperatures for forgings [16]

Alloy	Product Type	Solution Heat Treating Temperature, ^{o}F
2014	Die and Hand Forgings	925-945
2018	Die Forgings	940-970
2024	Die and Hand Forgings	910-930
2025	Die Forgings	950-970
2218	Die Forgings	940-960
2219	Die and Hand Forgings	985-1005
2618	Die and Hand Forgings	975-995
4032	Die Forgings	940-970
6053	Die Forgings	960-980
6061	Die and Hand Forgings, including Rolled Rings	960-1075
6151	Die and Hand Forgings, including Rolled Rings	950-980
7049	Die and Hand Forgings	865-885
7050	Die and Hand Forgings	880-900
7075	Die and Hand Forgings, including Rolled Rings	860-890
7076	Die and Hand Forgings	850-910

Table 11. Solutionizing temperatures for castings [16]

Alloy	Casting Type	Solution Heat Treating Temperature, ^{o}F
222.0	Sand and Permanent Mold	930-960
242.0	Sand and Permanent Mold	950-980
295.0	Sand	940-970
296.0	Permanent Mold	935-965
319.0	Sand	920-950
A336.0	Permanent Mold	940-970
355.0	Sand and Permanent Mold	960-990
C355.0	Permanent Mold	960-990
356.0	Sand and Permanent Mold	980-1010
A356.0	Sand and Permanent Mold	980-1010
520.0	Sand	800-820

The time interval of solution heat treatment is also another important parameter that influences the final properties of the aluminum and aluminum alloys. If enough time is not given to the material during solution heat treatment, there will not be enough solute in the solution during quenching. This means that there will be less precipitates at the end of precipitation hardening. This situation affects mechanical properties negatively.

During solution heat treatment, solutionizing time should be as short as possible. Therefore, keeping aluminum parts very long in the furnace can cause high temperature oxidation. This situation also causes blister problem especially in the 7xxx series of aluminum alloys. Long solutionizing time is also not good for electricity consumption. It can be critical for especially big companies that work with big furnaces because it affects the final price of the material directly. Solutionizing time should be determined by the thickness of the materials [16]. Solutionizing time for wrought and cast aluminum alloys according to the thickness can be seen in the Table 12 and 13. It should be noted that this thickness is in the inch scale in order not to make a mistake. During the heat treatment of aluminum and aluminum alloys, quenching follows solution heat treatment.

Table 12. Soaking time for solution heat treatment of all wrought products [16]

Thickness (inches)	Soaking Time (minutes)			
	Salt Bath		Air Furnace	
	Minimum	Maximum (alclad only)	Minimum	Maximum (alclad only)
0.016 and below	10	15	20	25
0.017-0.020	10	20	20	30
0.021-0.032	15	25	25	35
0.033-0.063	20	30	30	40
0.064-0.090	25	35	35	45
0.091-0.124	30	40	40	50
0.125-0.250	35	45	50	60
0.251-0.500	45	55	60	70
0.501-1.000	60	70	90	100
1.001-1.500	90	100	120	130
1.501-2.000	105	115	150	160
2.01-2.500	120	130	180	190
5.501-3.000	150	160	210	220
3.001-3.500	165	175	240	250
3.501-4.000	180	190	270	280

Table 13. Soaking time for solution heat treatment of cast alloys [16]

Alloy	Casting Type	Soaking Time (hours)
222.0	Sand and Permanent Mold	6-18
242.0	Sand and Permanent Mold	2-10
295.0	Sand	6-18
296.0	Permanent Mold	4-12
319.0	Sand	6-18
336.0	Permanent Mold	6-18
355.0	Sand and Permanent Mold	6-18
C355.0	Permanent Mold	6-18
256.0	Sand and Permanent Mold	6-18
A356.0	Sand and Permanent Mold	6-18
520.0	Sand	12-24

2.5.5 Quenching

Quenching is an important process that follows solution heat treatment in order to create supersaturated solid solution. It can be basically describe as rapid cooling process. It can be done in the water, oil or salt bath. There can be some additions in the bath in order to create rapid cooling condition because quenching time is an important step that affects the properties of the materials.

During quenching process, heterogeneous precipitation occurs. There are two important mechanisms during heterogeneous precipitation: degree of solute supersaturation and the diffusion rate as a function of temperature. When quenching process is applied, there is a big supersaturation in the material at elevated temperatures. Nevertheless, the diffusion rate is depended on the temperature so diffusion rate is also high. This situation causes precipitation occurring during quenching. It is not the desired condition because it prevents subsequent hardening by eliminating any further precipitation reactions. That is why materials should be kept in the moderate temperatures before quenching. The main aim is to create supersaturated solid solution in the materials with quenching by limiting diffusion with the help of rapid cooling [16, 17].

2.5.6 Natural Aging

There are some heat treatable alloys that can be hardened in the room temperatures with T3 or T4 conditions. In these alloys, supersaturated solid solution and vacancies can transform to the GP (Guiner-Preston) zones rapidly. In these alloys, strength increases so fast that it can even change the final shape of the material in 4-5 days. Even if material can have better mechanical properties, natural aging is not stable process because there can be still some changes in the material. Thus, natural gaining is not desired especially in some machined parts. In order to stop natural aging, aluminum and aluminum alloys should be kept below 0^oC after solution heat treatment and quenching. -40^oC is recommended in order to prevent all affects of the natural aging in the literature [16].

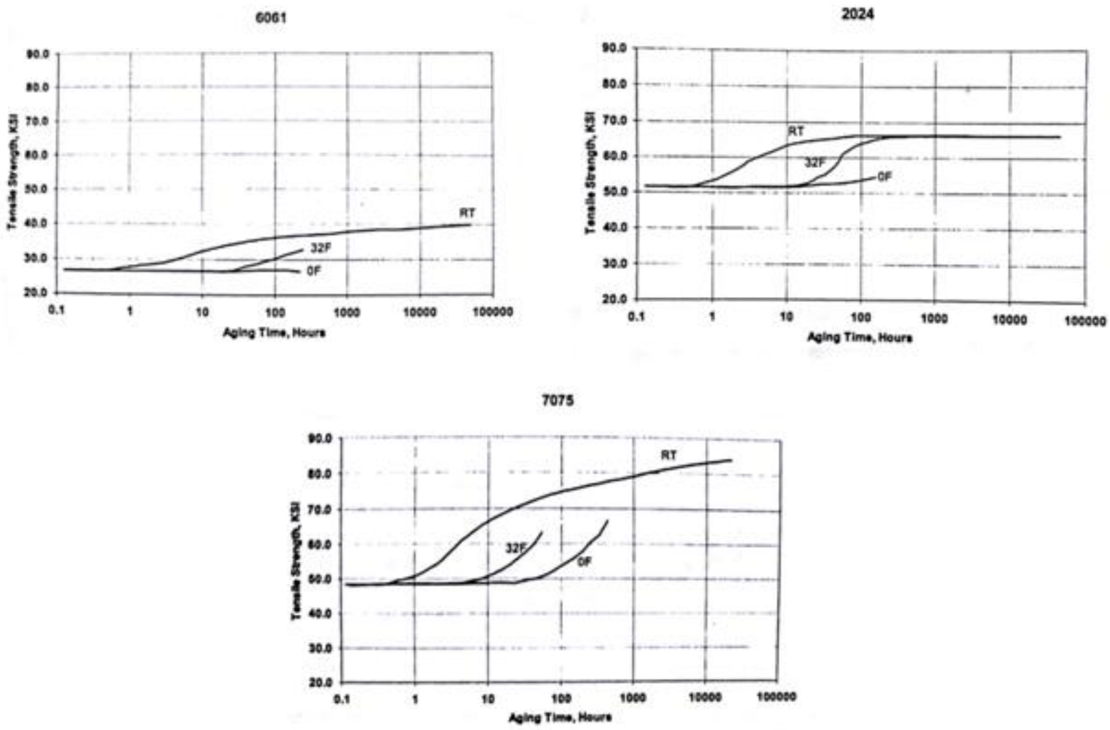


Figure 10. The effects of natural aging time and temperatures on three different alloys [16]

2.5.7 Precipitation Heat Treatment (Artificial Aging)

As it is known, pure aluminum has pure mechanical and physical properties. Alloying additions are used to improve these properties of aluminum. In addition, heat treatment is a good way to reach desired properties for different application areas. In this point, precipitation heat treatment is an important process in order to be able to get better mechanical and physical properties for heat treatable aluminum alloys.

Precipitation hardening includes heating the aluminum alloy in between 90 and 250^{o}C during a period of time [16]. In this temperature and time interval, supersaturated solid solution that is created by quenching just after solution heat treatment starts to dissolve. It brings about clustering solute atoms near the vacancies. After that, diffusion mechanism starts to work and atoms move towards to the clusters. With this way, coherent precipitates form. Due to the fact that solute atom clusters have a mismatch in the matrix, there are strain fields around these solute cluster. With the effect of time, these clusters get bigger and bigger and the matrix cannot support the strain anymore. This is the reason of formation semi-coherent precipitates. At the end, when semi-coherent precipitates reach enough size, matrix can no longer accommodate the crystallographic mismatch and equilibrium precipitates form. This is the basic precipitation hardening mechanism of precipitation hardenable aluminum alloys. Aging processes should be done just below a metastable miscibility gap that is named as “Guiner-Preston” GP zone because zone formation is relatively faster for vacancies thanks to diffusion.

Precipitation heat treatment causes drastically increasement in mechanical properties like hardness, yield strength and ultimate tensile strength just after rapid cooling in quenching process. As it was mentioned before, supersaturated solid solution, which is produced by quenching after solution heat treatment, is the driving force in the precipitation hardening mechanism. That is why it should be mentioned that the more supersaturated solid solution, the better mechanical properties in aluminum alloys. There are some precipitating systems in 7xxx aluminum alloys.

In the literature, it can be stated that coherent particles are shared by dislocations and this situation harden the aluminum alloys. Precipitates that locate in the matrix prevent the dislocation motion. In other words, dislocations are impeded by these particles and matrix and this situation makes difficult the motion. This is the basic precipitation hardening mechanism of aluminum alloys [16].

2.5.7.1 Al-Cu System

The equilibrium phase diagram of aluminum and copper is eutectic system as it can be seen in the Figure 11. In this system, Al_2Cu, θ phase has an important effects in the precipitation hardening in some aluminum alloys. After quenching, rapid cooling produces supersaturated solid solution and they transform to GP zones. GP zone transforms to coherent precipitate θ” and semi coherent precipitate θ’ respectively. At the end, stable precipitate θ, Al_2Cu, is formed. This is the main precipitation hardening mechanism of aluminum alloys that have copper content such as 2xxx series aluminum alloys [16].

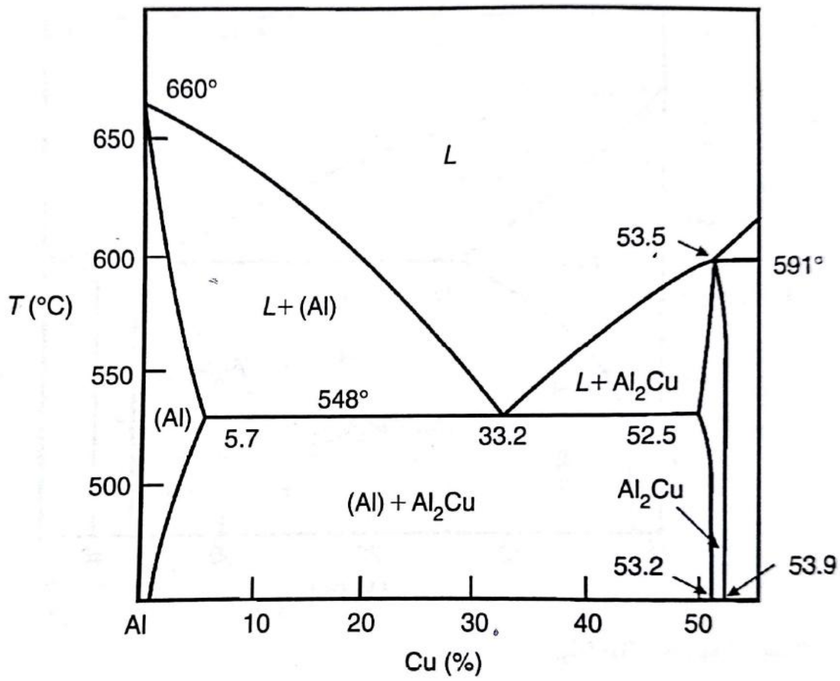


Figure 11. Eutectic phase diagram of Al-Cu [19]

2.5.7.2 Al-Cu-Mg System

This system is quite important for wrought type aluminum alloys. In the literature, it is mentioned that aluminum solid solution can be in the equilibrium with Al_2Cu and Al_8Mg_5 binary phases whereas, they can be also in the equilibrium with Al_2CuMg (S) and Al_6CuMg_4 ternary phases [19]. During precipitation hardening of this system, copper and magnesium atoms go towards GP zones and they form incoherent S' precipitates. Cold work after quenching process increase the density of S' dislocations and they produce fine distribution in the matrix as stable S precipitates.

SS ----- GP Zones ----- S' (Al_2CuMg) ----- S (Al_2CuMg)

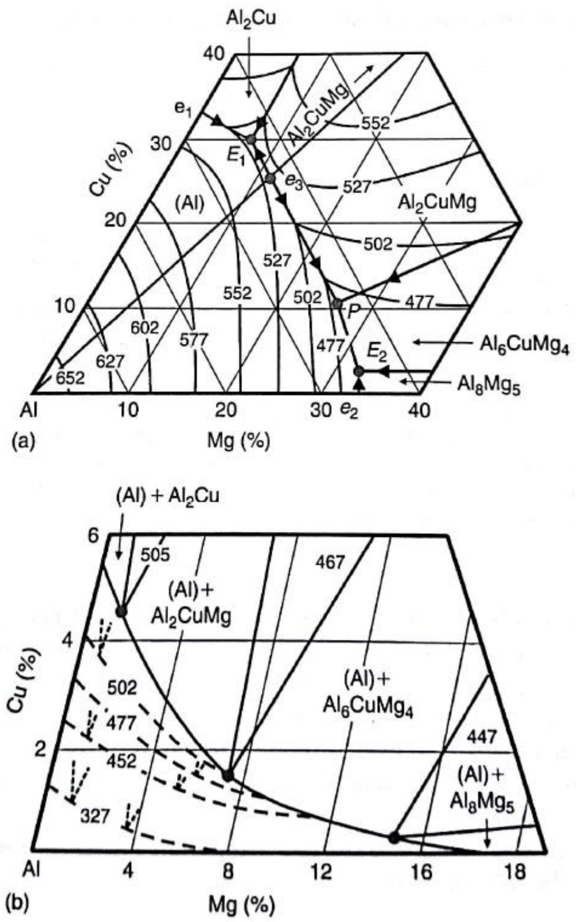


Figure 12. Ternary phase diagram of Al-Cu-Mg (a) liquidus projection (b) distribution of phase fields in the solid state [19]

2.5.7.3 Al-Mg-Zn System

Al-Mg-Zn is other important system in order to be able to better understand the properties of some aluminum alloys. The liquidus, solidus and solvus isotherms of this system can be seen in the Figure 13. Moreover, ternary reactions of Al-Mg-Zn system are shown in the Table 14. The most important systems in this ternary phase diagram are Al-$Al_2Mg_3Zn_3$ (489°C) and Al-$MgZn_2$ (475°C). In the literature, it is mentioned that solubility of magnesium and zinc in aluminum decrease in the relatively low temperatures. This situation causes dispersion hardening of metastable phases of $Al_2Mg_3Zn_3$ (T') and $MgZn_2$ (η'') [19].

Table 14. Non-variant phase reactions in ternary alloys of the Al-Mg-Zn system [19]

Phase reaction	T (°C)	Chemical composition, in phases[a] (%)							
		I		II		III		IV	
		Mg	Zn	Mg	Zn	Mg	Zn	Mg	Zn
$L \rightarrow Al + Mg_5Al_8 + Al_2Mg_3Zn_3$	447	30	12	13	2	34	10	30	26
$L \rightarrow Al + Al_2Mg_3Zn_3$	489	18	45	5	12	21	54	–	–
$L \rightarrow Al + MgZn_2$ $L \rightarrow Al + MgZn_2 + Mg_3Zn_3Al_2$	475	11.3	60.4	3	14	16	83	20	64
$L + MgZn_2 \rightarrow Mg_2Zn_{11} + (Al)$	368	3.5	92	15	85	7	92	1	78
$L \rightarrow Mg_2Zn_{11} + (Al) + (Zn)$	343	3	93	1	80	7	92	0.5	99

[a] I–IV: phases participating in reactions.

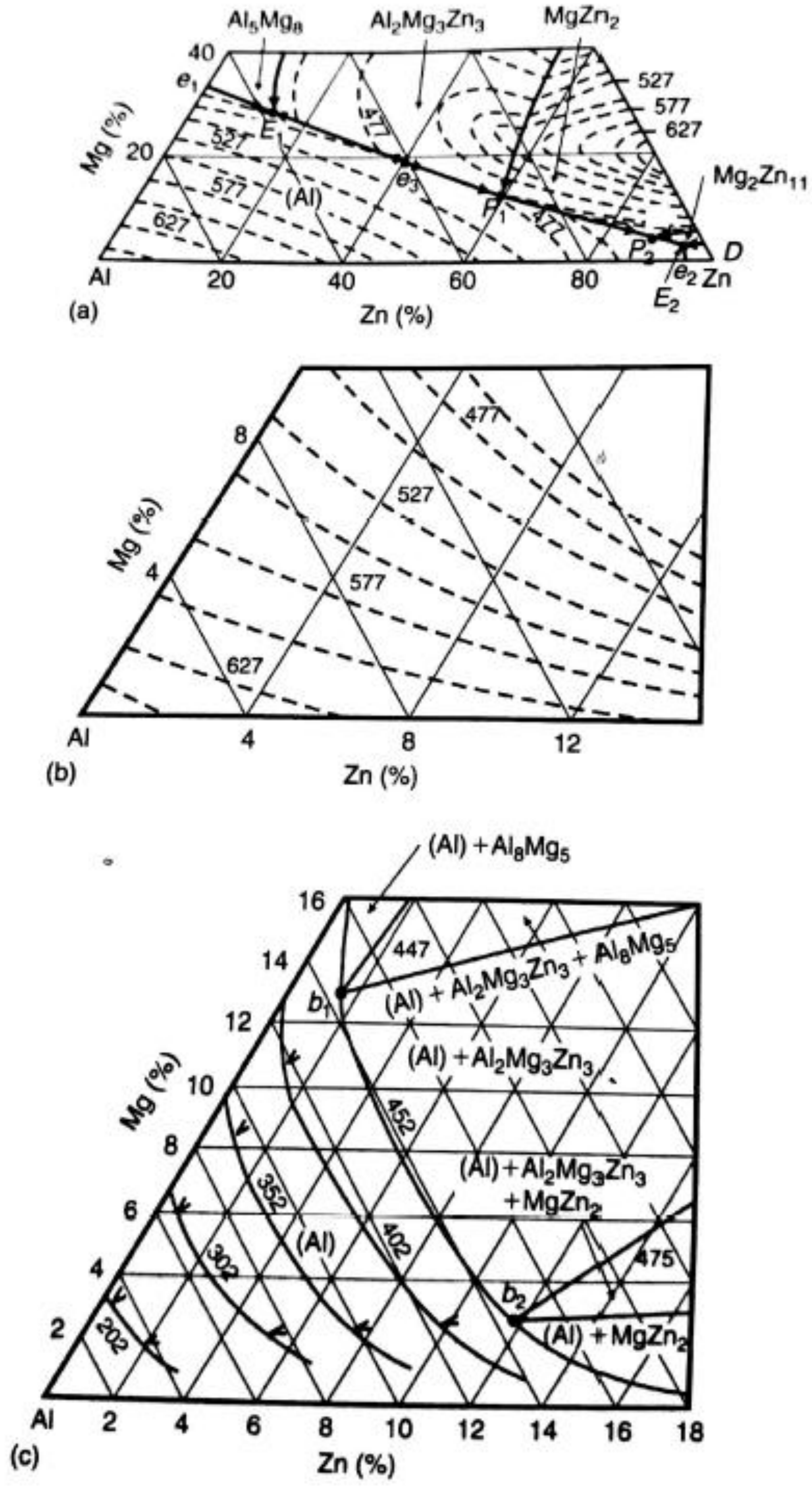


Figure 13. Ternary Phase Diagram of Al-Mg-Zn (a) liquid projection (b) distribution of phase fields in the solid state (c) solvus isotherm of Al corner [19]

2.5.7.4 Al-Zn-Mg-Cu System

There are some complex precipitation mechanisms in 7xxx series aluminum alloy because of Al-Zn-Mg-Cu system. Supersaturated solid solution transforms to precipitates with different precipitation sequences. There are four different sequences in this Al-Zn-Mg-Cu system as it can be seen as below.

- ✓ α_{sss} ----- S
- ✓ α_{sss} ----- T' ----- T
- ✓ α_{sss} ----- VRC ----- GPZ ----- η' ----- η
- ✓ α_{sss} ----- η

All of these precipitation sequences start with supersaturated solid solution that is produced by quenching following by solution heat treatment. These S, T and η precipitates represent Al_2CuMg, $Al_2Mg_3Zn_3$ and $MgZn_2$ respectively. In the first precipitation sequence, Al_2CuMg, S phase forms directly from supersaturated solid solution that is created by quenching. This precipitate is indicated as coarse intermetallic and it is insoluble at 465^{o}C in Al-Zn-Mg-Cu alloy systems. It is fine part precipitate [16].

There is T phase transformation in the second precipitation sequence. In this precipitation step, T' forms with the decomposition of supersaturated solid solution. It can be seen as intermediate phase in this phase transformation. After that, T phase that is incoherent with aluminum matrix forms with the formula of $Mg_{32}(Al,Zn)_{49}$. According to the Handbook of Aluminum Volume 1, T phase is formed as precipitates only above 200^{o}C [16].

The third sequence can be seen as one of the most important precipitation mechanism for especially 7xxx series aluminum alloys. Supersaturated solid solution decomposes to clusters near to the vacancy reached regions and they transform to GP zones. After that GP zones form semi-coherent η' and finally incoherent equilibrium phase η, $MgZn_2$ precipitates. The last sequence is almost the same with third sequence. The only difference is that supersaturated solid solution transforms to equilibrium η phase directly [16].

In the literature, it is mentioned that GP zones are pretty important step of the precipitation hardening because η’ precipitates are formed by this phase. This is a unique precipitation behavior of Al-Mg-Zn alloy systems. Copper can be also seen as important component of Al-Mg-Zn-Cu system since GP zones are copper rich regions. Even if copper does not have a direct affect to the precipitation sequences, it provides stability to η phase.

It should be mentioned that precipitation heat treatment is an important stage for heat treatable aluminum alloys. Therefore, it is also crucial for 7xxx series aluminums. With the help of precipitation heat treatment, these alloys can have better mechanical, physical and electrical properties. The hardness and conductivity values of some heat treated aluminum alloys can be seen in the Table 15 and 16.

Table 15. Hardness and conductivity values for heat treated aluminum alloys (Clad) [16]

Alloy	Temper	Sheet Thickness	Rockwell Hardness, minimum			Typical Conductivity
			B	E	15T	
2014	T6	.062 & Under	76	102	85	35.5-44.0
		.063 & Over	75	101	-	35.5-44.0
2024	T3	.062 & Under	57	91	79	28.5-35.0
		.063 & Over	60	93	-	28.5-35.0
	T4	.062 & Under	57	91	79	28.5-35.0
		.063 & Over	60	93	-	28.5-35.0
	T6	.062 & Under	60	93	81	35.0-45.0
		.063 & Over	62	94	-	35.0-45.0
	T8	All	65	97	82	35.0-45.0
2219	T6	.062 & Under	61	92	80	32.0-37.0
		.063 & Over	60	91	-	32.0-37.0
	T8	.062 & Under	64	96	82	31.0-37.0
		.063 & Over	63	95	-	31.0-37.0
6061	T6	All	84	74	-	40.0-53.0

Table 15. Continued

7075	T6	.032 & Under	78	103	86	30.5-36.0
		.033 - .062	76	102	-	30.5-36.0
		.063 & Over	75	101	-	30.5-36.0
	T76	.032 & Under	76	102	84	38.0-42.0
		.033 - .062	75	101	-	38.0-42.0
		.063 & Over	74	100	-	38.0-42.0
7078	T6	.036 & Under	79	104	86	29.0-34.0
		.037 - .062	78	103	-	29.0-37-0
		.063 & Over	76	102	-	29.0-37.0

Table 16. Hardness and conductivity values of heat treated aluminum alloys with various temper temperatures [16]

Alloy	Temper	Brinnel	Rockwell Hardness				Typical Conductivity
			B	E	H	15T	
1100	O	-	-	-	50 Max.	-	57.0-62
3003	O	-	-	-	65 Max.	-	44.5-50.5
5052	O	-	-	70 Max.	95 Max.	-	34-37
2014	O	-	22 Max.	70 Max.	95 Max.	-	43.5-51.5
	T3	100	65	95	-	82	31.5.1935
	T4	100	65	95	-	82	31.5-34.5
	T6	125	78	102	-	86	35.5-41.5
2024	O	-	22 Max.	70 Max.	95 Max.	-	46-51
	T3	110	69	94	-	82	28.5-32.5
	T4	100	63	94	-	82	28.5.1934
	T6	118	72	98	-	84	36.5-40.5
	T8	120	74	99	-	85	35-42.5
2124	T3	110	69	97	-	-	28.5-32.5
	T8	120	74	99	-	-	35.0-42.5
2219	O	-	22 Max.	95			44-49
	T3	98	60	92	-	79	26.0-31.0
	T37	99	62	93	-	81	27.0-31
	T4	96	58	90	-	78	28.0-32
	T6	99	62	93	-	81	32.0-35.0
	T8	116	71	98	-	83	31.0-35
	T67	124	75	100	-	84	31.0-35
6061	O	40 Max.	-	-	75 Max.	-	42.0-49
	T4	50	-	70	-	64	35.5-43.0
	T6	80	42	85	-	78	40.0-47.0

Table 16. Continued

6063	O	-	-	-	70 Max.		57.0-65.0
	T1	-	-	37	-	53	48.0-58.0
	T4	-	-	40	-	54	48.0-58.0
	T5	-	-	44	-	57	50.0-60.0
	T6	60	-	70	-	68	50.0-60.0
6066	O	-	-	40 Max.	-	-	42.0-47.0
	T4	-	-	85	-	76	34.0-41.0
	T6	102	65	95	-	82	38.0-50.0
7049	O	-	22 Max.	70 Max.	95 Max.		44.0-50.0
	T73	134	81	104	-	85	40.0-44.0
	T76	142	84	106	-	87	38.0-44.0
7050	O	-	22 Max.	70 Max.	95 Max.	-	44.0-50.0
	T73	134	81	104	-	85	40.0-44.0
	T736	140	82	105	-	86	40.0-44.0
	T76	142	84	106	-	87	39.0-44.0
7075	O	-	22 Max.	70 Max.	95 Max.	-	44.0-48.0
	T6	142	84	106	-	87	30.5-36.0
	T73	129	78	102	-	85	40.0-43.0
	T76	136	82	104	-	86	38.0-42.0

2.6 PRODUCTION METHODS

In the industry, there are big varieties of processes that are preferred for the production of metal and composite materials. Especially for metals, melting and casting processes can have big importance whereas, metal infiltration technique can be crucial for the production of metal matrix composite materials. Different processes are used in order to get different properties in the different materials. Therefore, production methods affect the features of the end products directly. It is the reason of why production methods should be chosen carefully.

2.6.1 Squeeze Casting

Squeeze casting is a generic term to specify a fabrication technique in which solidification is promoted under high pressure within the die [13]. In this process, molten metal is injected into a die and then high pressure is applied. This means that cooling and solidification occurs under high pressure. It can be said that it is a metal-forming process, which combines permanent mould casting with die forging into a single operation where molten metal is solidified under applied hydrostatic pressure. Even if squeeze casting is accepted as a term for this casting process, it is also known as extrusion casting, liquid pressing, pressure crystallization and squeeze forming.

In squeeze casting, pressure that is applied during this process plays very important role. The effect of high pressure on the properties of casting products is very important for final properties [14]. The main advantage of application of high pressure is that it enhances the heat transfer coefficient by several orders of magnitude. This improvement is due to the establishment of direct contact between the liquid metal and the die wall. In this process solidification is achieved quickly because of high heat flux at the boundaries. The applied pressure has another effect in increasing the melting temperature of molten metal. The reason of this situation is related to Clausius-Clapeyton equation [14].

There are some important parameters and equipment in squeeze casting process. These parameters are very significant because they have important effects on the properties of final cast parts. The most important equipment in permanent mould casting processes like die-casting or squeeze casting is the die. Especially design of the die, which includes selection of the suitable material, appropriate heat treatment, manufacturing processes and maintenance in the practice, is very crucial. In the squeeze casting process, die is exposed to high thermal and mechanical cyclic loading since this process is applied at high temperature and pressure. In order not to face with any problems during production, the properties of the die should be determined very carefully because die material is able to be resistant against thermal fatigue, cracking, erosion, corrosion and indentation. In this aspect, hot work tool steels are generally suitable as the mould material of squeeze casting. This tool steels must have good hardness, high temper resistance, adequate toughness, high degree of cleanliness and uniform microstructures.

As the features, there are two main forms of casting process that may be distinguished depending on whether the pressure is applied directly on the solidifying cast product via upper punch or the applied pressure is exerted through an intermediate feeding system as it can be seen in Figure 14. In other words, squeeze casting process can be divided into two parts as direct and indirect squeeze casting [13]. There are some basic differences in these processes.

Direct squeeze casting is more preferred technique because it is simpler than indirect squeeze casting process. In the direct squeeze casting method, there are two forms in terms of metal displacement because of punch movement. Not only casting can be operated by metal movement but it can be also done without metal movement. With the help of mold design, some simple shapes like ingot types of components can be produced whereas, this technique can be used for the production of complex casting parts which require high versatility.

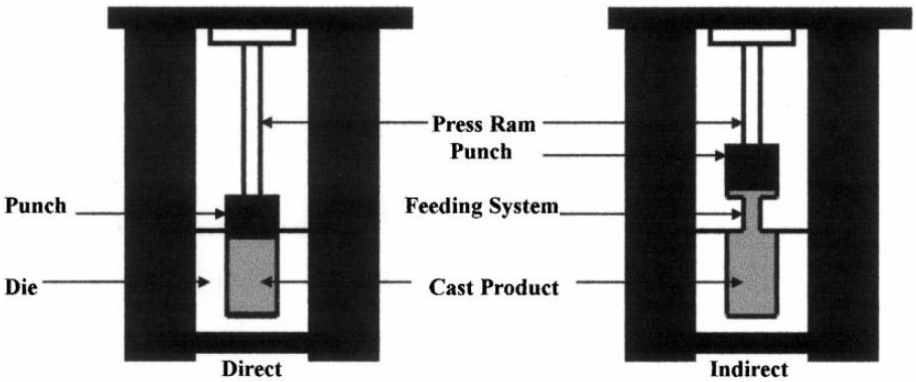


Figure 14. Schematically vies of direct and indirect squeeze casting processes [13]

There are lots of different kinds of squeeze casting machines that are used in the industry. They are either designed by researchers themselves or manufactured by machine tools companies on a mass production basis. The direct squeeze casting machines are simple and straight forward whereas, indirect squeeze casting machines can be categorized as (i) vertical die closing and injection, (ii) horizontal die closing and injection, (iii) horizontal die closing and vertical injection and (iv) vertical die closing and horizontal injection. These machines can be chosen to use according to the production routes of different casting parts. However, if the simplicity of the process is taken into consideration, direct squeeze casting machines are preferred more than indirect squeeze casting machines in the industry.

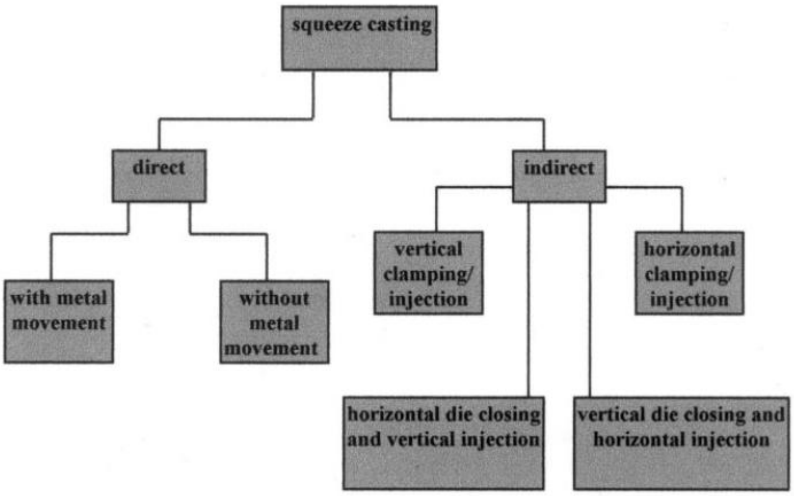


Figure 15. Categorization of squeeze casting processes [13]

The engineering components that are produced by squeeze casting are fine grained with excellent surface finishing. Moreover, they have almost no porosity. That is why squeeze casting can be perceived as near net shape process because some other secondary processes are not needed in some cases. As it is known, the quality of cast products is highly depended on microstructure. Because of the very high cooling rates at high pressure, the dendrite cell size and closer spacing of alloying elements lead to the improvement of mechanical properties. In the literature, it is reported that yield strength is improved 10-15% whereas, elongations and fatigue strength is improved as much as 50-80% [15]. Moreover, squeeze casting components have superior weldability and heat treatability. Besides these, squeeze casting may be carried out without any feeding system, runners, gating system, shrinkage compensating units and risers. Thus, this situation is a very big advantage for casting process. Unlike forging and other deformation techniques, squeeze cast components are fabricated in single action operation with lower energy requirement.

In the practice, squeeze casting method can be used for all kinds of metals. However, this process was developed by GKN technology in UK for the pressurized solidification of aluminum alloy in reusable dies [13]. As it is known, aluminum and aluminum alloys has commonly used in industrial and engineering applications lately. This engineering metal has some important properties that can explain why it is preferred in industrial areas. Some of these important properties are that aluminum is soft, durable, lightweight and ductile material. Furthermore, aluminum can be used in composite structure in order to be able to improve mechanical and physical properties of some materials according to their working environments. Therefore, it is so obvious to say that aluminum is one of the most important engineering materials that can be produce by squeeze casting.

Similarly, it is also possible to produce composite materials with the help of squeeze casting. Pressurized melt infiltration technique can be shown as a good example of the composite production method. Composite production can be achieved by this casting process. Some reinforcement materials such as solid particles or ceramic preforms may be put into the mold and liquid metal can be just pored to the mold.

2.6.2 High Pressure Die Casting

According to the literature, high pressure die casting (HPDC) can be seen as fast casting method in which liquid metal is injected to the mold cavity in order to produce geometrically complex metal casting parts [16]. This means that high kinetic energy of liquid metal is used during this casting process. HPDC can be also seen as a kind of permanent mold casting [20]. During this process, high pressure is applied with high speed thanks to some special casting machines. Moreover, pressure is also applied during solidification processes. This method is used to create large surface areas with good surface properties for intricate casting parts [20].

As all other processes, there are some disadvantages of HPDC as well. The first one is that both of high pressure die casting machine and its dies are pretty expensive. That is why they are generally preferred for mass production. The other disadvantage is that this process brings about turbulent filling in the mold [20]. Therefore, turbulent flow causes gas inclusions and porosity in the casting parts. This situation can be also problematic during heat treatment processes since gas inclusions and porosities turn to blisters when different heat treatments are applied. In order to prevent this problem, some vacuum equipment is used together with this machine. This means that if there is no vacuum process, it is expected to see porosity problem. The schematically view of high pressure die casting machine can be seen in the below figures.

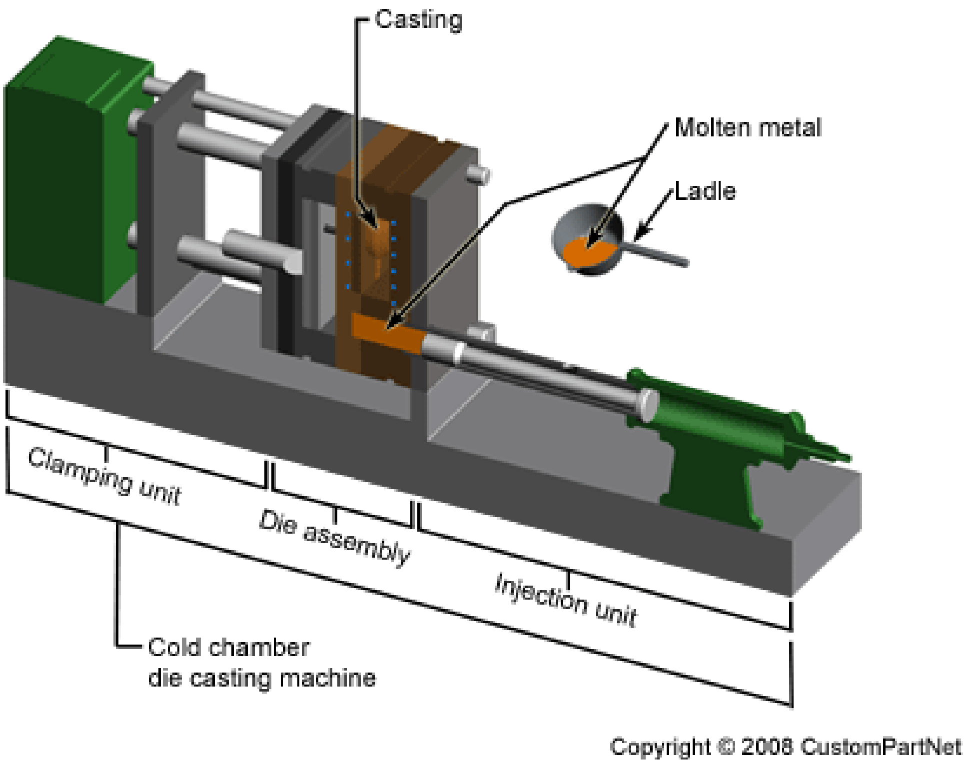


Figure 16. Schematically view of cold chamber HPDC machine [21]

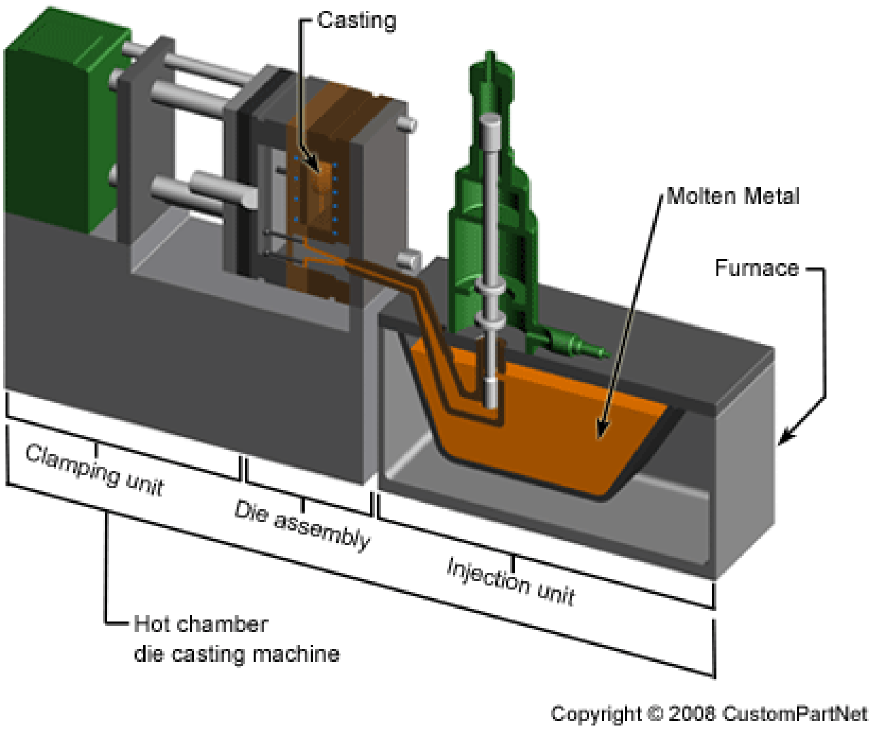


Figure 17. Schematically view of hot chamber HPDC machine with vacuum unit [21]

In the high pressure die casting process, mold and mold design is pretty important in terms of final features of the casting parts. It is possible to eliminate defect with effective mold design in the industry. That is why it is very important step of the production. Opened and closed mold can be seen in the Figure 18 whereas, mold components are shown in the Figure 19. Examples of the casting parts that are produced by HPDC can be also seen in the Figure 20.

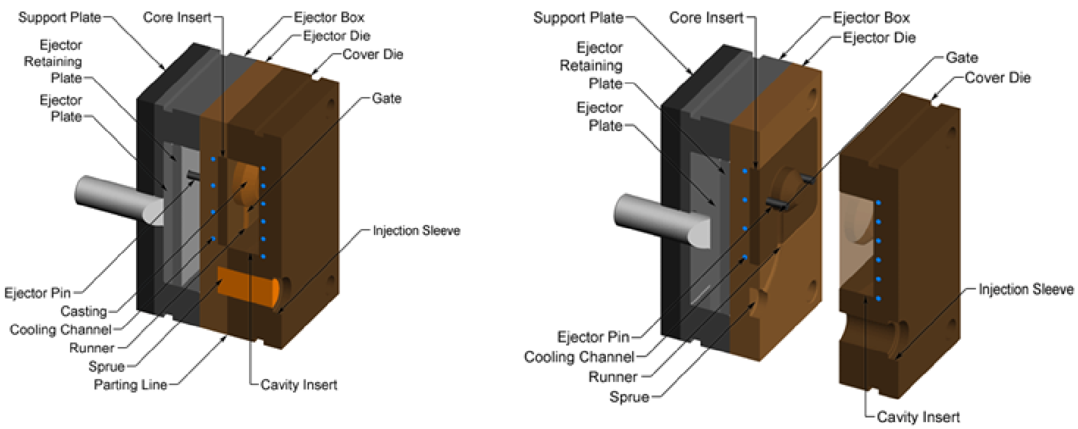


Figure 18. Opened and closed positions of the mold [21]

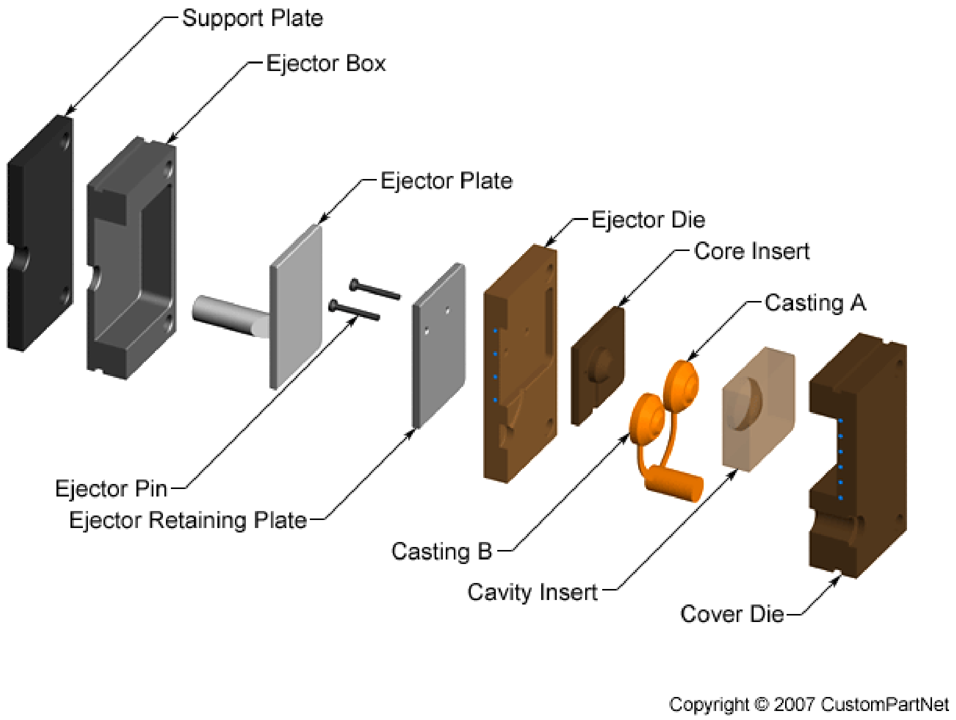


Figure 19. The components of the mold that is used in HPDC [21]

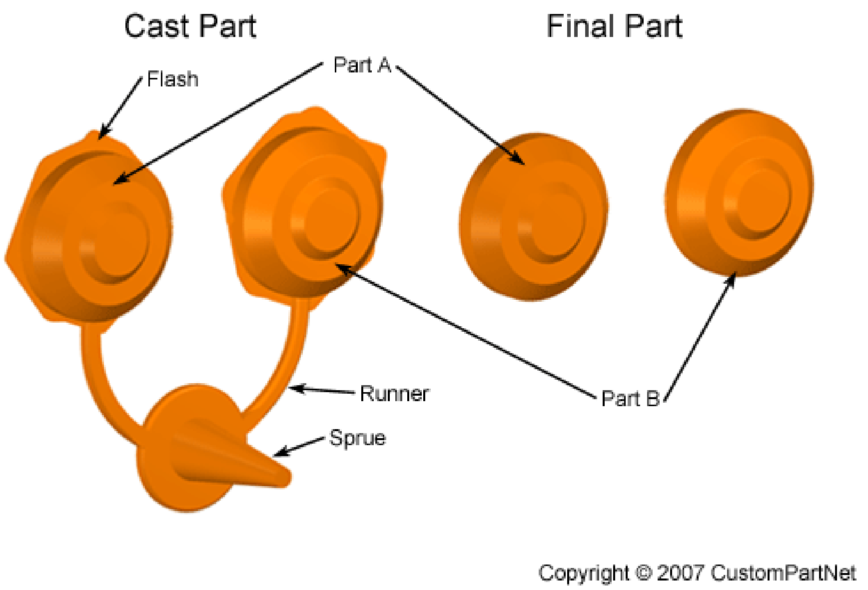


Figure 20. Examples of cast and final parts that are produced by HPDC [21]

High pressure die casting is a good method for especially non-ferrous alloys of zinc, magnesium and aluminum. Especially the usage of aluminum is really common process in the industry. It is possible to produce various casting parts in different size and weight. Pistons, cylinder heads, engine blocks, bosses, ribs, housings and enclosures can be seen as basic examples casting parts that may be produces by this method.

2.6.3 Permanent Mold Casting

Permanent mold casting is a casting method in which mold is not destroyed after each casting processes. It is also named as gravity die casting and this method is suitable for mass production of simple cast parts. The mold is produced by metals that are used in this casting operation and it includes two or more parts. After that, molten metal is just poured into the mold and it moves because of gravity and fills all cavities. Especially in automated casting lines, permanent mold casting is generally preferred because it is possible to use metal molds in casting machines. However, this technique is not applicable for complex casting parts.

There are some important parameters that should be controlled in permanent mold casting process. The most important one is temperature. Casting temperature and mold temperature are critical in this method because it affects the properties of the casting parts. If casting temperature is too high, oxidation problem can be seen. That is why properties of casting parts will decrease. Similarly, if casting temperature is too low, cold shuts and misruns can be obtained after casting. Sometimes feeding is not so good and it causes hot tearing problem. Therefore, temperature is very important parameter for permanent mold casting process.

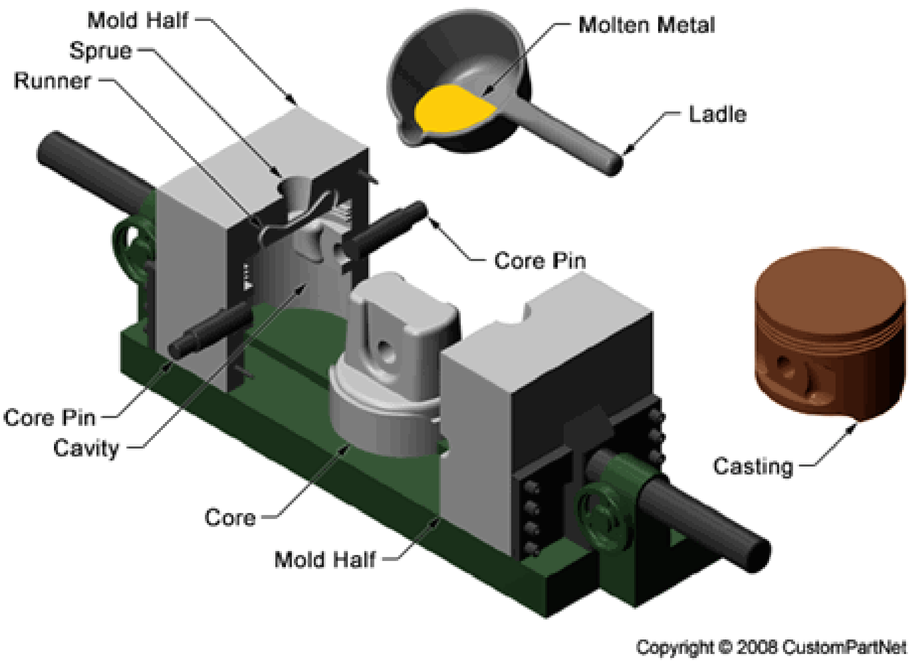


Figure 21. Schematically view of permanent mold casting [22]

Mold design is also another important issue in this casting method. Generally preheating is applied to the mold in permanent mold casting in order to decrease temperature difference in between metal mold and hot metal. If there is a big temperature difference, shrinkage can occur and it deteriorates mechanical properties. Another important issue is that mold should be coated to prevent erosion of the hot metal, increase service life and improve surface quality of the casting parts. Permanent mold casting can be used for steel, iron, lead, nickel, tin, titanium, zinc, copper and aluminum metals.

2.6.4 Sand Casting

Sand casting method can be seen as the most common casting method in the industry. Almost all metals can be produced with this way and it is cheap casting method. Metals are just melted in the furnace and poured into the mold cavity in this casting method. Sand casting can be used for a large variety of metals that are in different designs, shapes and sizes. In the sand casting; silica, zirconia, olivine or chromite sand can be chosen for different materials although silica and zircon are the most common sand types for casting of aluminum.

Silica sand basically consists of SiO_2 (quartz) that is pretty inexpensive material. However, there can be some impurities in this sand like $FeO\text{-}TiO_2$, FeO_3 or $(Mg,Fe_2)SiO_4$. In the literature, it is mentioned that volume change can happen when silica is heated during casting process. Silica is stable up to 573^{o}C because of the phase change in the quarts. In that temperature, α quartz turns to β quartz which causes %1.6 volume change. This situation can change the tolerance of the casting parts so it should be taken into consideration for critical parts. There is also another phase transformation at 867^{o}C in which β quartz transform to tridymite and it results in shrinkage in the mold.

Zirconia sand includes zirconium silicate $ZrSiO_4$, which has good refractory characteristics. Therefore, zirconia sand has low thermal expansion, high thermal conductivity, good bulk density and low reactivity with hot metal.

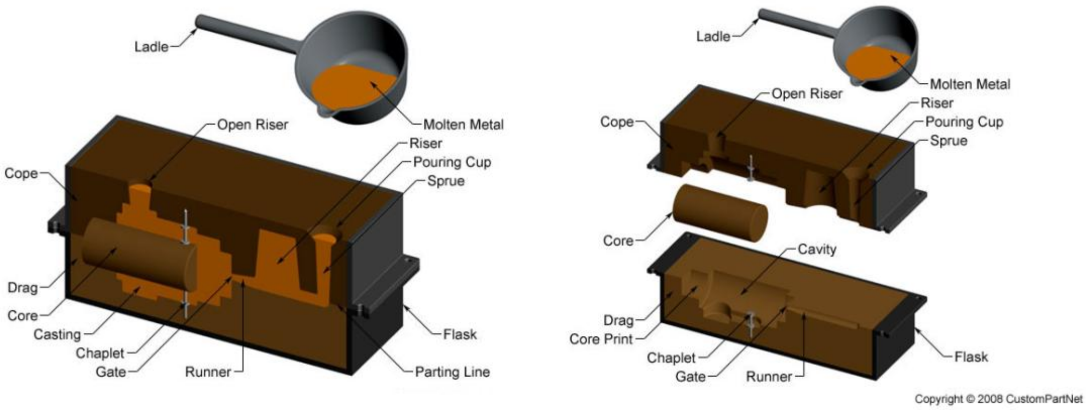


Figure 22. Opened and closed sand mold for sand casting method [23]

In this production method, the properties of the sand has important effects on the casting products. The size, shape and distribution of the sand influence the final properties directly. Especially the size distribution and sand shape are important for the quality of the mold. Permeability of the sand should be checked in order to ensure the size distribution. On the other hand, the binder material depends on the surface of the sand. If sand particles are more rounded, sand grains will have low surface area to volume ratio and it results in low amount of binder that is suitable for core making. Unlikely, angular sands have the biggest surface area and it needs more agglomerates. It should be mentioned that binder amount should be maximized for better mechanical properties.

2.6.5 Melt Infiltration Technique

In order to be able to fabricate metal matrix ceramic or fiber composites melt infiltration method can be considered as good alternative. Infiltration can be described as a liquid state method of composite materials fabrication, in which a preformed dispersed phase such as ceramic particles, some fiber materials and pressed or sintered preforms are soaked in a molted matrix metal by filling the space in between the dispersed phase inclusions. The important force of an infiltration process may be either capillary force of the dispersed phase or an external pressure applied to the liquid matrix phase. Melt infiltration method under vacuum can be used in order to overcome wetting problem of different materials during production procedure. In other words, the composite may be formed by vacuum assisted infiltration method in the industry.

Currently, with the help of melt infiltration method, composite materials with metallic matrix have been manufactured in the industry because of some profits. Nowadays, the usage of this process can be seen as high profitable technology that is able to be used in the wide range of composite materials fabrication processes. These technological and organizational profits are:

- ✓ the possibility of obtaining the composite products of precise shape mapping and the high quality surface (near net shape)
- ✓ adaptation of the process to the mass scale production
- ✓ free variability of reinforcing phase and matrix materials
- ✓ high productivity process with relatively low cost of production
- ✓ the possibility of local reinforcement of the products [24]

According to the literature, melt infiltration technique can be divided into two groups with pressure and without pressure. Melt infiltration technique without pressure is able to be applied in a furnace and molten metal is sucked by preform without any pressure. Capillary force and gravitational force can be seen as the main factors that provide infiltration. On the other hand, some special equipment is needed for metal infiltration with pressure. In most of cases, autoclave is needed because it can apply temperate and pressure at the same time. In addition, some special casting processes may be also preferred for metal infiltration with pressure. To illustrate, squeeze casting can be given as example because molten metal can be poured on the preform into the mold and melt infiltration condition can be provided.

2.7 ARMOR DESIGN

In the literature, there are lots of various kinds of ballistic applications with very different kinds of materials. These materials can be very simple armor steels whereas; they can be very high engineering materials at the same time. In this point, it can be though that there are three main ballistic materials such as metals, ceramics and fibers that are used as armor materials. Without a doubt, metals are still very common materials in ballistic applications. Steels and aluminum alloys are still preferred as one of the most important ballistic materials. Besides metals, technical ceramics are other important ballistic materials. Because of their hardness and compressive strength, they can deform projectile and it can supply protection in the battlefield. In addition, different fibers are common material in ballistic application because of their high energy absorption capacity as it was mention before.

No matter how metals, ceramics and fiber are improved, it is not possible to stop some kinds of threats with these single materials in some circumstances. This situation makes design criteria very important. With different combinations of different materials, the properties of armors can be maximized in order to be able to eliminate these treats. The usage of these materials affects the performance of the armor directly. Composite materials enables to use different properties of the different materials at the same time. Therefore, they can be good material structures of ballistic applications in the defense industry.

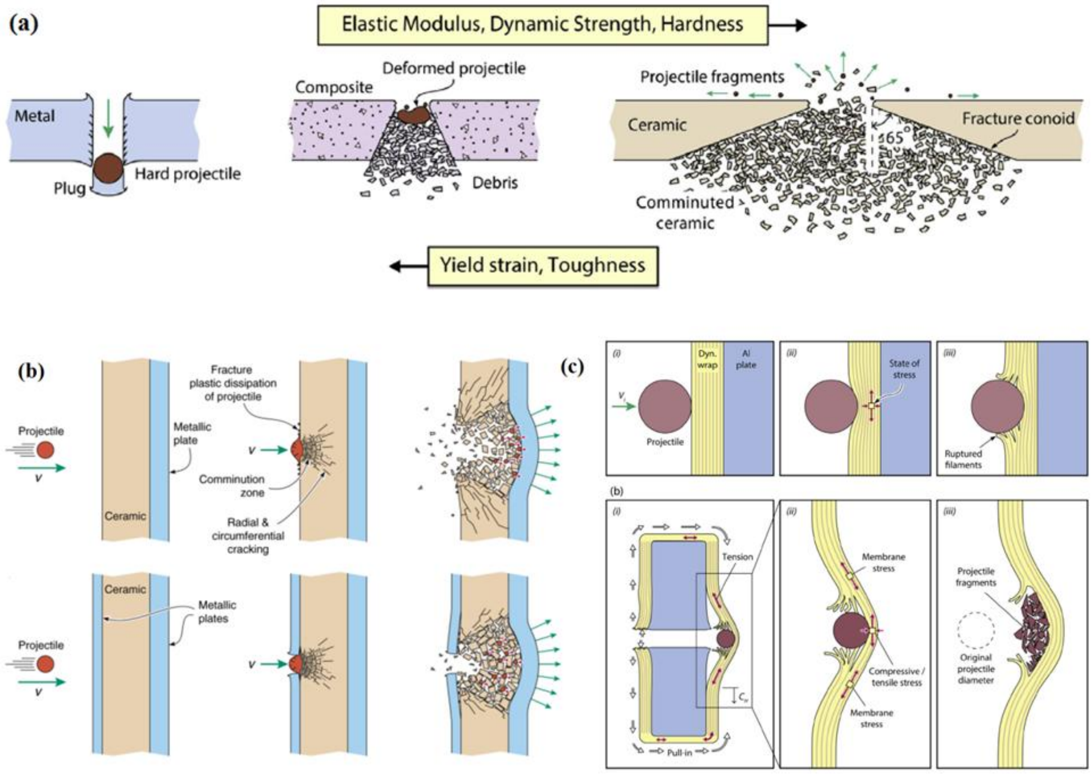


Figure 23. Design criteria for ballistic composites [3] [5] [25]

In the literature, it can be seen that elastic modulus, dynamic strength, hardness, yield strain and toughness are main important parameters in ballistic applications. It was observed that if one of these properties reaches its maximum value, it may cause some deterioration in other properties. Therefore, optimization of mechanical and physical properties can be perceived as a point about motivation in armor design. In that point, metal matrix ceramic composites can be good candidates to minimize fracture as it can be seen in the Figure 23 (a). In addition, if this composite structure is put in between two high strength metal plates like in Figure 23 (b), it will be easier to be stopped the threat. Moreover, different kinds of fibers can be located between metal plates and as in below Figure 23 (c) in order to make an effective design. By this way, the speed of the threat is able to be decreased before collusion. Therefore, Figure 23 may be seen as a brief summary of motivation for armor materials.

There are some conditions that are required to obtain good ballistic performance for materials. These conditions are:

- ✓ The hardness of the armor material should be higher than the hardness of the projectile. With this way, the projectile can be abraded.
- ✓ The thickness of the armor should be at least the half diameter of the ammo.
- ✓ It is better to produce armor with at least two components. Front one should have high hardness in order to crush the projectile and backing plate should be a ductile material in order to conserve the integrity of the armor.
- ✓ The thickness of the front plate should be 1/3 thickness of the armor whereas, backing plate should have 2/3 thickness of the whole armor [26].

These conditions can be seen as the key that improves the performance of the armor. Therefore, this information should be taken into consideration during the design step of the armor after material selection. It should be noted that, it is possible to prevent the penetration of the threat into the material with effective design.

In the literature, it is reported that ceramics and fibers, which are used to produce composite for ballistic applications, should have high tensile strength, high strain, high elastic modulus, high impact toughness and low density. O'Masta and his co-workers in their study about mechanism of projectile penetration states that polymeric fibers are good materials for low projectile speeds whereas, ceramics should be chosen for high projectile speeds. According to their research, some ceramics and polymeric fibers were determined as in the Figure 24. These graphs show that, some properties like specific energy absorption capacity, tensile strength and Young's modulus should be optimized for ballistic materials. In that point, kevlar (aramid), carbon fiber and e-glass can be chosen as fibers whereas boron carbide, silicon nitride/carbide and boron carbides may be good alternatives as suitable ballistic materials for armor application. This can be considered as material selection philosophy for producing composite ballistic armor.

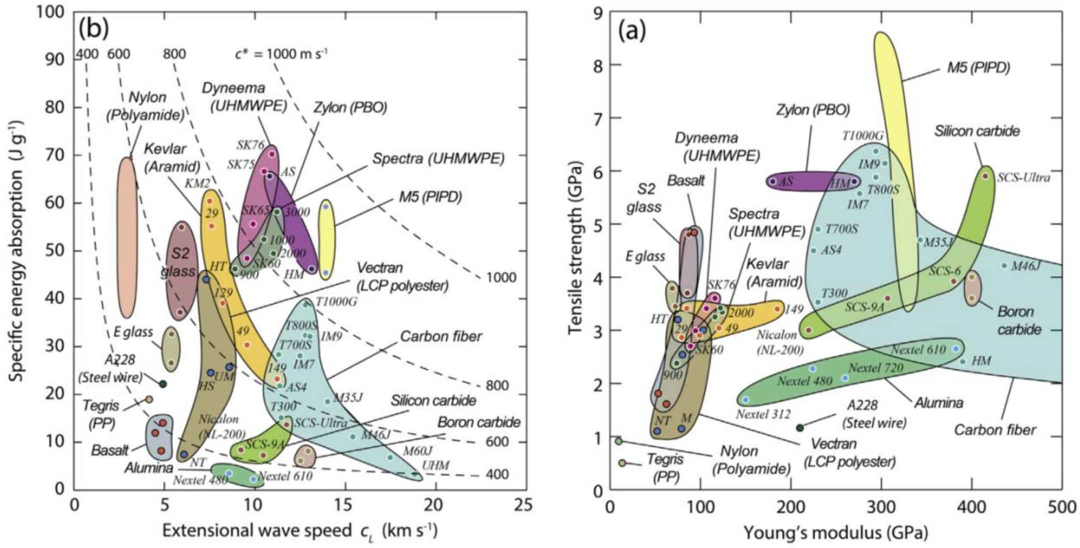


Figure 24. Material selection graphs for armor applications [5]

CHAPTER 3

EXPERIMENTAL PROCEDURE

In this chapter, experimental procedures that are employed during this thesis study were explained with all details and all information was given about different processes. Several methods were used during the experiments. The production methods of aluminum alloys and metal matrix composite were explained clearly whereas; casting experiment details were also mentioned. Furthermore, material characterization methods and equipmentswere also given at the end of this chapter. In this chapter, it is also aimed to explain information obtained from production of aluminum alloys and charge calculation, squeeze casting, permanent mold casting, high pressure die casting and pressure infiltration experiments.

3.1 PRODUCTION OF ALUMINUM ALLOYS AND CHARGE CALCULATION

In the beginning of this thesis study, required aluminum alloys were produced with alloying and casting methods. While alloys were prepared by induction furnace whereas, it was pour into permanent molds most of the time. For 7075 aluminum alloy, scraps that were taken from the industry were used and the composition of molten metal was measured with optic emission spectrometer analysis. It was done just before the processing such as squeeze casting, permanent mold casting and high pressure die casting. Metal was kept hot until desired compositions were obtained. On the other hand, 7085 aluminum alloy were produces with the mixing of alloying elements and pure aluminum. An excel charge calculation table were written as it can be seen in the Appendix A. According to the weight percentage of alloying elements, all calculations were done in accordance with total pure aluminum weight and final amounts were calculated. For the addition of zinc, magnesium and copper; pure metals were used whereas, the addition of zirconium was achieved by ZirMax master alloy during the production of 7085 aluminum alloy. ZirMax is a master alloy that contains magnesium and zirconium. While metal is still hot, the compositions were determined by optic emission spectrometry and necessary addition were done until suitable alloy compositions were obtained. Most of the time, 7085 aluminum alloy were produces as ingot with big amounts and these ingots were prepared for the further casting experiments.

Figure 25. Melting and casting laboratory in which alloy production was operated

3.2 SQUEEZE CASTING EXPERIMENT

In these series of experiments, aluminum specimens were produced by two different squeeze casting units. 7075 and 7085 aluminum alloys were melted and they poured into metal molds that are located in the vertical squeeze casting machines. In the beginning, automatic machine was used to produce aluminum disks. However, it was seen that this process is longer than manual machine because it turn off casting unit with special equipment. Therefore, manual machine was more often used. Before casting operation, molds were preheated up to 250^{o}C by torch in order to decrease temperature differences in between metal mold and liquid metal. By doing this, it was aimed to prevent shrinkage and hot tearing problems in the specimens. Alumina based thermal papers were also used inside to mold in order to decrease hot tears.

Two different metal molds were used during squeeze casting experiments. The first one has a mold cavity with 90mm diameter in order to produce discs whereas other mold enables to produce square plates with 110x110mm dimensions. Manual press can apply 70tons and it means that discs were produced under 100MPa pressure. More pressure can be achieved by automatic squeeze casting machine. 100 tons can be applied and it means that metal plates were produced under 80MPa pressure. Vertical hydraulic double action presses can be seen in the Figure 26. Disc and plate specimens can be also seen in the same below Figure. These discs and plates were used in different heat treatment experiments and all of them were characterized.

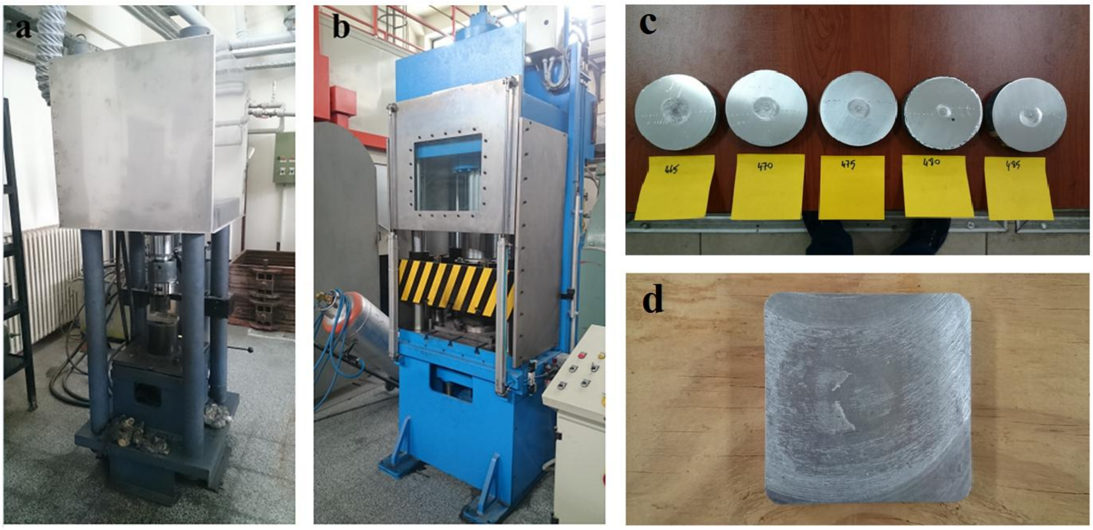


Figure 26. Vertical hydraulic double action squeeze casting machines (a) manual (b) automatic with the specimens (c) disc (d) plate

3.3 PERMANENT MOLD CASTING EXPERIMENT

Permanent mold casting process was also used to produce some aluminum specimens in the sheet form. A series of aluminum 7075 and 7085 plates were obtained with the help of copper mold. First of all, the mold was preheated up to 250^{o}C by torch in order to eliminate shrinkage problem and cracks on the edges of the sheets. Alloys were melted in the induction furnace and they are casted into the metal mold. The copper mold was located as 45^{o} inclined with horizontal in order to remove gas bubbles from the setup. By this way, gas porosities were eliminated in the aluminum sheets. After this experiment, sheets were obtained with 7mm thickness, 60mm width. The copper mold and casted specimen can be seen in the Figure 27.

These 7075 and 7085 aluminum sheets were used in rolling experiments under different conditions. Moreover, they were also heat treated in different experiments. Hot rolling processes were operated to these sheets and their new properties were investigated. Therefore, it can be said that thermo-mechanical processes were applied to these aluminum sheets. After all, they were characterized with different methods.

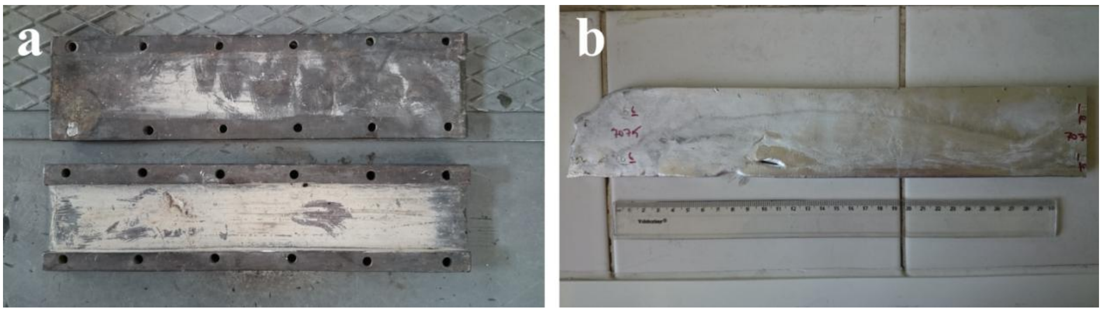


Figure 27. Copper mold and aluminum plate that was produced by permanent mold casting

3.4 HIGH PRESSURE DIE CASTING EXPERIMENT

The aim of high pressure die casting (HPDC) experiment is to produce specimens in order to be able to examine some heat treatments on 7075 and 7085 aluminum alloys.

Their mechanical properties are tried to improve with heat treatments. Therefore, three point bending and tensile test specimens were produced with high pressure die casting machine from 7075 and 7085 aluminum alloys. During these experiments, industrial size horizontal high pressure die casting machine was used in the foundry, metal processing and automotive materials laboratory without vacuum unit as it can be seen in Figure 28. This machine is able to apply 15 tons during injection, and 200 tons during mold closure stages.

Figure 28. Horizontal high pressure die casting machine

Metal mold has to be used in this machine so it was preheated up to 250^{o}C by touch as in the other casting processes. Moreover, the system was heated up by liquid metal just before the casting process so trial casting was operated in the beginning. The mold that was used during this experiment can be seen in the Figure 29. This mold was designed to get one tensile test specimen and two three point test specimens in a single run. The gating of this mold is in the bottom as it can be seen in the same figure. After this process, specimens were heat treated and characterized with suitable methods.

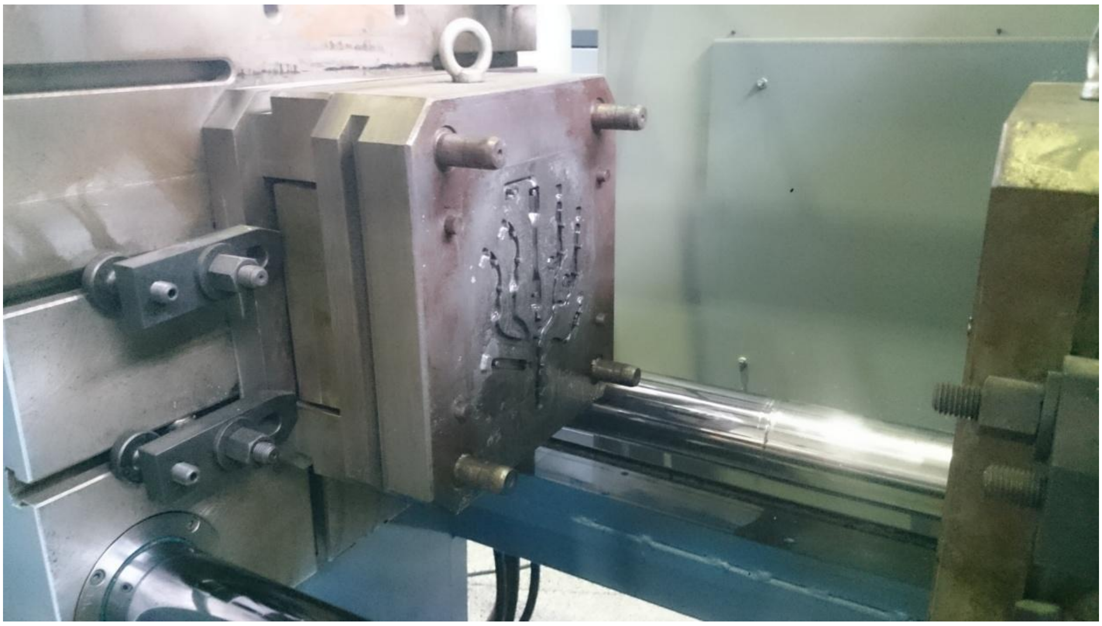


Figure 29. Metal mold that is used during HPDC experiment

3.5 THERMO-MECHANICAL TREATMENTS

Heat treatments were performed to achieve high strength values in this study. Different heat treatments were operated for 7075 and 7085 aluminum alloys in order to improve their mechanical properties. The meaning of thermo-mechanical treatment is application of thermal and mechanical processes at the same time. As a test alloy, 7075 and 7085 aluminum alloys belong to the heat treatable and wrought aluminum series. Therefore, different heat treatment and mechanical processes were applied to different specimens in order to reach the high strength values. Thermo-mechanical processes can be divided into three groups as T6 heat treatment, hot forging and hot rolling processes in this study.

3.5.1 T6 Heat Treatment

T6 heat treatment can be applied for 7xxx series aluminum alloys to achieve high strength. This heat treatment includes solution heat treatment, quenching and artificial aging stages. T6 heat treatment was applied to the all specimens except for as cast specimens. First of all, the suitable solutionizing temperatures were determined for both of 7075 and 7085 aluminum alloys. Specimens were solutionized in different temperatures and the best options were revealed for these aluminum alloys. During solutionizing process, muffle furnaces were used as it can be seen as below. After that samples were quenched in the water and they are aged artificially in another furnace that is suitable for relatively lower temperature heat treatments. Aging processes were applied at 120^{o}C during 24 hours for all samples. Aging furnace used during experiments as given in Figure 30.

Figure 30. (a) Muffle and (b) aging furnaces that were used during T6 heat treatment

In the beginning, discs and plates that were produced by squeeze casting experiments were heat treated with different ways. T6 heat treatment was operated with different solutionizing temperatures for 7075 and 7085 aluminum alloys. Five different solutionizing temperatures were used for each alloys in order to determine the best mechanical properties. For 7075 aluminum alloy, solution heat treatment was done at 465, 470, 475, 480 and 485^{o}C for different specimens. There is no enough information about 7085 aluminum alloy in the literature. Therefore, heat treatment of 7075 was taken as reference point for heat treatment of 7085 aluminum alloy. Thus; 470, 480 and 490^{o}C were determined as solutionizing temperatures in the beginning but 460 and 465^{o}C were also studied to get better results for 7085 aluminum alloy. All specimens were held in the muffle muffle furnace during 90 minutes that is determined according to the thickness of the specimens from ASM Aluminum Handbook. After that, all specimens were quenched in water and aging process was applied to the discs at 120^{o}C during 24 hours. Same aging processes were also applied for both of 7075 and 7085 aluminum. After optimum conditions were determined for 7075 and 7085 aluminum alloys, these conditions were used for further experiments.

T6 heat treatment was also applied to the discs that were hot forged and sheets that were produced by hot rolling process. Before these deformation processes, their microstructures were refined in order to prevent cracking and failure problems.

3.5.2 Hot Forging

Hot forging process is applied to 7075 and 7085 aluminum disks after they were treated with T6 heat treatment. The specimens were preheated at 260^{o}C during 90 minutes and it was hot forged with forging machine. It was aimed to provide %75 deformation but it could not be achieved. Only %25 percent deformation could be achieved in the discs after two passes. The discs were also preheated at the same temperature during 30 minutes in between two passes. Then, recrystallization process was applied to the discs at 516^{o}C during 20 hours and specimens were characterized. At the same time, 3 point bending test specimens were machined from these discs for mechanical tests. Rolling machine capable of applying pressure of 10 tons can be seen in the Figure 31.

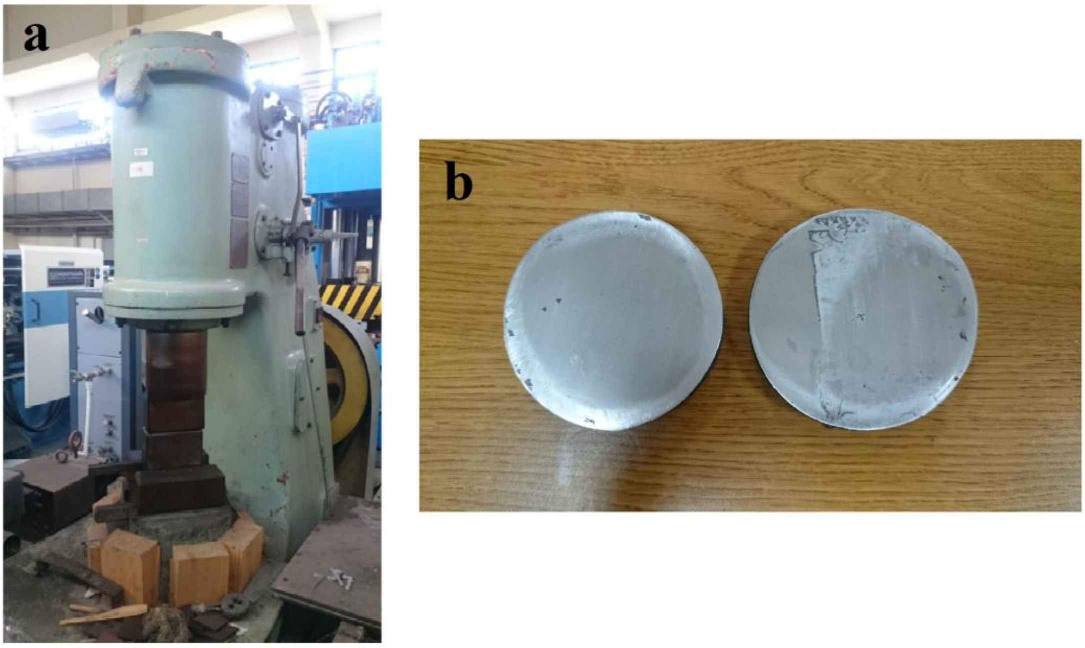


Figure 31. (a) Forging machine and (b) hot forged 7075 and 7085 aluminum discs

3.5.3 Hot Rolling

Hot rolling process was applied to 7085 aluminum alloy in order to refine the grain size after recovery and recrystallization. 7085 sheets that were produced by permanent mold casting process were used in hot rolling experiment. Several heat treatment processes were applied to these sheets. First of all, T6 heat treatment was achieved successfully. After that, specimens were over-aged at 400^{o}C during 6 hours. They were also preheated at 250^{o}C and hot rolling process was achieved by the rolling machine. At the end, recrystallization process was applied at 465^{o}C during 1, 2, 3 and 4 hours respectively. With this experiment, the effects of recrystallization time on grain size was investigated for 7085 aluminum alloy. After all of these thermo-mechanical processes, specimens were characterized. Microstructures were determined from the both of front and top sides of the sheets in order to better understand the changes in the microstructure. The rolling machine can be seen in the Figure 32.

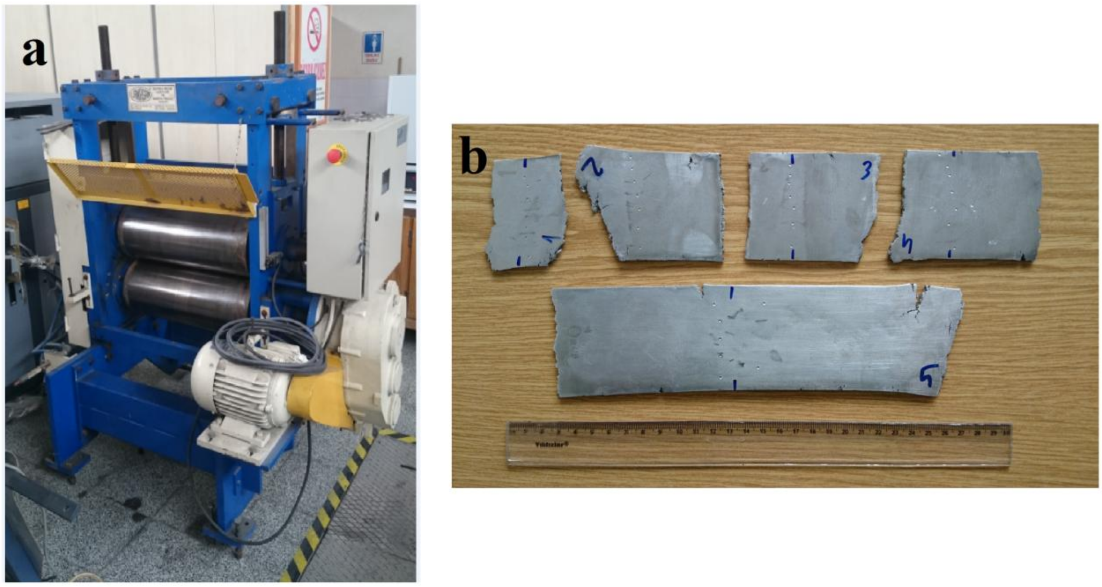


Figure 32. (a) Rolling machine that was used during experiments and (b) hot rolled 7085 aluminum sheets

3.6 MELT INFILTRATION UNDER PRESSURE

In this work, melt infiltration method was used as main process in order to produce high strength aluminum matrix composites. During these experiments, squeeze casting technique was used to achieve melt infiltration method with ceramic preforms. There are some reasons why squeeze casting process was preferred to form metal matrix composites. First of all, squeeze casting technique not only provides high pressure after hot metal is poured on top of the preforms, but also it is a way of rapid solidification. In other words, it is pretty rapid process to produce aluminum matrix composite materials. During this process, manual squeeze casting machine was used and composites were produced with good surface qualities. Secondly, squeeze casting technique has some advantages. The one of the most important advantage is that this casting technique is highly suited to mass production in the industry. This means that it is very economical process if it is aimed to produce great number of products. Thirdly, casting operation can be used to produce complex geometries in casting parts. Casting process can be performed using any metal that can be heated to the liquid state. Furthermore, there is no shrinkage in squeeze casting process because of applied pressure.

During squeeze casting process, the mould is heated up to 250^oC in the beginning in order to prevent high heat flow from liquid metal to the metallic mould. At the same time, ceramic preforms were also heated up to 1000^oC in the muffle furnace. After that, preform is placed into the mould cavity and hot metal is poured very quickly. At the end, pressure was applied by squeeze technique technique and composites were obtained after solidification. At the same time, melt infiltration under high pressure was achieved. During these experiments, thermal paper was also used in order to eliminate hot tears. Al_2O_3 and B_4C ceramic preforms were infiltrated with 7085 and 7075 aluminum alloys respectively.

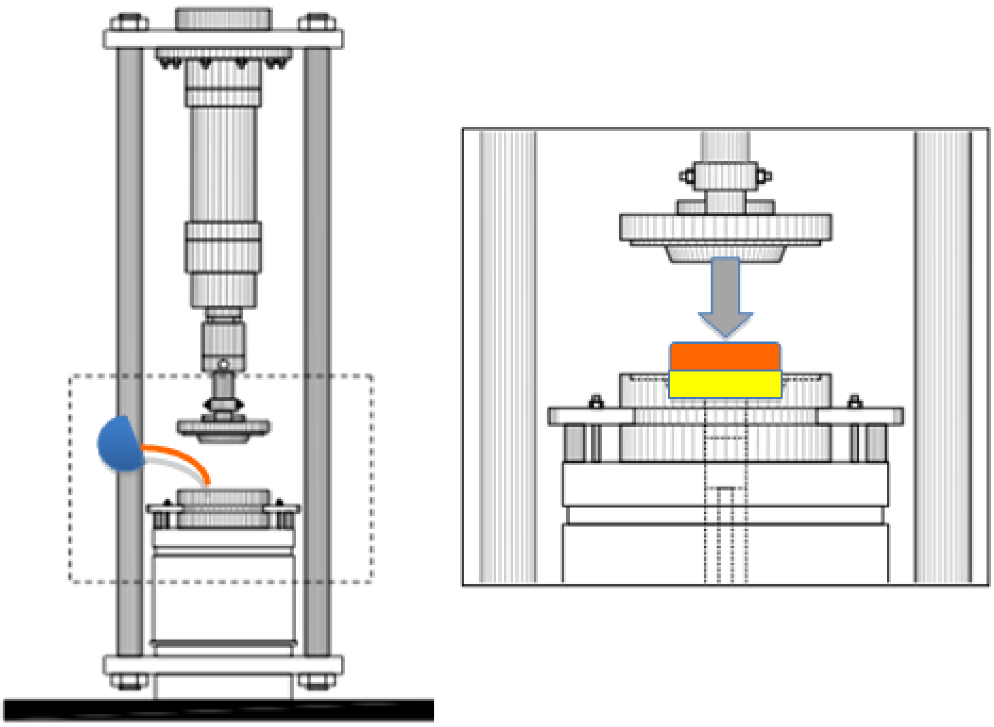


Figure 33. Schematically view of metal infiltration process to produce metal matrix composite

3.7 MATERIAL CHARACTERIZATION

In this section, material characterization was done for all samples that were produced by different experiments. Materials characterization was divided into nine different steps in this work. Therefore, specimen preparation, microstructural examination, hardness measurement, grain size measurements, phase analysis, scanning electron microscope (SEM) examination, mechanical testing, XRD analysis and optic emission spectrometer analysis were performed to characterized the specimens produced.

3.7.1 Specimen Preparation

During specimen preparation, classical metallographic methods that includes mounting, grinding, polishing and etching were used. For aluminum alloys, the specimens were cut with Metacut 251 machine and mounting was done by bakalite with the special equipment. After that, samples were grinded by grinding papers with different grids. Polishing was operated with special broadcloths and diamond and Al_2O_3 solutions were used with 3 and 1μ particle sizes respectively. At the end, specimens were etched with Keller's reagent for aluminum alloys. Samples were held in the solution during one and half minutes and they were cleaned by alcohol just after etching operation. By this way, proper contrast and clean microstructures were obtained without and scratches. Keller's reagent was prepared with 2ml HF, 5ml HNO_3, 3ml HCl and 190ml H_2O.

For ceramic and composite materials, it is not possible to apply etching process because these materials have some different properties. Therefore, they were just examined after grinding and polishing steps. Metallography equipment can be seen in the below picture.

Figure 34. Equipment for metallography (left to right) grinding and polishing machine, mounting machine and metal cutter

3.7.2 Optical Microscopy

Optical microscopy is a way to examine microstructures of different materials. In this thesis study, SOIF XJP-6A optical microscope was used in order to work on the microstructures of the specimens and take some pictures. This microscope was also connected to a computer having a software whose name is DeWinter Material Plus 4.1 Image Analysis Software. It was used to take some microstructure images and determined grain size according to ASTM standards. Thus, this microscope enabled to measure average grain size for different microstructures. It is important to note that all grain size measurements were done from the images that are taken under 100X magnification. Moreover, it is also possible to do phase analysis in order to determine the porosity percentage in aluminum alloys. In addition, it was also used to determined metal and ceramic phases in the composite. During phase analysis, the software create different colors for different phases thanks to contras differences. The light source of this microspore is located in the below and it makes possible to take some images from the specimens no matter how their sizes are. The picture of this microscope can be seen in Figure 35.

Figure 35. The picture of SOIF XJP-6A optical microscope system

3.7.3 Hardness Measurement

During hardness measurement, Universal Emco M4U-025 hardness test machine was operated to determine hardness of the samples. During hardness measurements, Brinell hardness scale was used because it is possible to use this scale for both of aluminum and composite materials. Hardness values were measured according to the ASTM E10-01 Standard Test Methods for Brinell Hardness of Metallic Materials [27]. In the hardness measurement of this scale, 187.5 kg load was applied and tungsten carbide ball with 2.5mm was used. This scale is names as HB 2.5 and it was used during hardness measurement experiments.

3.7.4 Scanning Electron Microscopy (SEM)

Scanning electron microscopy was used in order to get some detailed images from the microstructures of the specimens with relatively high magnifications. Two different SEM were used in scanning electron microscope sessions and the names of these machines are JEOL JSM-6400 and NOVA NANO SEM430. While JEOL JSM-6400 has secondary and backscattered sensors, NOVA NANO SEM430 has energy dispersive spectroscopy (EDS) analysis.

3.7.5 X-Ray Diffraction

During XRD analysis of the samples, Rigaku D/Max 2200/PC X-Ray diffractometer was used. Specimens were scanned with high angle such as 0 to 120^o and the speed was determined as 2^o per minute. It should be noted that Cu-Kα radiation is used for diffraction with 40kV voltage in this machine. After that, results were evaluated according to the reference cards.

3.7.6 Optic Emission Spectrometer Analysis

It is possible to determined the chemical compositions of the metals with optical emission spectrometer analysis for metals. The results are given as weigh percentage from this spectrometer. WAS Foundrymaster optic emission spectrometer was used in order to determine the chemical compositions of the produced aluminum alloys. There is a special mold that has medal shape and liquid metal is poured into this metal mold in order to get the sample. The composition is checked immediately before casting processes because it must be correct according to alloying element instruction. WAS foundrymaster optic emission spectrometer was used under argon atmosphere in order to eliminate some errors that comes from the environment. The picture of this spectrometer can be seen in the Figure 36.

Figure 36. WAS Foundrymaster optical emission spectrometer

3.7.7 Mechanical Testing

After all the experiments, some mechanical tests were performed in order to be able to test mechanical performance of the specimens. In this point, three point bending test, tensile test and charpy impact test were done for different specimens. There are two different tensile test machines. The first one is Mares tensile test machine that can apply 50 tons of hydraulic loads. The other machine is Instron 5582 tensile test machine that can apply 100kN.

3.7.7.1 Three Point Bending Test

Three point bending test is a mechanical test to determine fractural strength of the materials. It is an important test in order to determine bending and fracture behavior of the materials. That is why it can be considered as good test for ballistic applications because projectile shows almost the same effects on the materials when collusion occurs. During three point bending test, only Instron tensile test machine was used and specimens were prepared 65x10x10mm dimensions and span length was used as 50mm. Strain rate was measured as 2mm/min for all specimens during three point bending test. The aluminum specimens that were produces by squeeze casting were tested with this method. Moreover, aluminum matrix ceramic composite specimens were also investigated with this test method.

There are some calculations that are used in three point bending test. These calculations can be done according to the dimensions of the specimens. Therefore, flexural stress can be calculated with this information as it can be seen in the Figure 37. The letters P, t, b and L represent load, thickness, width and span length of the specimens respectively.

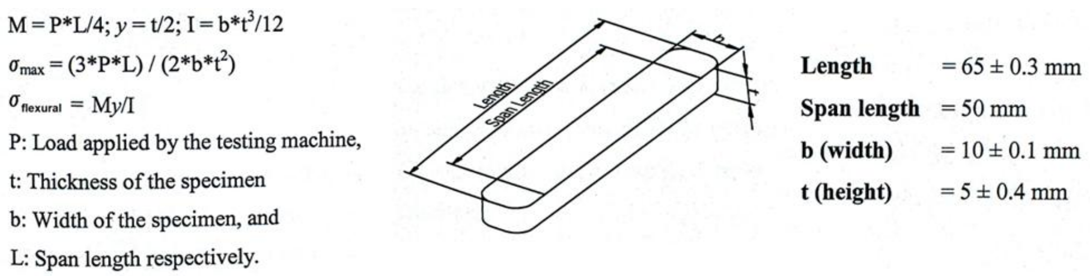


Figure 37. Three point bending test calculations and the dimensions of the specimen

3.7.7.2 Tensile Test

Instron and Mares test machines were used to operate tensile test. Tensile tested were done according to the standard of ASTM B 557M-10 whose names is “Standard Test Methods for Tension Testing Wrought and Cast Aluminum and Magnesium Alloy Products”. Strain rate was taken as 2mm/min during all tensile tests. The specimens that were manufactured by squeeze and high pressure die casting methods were tested with tensile test methods. Mares tensile test machine can be seen in the below image.

Figure 38. Mares tensile test machine

3.7.7.3 Charpy Impact Test

Charpy impact rest is a test method that is operated under the high strain rate in order to determine energy absorption ability of the materials. There is a V notch on the specimens and failure starts from this point. Absorbed energy is used to measure toughness and acting of the material about ductile to brittle transition behavior. This test was operated to some aluminum specimens that were produced by squeeze casting method in the room temperature. The testing setup was used in the mechanical laboratory of Metallurgical and Materials Engineering Department. The dimensions of the specimens is 55x10x10mm according to the standard.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter is devoted to discuss all results of the experiments that have been conducted during this study. The specimens produced with the experiments were characterized and all results were evaluated in this chapter. Firstly, aluminum alloy production, heat treatment and thermo-mechanical treatment results were examined for 7075 and 7085 aluminum alloys. The results of squeeze casting, permanent mold casting and high pressure die casting were compared to each other in order to find the better technique for processing of 7000 series armor backing plate. Then, metal matrix composite with 7000 series matrix specimens were examined after melt infiltration technique and these specimens were also characterized. At the end, all results were evaluated in order to be able to obtain the best composite backing plate structure with different materials for ballistic armor.

4.1 ALUMINUM ALLOY PRODUCTION

As an initial stage of processing, 7075 and 7085 aluminum alloys were produced before casting experiments. Due to the fact that the original alloy scraps were used in order to produce 7075 aluminum alloy, this alloys was just melted and casted as ingot for different experiments. However, 7085 aluminum alloy was produced in the foundry laboratory with designed charge calculation excel program as it can be seen in the Appendix A. After that, alloy composition was checked with optical emission spectroscopy method and the result of one casting experiment can be seen as below.

ORTA DOĞU TEKNİK ÜNİVERSİTESİ
METALURJİ VE MALZEME MÜHENDSİLİĞİ BÖLÜMÜ
DÖKÜM VE KATILAŞMA LABORATUARI
İNÖNÜ BULVARI
TEL: (0312) 210 59 29
FAX: (0312) 210 25 18

SPEKTROMETRE ANALİZ SONUÇLARI (%)

Talep Sahibi:
Rutin No:
Tarih: 01.10.2014
Kalite: Alüminyum 7085

	Composition (% weight)						
	Al	Si	Fe	Cu	Mn	Mg	Zn
1	88.9	0.0776	0.066	1.52	< 0.0010	1.6	7.51
2	89.4	0.0846	0.0628	1.56	< 0.0010	1.44	7.16
3	88.9	0.0893	0.0679	1.61	< 0.0010	1.53	7.47
Ort	**89.1**	**0.0838**	**0.0656**	**1.57**	**< 0.0010**	**1.52**	**7.38**
	Composition (% weight)						
	Cr	Ni	Ti	Be	Ca	Li	Pb
1	0.0037	< 0.0050	0.0169	< 0.0001	0.005	0.0002	0.0147
2	0.0035	< 0.0050	0.0162	< 0.0001	0.0027	0.0002	0.0069
3	0.0044	< 0.0050	0.0145	< 0.0001	0.0076	0.0002	0.0124
Ort	**0.0039**	**< 0.0050**	**0.0159**	**< 0.0001**	**0.0051**	**0.0002**	**0.0113**
	Composition (% weight)						
	Sn	Sr	V	Na	Bi	Zr	B
1	0.0473	< 0 .0001	0.0098	0.0015	0.007	0.152	0.0037
2	0.0135	< 0 .0001	0.009	0.0012	< 0.005	0.152	0.0037
3	0.018	< 0 .0001	0.0093	0.0051	< 0.005	0.149	0.0044
Ort	**0.0263**	**< 0 .0001**	**0.0094**	**0.0026**	**< 0.005**	**0.151**	**0.0039**
	Composition (% weight)						
	Ga	Cd	Co	Ag	Hg	In	
1	0.0092	0.001	< 0.003	0.0049	< 0.003	0.002	
2	0.0086	< 0.001	< 0.003	0.0041	< 0.003	0.002	
3	0.0083	0.0018	< 0.003	0.0045	< 0.003	0.002	
Ort	**0.0087**	**0.0012**	**< 0.003**	**0.0045**	**< 0.003**	**0.002**	

Figure 39. Optical emission spectrometer report for 7085 aluminum alloy

As it can be seen in the Figure 39, it is so clear that compositions of critical alloying elements like zinc, magnesium, copper and zirconium was measured in between correct composition range. The composition of 7075 scrap was also controlled after melting process.

4.2 T6 Heat Treatment Results

In this section, heat treatment results were shown with all details. First of all, squeeze cast specimens were used and they were examined in order to determine suitable solutionizing temperature of T6 heat treatment for each of 7075 and 7085 aluminum alloys. Then, all specimens were characterized and microstructures were examined by optical microscope and SEM for squeeze cast specimens. And then, grain size were measured for all specimens and these results were correlated by three point bending test results. At the same time, XRD examination was done in order to see the existence of the precipitates in the microstructure. With T6 heat treatment, it was aimed to reach 150HB hardness value.

4.2.1 7075-T6 Aluminum Alloy

According to the literature, solutionizing temperature of 7075 aluminum alloy is given in between 466 and 482^{o}C [16]. By taking into consideration of this information, five different solutionizing temperatures 465, 470, 475, 480 and 485^{o}C were used for solution heat treatment of 7075 aluminum alloys. Squeeze cast specimens were held at these temperatures separately during 90 minutes and they were quenched in the water. At the end, all specimens were artificially aged at 120^{o}C during 24 hours. By this way, aging condition was not changed and it enables to determined the best solution heat treatment condition for 7075 aluminum alloy.

4.2.1.1 Hardness Measurement

After T6 heat treatment, the hardness values of 7075 aluminum alloy was measured as given in Table 17 in accordance with different solutionizing temperatures. Fifteen different hardness values were taken from discs that were produces by squeeze casting. The effects of the solution heat treatment condition on hardness values were obtained. Hardness distribution of the specimens can be also seen in the Figure 41.

Table 17. Hardness values of T6 heat treated 7075 aluminum alloy with different solutionizing temperatures

	Hardness (2.5 HB)				
	Sol. 465°C + quenching + Aging. 120°C/24h.	Sol. 470°C + quenching + Aging. 120°C/24h.	Sol. 475°C + quenching + Aging. 120°C/24h.	Sol. 480°C + quenching + Aging. 120°C/24h.	Sol. 485°C + quenching + Aging. 120°C/24h.
1	165	163	200	144	174
2	167	160	170	161	160
3	166	166	180	178	173
4	155	171	183	174	184
5	163	165	184	179	172
6	156	169	175	171	166
7	158	170	177	169	177
8	159	173	172	167	178
9	167	174	167	173	171
10	161	159	178	178	179
11	157	163	172	173	181
12	158	170	174	170	164
13	162	161	180	157	147
14	170	172	170	172	145
15	163	161	182	153	157
Average	**162 ± 2**	**166 ± 3**	**178 ± 4**	**168 ± 5**	**169 ± 6**

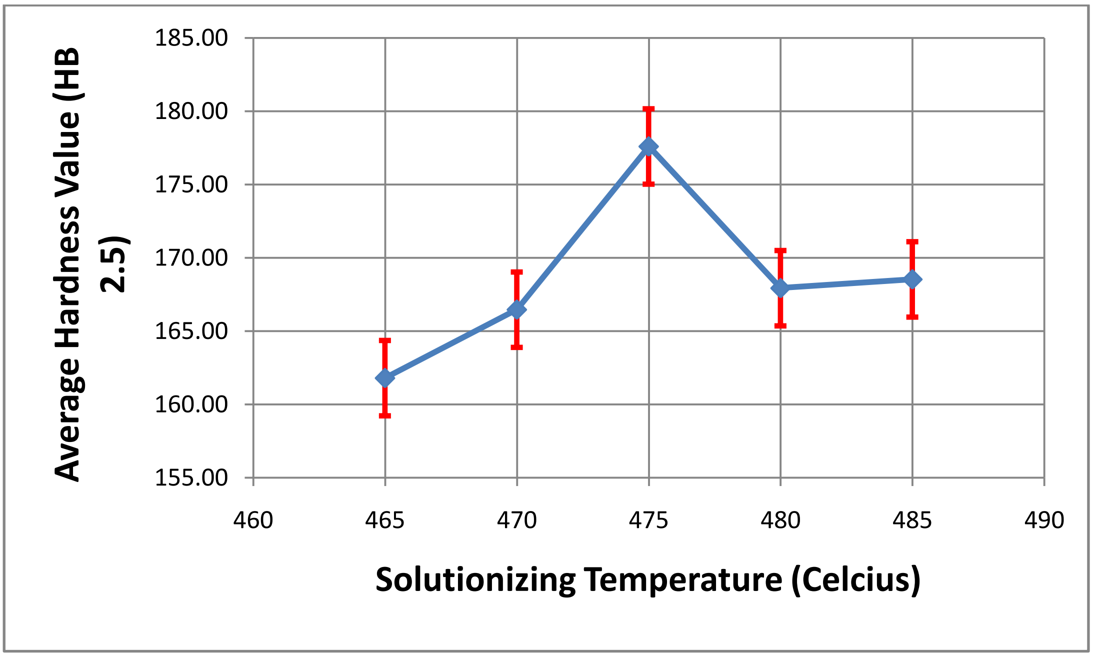


Figure 40. The effects of solutionizing temperatures on hardness values of 7075 aluminum alloy

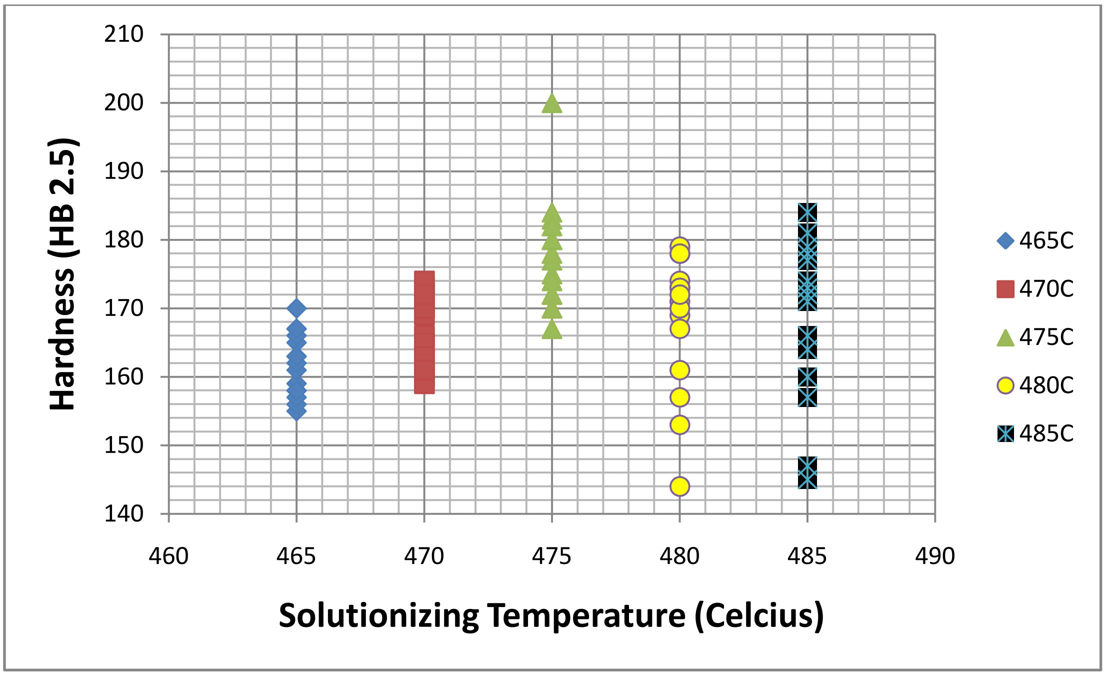


Figure 41. Hardness distribution of heat treated 7075 aluminum alloy for different solutionizing temperatures

It can be seen that 475°C is the best temperature for solution heat treatment of 7075 aluminum alloy according to the hardness values (Figure 40). The average hardness of the specimens that were solutionized at 475°C was measured as 178 HB and it was noted as the best hardness result after T6 heat treatment of squeeze casted 7075 aluminum alloy.

4.2.1.2 Three Point Bending Test

After hardness measurement, it was needed to check the result with mechanical testes. Since fracture behaviors of the materials is important for ballistic applications, three point bending test was done for T6 heat treated 7075 aluminum alloys with different solutionizing temperatures. The test specimens were machines from 7075 discs that were produces by squeeze casting. The test results can be seen in Figure 42 and 43. As it can be seen in the Figure 42, flexural stress is about 300MPa for as cast 7075 aluminum alloy. Three point bending test results can be seen in Appendix F.

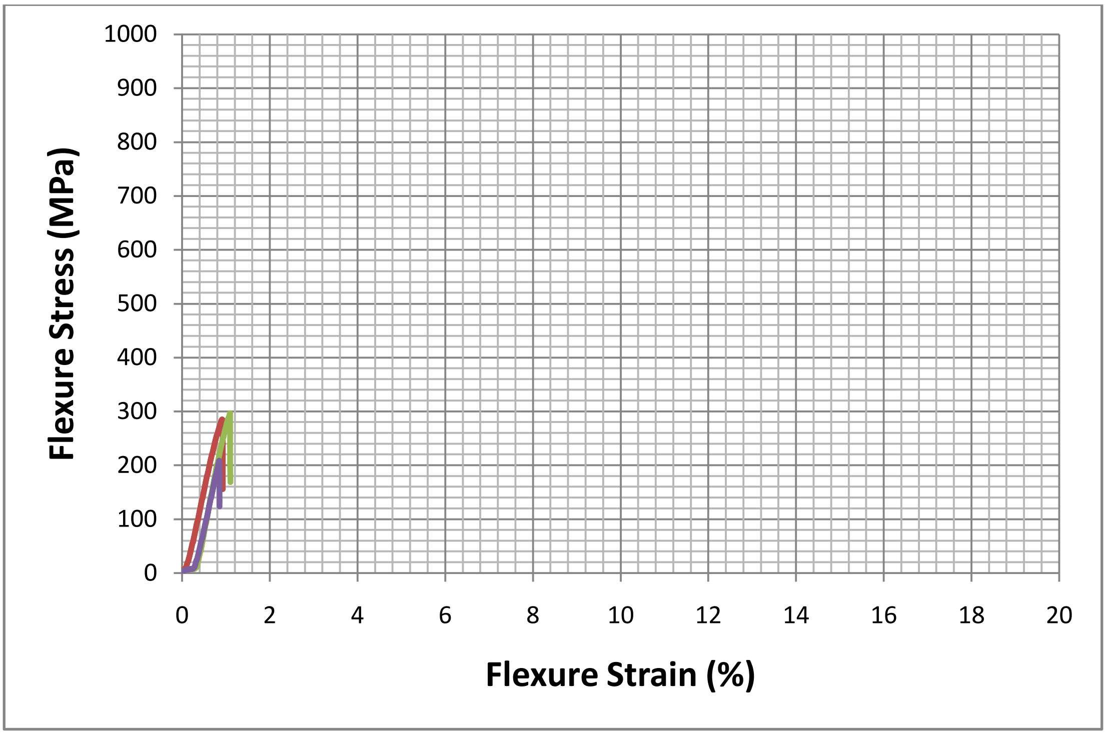


Figure 42. Three point bending test results of as cast 7075 aluminum alloy

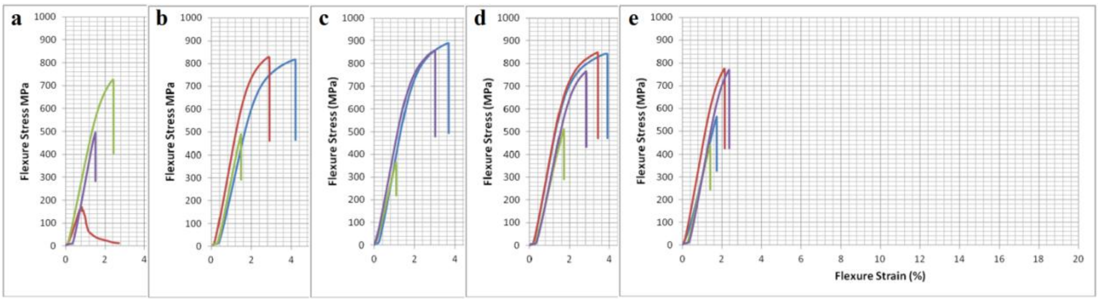


Figure 43. Comparison of three point bending test results of T6 heat treated 7075 aluminum alloy specimens with different solutionizing temperatures (a) 465°C, (b) 470°C, (c) 475°C, (d) 480°C, (e) 485°C

It can be seen that three point bending test results are in good agreement with hardness test results because the higher mechanical properties were observed in the specimens that were heat treated with 475°C solutionizing temperature. In this group of specimens, it should be noted that flexural stress can reach 900MPa and it is a good result for ballistic armor applications.

4.2.1.3 Microstructural Characterization and Grain Size Measurement

Microstructures were determined with optical microscope and average grain size was measured for each specimen with the help of Dewinter Material Plus image analysis software. The microstructures can be seen in the Figure 44. The average grain size was measured as 122 micron for as cast specimen whereas, it was measured as 106, 144, 94, 83 and 127 micron for 465, 470, 475, 480 and 485°C solutionizing temperature respectively. When these microstructures were examined, equiaxed dendritic structures can be seen in the as cast specimen. Grain size has a trend to decrease up to 480°C and it starts to increase with grain growth mechanism after this temperature. Same as hardness and mechanical test results, 475°C gave good results in the microstructural examination. Because of the low grain size at 480°C solutionizing condition, the best condition can be chosen as both 475 and 480°C. Grain size measurement results and calculations can be seen in the Appendix B.

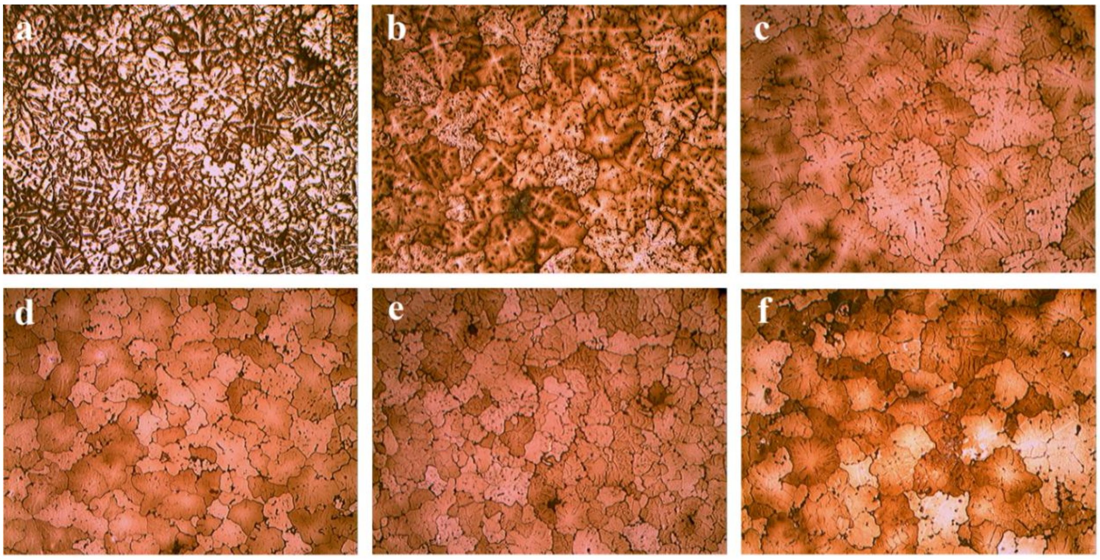


Figure 44. Microstructures of as cast and T6 heat treated 7075 specimens under 100X magnification (a) as cast, (b) 465°C, (c) 470°C, (d) 475°C, (e) 480°C, (f) 485°C

The summary of the grain size measurement according to the solutionizing heat treatment during T6 heat treatment of 7075 aluminum alloy can be seen in the Figure

43. It was noted that the highest hardness values and flexural strength values were determined in the specimen that was T6 heat treated at 475°C solutionizing temperature. After grain size measurement, it was seen that 475°C solutionizing temperature yielded one of the lowest grain size among all specimen sets. When the relation in between grain size and mechanical properties was taken into consideration (Hall Petch Equation), it can be said that 475°C can be assumed as the best condition for solution heat treatment of 7075 aluminum alloy. Nevertheless, since the lowest grain size was obtained at 480°C, it can be also used for T6 heat treatment of 7075 aluminum alloy.

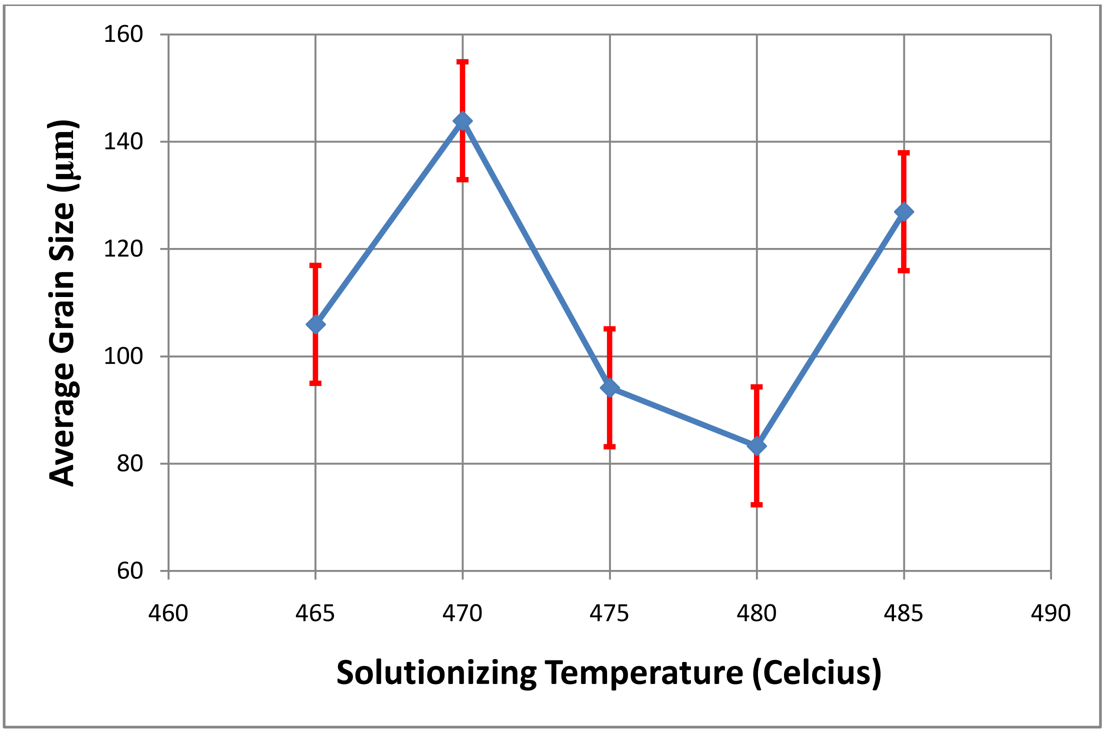


Figure 45. The relations in between solutionizing temperature and average grain size of T6 heat treated 7075 aluminum alloy.

Besides optical microscope, squeeze cast specimens were also examined by scanning electron microscope (SEM) after T6 heat treatment of 7075 aluminum alloy. SEM images can be seen in Appendix C. When the as cast microstructure of 7075 was examined, dendritic structures were observed due to element segregation during solidification. Moreover, there were lots of precipitations in the grain boundaries.

These precipitates were determined as Al_2Cu with the help of EDX analysis. After T6 heat treatment, it was seen that precipitates moves from the grain boundaries and they precipitated in the grains. Moreover, grains were observed at different magnifications in the SEM.

4.2.1.4 X-Ray Diffraction

In order to understand precipitation hardening mechanism of the T6 heat treatment of 7075 aluminum alloy, X-Ray diffraction (XRD) measurement was also done. According to the literature, $MgZn_2$ had a main role in the precipitation hardening mechanism of 7xxx series aluminum alloy. Nonetheless, it is not that easy to determine this tiny phase with XRD and SEM examinations. It is noted that transmission electron microscope (TEM) examination is needed in order to get some information about this micro or nano-size phase.

XRD results can be seen in the Appendix D for T6 heat treated 7075 aluminum alloy with different solutionizing temperatures. When these results were investigated, it cannot be talked about a big difference in between X-Ray patterns. The intensity differences of these graphs may be related to the formation of forging or rolling related texture in the specimens.

4.2.2 7085-T6 Aluminum Alloy

After T6 heat treatments of 7075 aluminum alloy, 7085 aluminum alloy was also studies since there is no enough information about 7085 in the literature. The critical temperatures were determined for this alloy with the help of date obtained for 7075 alloy experiments. Therefore; 470, 480 and 490^{o}C was used as solutionizing temperatures and T6 heat treatment was applied with quenching and aging at 120^{o}C during 12, 24 and 36 hours to the discs that were produced by squeeze casting. After that, it was decided to try below 470^{o}C so that it can result in better mechanical properties. Thus, experiments were repeated for 460, 465 and 470^{o}C one more time but aging condition was applied only at 120°C during 24 hours. With this way, 470°C was taken as the reference that enables to compare the results with the first step of the experiments. At the end, all results were evaluated with the details.

4.2.2.1 Hardness Measurement

T6 heat treatment was applied in two steps for 7085 aluminum alloy. In the first step, solution heat treatment was applied at 470, 480 and 490°C during 90 minutes and they are quenched. After the aging was performed at 120°C during 12, 24 and 36 hours. Hardness values were measured for all specimens as it can be seen in Table 18.

Table 18. Hardness values of 7085 aluminum alloy according to different solution heat treatment and aging conditions

	Hardness (2.5 HB)										
	Solutionizing at 470°C				Solutionizing at 480°C				Solutionizing at 490°C		
	12 hr	24 hr	36 hr		12 hr	24 hr	36 hr		12 hr	24 hr	36 hr
1	159	169	167		147	146	146		160	169	145
2	158	159	161		144	147	150		154	161	155
3	164	161	157		143	157	154		145	155	161
4	165	161	155		149	158	157		149	155	159
5	160	158	167		163	161	159		155	158	166
6	164	160	170		155	161	159		160	159	157
7	174	178	167		155	167	163		165	182	169
8	167	171	159		150	168	166		168	166	162
9	164	167	179		160	170	172		163	169	160
10	150	161	176		156	158	172		170	156	175
11	145	173	174		142	175	159		165	157	175
Avg	**161±5**	**165±4**	**167±5**		**151±4**	**161±5**	**160±5**		**159±5**	**162±5**	**162±5**

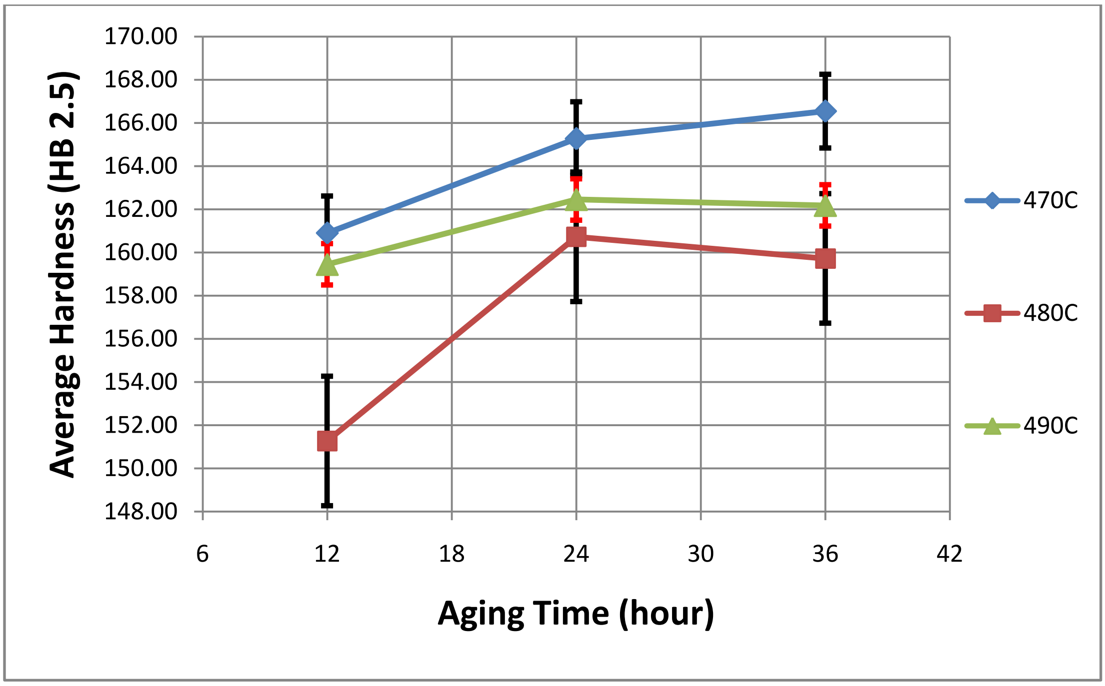


Figure 46. The relations in between average hardness values, solutionizing temperatures and aging times for 7085 aluminum alloy

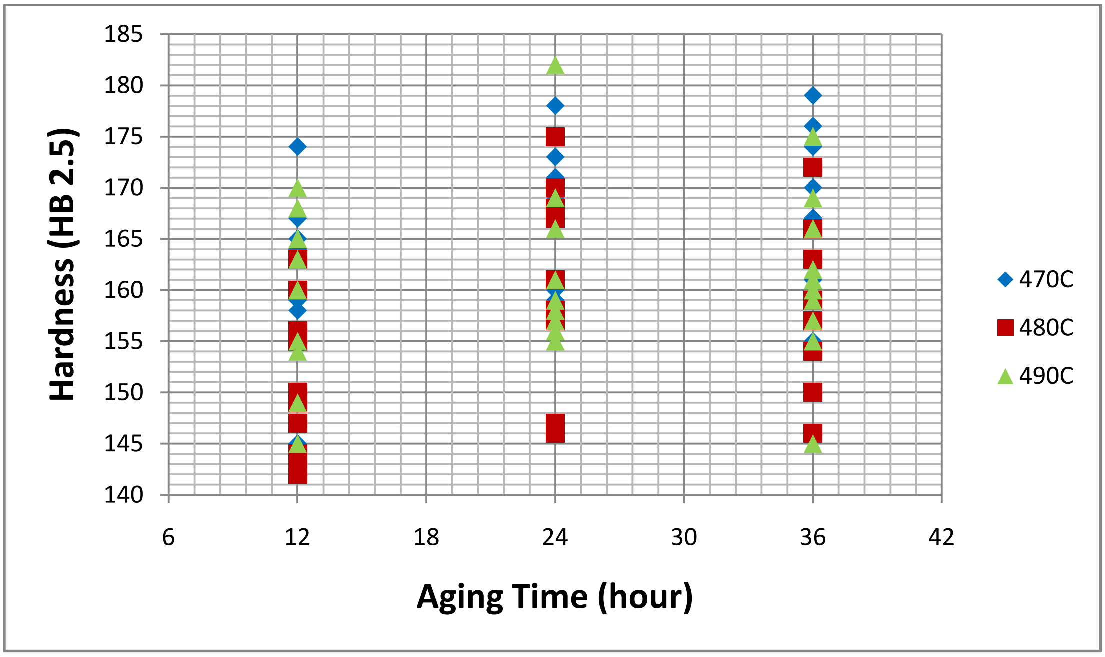


Figure 47. Distribution of hardness values for different solution heat treatment temperatures and aging times for 7085 aluminum alloy

According to hardness results, it can be easily said that 470°C is the best solution heat treatment temperature compare to 480 and 490°C. When Figure 46 is taken into account, it can be seen that 36 hours yield better results in terms of hardness as 167HB for 470°C solutionizing temperature. However, hardness values have tendency to decrease after 24 hours for 480 and 490°C solution heat treatment temperature. Therefore, it was thought that grain growth mechanism starts to be activated after 24 hours at 120°C. Therefore, aging condition was determined as holding at 120°C during 24 hours for 7085 aluminum alloy.

After these results, it was decided to investigate temperature below 470°C as solution heat treatment temperature. Therefore, T6 heat treatment was also applied at 460 and 465°C solutionizing temperatures and these hardness results are given in Table 19.

Table 19. Hardness values of 7085 aluminum alloy for different solutionizing temperatures

	Hardness (2.5 HB)		
	Solutionizing at 460°C/90min + quenching + Aging at 120°C/24 saat	**Solutionizing at 465°C/90min + quenching + Aging at 120°C/24 saat**	**Solutionizing at 470°C/90min + quenching + Aging at 120°C/24 saat**
1	173	173	170
2	174	171	174
3	171	173	173
4	168	176	167
5	174	169	170
6	172	171	165
7	174	184	168
8	163	173	166
9	175	170	175
10	172	169	168
11	177	175	171
12	173	179	172
13	169	173	170
14	171	174	173
15	170	171	174
Avg	**172 ± 2**	**173 ± 2**	**170 ± 2**

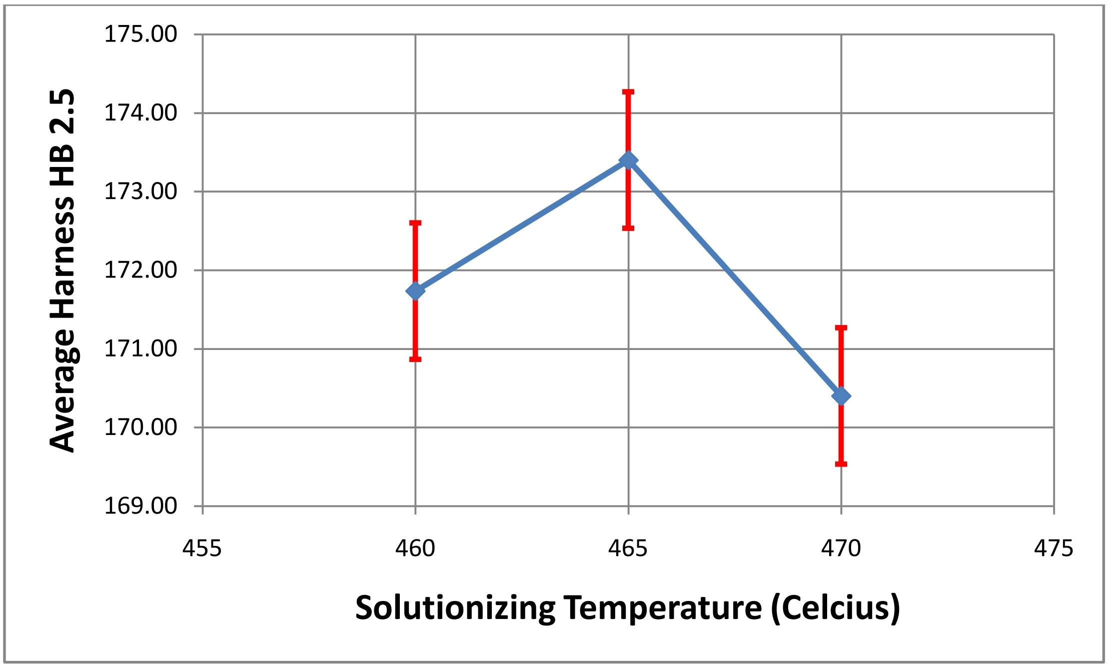


Figure 48. The relations in between average hardness values and solutionizing temperatures for 7085 aluminum alloy

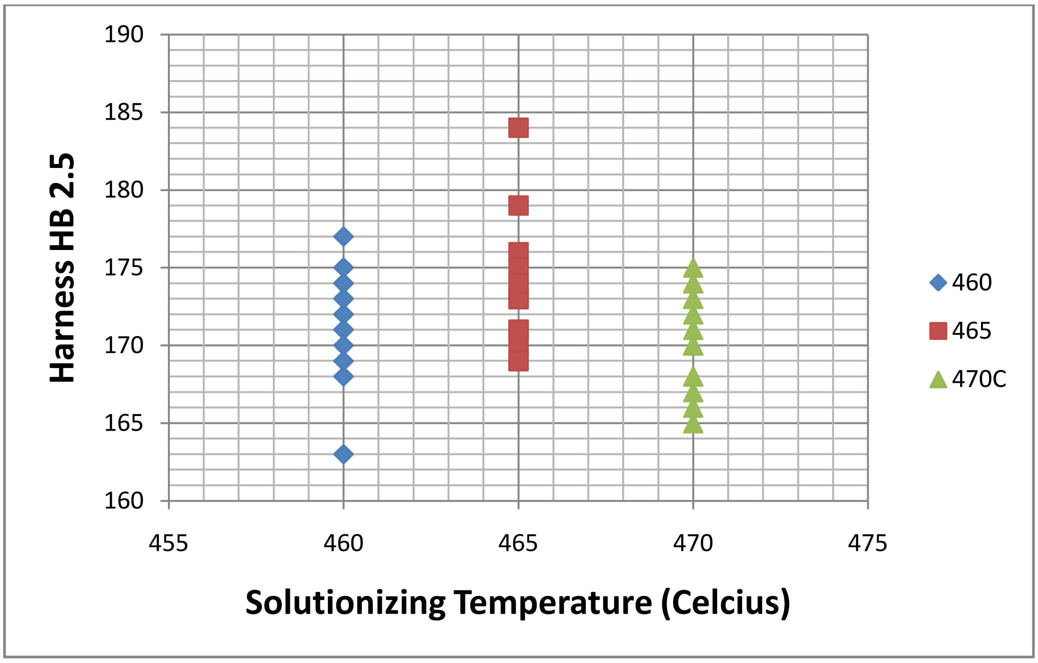


Figure 49. Distribution of hardness values for different solution heat treatment temperatures for 7085 aluminum alloy

According to these results, average hardness values were measured as 172, 173 and 170 for 460, 465 and 470°C solutionizing temperature respectively. It means that the specimens that were solution heat treated at 465°C had higher average hardness value than the specimens that were solution heat treated at 470°C. With the light of this information, 465°C is the best solutionizing temperature for the heat treatment of 7085 aluminum alloy according to the hardness values. After that, these results were correlated with mechanical tests.

4.2.2.2 Three Point Bending Test

After hardness measurement, the results were compared with the mechanical test results. Thus, three point bending test was done with the specimens obtained from the discs after squeeze casting experiment of 7085 aluminum alloy. It was seen that, flexural stress values of the specimens that were heat treated with 465°C solutionizing temperature had the higher values. Therefore, it is clear that 465°C is the best temperature for solution heat treatment of 7085 aluminum alloy. Three point bending test results can be seen in the Appendix F.

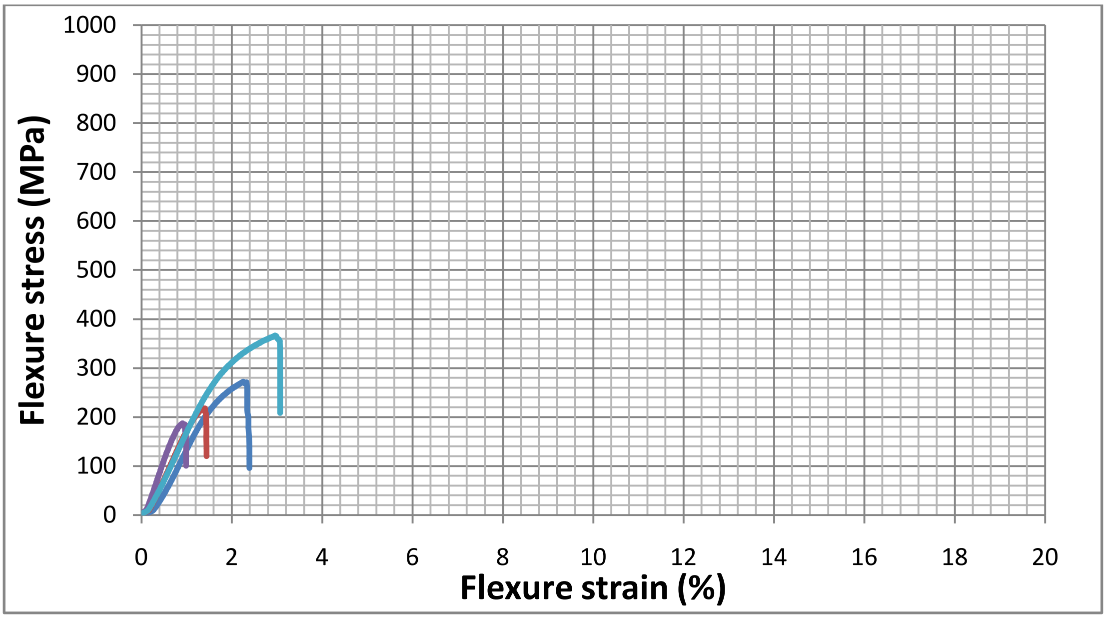


Figure 50. Three point bending test results of as cast 7085 aluminum alloy

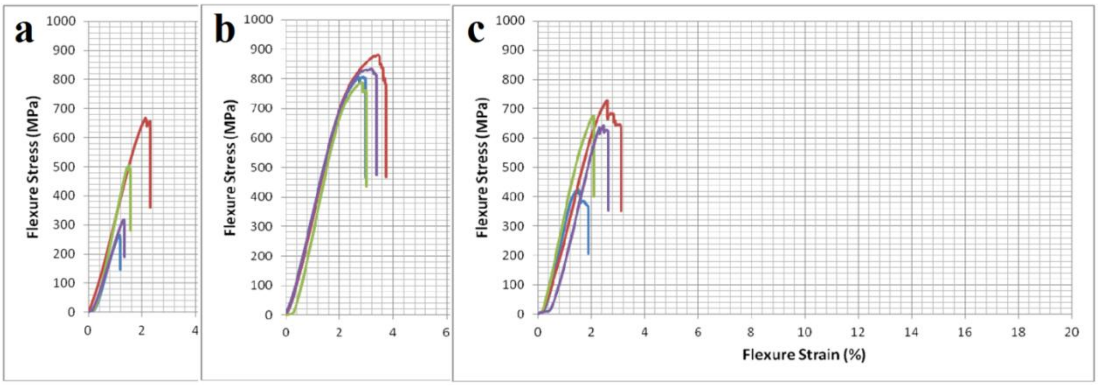


Figure 51. Comparison of three point bending test results of T6 heat treated 7085 aluminum alloy specimens with different solutionizing temperatures (a) 460^{o}C, (b) 465^{o}C, (c) 470^{o}C

4.2.2.3 Charpy Impact Test

Charpy impact test was also done to the 7085 aluminum alloy after T6 heat treatment process. This means that these specimens were solution heat treated at 470^{o}C during T6 heat treatment. At the end, these results were obtained as it can be seen in Table 20. After this test, the average impact energy was measured as 7 joule for this aluminum alloy after heat treatment processes.

Table 20. Charpy Impact Test results of T6 heat treated 7085 aluminum alloy

Specimen	Impact Energy (Joule)
1	7
2	6
3	9
4	6
5	5
Average	**7 ± 1**

4.2.2.4 Microstructural Characterization and Grain Size Measurement

As an initial step of the microstructural characterization, as cast specimens were investigated under optical microscope after squeeze casting process. When these microstructures were investigated, dendritic structures can be seen as it was expected. Moreover, average grain size of these microstructures were also determined as in the Appendix B. The average grain size was determined as 120 micron for as cast 7085 aluminum alloy after squeeze casting.

As cast specimens of 7085 aluminum alloy were also examined under SEM and images were taken at various magnifications. These images can be seen in the Appendix C. Moreover, some precipitated were also determined at the grain boundaries as it can be seen Figure 53. EDX data were taken from these particles and they are determined as Al_2Cu precipitates. It shows that precipitation occurs in the grain boundaries of as cast structures before heat treatment due to fast cooling condition into the metal mold of squeeze casting machine. Mg and Zn were also determined in the EDX results. It can be thought that these peaks come from the background of these precipitates. In other words, they come from the aluminum alloy itself that located behind the precipitates.

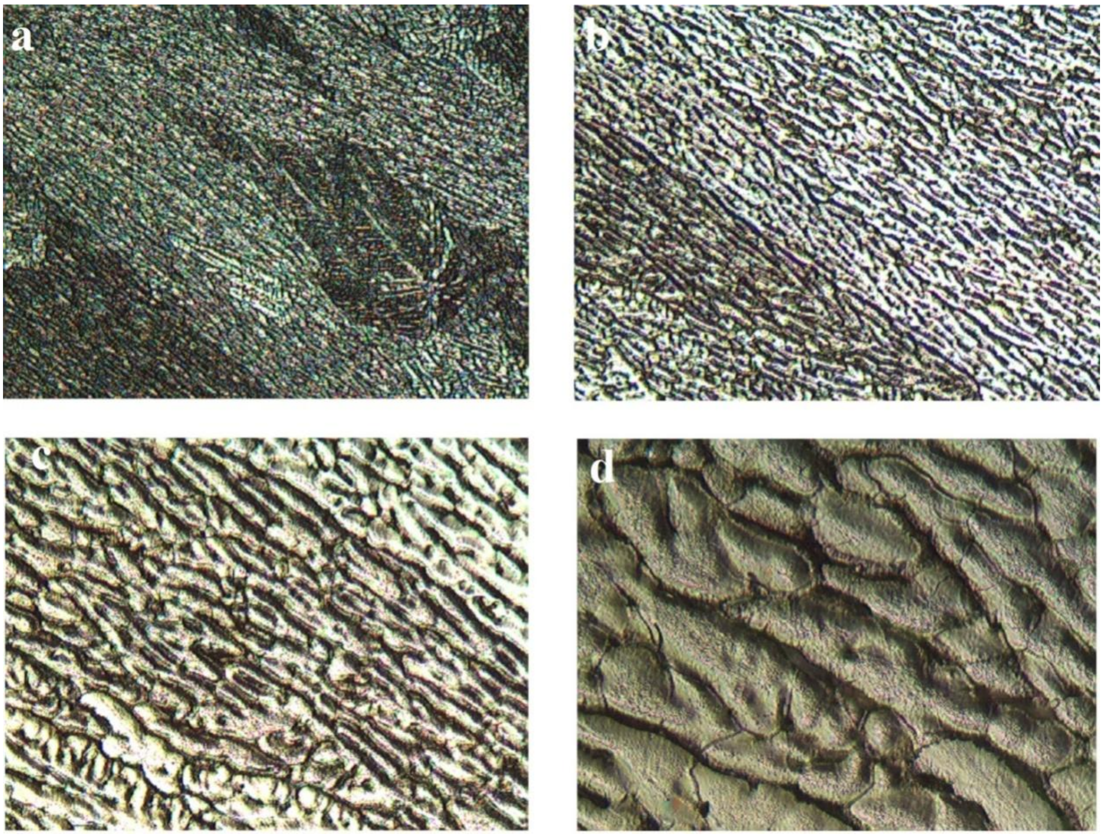


Figure 52. As cast microstructures of 7085 aluminum alloy with various magnifications after squeeze casting (a) 50X, (b) 100X, (c) 200X, (d) 500X

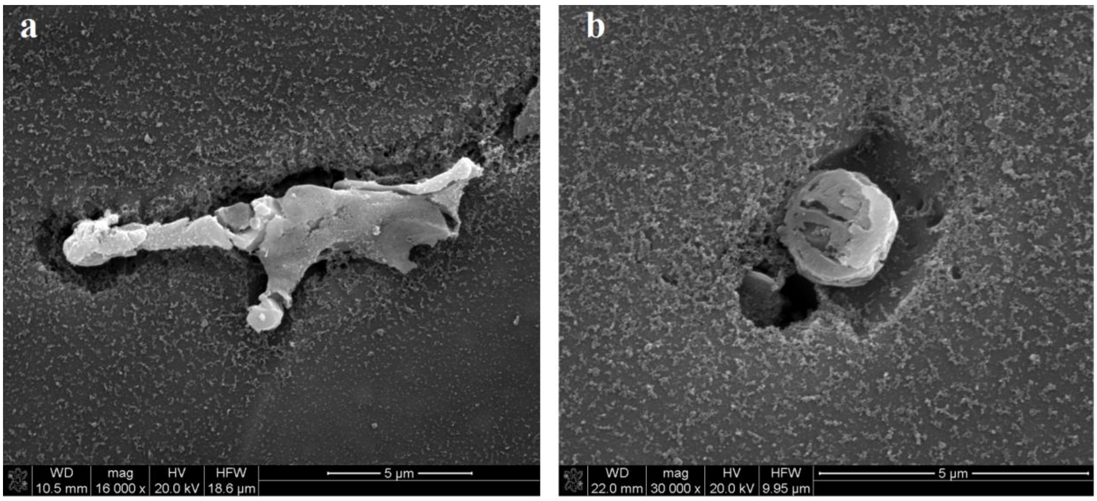


Figure 53. Al_2Cu precipitates in the grain boundaries with different shapes

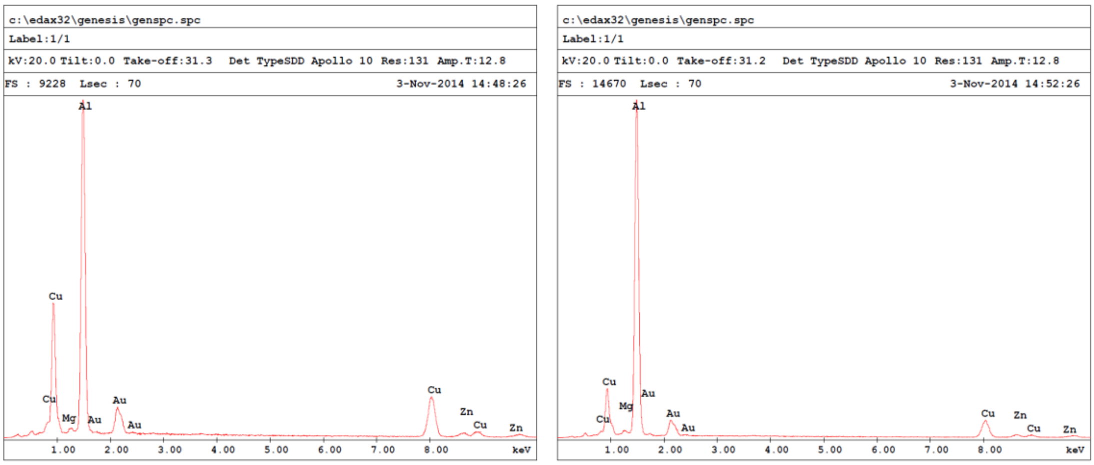


Figure 54. EDX data of the particles (left) Figure 53/a (right) Figure 53/b

After microstructural characterization of as cast specimens, T6 heat treated specimens were also investigated with the help of SEM. These SEM images can be seen in the Appendix C with all details. Generally, Al_2Cu intermetallic precipitate (θ phase) was determined in the microstructures after T6 heat treatment thanks to EDX. However, $MgZn_2$ precipitates (η phase) could not be seen with the help of SEM. The reason of this situation can be related to homogeneous distribution of tiny particles inside the matrix. That is why it was thought that they can be detected by TEM examination in order to better understand the precipitation hardening of 7xxx series of aluminum alloys.

When the microstructure of 7085 aluminum alloy was investigated, high grain size was measured as it can be seen in the Figure 55. SEM images were taken for different specimens that were heat treated with different solutionizing temperature such as 460, 465 and 480^{o}C and grain size was determined even bigger than even 300 micron in some points for squeeze cast 7085 aluminum specimens. It was observed that a decrease of grain size after thermo-mechanical process including T6 heat treatment of 7085 aluminum alloy was decided in the next stage of the studies.

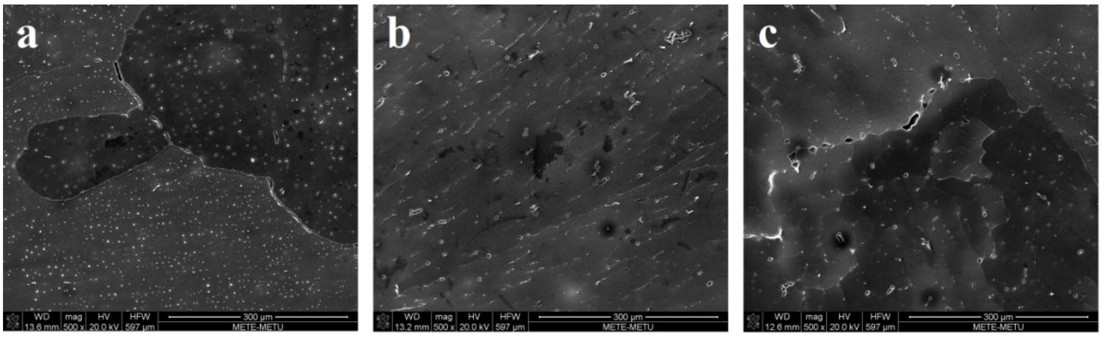


Figure 55. SEM images of T6 heat treated 7085 aluminum alloy after squeeze casting with different solutionizing temperatures (a) 460^{o}C , (b) 465^{o}C, (c) 470^{o}C

4.2.2.5 X-Ray Diffraction

In order to be able to determine the precipitates that form after T6 heat treatment, XRD measurement was also done for 7085 aluminum specimens solutionized at 460, 465 and 470^{o}C. XRD patterns of these specimens can be seen in Appendix D. According to these results, it was seen that it is also not possible to determined these precipitates with this way due to the fact that peaks overlapped and they stayed in the background of aluminum peaks. Only the peaks of α aluminum were determined like 7075 aluminum alloy.

4.3 THERMO-MECHANICAL TREATMENT RESULTS

In this section, results of thermo-mechanical treatments were given for both of 7075 and 7085 aluminum alloys. The main reason of doing thermo-mechanical treatment is to improve mechanical properties of the 7000 series aluminum alloys. At the beginning, the grain size of 7085 aluminum alloy was tried to be reduced. The aim was to increase toughness and other mechanical properties. Therefore, hot rolling and hot forging processes were used for 7085 aluminum alloy. After that, same operations were also repeated for 7075 aluminum alloy.

4.3.1 Thermo-Mechanical Treatments of 7085 Aluminum Alloy

For 7085 aluminum alloy, hot rolling and hot forging processes were applied under different conditions. For hot rolling process, metal sheets that was produced by permanent mold casting were used whereas, squeeze cast discs were used for hot forging experiments.

4.3.1.1 Hot Rolling

After large grain size was observed in the microstructures of T6 heat treated 7085 aluminum alloy, hot rolling process was decided to be applied in order to decrease grain size. First of all, T6 heat treatment was applied to these sheet in order to perform grain refinement and to increase mechanical properties. The best conditions were used for T6 heat treatment so sheets were held at 465^{o}C during 90 minutes and they were quenched. After that, aging was applied at 120^{o}C during 24 hours. In order to eliminate the casting microstructure of permanent mold casting method, T6 heat treatment was applied twice. Then, sheets were over-aged at 400^{o}C during 6 hours. With this heat treatment, it was aimed to have larger grains and decrease the hardness value before mechanical processing. At the same time, it was also aimed to have more supersaturated α solid solution in the aluminum matrix that does not affects mechanical properties negatively. Then, sheets were preheated at 250^{o}C and hot rolling process was applied by rolling machine. This thickness of the specimens was decreased to 5mm from 7mm after the first pass. Same procedure was followed one more time and it was decreased to 3.5mm from 5mm. This means that 50% deformation was achieved. At the end, recrystallization was done with different time interval as 1, 2, 3 and 4 hours. By this way, the effects of the recrystallization time were also revealed.

First of all, hardness values were measured after hot rolling process for different recrystallization times. As it can be seen in Table 12 and Figure 56, recrystallization time has an important effect on the hardness values of 7085 aluminum alloy after hot rolling process. However, recrystallization time does not have an important effect on the hardness values because there is no considerable difference between these values for different time intervals.

Beside this information, it was seen that hardness values decreased after hot rolling process according to the T6 heat treatment. Although it was not possible to produce test specimens from these sheets, it was seen that hardness values are higher after recrystallization. In order to understand the difference, microstructural characterization and grain size measurement were also done for these specimens.

Table 21. Hardness values of hot rolled 7085 aluminum alloy with different recrystallization time intervals

	Hardness (2.5 HB)	
	1 hour recrystallization	**2 hours recrystallization**
1	119	123
2	116	120
3	120	119
4	118	122
5	122	121
6	121	124
7	118	121
Average	**119 ± 2**	**121 ± 1**

	Hardness (2.5 HB)		
	3 hours recrystallization	**4 hours recrystallization**	**After hot rolling**
1	122	123	76.4
2	120	121	77.8
3	120	119	79
4	121	118	77.9
5	122	120	79.5
6	124	120	77
7	119	120	78.7
Average	**121 ± 1**	**120 ± 1**	**78 ± 1**

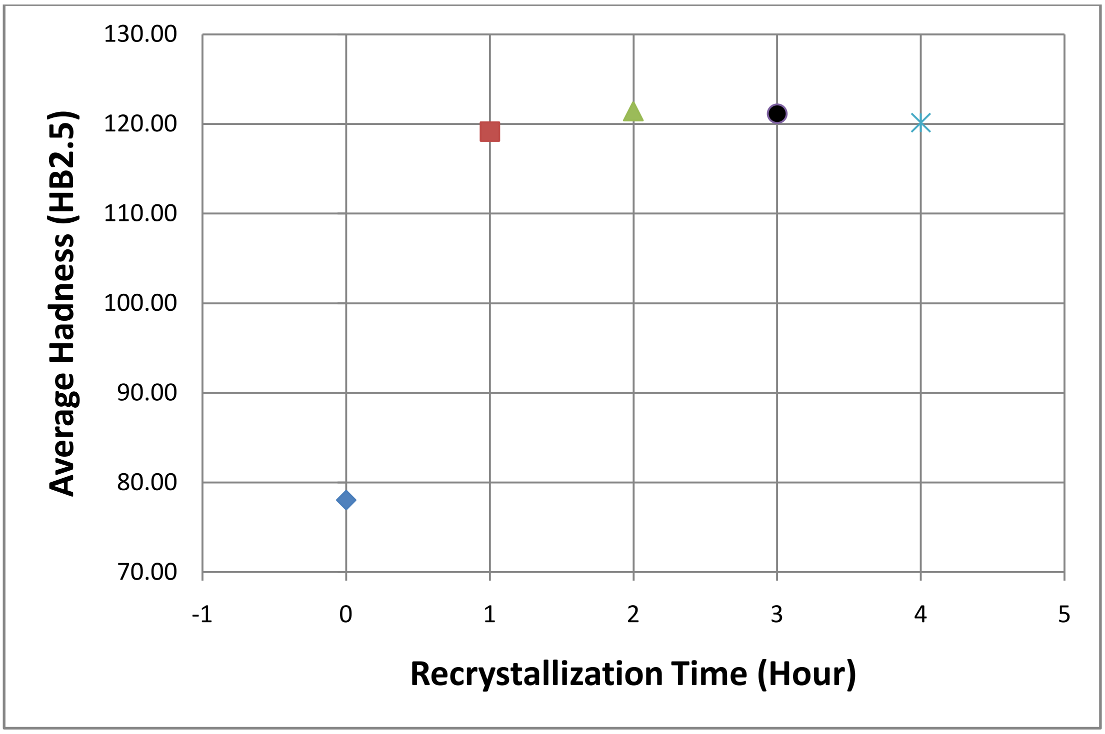


Figure 56. The relations in between recrystallization time and average hardness values before and after hot rolling process for 7085 aluminum alloy

After hardness measurement, microstructural characterization was also done. During this study, two samples were prepared from all aluminum sheets. Microstructures were determined from top and from views. At the same time, grain size measurement was also carried out. Average grain size values and calculations can be seen in the Appendix B for all different recrystallization times.

The microstructures were given in Figure 57. Elongated grains can be seen in these microstructures because of rolling operation and plastic deformation. It means that grain size of 7085 aluminum alloy was decreased successfully as it was aimed. Moreover, it can be realized that grain size increases with recrystallization time as it was given in Figure 58.

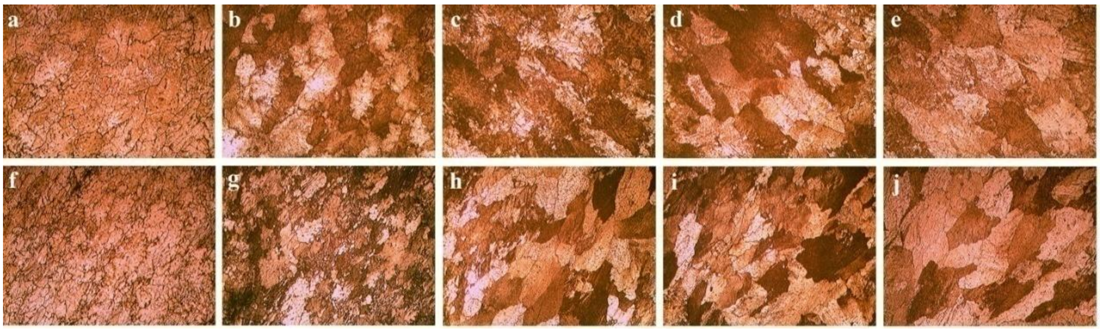


Figure 57. Microstructures (a-f) before and after recrystallization processes under 100X magnification for (b)-(g) 1 hour, (c)-(h) 2 hours, (d)-(i) 3 hours, (e)-(j) 4 hours (above images were taken from the top view while below images were taken from the front view of the 7085 aluminum sheets)

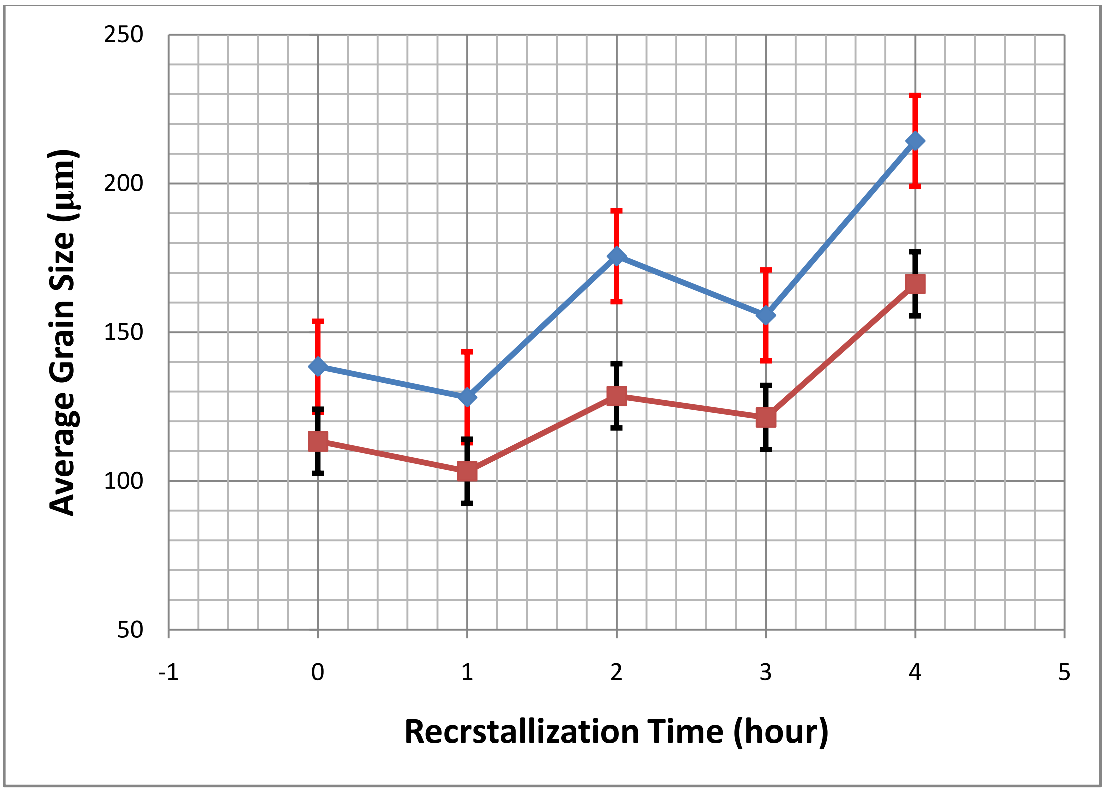


Figure 58. The relations in between average hardness value and recrystallization time for hot rolled 7085 aluminum alloy from (blue lines) top view (red lines) front view

It should be noted that there is a decrement in the grain size of 1 hour recrystallized specimens (Figure 58). The reason of this decrease can be attributed to the formation of new grains by decreasing the average grain size after 1 hour recrystallization. Even if there is also decrease after 3 hours recrystallization process, this may be due to experimental error. At the end, it should be noted that there is a grain growth with time elapse for these specimens.

4.3.1.2 Hot Forging

After hot rolling process, hot forging process was also applied to aluminum 7085 discs in order to be able to improve mechanical properties. Before hot forging process, T6 heat treatment was applied to three specimens at 465^{o}C solutionizing temperatures. After that, specimens were held at 260^{o}C during 90 minutes and they were forged. With this process, it was aimed to decrease the thickness of the specimens 75% but it could not be achieved. Only 25% deformation could be done to these specimens with the help of forging machine. At the end, recrystallization step was applied and specimens were kept in the muffle furnace at 516^{o}C during 20 hours and they were quenched at the end of this process. After hot forging operation, all specimens were characterized and mechanical test was performed. First, hardness values of these specimens were determined. As it was expected, hardness values decreased due to recrystallization process.

Table 22. Hardness values of hot forged specimens

	Hardness (2.5 HB)		
	Specimen 1	**Specimen 2**	**Specimen 3**
1	139	129	134
2	128	136	135
3	130	140	136
4	127	132	142
5	129	130	135
6	131	134	134
Average	**131 ± 3**	**134 ± 3**	**136 ± 2**

At the same time, SEM examination was also done to these specimens as it can be seen in Figure 59. It can be said that second phases that are located in the grain interior were almost disappeared in the microstructure thanks to the diffusion mechanism at relatively high temperature during recrystallization. This means that, intermetallic phases dissolved in the aluminum matrix and it is expected to see increase of the mechanical properties. Therefore, three point bending test was done to these specimens. It can be also see that there is new recrystallized grains in the microstructure. As it can be seen in the Figure 59-b, grain size was measured as 125 micron. It means that grain size was also decreased after hot forging process.

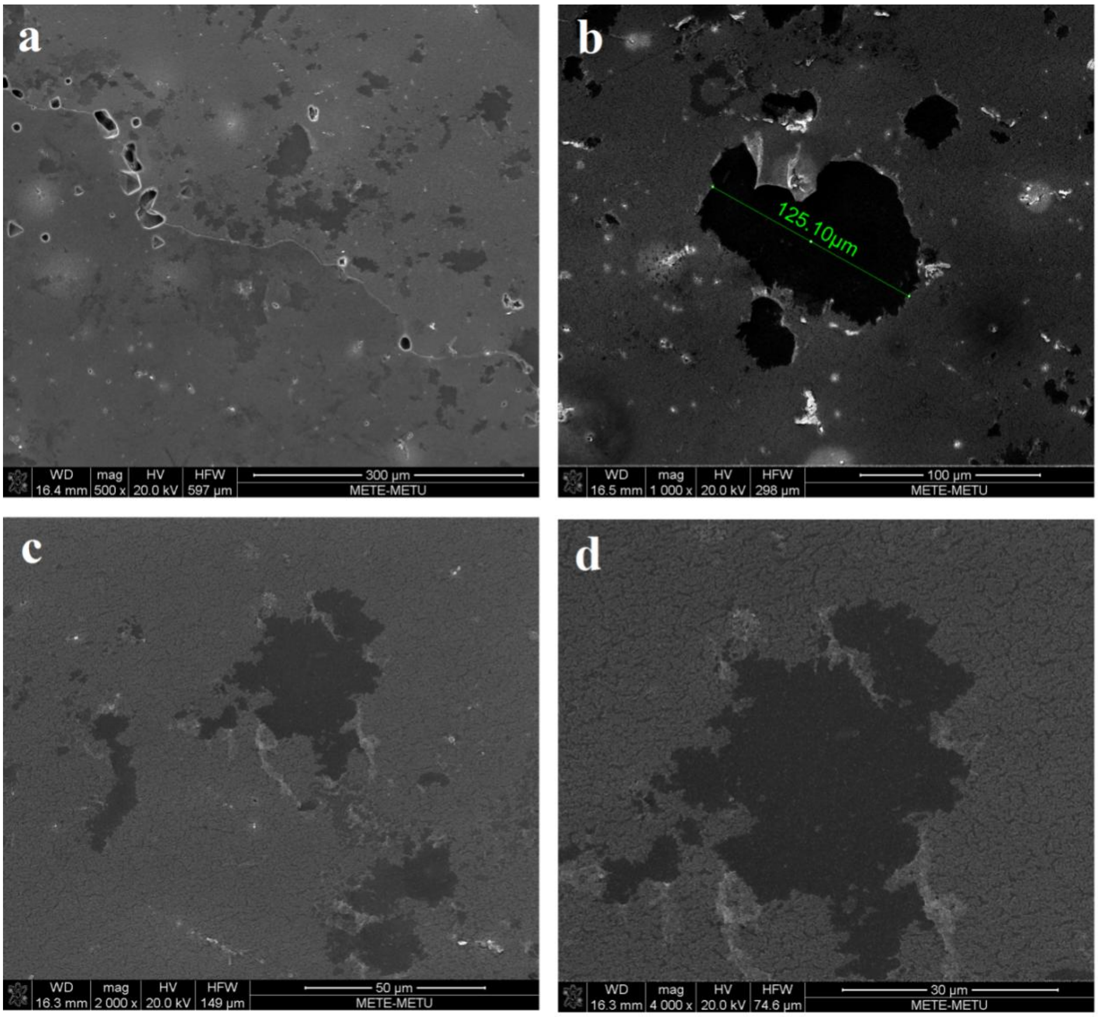


Figure 59. SEM images of hot forged and recrystallized 7085 aluminum alloy with various magnifications

After SEM examination, three point bending test was also done to hot forged specimens. It is possible to compare the result with the best T6 heat treatment condition in Figure 60. There is no doubt that flexure strain was improved very well and it can even reach up to 18%. This can be considered as a good improvement in terms of especially toughness of 7085 aluminum alloy. Moreover, flexural stress was observed even above 900MPa. Therefore, it should be noted that hot forging process as a good alternative process that increase the mechanical properties of 7xxx series aluminum alloys. Three point test results can be seen in the Appendix F.

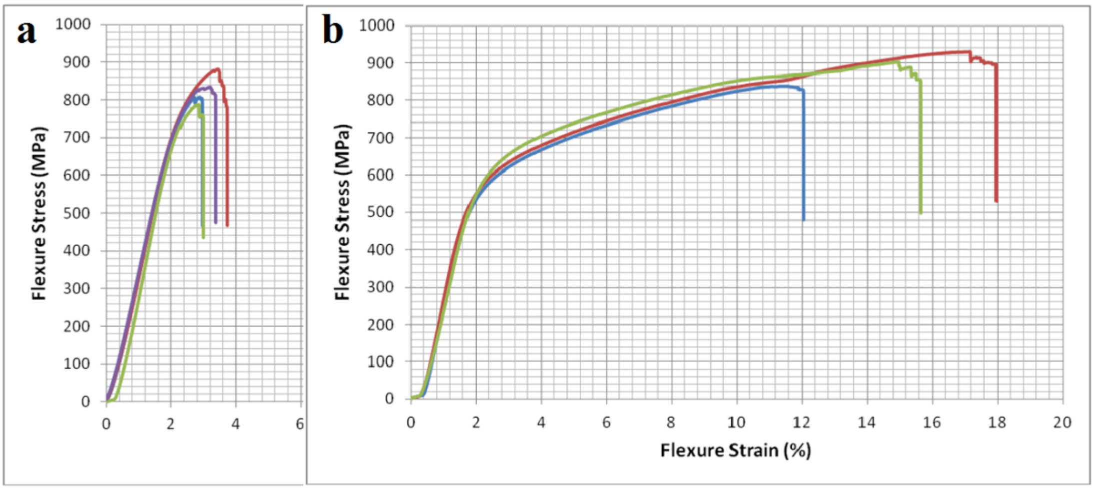


Figure 60. Comparison of three point bending test result for (a) the best T6 heat treatment condition, (b) hot forced at 260°C and recrystallization at 516°C during 20 hours after T6 heat treatment

Beside these characterization works, XRD analysis was also examined for these specimens. XRD results can be seen in Appendix D. There is no considerable difference in the XRD patterns of hot forged 7085 aluminum alloy. The only difference is that intensities of some peaks are bigger than T6 heat treated specimens. The reason of this situation can be related to the pattern formation after deformation during hot forging process. The main precipitation hardening intermetallic $MgZn_2$ could not be detected as well due to the low volume fraction in the α aluminum matrix.

4.3.2 Thermo-Mechanical Treatments of 7075 Aluminum Alloy

For 7075 aluminum alloy, hot rolling process was applied under different conditions same as 7085 aluminum alloy. The metal sheets that was produced by permanent mold casting were used for hot rolling process. After hot rolling, hot forging process was intended to operate but blister problem appeared after heat treatment. Therefore, hot forging process could not be performed correctly.

4.3.2.1 Hot Rolling

After hot rolling process of 7085 aluminum alloy, same thermo-mechanical treatments were applied to 7075 aluminum alloy as well and their effects were investigated. Similar to 7085 experiments, 7075 aluminum specimens were produced by permanent mold casting in sheet form. After that, T6 heat treatment was applied twice in order to be able to get better microstructure and 475^{o}C was used as solution heat treatment temperature during this heat treatment. Then, over-aging process was applied at 400^{o}C during 6 hours and specimens were rolled at 250^{o}C with two passes. At the end, 50% deformation was obtained by the decreasing thickness from 7mm to 3.5mm. Finally, recrystallization was done with different time intervals as 1, 2, 3 and 4 hours. As the final step, these specimens were characterized.

Hardness values of these specimens were measured as given in Table 23. When these values were taken into consideration, it can be stated that there is a decrement in the hardness values after recrystallization. Unlike 7085 aluminum alloy, the hardness values decrease just after recrystallization process. In other words, the hardness values of hot rolled specimens is higher than recrystallized specimens. This reveals that there are different precipitation hardening mechanism in 7075 and 7085 aluminum alloys. It was thought that grain size mechanism is just more dominant in 7075 aluminum alloy. Therefore, grain size measurement and calculations were also done for these specimens. These calculations and microstructures can be seen in the Appendix B.

Table 23. Hardness values of hot rolled 7075 aluminum alloy with different recrystallization time intervals

	Hardness (2.5 HB)		
	After Hot Rolling	**1 Hour Recrystallization**	**2 Hours Recrystallization**
1	125	103	100
2	128	105	103
3	127	108	102
4	127	106	99.7
5	124	106	102
6	127	104	103
7	126	111	106
8	131	109	102
9	131	105	101
10	124	107	104
Average	**127 ± 2**	**106 ± 1**	**102 ± 1**

	Hardness (2.5 HB)	
	3 Hours Recrystallization	**4 Hours Recrystallization**
1	106	94.5
2	111	93.8
3	109	97.3
4	108	99
5	110	101
6	105	98
7	108	100
8	111	101
9	108	99.3
10	110	101
Average	**109 ± 1**	**98 ± 1**

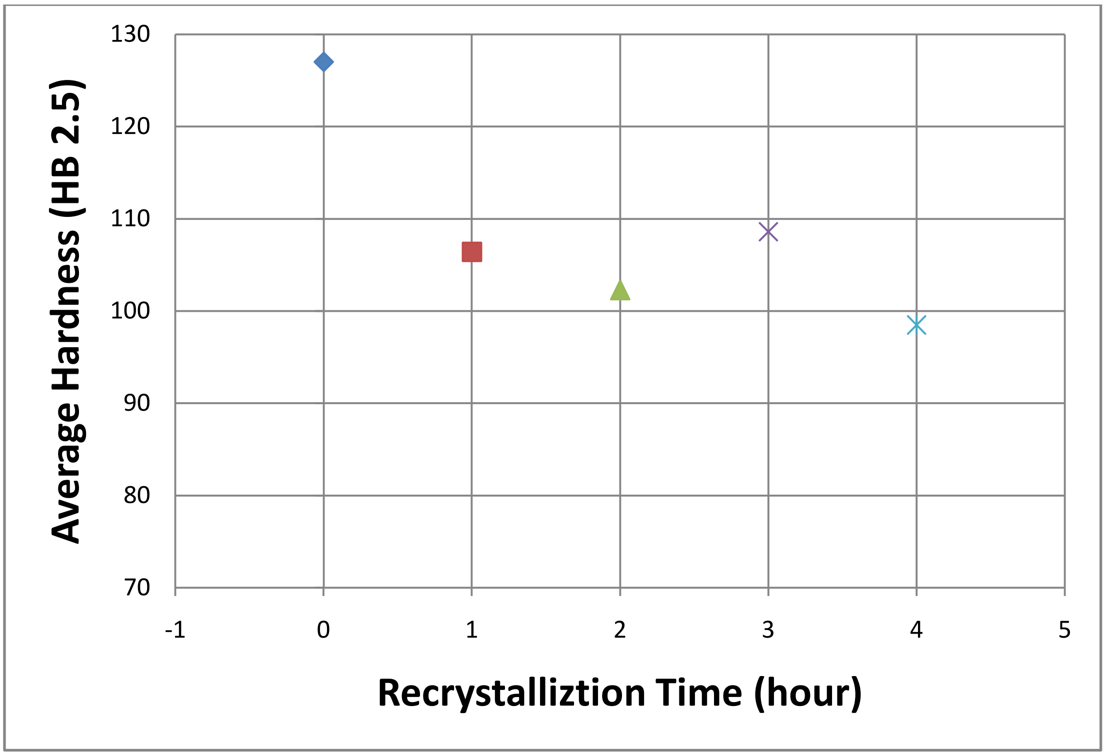


Figure 61. The relations in between average hardness values and recrystallization times of hot roller 7075 aluminum sheets, which are produced by permanent mold casting

According to the grain size measurement, the grain size of as cast structure of permanent mold casted 7075 aluminum alloy was determined as 119 micron whereas, it was observed as 127 micron after first T6 heat treatment. Grain size was decreased to 104 micron after second T6 heat treatment. It proves that double T6 heat treatment has positive effects on grain refinement and it can be stated that it has a positive effects on mechanical properties.

After recrystallization process, there is no big difference in the grain size for different time intervals as it can be seen in Figure 62. It can be said that there is a decrement after 1 hour recrystallization and it can be the evidence of formation of new grains in the microstructure. However, average grain size also decrease after 4 hours recrystallization. This situation may be due to the experimental errors because it is expected to see increasing trend because of grain growth mechanism. This situation can also be seen in decreasing hardness.

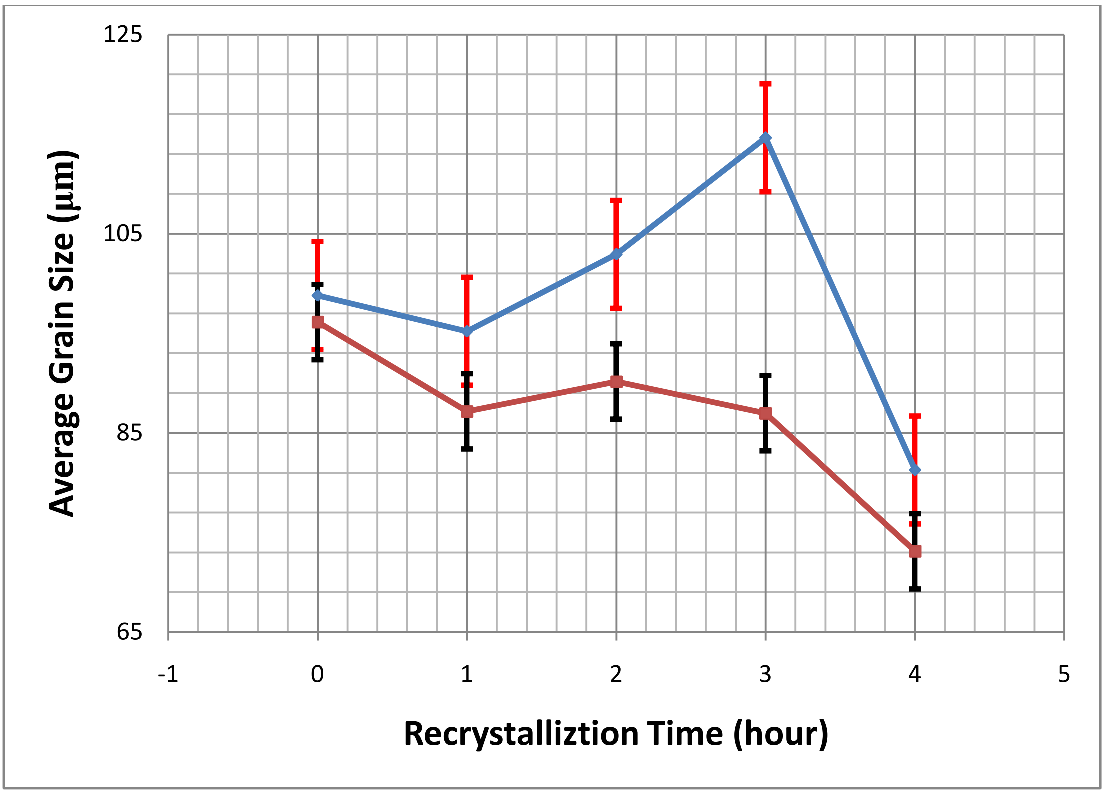


Figure 62. The relations in between average grain size and recrystallization times of hot roller 7075 aluminum sheets, which are produced by permanent mold casting (blue) top view, (red) front view

After these characterization studies, XRD analysis was not done for these specimens because it was not expected to see something different than other XRD results. It can be said that the precipitation of 7xxx series aluminum alloy, $MgZn_2$, cannot be detected with this method because of homogenous distribution of very small particles and overlapping problem that comes from aluminum alloy matrix.

4.3.2.2 Hot Forging

After hot rolling thermo-mechanical treatment, hot forging treatment was not thought to apply for 7075 aluminum alloy. Therefore, same procedure was followed as 7085 aluminum alloy. Specimens were held at 260^{o}C during 90 minutes after T6 heat treatment and they were forged. During these experiments, squeeze cast 7075 aluminum plates were used. However, it was seen that blister problem appeared after recrystallization step at 516^{o}C as it can be seen Figure 63. In the light of this information, Forging process could not be used for 7075 aluminum alloy squeeze cast square preforms produced during this work successfully.

Figure 63. Blister problem of 7075 aluminum alloy after recrystallization step of hot forging thermo-mechanical treatment

4.4 ALLOY DEVELOPMENT

As it was mentioned, two different metal molds were used in the squeeze casting experiments. the circular mold is not big enough to produce tensile test specimen. Therefore, square mold was designed for squeeze casting machine and it enabled to produce sufficiently large specimens that make possible to machine tensile test specimens. However, unexpected problems were faced with these square mold. Because of the geometry of the mold, hot tear problem was faced with in the middle of the castings due to unidirectional shrinkage during solidification. Although it was possible to produce some specimens with the help of alumina based thermal paper, micro cracks were obtained inside the square plates. Therefore, high pressure die casting machine was used as an alternative way to develop ballistic aluminum alloy for backing plate. During the production, the speed of injection unit of high pressure die caster was decreased and rheocasting was achieved. Thus, it can be said that specimens were produced by rheocasting with high pressure die casting machine.

During these experiment, a special mold was used that give 2 billets to machine tensile test specimens that were produced by rheocasting technique. Before machining, T6 heat treatments were operated for these specimens with the best conditions. These means that, 475^{o}C was used as solutionizing temperature for 7075 aluminum alloy whereas, 465^{o}C was used as solutionizing temperature for 7085 aluminum alloy. After that specimens were quenched in the water and they were aged at 120^{o}C during 24 hours. And the end, tensile tests were performed by tensile test machines and these results were obtained as it can be seen in Figure 64.

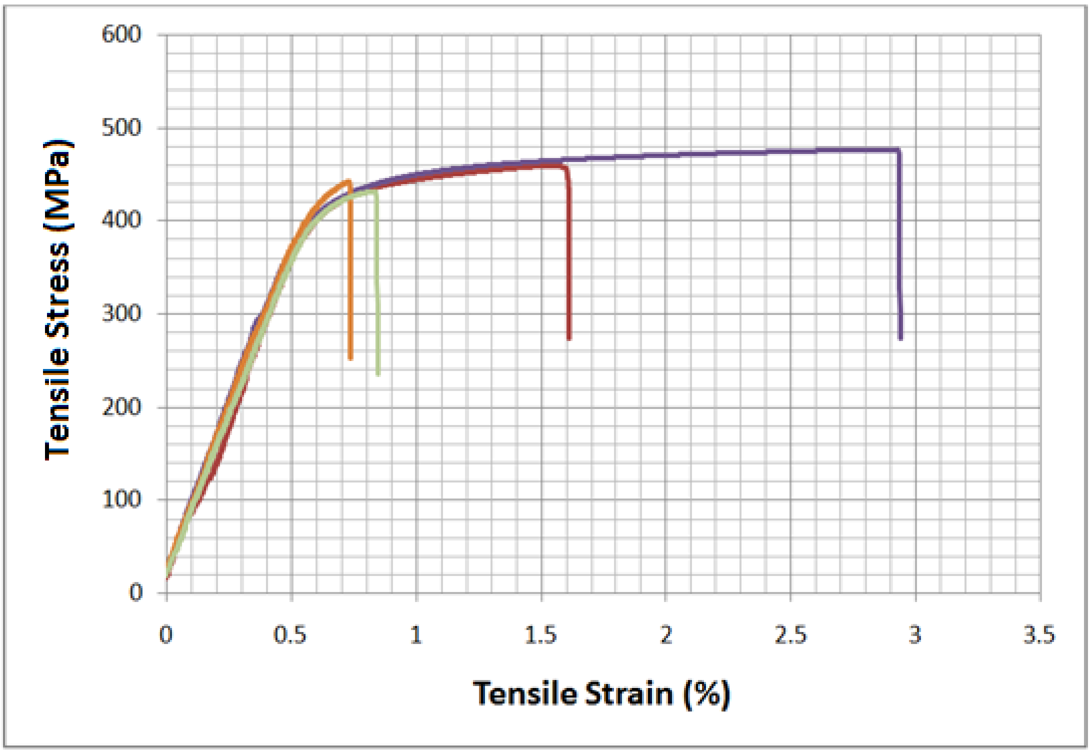


Figure 64. Tensile test results of 7075 aluminum alloy specimens, which are produced by rheocasting, after T6 heat treatment

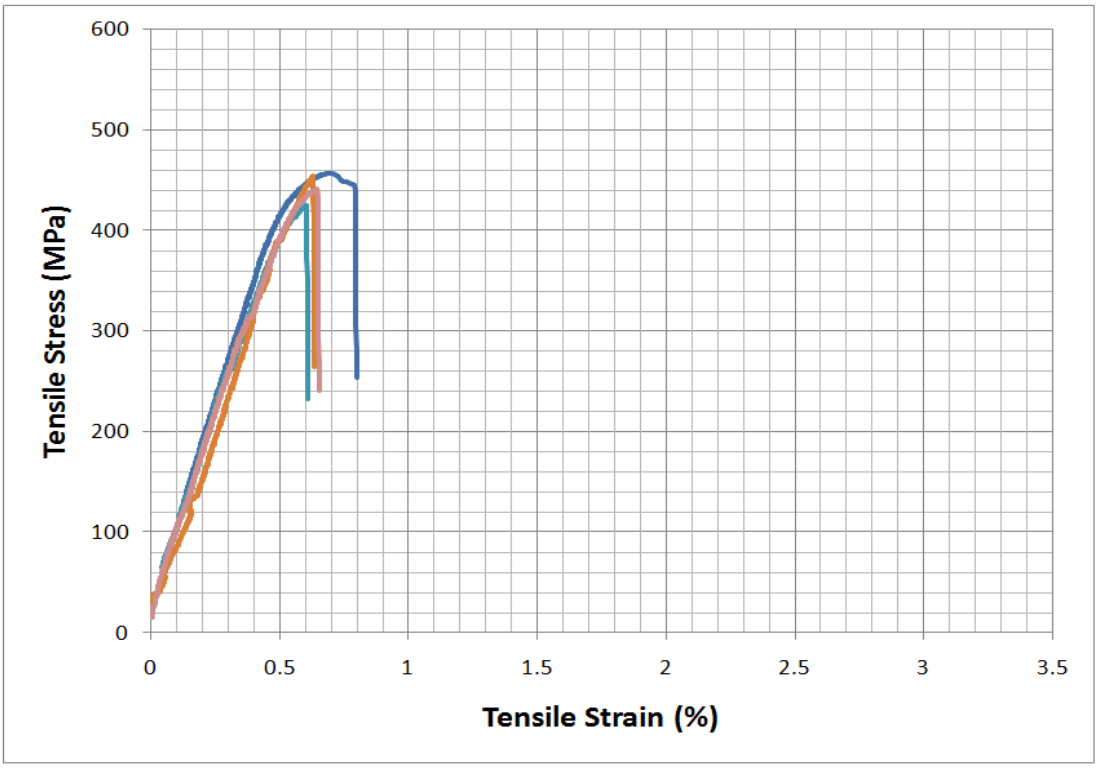


Figure 65. Tensile test results of 7085 aluminum alloy specimens, which are produced by rheocasting, after T6 heat treatment

According to tensile test results, it was seen that tensile strength of these aluminum alloys reached up to 500MPa as it was aimed in the beginning even if these specimens were produces by high pressure assisted rheocasting process. In the literature, 500MPa was reported for extruded specimens whereas, results shows that it is possible to reach these values by rheocasting technique. Therefore, this casting process can be also used to manufacture backing plates for armors. Especially curved structures can be produces with this method for laminate armor designs as a part of composite structures because 7075 and 7085 aluminum alloys are not suitable for high pressure die casting because of hot tear problem.

4.5 COMPOSITE PRODUCTION

In this part of the thesis is devoted to evaluate results about composite materials that were produced during research studies. Melt infiltration method was used to fabricate different composite structures with alumina (Al_2O_3), boron carbide (B_4C) and carbon fiber. The ceramic reinforcements were taken as alumina and boron carbide preforms and melt infiltration process were operated with 7075 and 7085 aluminum alloys. In addition, carbon fiber is also melt infiltrated as multi layer structure with these aluminum alloys. In the beginning, alumina and boron carbide powders, which were used to get ceramic preforms, were characterized. After that, all samples were investigated with all details.

4.5.1 Production of Ceramic Preforms

Even if ceramic reinforcements that were used during melt infiltration process were taken as ceramic preforms, the powders were obtained for the production of these materials. Therefore, these powders were characterized by SEM and XRD analysis. The SEM images of boron carbide can be seen in the below figure.

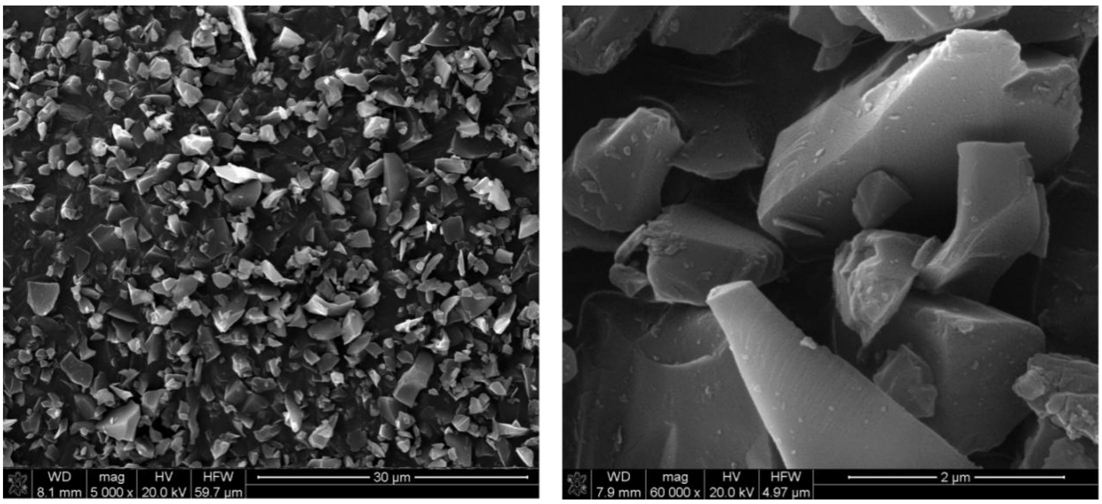


Figure 66. SEM images of boron carbide powder with various magnifications

With this SEM examination, the characterization parameters of boron carbide powder were corrected. It was known that this boron carbide powder particles is between 1 and 3 micron particle size and it is 99% percent pure. This information was corrected with SEM.

Moreover, XRD measurement was also done for this powder and XRD pattern was measured as below. As it can be seen, the patterns of boron carbide was measured (Figure 67).

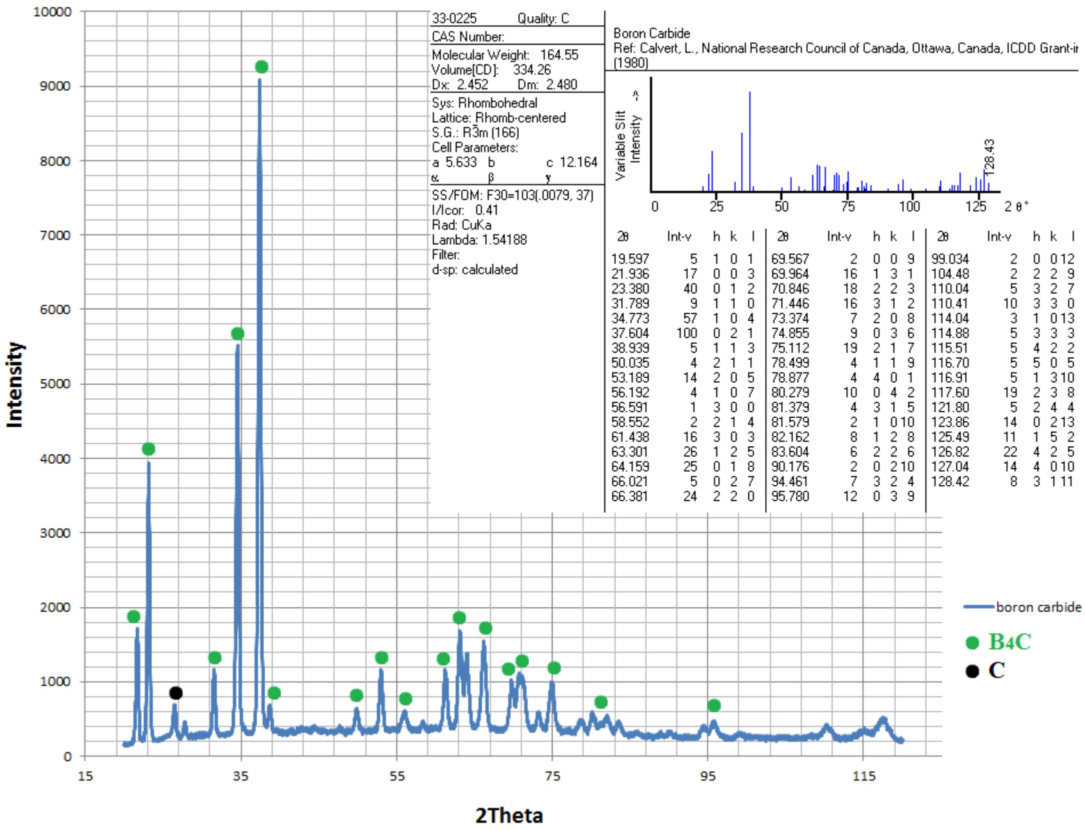


Figure 67. XRD pattern of boron carbide powder

Even if the production of ceramic preforms was also carried out as a part of research project, some information about the production of ceramic preforms was taken. Melt infiltration was applied to 2 groups of alumina preforms. In the first group, partial sintering was one at 1000, 1100, 1200 and 1300^{o}C whereas; sintering was operated at 1300, 1400 and 1450^{o}C for the second group of alumina preforms.

In the beginning, alumina powder was mixed with some other materials such as zeolite and magnesium oxide in order to be able to create suitable sintering conditions. The weight percentages of these materials are 10 and 0.2% respectively. After that, this powder mixture formed by press that can apply 30MPa. This is the production route of the ceramic preforms. Same procedures were followed for the production of boron carbide.

4.5.2 Melt Infiltration

With the help of melt infiltration technique, three different composite structures were produced. First of all, alumina – 7085 aluminum composites were obtained. After that, boron carbide – 7075 aluminum composites were fabricated. At the end, carbon fiber - aluminum 7075 composites were also produced. During melt infiltration technique, squeeze casting machine was used same as squeeze casting process. Preforms and the mold were heated at the beginning and liquid metal was poured into the preforms. While ceramic preforms are heated up to 1000^{o}C whereas, metal mold is heated as 250^{o}C. After that the machine was operated so fast that composite materials were just obtained in seconds. This process is named as melt infiltration under pressure.

4.5.2.1 Alumina – 7085 Aluminum Composite Production

In the beginning, melt infiltration process was done by the first group of alumina preforms that were sintered at 1000, 1100, 1200 and 1300^{o}C whereas, only two of them were characterized. Metal matrix composites that were produces by the preforms sintered at 1000 and 1300^{o}C were investigated by SEM. In addition, three point bending test was operated for the specimens that give the best results. Moreover, hardness and phase analysis were done for all specimens. After melt infiltration method, ceramic preform is confined by molten metal. In order to be able to investigate the microstructure and interfaces in between ceramic reinforcement and aluminum metal, these specimens were machines and metal matrix ceramic was appeared as it can be seen in below figure.

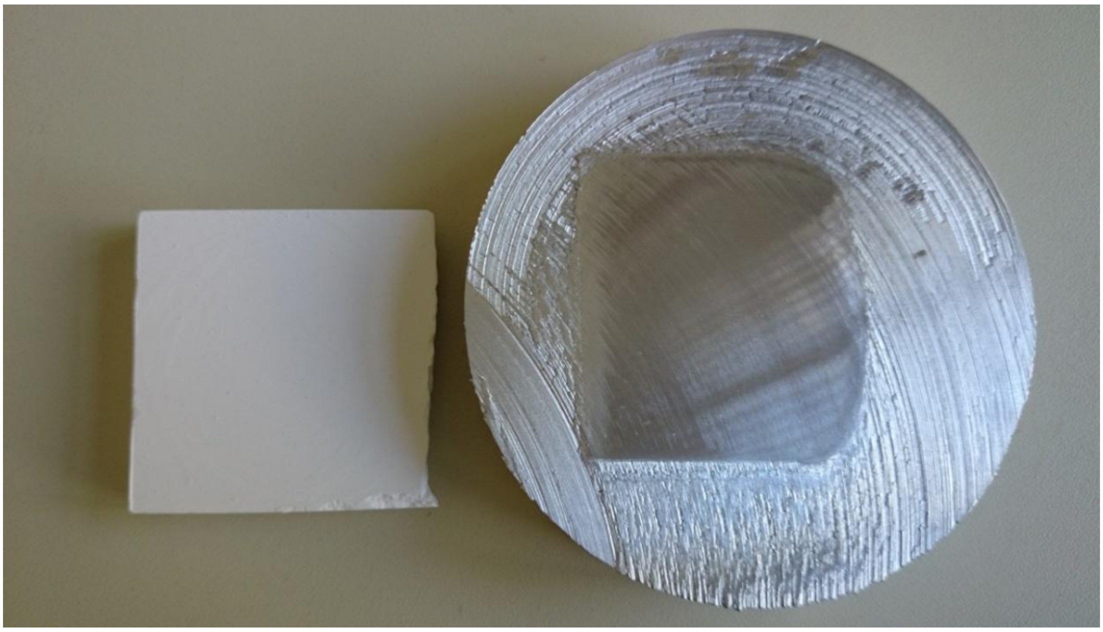


Figure 68. Alumina preform and the preform in the metal matrix composite after melt infiltration process

After the production of alumina – 7085 aluminum matrix composite, the surfaces were prepared by metallographic methods. Then, hardness measurement was done for all specimens. These hardness values were taken from both of aluminum and composite parts of the specimens as it can be seen in the below table. According to this table, it can be said that the hardness values of the composites that were manufactured by preforms whose sintering temperatures are 1000, 1100 and 1200°C are not so different than each other. Nevertheless, the hardness of the composited whose preform was sintered at 1300°C is higher than all other specimens. Therefore, it can be stated that sintering conditions at 1300°C is much better than 1000, 1100 and 1200 because there is big difference in the hardness values. The average of this specimens was measured as 237 HB. This results show that alumina preforms should be sintered at least 1300°C before melt infiltration process.

Table 24. The hardness values of 7085 aluminum alloy and alumina – 7085 aluminum metal matrix composites according to the sintering temperatures of the alumina preforms

	Hardness (2.5 HB)			
NO	**Al 7085 - 1300C sintered Alumina**		**Al 7085 - 1200C sintered Alumina**	
	Aluminum Matrix	Ceramic Part	Aluminum Matrix	Ceramic Part
1	90.5	231	93.5	164
2	88.5	224	112	145
3	86	226	98.1	138
4	93.1	239	81.1	146
5	102	239	86.7	140
6	105	243	87.5	148
7		238		
8		239		
9		249		
10		230		
11		248		
Average	**94 ± 6**	**237 ± 5**	**93 ± 9**	**147 ± 7**

	Hardness (2.5 HB)			
NO	**Al 7085 - 1100C sintered Alumina**		**Al 7085 - 1000C sintered Alumina**	
	Aluminum Matrix	Ceramic Part	Aluminum Matrix	Ceramic Part
1	95.9	153	92.8	150
2	94.1	158	91.5	148
3	99.5	147	96.1	152
4	96.6	171	97.4	154
5	102	153	93	155
6	100	162		
7		150		
8		149		
9		160		
10		149		
11		150		
Average	**98 ± 2**	**154 ± 4**	**94 ± 2**	**152 ± 3**

After hardness measurement, SEM examination was also done for the composite structures that were produces by alumina preforms whose sintering temperatures are 1000 and 1300^{o}C. These SEM images were taken from the interface region of the composites. Therefore, the left hand sides of the pictures is 7085 aluminum alloy whereas, the right hand side is the microstructures of the composite.

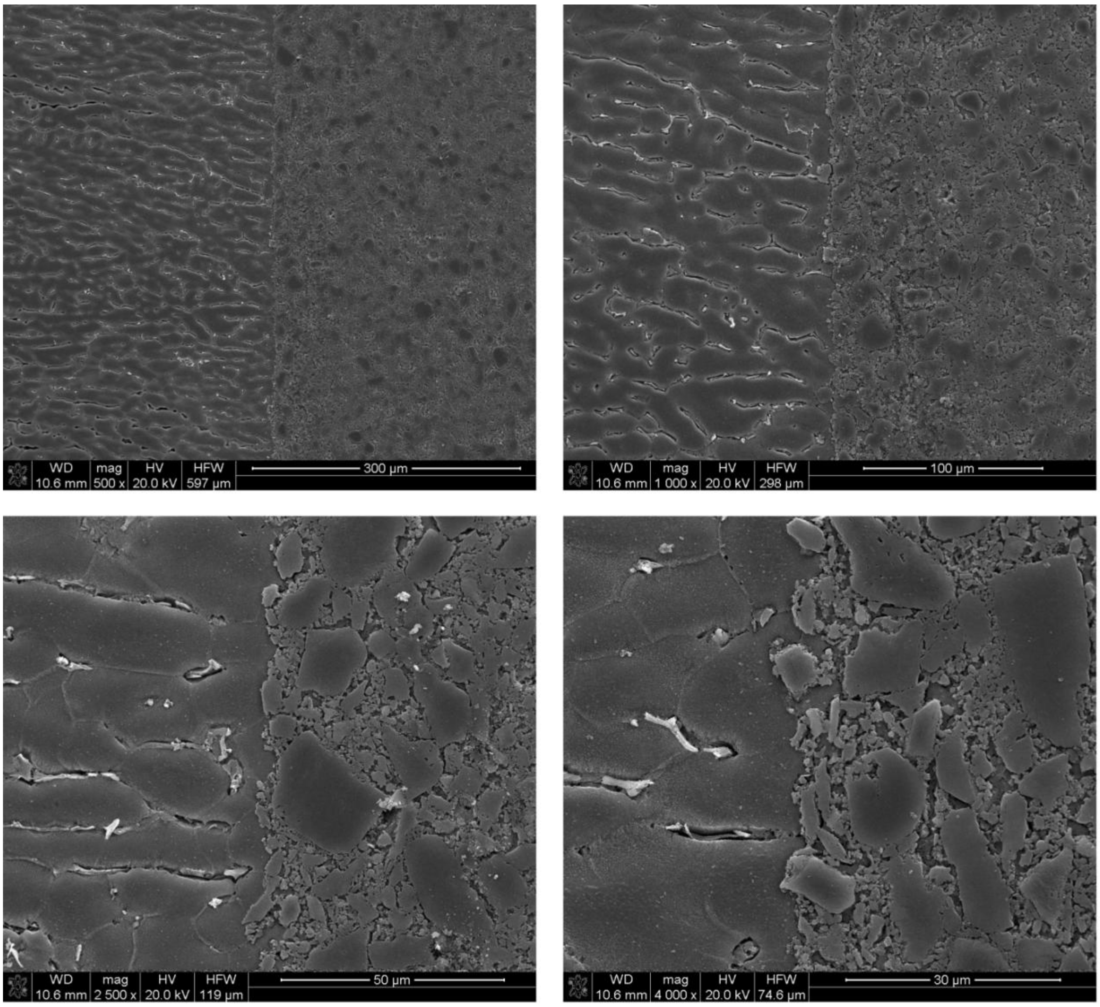


Figure 69. SEM images of the interface of alumina – 7085 aluminum alloy composite with various magnifications for 1000^{o}C alumina preform sintering temperature

When these microstructures were investigated, it can be said that there is no difficulty in wetting between 7085 aluminum alloy matrix and alumina reinforcement. Aluminum matrix is even detected in the pours of the alumina reinforcement. Therefore, melt infiltration condition was achieved by squeeze casting successfully under the applied pressure. Therefore, it should be noted that there is enough opened pours in the alumina preforms that were sintered at 1000 and 1300^{o}C.

According to this result, the same things were expected for the composites whose alumina preforms were sintered at 1100 and 1200^{o}C. However, it should be remembered that 1300^{o}C preform sintering temperature is the best condition for mechanical properties among these specimens.

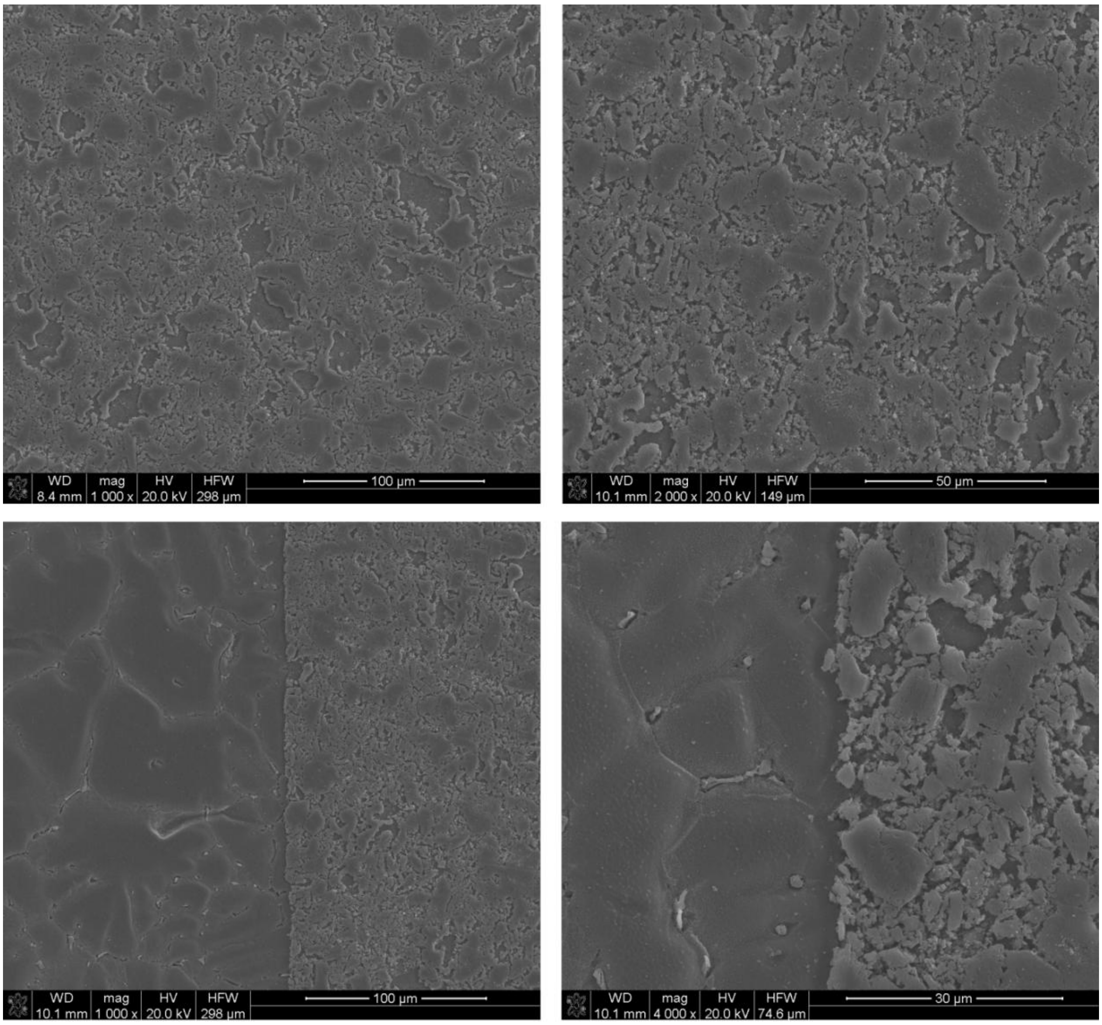


Figure 70. SEM images of the interface of alumina – 7085 aluminum alloy composite with various magnifications for 1300^{o}C alumina preform sintering temperature

After SEM examination, XRD measurement was also done for the composite materials whose alumina preforms were sintered at 1000^{o}C and 1300^{o}C. these XRD results can be seen in the Appendix D. According to these results there is no unexpected phases formation. Only Al and Al_2O_3 phase were determined with the help of the peaks.

In addition, phase analysis was operated to all specimens with the help of DeWinter phase analysis software. These results can be seen in Appendix E. When these results were taken into consideration, there is no big differences in the optical microstructures. However, it can be said that the composite produced by the alumina preform with 1300°C sintering temperature seems more homogenous than other specimens. In the phase analysis, there is two colors that represent different phases. Red color means alumina whereas, green one represent 7085 aluminum alloy. Even if aluminum amounts of the composites are close to each other, composite has less aluminum amount with 1300°C preform sintering temperatures. Therefore, it can be said that sintering process was achieved better than other specimens and less open pores remained into the ceramic preform. Hence, this situation increased the hardness of the composite as it was revealed.

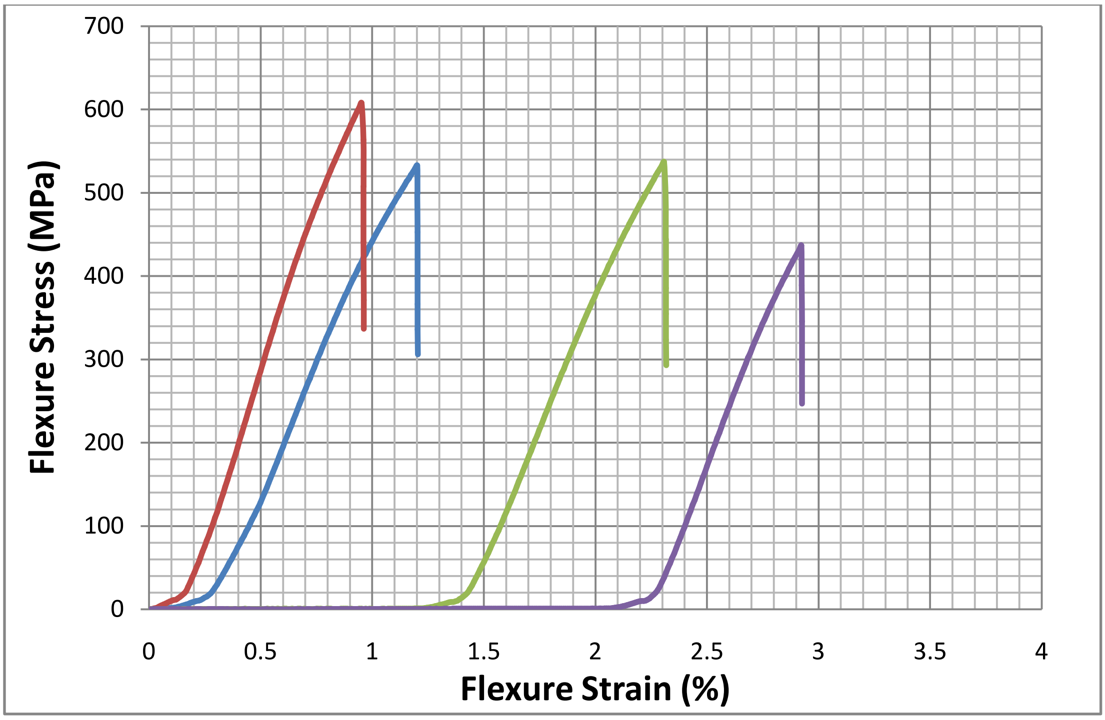


Figure 71. Three point bending test results of Alumina – 7085 Aluminum composite whose alumina preform sintering temperature is 1300°C

At the end, three point bending test was applied to the composite specimens that gave the best hardness results. According to these results, it was observed that flexural stress values of these specimens can reach even higher than 600MPa whereas, flexure strain % values can be in between 2-3 %. If the limited strain values of the ceramic materials is taken into consideration, it can be said that mechanical properties of the ceramic was improved by aluminum infiltration into the ceramic. It can be considered as one of the best results of melt infiltration process.

After first group of the preforms, second groups were used in the melt infiltration process. Sintering temperatures of these preforms are 1300, 1400 and 1450^{o}C. After melt infiltration, four different composite discs were obtained for each of the preform sintering temperature. These specimens can be seen in Figure 72 and 73. They are machines and composite structures were investigated from their surfaces.

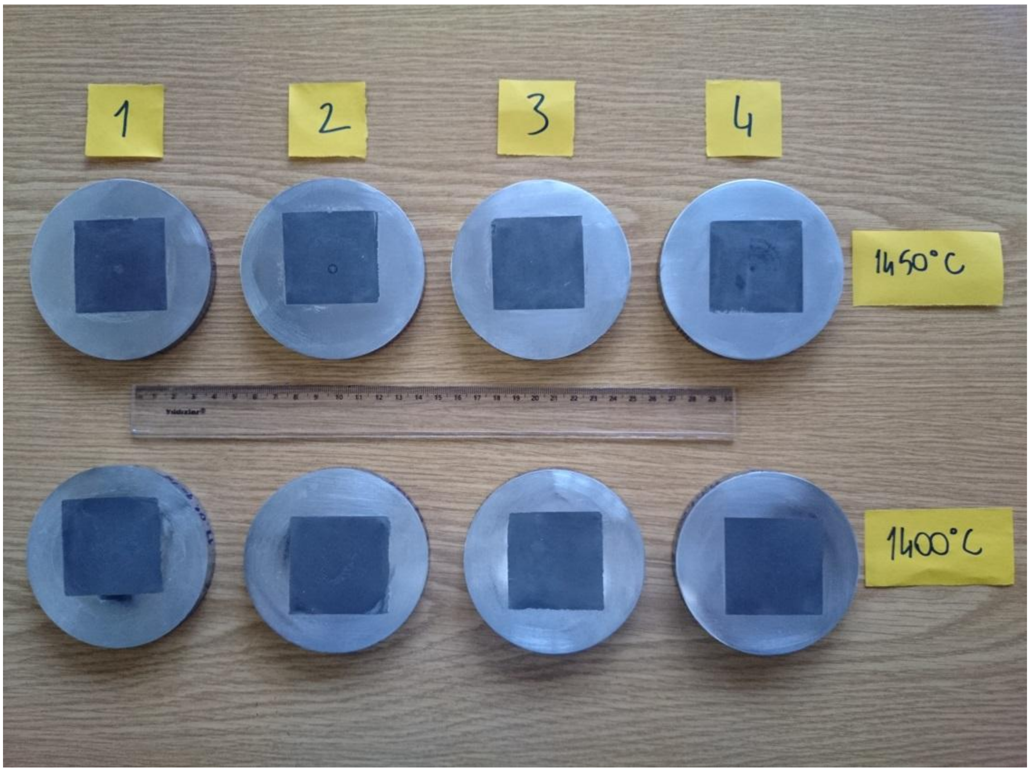


Figure 72. Alumina – 7085 Aluminum composites whose alumina preform sintering temperatures are 1400 and 1450^{o}C

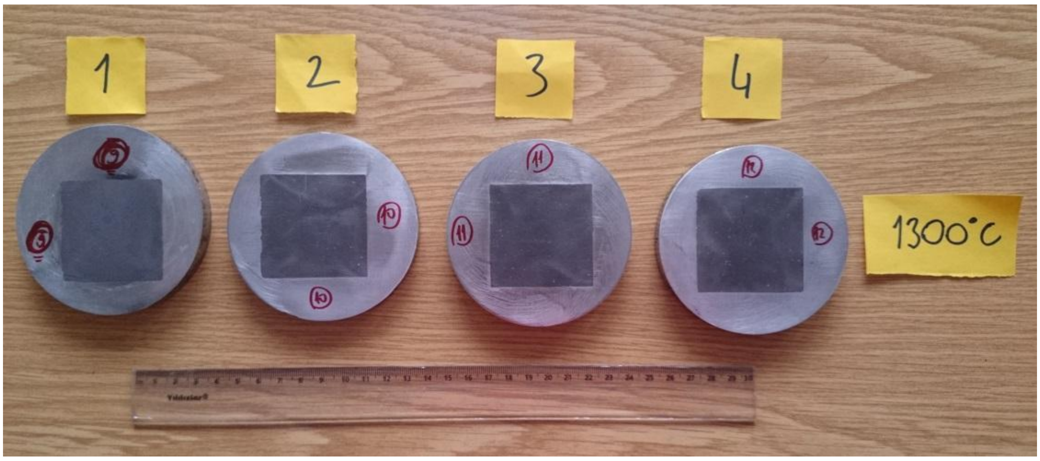


Figure 73. Alumina – 7085 Aluminum composites whose alumina preform sintering temperatures are 1300^{o}C

Hardness values of these composites were measured as it can be seen in the below table. It was realized that the hardness values are pretty higher in these specimens according to the composites produced by preforms whose sintering temperatures are 1000, 1100, 1200 and 1300^{o}C.

Table 25. Average hardness values of the Alumina – 7085 Aluminum composites whose alumina preform sintering temperatures are 1300, 1400 and 1450^{o}C

	Hardness (2.5 HB)			
	1450C sintered alumina + Al 7085 MMC			
	specimen 1	specimen 2	specimen 3	specimen 4
1	562	533	581	523
2	641	523	557	513
3	564	585	539	573
4	596	590	482	539
5	620	600	497	530
6	557	576	564	530
7	530	511	507	504
8	527	491	510	511
9	550	514	519	590
10	560	545	517	549
Average	**571 ± 23**	**547 ± 24**	**527 ± 20**	**536 ± 17**
All Avg.	**545 ± 18**			

Table 25. Continued

	Hardness (2.5 HB)			
	1400C sintered alumina + Al 7085 MMC			
	specimen 5	**specimen 6**	**specimen 7**	**specimen 8**
1	463	468	488	459
2	472	426	437	427
3	446	422	487	426
4	454	443	490	451
5	427	461	462	418
6	448	451	430	417
7	430	472	446	419
8	441	435	451	422
9	453	451	435	433
10	435	442	470	429
Average	**447 ± 9**	**447 ± 10**	**460 ± 14**	**430 ± 9**
All	**446 ± 12**			

	Hardness (2.5 HB)			
	1300C sintered alumina + Al 7085 MMC			
	specimen 9	**specimen 10**	**specimen 11**	**specimen 12**
1	327	275	311	291
2	308	293	287	248
3	313	283	304	276
4	305	268	303	276
5	316	255	289	256
6	297	265	308	289
7	305	291	291	278
8	276	294	291	287
9	289	274	303	274
10	315	287	279	277
Average	**305 ± 9**	**279 ± 8**	**297 ± 7**	**275 ± 9**
All	**289 ± 14**			

According to the hardness measurement results, it was noticed that the hardness of the composite materials increases with the increasement of preform sintering temperatures as it can be seen in below figures. Especially the specimens whose preforms were sintered at 1450^{o}C is so hard that, it has even higher hardness than tool steels. In order to understand the reason of this high hardness values, phase analysis and microstructural characterization were performed for the composite discs. Phase analysis results can be seen in the Appendix E.

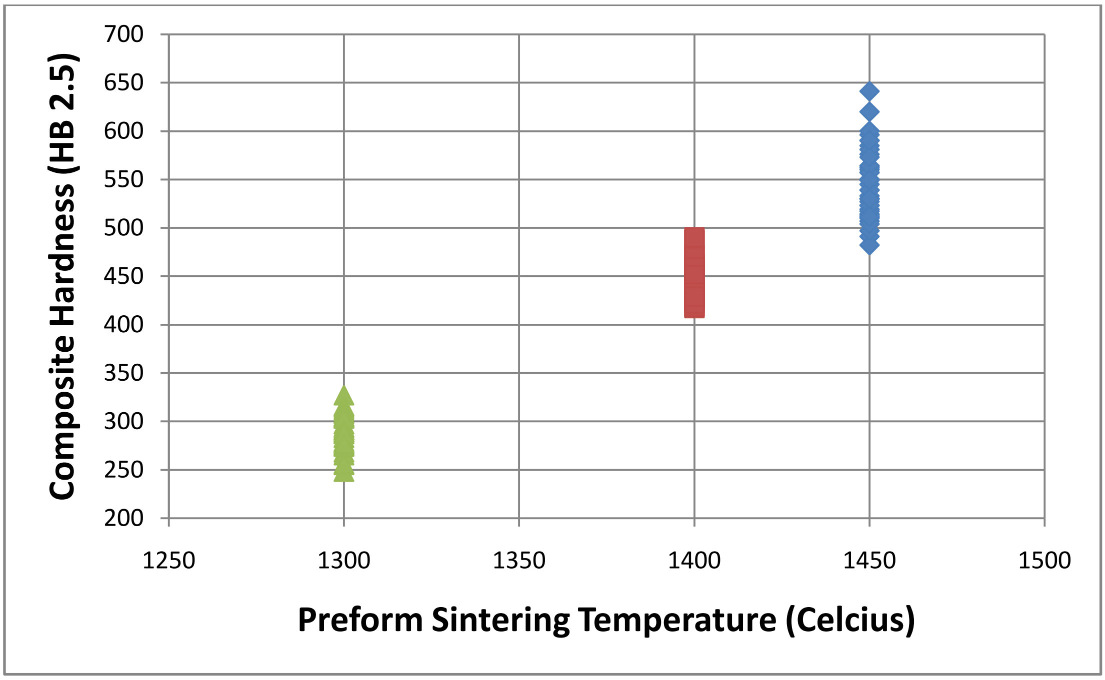


Figure 74. Distribution of composite hardness values according to preform sintering temperature

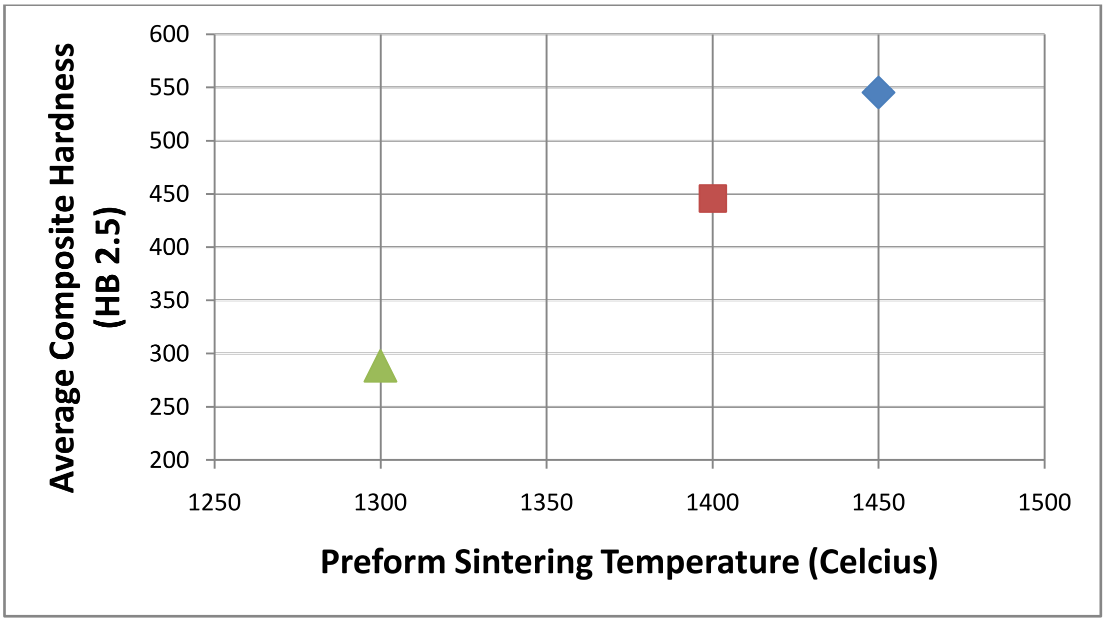


Figure 75. Relations in between average composite hardness values and preform sintering temperatures

According to the phase analysis of composites produced by second groups of preforms, it was seen that aluminum phase amount is much lower than the composites that were produced with first group of preforms. This means that opened pore amount of the second group preforms is much lower than first group of preforms. The aluminum phase amount changes in between 13 and 20% for composites that were produced by first group of the preforms whereas; same phase amounts is in between 27 and 43% in the composites, which were produces with the first group of preforms. After these results, it is so obvious that open pore content is the most important factor that determines the hardness of the Alumina – 7085 Aluminum metal matrix composite.

In addition, obtaining high hardness values can be a good news for the ballistic applications due to the fact that high hardness values are needed in order to be able to abrade the projectile. As it was thought that the hardness of the tool steels is about 530 HB, the average composite hardness 545 HB can be considered as a good results for ballistic armor material. Therefore, Alumina – 7085 aluminum composites can be a good candidate for these applications.

After these characterization processes, microstructures of these composites were examined. Composites, which were produced by preforms whose sintering temperatures are 1300 and 1450^{o}C from the second group, were examined by SEM. These SEM images were taken from the microstructure of these specimens and their metal-composite interfaces.

From these microstructures, it can be mentioned that even if high temperature sintering conditions and low opened pore content contributes the hardness values, they have negative effects on the wetting properties of the aluminum alloy on alumina. The problem in the interface was revealed especially in the composite whose aluminum preform was sintered at 1450^{o}C. Therefore, optimum conditions should be preferred for the better mechanical properties. It was aimed that hardness values should be high as much as possible but there should not be any problem in the interfaces. Interface defects are one of the biggest problems of the composite materials because these defects make composite weak. Therefore, they fail under high stressed environmental conditions. Especially for the ballistic applications in which high impact toughness is needed, interface problems are not allowed for backing plate design.

Even if there is a problem about interfaces, melt infiltration was achieved successfully since aluminum phases were detected in the pores of alumina structure as it can be seen in below figures. In other words, 7085 aluminum alloy was completely sucked by alumina preform with the help of squeeze casting. This shows that squeeze casting is a good method to produce metal matrix composites if interface problems are able to be solved.

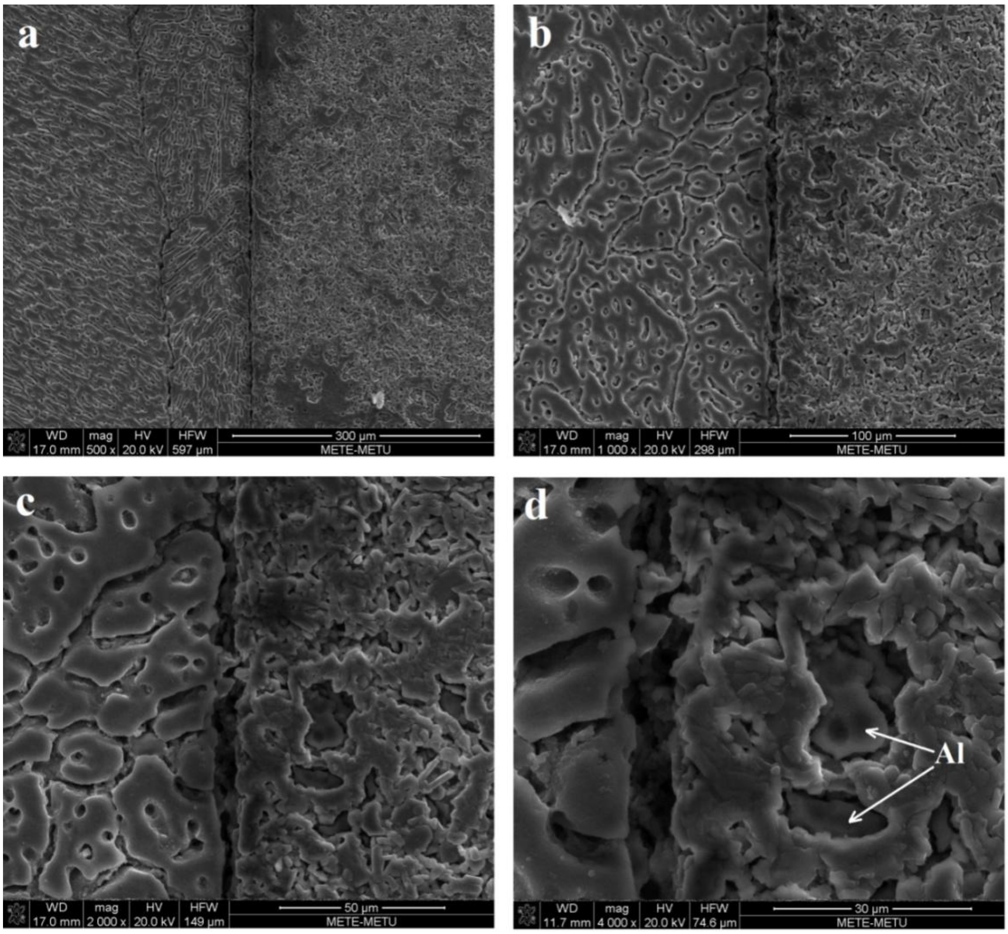


Figure 76. SEM images of the interface of alumina – 7085 aluminum alloy composite with various magnifications for 1300°C alumina preform sintering temperature (second group)

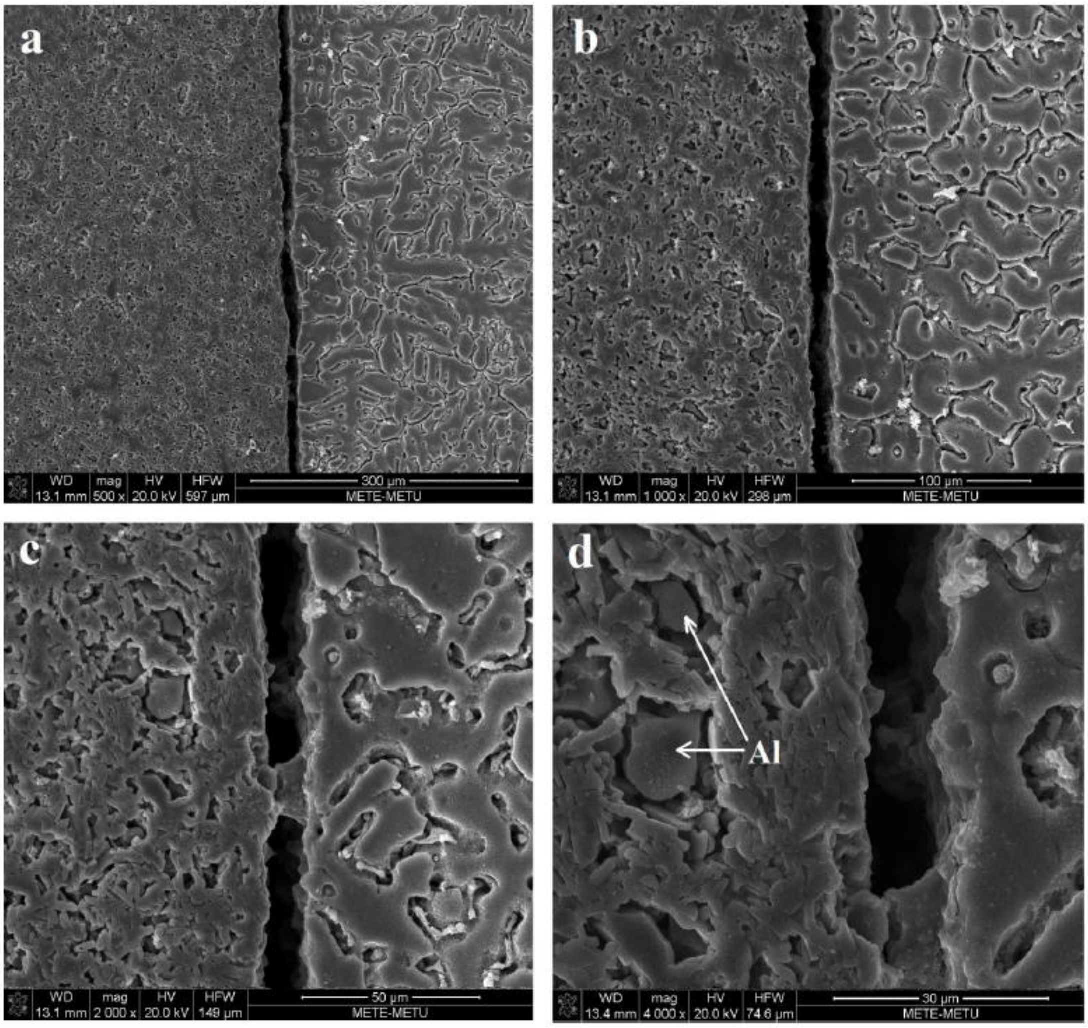


Figure 77. SEM images of the interface of alumina – 7085 aluminum alloy composite with various magnifications for 1450^{o}C alumina preform sintering temperature (second group)

4.5.2.2 Boron Carbide – 7075 Aluminum Composite Production

After the production of Alumina – 7085 Aluminum composite, researches were continued with the production of Boron Carbide – Aluminum 7075 composite production. During these experiments, 7075 aluminum alloy was used as metal matrix and four different melt infiltration experiments were conducted. 1-3 micron size boron carbide powder was mixed with binders and they were cold pressed in the beginning. Metal powders were also added to specimens number 3 and 4 in order to provide better sintering conditions. And then, all specimens were sintered at 1000^{o}C in the muffle furnace under argon atmosphere. After sintering operation, melt infiltration technique was operated in order to obtain composite discs as it can be seen in Figure 78.

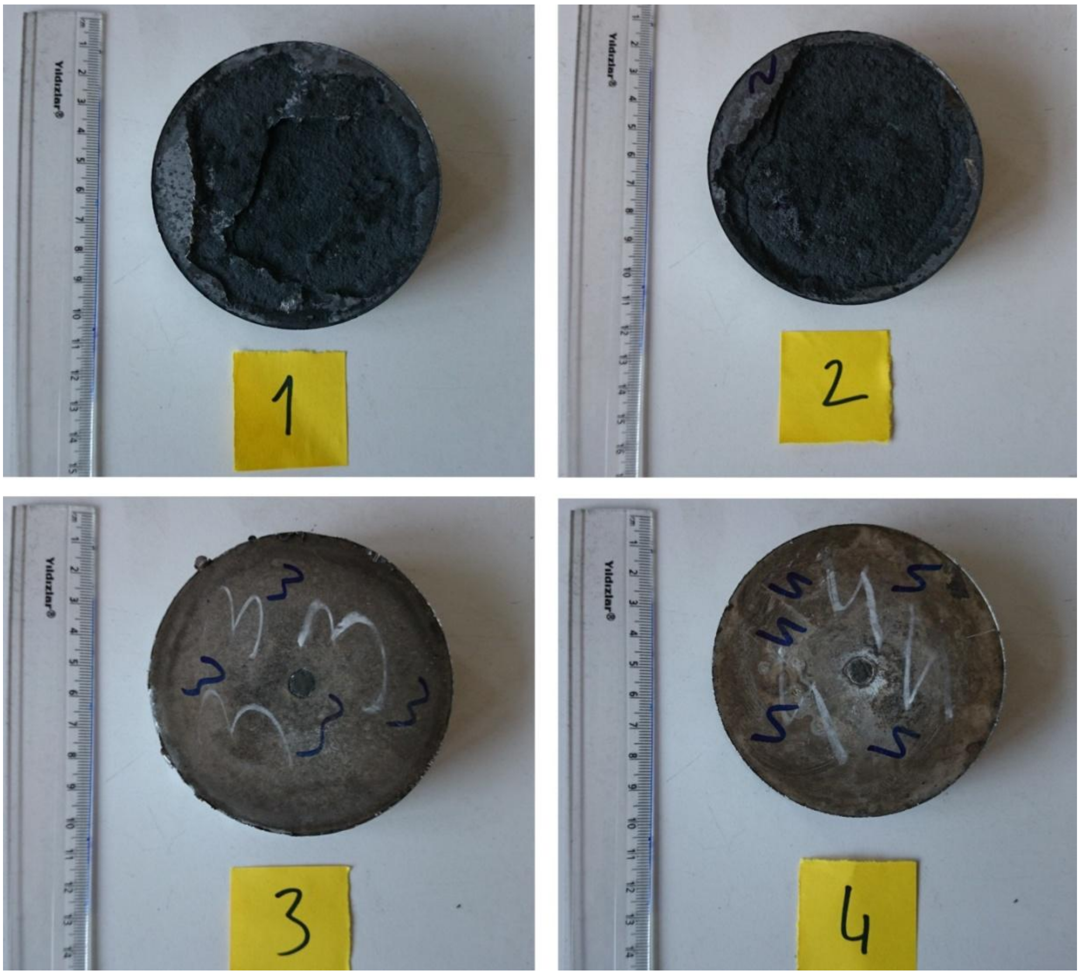


Figure 78. Boron Carbide – 7075 Aluminum composites that were produced by melt infiltration

After this experiments, it was seen that a mixture of aluminum and copper powder is needed to provide a network necessary to improve strength during sintering at 1000^{o}C. It was seen that metal phase decreased the sintering temperature and it enables to achieve melt infiltration process for the production of metal matrix ceramic composite. Even if it was seen that there is no difficulty in melt infiltration technique, specimens were characterized under SEM. First of all, the metal surface was machines and 7075 aluminum layer was cleaned for specimens number 3 and 4. After that, one of these specimens were cut and its interface properties were investigated. During cutting process, diamond cutting tools were used and some cracks appeared as it can be seen in the image of specimen number 3.

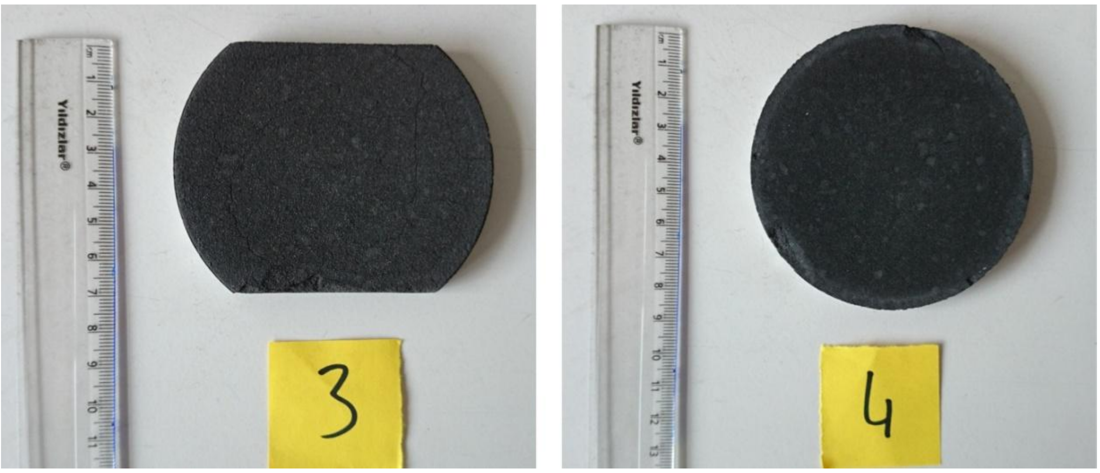


Figure 79. Boron Carbide – 7075 Aluminum composite structure

During the SEM examination; first of all, it was seen that metal phase worked as support in between boron carbide particles as it can be seen in the Figure 80. Copper and aluminum powders with different compositions were used as metal powder inside the mixture. These elements were determined in the microstructure after sintering. It can be said that, these metal phases hold the boron carbide powders even if sintering process were done at only 1000^{o}C that is relatively low temperature for the sintering process of boron carbide. With this way, wetting condition was achieved with melt infiltration technique although it can still be improved.

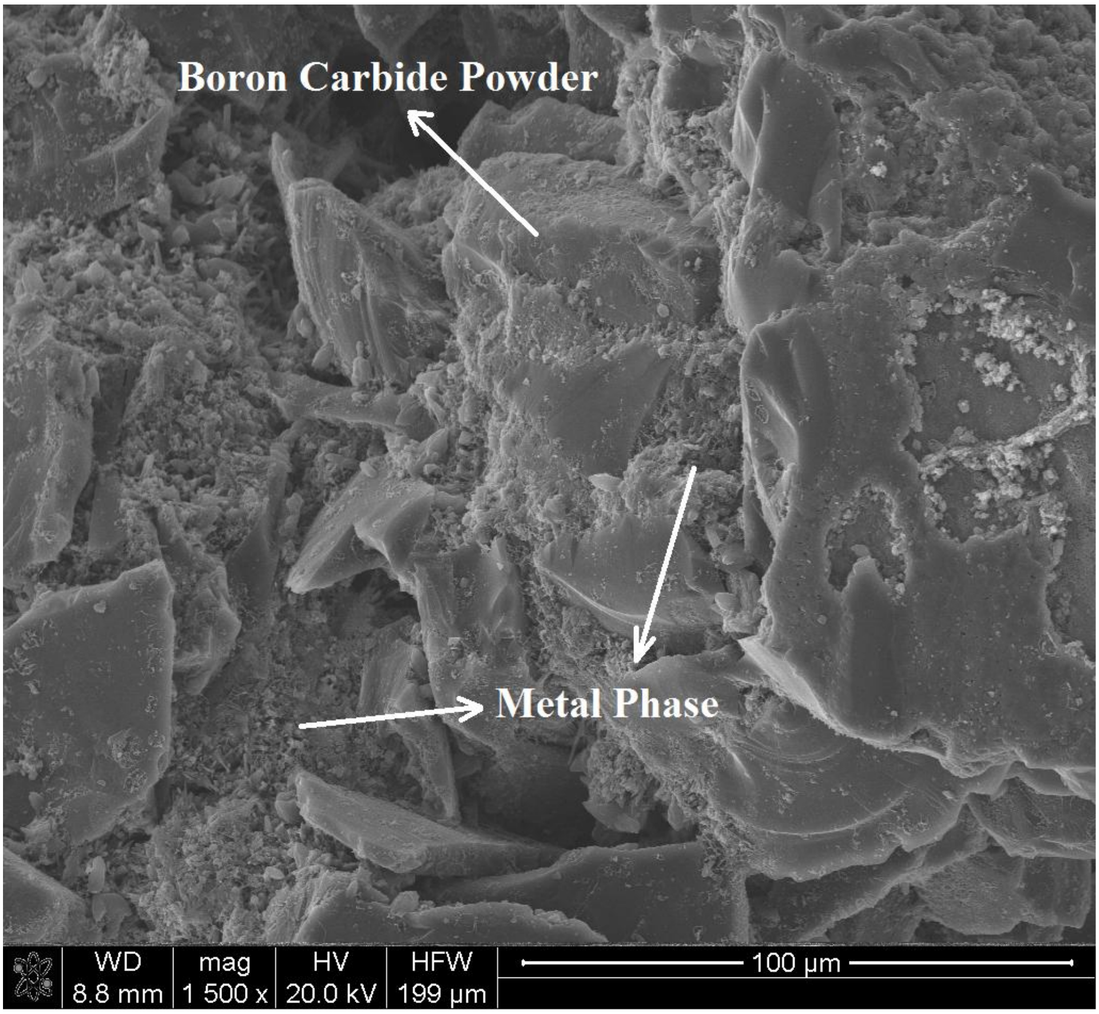


Figure 80. Microstructure of Boron Carbide – 7075 Aluminum composite

After the SEM examination of the composite structure, interface of the composite was also investigated as it can be seen in Figure 81. Aluminum 7075 alloy can be seen in the left hand side of the figures, microstructure of boron carbide – 7075 aluminum composite can be seen in the right hand side of the images. It should be noted that there is no wetting problem in the interface. However, grain size of the boron carbide is so small that it prevent to infiltration of the molten aluminum in between the particles. Therefore, it is believed that wetting properties can be improved. In this point, it was thought that boron carbide powder with larger grain size can be used for the production of these composite materials.

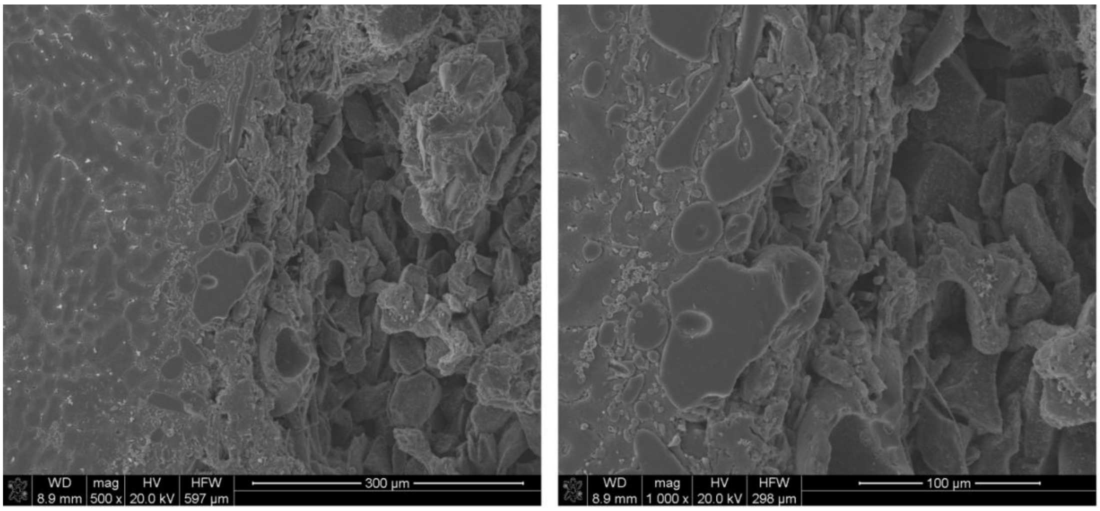


Figure 81. SEM images of Boron Carbide – 7075 Aluminum composite interface

After SEM examination, specimens were also tested by non-destructive test methods in order to understand whether there is a cracks or not inside the specimens. ultrasonic test method was used to understand the defects of the specimen 4 with special probs. It was seen that there is no crack formation inside the specimens. This test was done in the NDT laboratory of METU Welding Technology and NDT Center.

After the production of the boron carbide – 7075 aluminum composites, confinement experiment was done for these composites. In this experiment, square shaped Boron carbide – Aluminum composite that was produced by melt infiltration without pressure was used. As it is known, corrosion is an important issue for boron carbide composites. With this experiment, it was aimed to improve corrosion behavior of these composite structures. The main aim is to cover boron carbide composite with aluminum under the pressure. Therefore, squeeze casting was also used in order to achieve aluminum. In the beginning, ceramic plate was preheated at 500^{o}C during 90 minutes. At the same time, mold was also heated up to 250^{o}C. Composite plate was just put inside the mold and molten 7085 aluminum is poured in the cavity and squeeze casting was performed. At the end of this experiment, crack formation was seen in the center of composite as it can be seen in the below figure. Therefore, it should be noted that confinement operation is not possible with squeeze casting process for boron carbide – aluminum composite structures because of different thermal expansion coefficient, too fine carbide size and wetting difficulties for these materials.

Figure 82. Crack formation on the Boron Carbide – 7075 Aluminum composite after encapsulation experiment

4.5.2.3 Carbon Fiber – 7075 Aluminum Composite Production

After the production of metal matrix ceramic composites, it was also tried to fabricate metal matrix carbon fiber composite at the same time. In the beginning, the wetting properties of 7075 aluminum alloy on carbon fiber were improved. In this point, some special coatings with metal powder additions was were used. These coatings were applied to the carbon fiber fabric and molten 7085 aluminum alloy was poured on top of the fabric. After that squeeze casting process was carried out. The microstructure of this composite structure was investigated. After that, sandwich composite was produces with five carbon fiber layers with the same way. And then, these specimens were examined under SEM.

In the beginning, three different squeeze casting experiments were done in order to improve the wetting ability of carbon fiber and 7075 aluminum alloy. As it can be seen in the below figures, there is an important improvement in the wetting abilities. It was seen that the addition of the special metal powder additions (aluminum and copper) is really effective in order to be able to increase the wetting in the carbon fiber – aluminum interface.

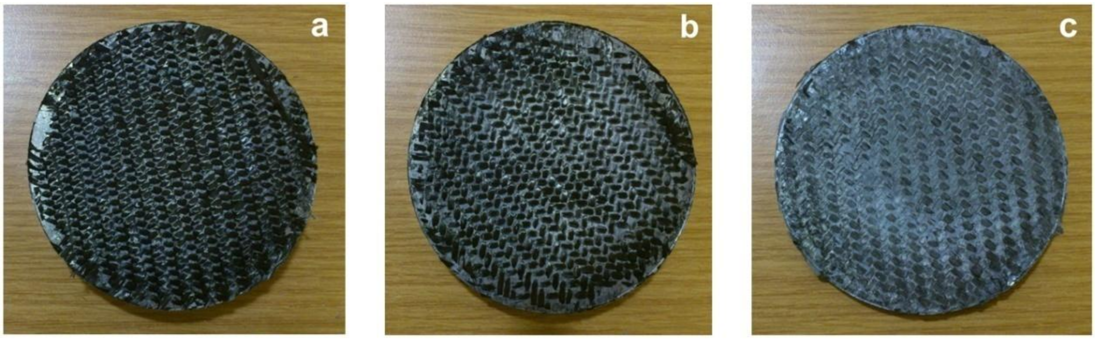


Figure 83. Improvement on the wetting abilities of Carbon Fiber and 7075 Aluminum Alloy

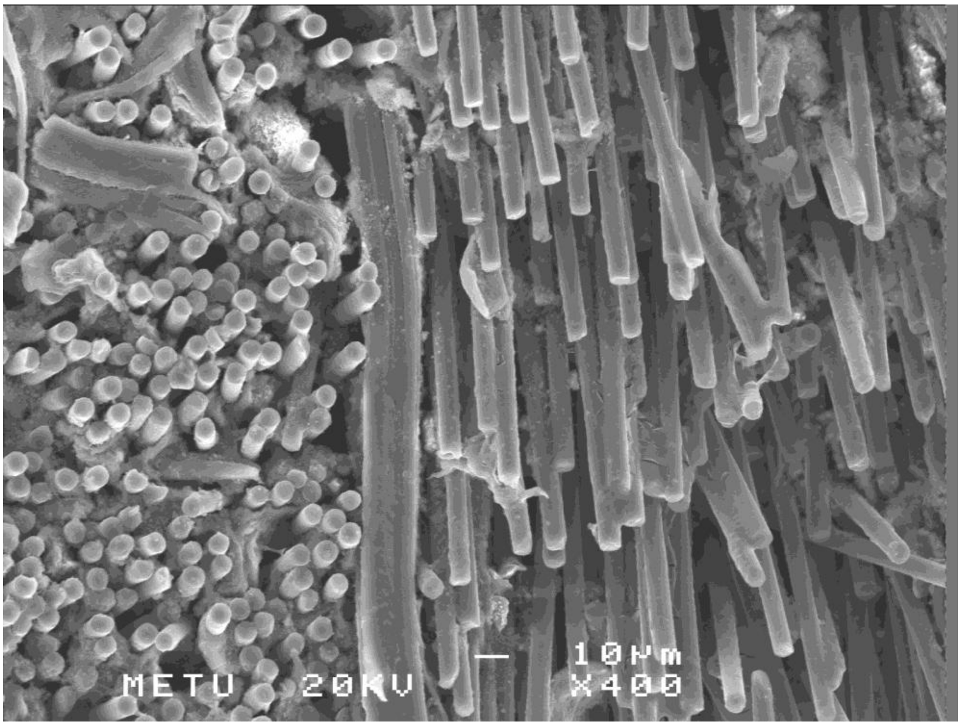


Figure 84. Microstructure of Carbon Fiber – 7075 Aluminum composite

As it can be seen in Figure 85, aluminum phase was determined in between carbon fibers thanks to EDX analysis. From this SEM image, it can be said that the wetting problem was solved for carbon fiber and 7075 aluminum alloy with the help of some special surface coating agents and high pressure casting process. It was also noticed that applied pressure has an important effect on the wetting condition. The orientations of the carbon fibers can be seen in this SEM image.

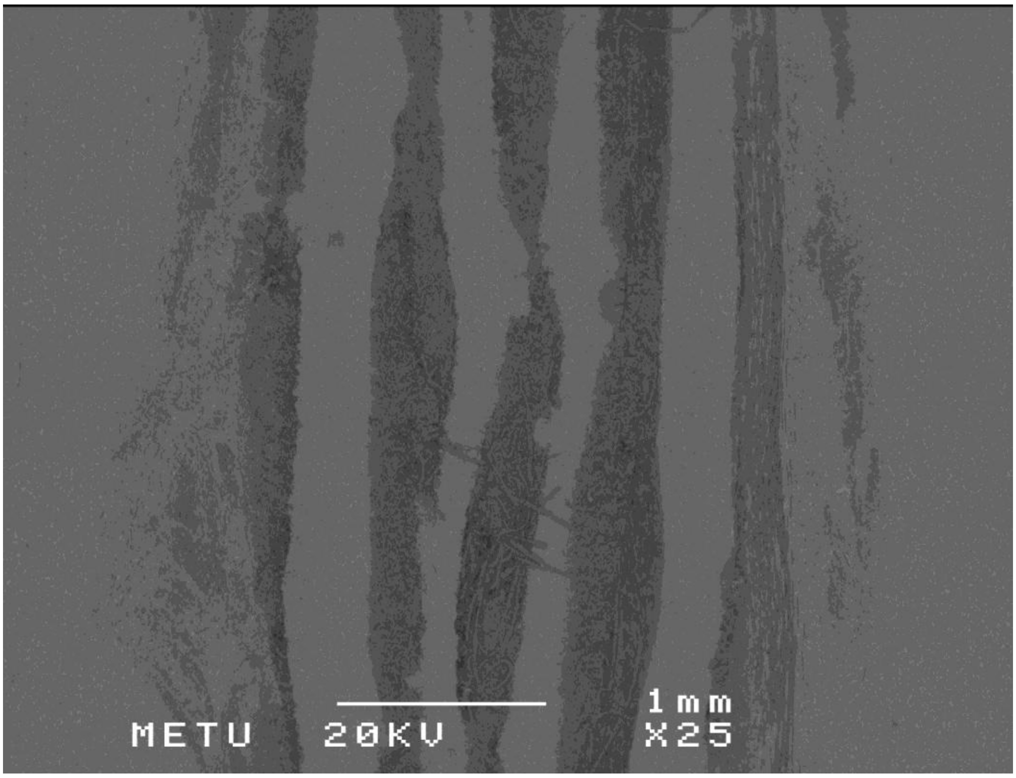


Figure 85. Microstructure of sandwich Carbon Fiber – 7075 Aluminum composite

After squeeze casting of Carbon Fiber – 7075 Aluminum composite, the cross section microstructure of sandwich composite structure was investigated by SEM as it can be seen in Figure 85. Seven layers of carbon fiber texture can be seen in between 7075 aluminum alloy layers. Wetting problem was not obtained during the production of these composite. Even if it was not possible to do mechanical tests, it can be stated that the more carbon layers, the better mechanical properties can be achieved for ballistic applications. Therefore, it is possible to improve mechanical properties with the addition of more layers.

CHAPTER 5

CONCLUSIONS

5.1 GENERAL CONCLUSIONS

The aim of this thesis is to develop high strength aluminum matrix composite backing plates for ballistic armor. Ballistic material developments are really important for defense industry. The main purpose of these materials is to protect people or vehicles from some kinds of threats that come from the environment and terror attacks. A series of experiments were conducted in order to improve the properties of aluminum and aluminum matrix composite materials.

At the end, the following conclusions are able to be drawn from the results of this study:

- ✓ Production of 7085 aluminum alloy with the addition of Mg - 33%Zr master alloy in the laboratory conditions using a basic charge calculation was performed to achieve target composition.

- ✓ For T6 heat treatment of 7075 aluminum alloy, 475^{o}C was determined as the most suitable solutionizing temperature in order to obtain the lowest grain size (94µm), the highest hardness value (178 HB) and the best mechanical properties, whereas 465^{o}C was determined as optimum temperature of T6 heat treatment for 7085 aluminum alloy having the lowest grain size and maximum hardness. Furthermore, 24 hours aging time is the most suitable time at 120^{o}C for aging step of T6 heat treatment of these 7000 series aluminum alloys produced in this study.

- ✓ According to the results obtained from the present experiments for 7085 aluminum alloy, it was concluded that no matter how grain size is large, mechanical properties were improved after thermo-mechanical treatments containing rolling and forging after T6 heat treatment. The reason is related to some complicated precipitation mechanisms and sequences of Al_2Cu (θ) and $MgZn_2$ (η) in this series of aluminum alloys.

- ✓ If there is more than one mechanism in a system, the slowest one is the most dominant one. It is clear that precipitation hardening mechanism is the crucial hardening mechanism for 7000 series aluminum alloys. In this work, particularly coarse precipitates could not be detected at the grain boundaries. Thus, it is so obvious that precipitate size is so fine enough, and they are mostly distributed homogenously within the matrix. During new grain formation and growth, they obviously interfere with boundaries and control the growth rate of grains. Nano size precipitates result in considerable improvement in mechanical properties especially after some thermo-mechanical processes.

- ✓ It was revealed that applying T6 heat treatment causes grain refinement of the 7075 and 7085 aluminum alloys. It is clear that grain refinement is provided after second T6 heat treatment. It was seen that grain size decreased from 127μm to 106μm in the 7075 permanent mould cast specimens after second T6 heat treatment.

- ✓ It was achieved that the toughness of the 7085 aluminum alloy was improved due to hot forging and recrystallization processes after T6 heat treatment. 18% flexure strain was obtained and flexure stress was even higher than 900MPa after hot forging process. Since impact toughness is an important parameter for ballistic applications, T6 heat treatment, forging and recrystallization are considered as an important thermo-mechanical process in order to be able to enhance mechanical properties.

- ✓ It should be noted that blister problem was faced with during the heat treatment of the squeeze cast 7075 aluminum alloy especially in the relatively high temperatures like 500^{o}C. In order to be able to eliminate this problem, degassing process should be applied or casting must be performed under the vacuum condition.

- ✓ High mechanical properties at specimens produced by rheocasting using high pressure die caster were obtained for the 7075 and 7085 aluminum alloys as if they are produced by extrusion process. Therefore, it can be said that tensile strength of the rheocast specimens even reached to 500MPa.

- ✓ Melt infiltration technique was proved to be an alternative technique to produce metal matrix composite components. Not only it is a simple process, but also it is so fast to fabricate more products according to alternative methods. Squeeze casting method was successfully applied for melt infiltration of ceramic preforms as near net shape process.

- ✓ During the production of aluminum matrix alumina composites, the volume fraction of the pores was determined to be a key parameter that influence both mechanical and physical properties. It was figured out that wetting difficulties can cause insufficient penetration of liquid in ceramic preform especially at the interfaces of the composite. At the same time, preform sintering temperature is also an important parameter for the structure of the composites. The higher sintering temperature, the lower porosity. Therefore, both of these parameters, total pore volume and preform sintering temperature, should be optimized for the best properties of the metal matrix composites. Total pore volume fractions were obtained in the range of 13 and 43% before infiltration.

- ✓ Sintering temperature of boron carbide ceramic preforms was decreased with the addition of 1-2 weight% copper and aluminum powders that create low melting point liquid phases. Therefore, metal powders yielded the production of aluminum matrix boron carbide composites in a relatively low temperatures for sintering at 1000^{o}C.

- ✓ Confinement of Boron Carbide – 7075 aluminum composite with aluminum was not possible by melt infiltration applied by vertical squeeze casting technique. It causes crack formation in the metal matrix composite because of large thermal expansion coefficient difference between composite and aluminum alloy matrix.

- ✓ Surface treatment of carbon fiber texture by some special coatings and powders were contributed to decrease contact angle between 7075 aluminum alloy and carbon fiber texture. Therefore, this method was promising solution to prevent deterioration of the mechanical and physical properties originating from insufficient wetting of fibers by liquid aluminum.

- ✓ Even if it is possible to reach high mechanical properties for 7000 series aluminum alloys with the help of T6 heat treatment and thermo-mechanical treatments, these treatments should not be applied for aluminum matrix composites due to differences in thermal expansion coefficient. Therefore, these materials should be treated separately and they should be integrated with some adhesive bonding techniques such as binders like thermoset resins or special adhesives.

5.2 RECOMMENDATIONS AND FURTHER STUDIES

At the end of this study, it is recommended that heat treated aluminum specimens should be investigated under transmission electron microscope (TEM) to understand the type and crystal structures of precipitates. Especially the existence and size of $MgZn_2$ precipitates, which plays the most important role in the hardening mechanisms of 7000 series aluminum alloys, should be revealed.

It is also suggested that FVS812 aluminum alloy should be used as the ballistic aluminum alloy for the developing composite backing plates. It would be beneficial to investigate and characterize the properties of this alloy with some heat treatments and thermo-mechanical treatments. As it was mentioned before, it is a good candidate as ballistic aluminum alloy. Therefore, this alloys can be also studied in the future studies.

In addition, due to the fact that some problems about the production of boron carbide – aluminum composites under pressure, melt infiltration process can be apply without pressure as a production route for these composites. Even if it is needed a furnace that can work in relatively high temperature, it can give good results for the production of aluminum matrix boron carbide composites. Melt infiltration without pressure can be also applied for the production of other metal matrix composites.

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APPENDIX

A. CHARGE CALCULATION

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Al Charge (gr)	1000.000												
2														
3														
4														
5														
6		Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Al			
7	Alloy Composition (%)	0.06	0.08	1.6	0.04	1.5	0.04	7.5	0.06	0.12	89.000			
8														
9	Required Materials (gr)	0.674	0.899	17.978	0.449	16.854	0.449	84.270	0.674	1.348	1000.000			
10														
11												Total alloy (gr)	1123.596	
12	Required Cu (gr)	17.978												
13	Required Zn (gr)	84.270												
14	Required Zirmax (gr)	4.045												
15	Required Mg (gr)	14.157												
16														
17														

Figure A. 1. Charge calculation Excel sheet for 7085 aluminum alloy

This charge calculation is based on the total amount of the pure aluminum that is used in the aluminum alloy. According to the chemical composition that is determined in the beginning, the amounts of other alloying elements are calculated. This calculation is simply done with the help of the chemical composition and amount of the pure aluminum. At the end, required materials are listed as it can be seen in the Excel sheet. This simple charge calculation may be also modified for all kinds of aluminum alloys. The important thing is to enter chemical composition of the alloy correctly.

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Al 7085

SPEKTROMETRE ANALiZ SONUÇLARI (%)

Talep Sahibi :

Rutin No:

Tarih: 01. 10.2014

Kalite:

	Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ni	Ti
1	88,9	0,0776	0,0660	1,52	< 0,0010	1,60	7,51	0,0037	< 0,0050	0,0169
2	89,4	0,0846	0,0628	1,56	< 0,0010	1,44	7,16	0,0035	< 0,0050	0,0162
3	88,9	0,0893	0,0679	1,61	< 0,0010	1,53	7,47	0,0044	< 0,0050	0,0145
Ort	89,1	0,0838	0,0656	1,57	< 0,0010	1,52	7,38	0,0039	< 0,0050	0,0159

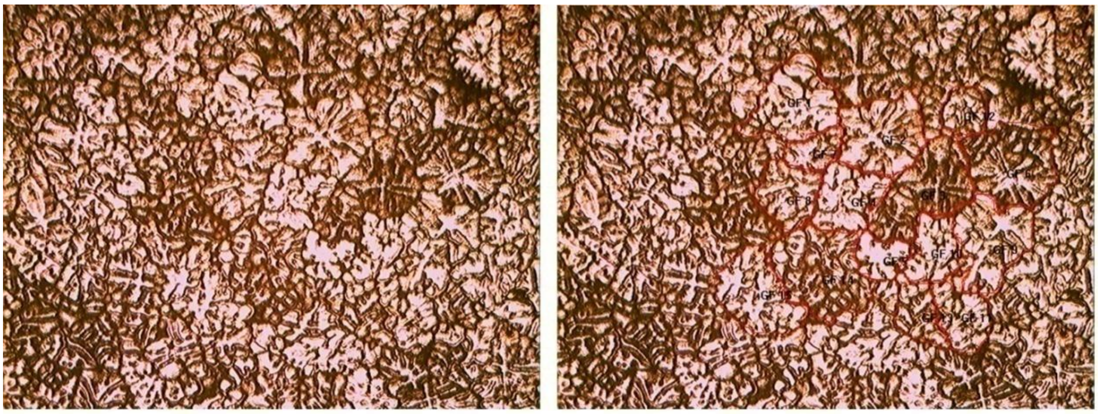
	Be	Ca	Li	Pb	Sn	Sr	V	Na	Bi	Zr
1	< 0,0001	0,0050	0,0002	0,0147	0,0473	< 0,0001	0,0098	0,0015	0,0070	0,152
2	< 0,0001	0,0027	0,0002	0,0069	0,0135	< 0,0001	0,0090	0,0012	< 0,0050	0,152
3	< 0,0001	0,0076	0,0002	0,0124	0,0180	< 0,0001	0,0093	0,0051	< 0,0050	0,149
Ort	< 0,0001	0,0051	0,0002	0,0113	0,0263	< 0,0001	0,0094	0,0026	< 0,0050	0,151

	B	Ga	Cd	Co	Ag	Hg	In
1	0,0037	0,0092	0,0010	< 0,0030	0,0049	< 0,0030	< 0,0020
2	0,0037	0,0086	< 0,0010	< 0,0030	0,0041	< 0,0030	< 0,0020
3	0,0044	0,0083	0,0018	< 0,0030	0,0045	< 0,0030	< 0,0020
Ort	0,0039	0,0087	0,0012	< 0,0030	0,0045	< 0,0030	< 0,0020

ONAY

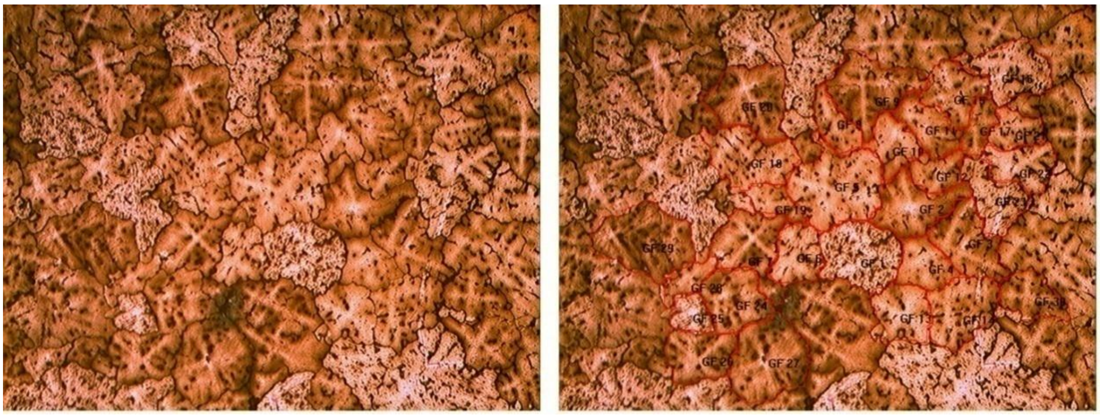
Figure A. 2. Optical emission spectrometer result for 7085 aluminum alloy

B. GRAIN SIZE MEASUREMENT



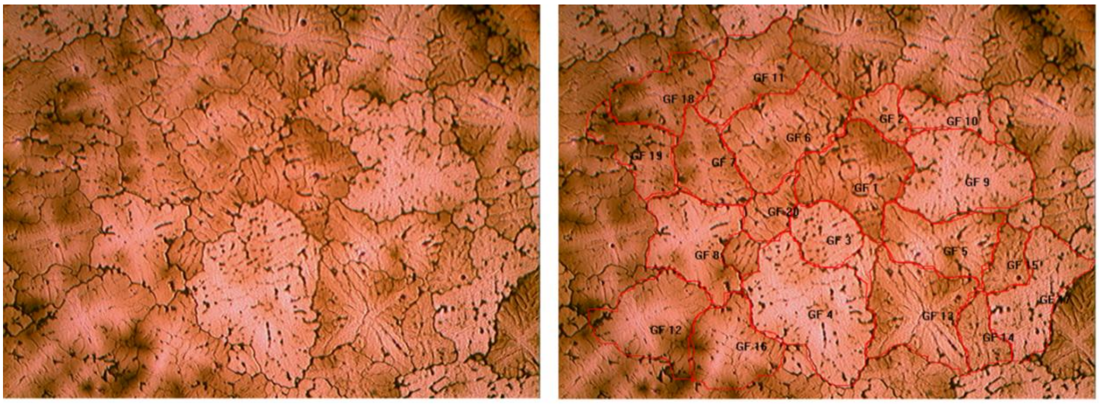
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	26002.23	147.25	2.00	27550.00
GF 2	26621.65	147.25	2.00	27550.00
GF 3	30425.22	147.25	2.00	27550.00
GF 4	17722.10	123.80	2.50	19450.00
GF 5	8531.25	87.55	3.50	9730.00
GF 6	29722.10	147.25	2.00	27550.00
GF 7	7781.25	73.65	4.00	6880.00
GF 8	15395.09	104.10	3.00	13750.00
GF 9	24723.21	147.25	2.00	27550.00
GF 10	12750.00	104.10	3.00	13750.00
GF 11	14691.96	104.10	3.00	13750.00
GF 12	8678.57	87.55	3.50	9730.00
GF 13	11347.10	87.55	3.50	9730.00
GF 14	32748.88	175.15	1.50	38950.00
GF 15	23608.26	147.25	2.00	27550.00
Average	**19383.26**	**122.07**	**2.63**	**20068.00**

Figure B. 1. As cast microstructure and grain size measurement of squeeze cast 7075 aluminum alloy



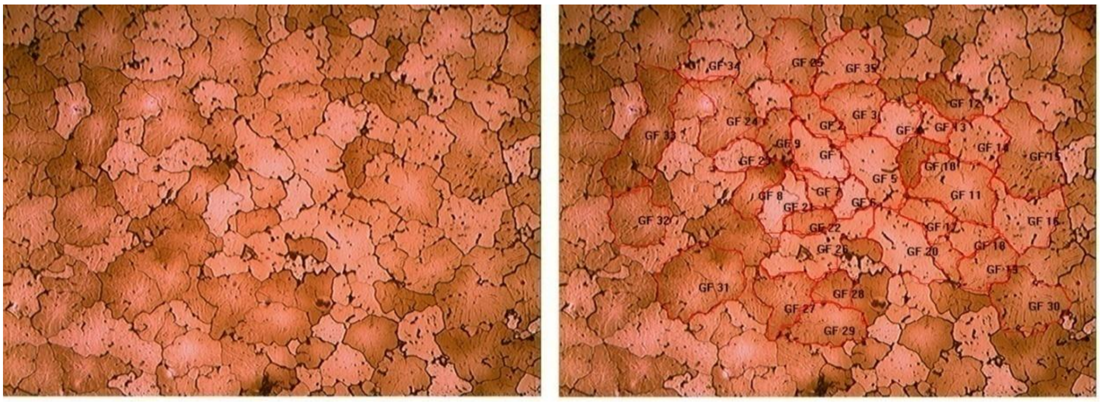
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	21696.43	123.80	2.50	19450.00
GF 2	17414.06	123.80	2.50	19450.00
GF 3	17651.79	123.80	2.50	19450.00
GF 4	10861.61	87.55	3.50	9730.00
GF 5	28094.87	147.25	2.00	27550.00
GF 6	11608.26	104.10	3.00	13750.00
GF 7	18579.24	123.80	2.50	19450.00
GF 8	8497.77	87.55	3.50	9730.00
GF 9	21917.41	123.80	2.50	19450.00
GF 10	10225.45	87.55	3.50	9730.00
GF 11	10998.88	87.55	3.50	9730.00
GF 12	7794.64	73.65	4.00	6880.00
GF 13	13928.57	104.10	3.00	13750.00
GF 14	18267.86	123.80	2.50	19450.00
GF 15	13345.98	104.10	3.00	13750.00
GF 16	17367.19	123.80	2.50	19450.00
GF 17	6291.29	73.65	4.00	6880.00
GF 18	19851.56	123.80	2.50	19450.00
GF 19	6569.20	73.65	4.00	6880.00
GF 20	21368.30	123.80	2.50	19450.00
GF 21	8099.33	87.55	3.50	9730.00
GF 22	11678.57	104.10	3.00	13750.00
GF 23	14095.98	104.10	3.00	13750.00
GF 24	15960.94	104.10	3.00	13750.00
GF 25	5969.87	73.65	4.00	6880.00
GF 26	14514.51	104.10	3.00	13750.00
GF 27	24897.32	147.25	2.00	27550.00
GF 28	5949.78	73.65	4.00	6880.00
GF 29	26022.32	147.25	2.00	27550.00
GF 30	11102.68	87.55	3.50	9730.00
Average	**14687.39**	**105.94**	**3.02**	**14891.00**

Figure B. 2. Microstructure and grain size measurement of squeeze cast 7075 aluminum alloy after solutionizing at 465°C/90 minutes, quenching in the water and aging at 120°C/24 hours



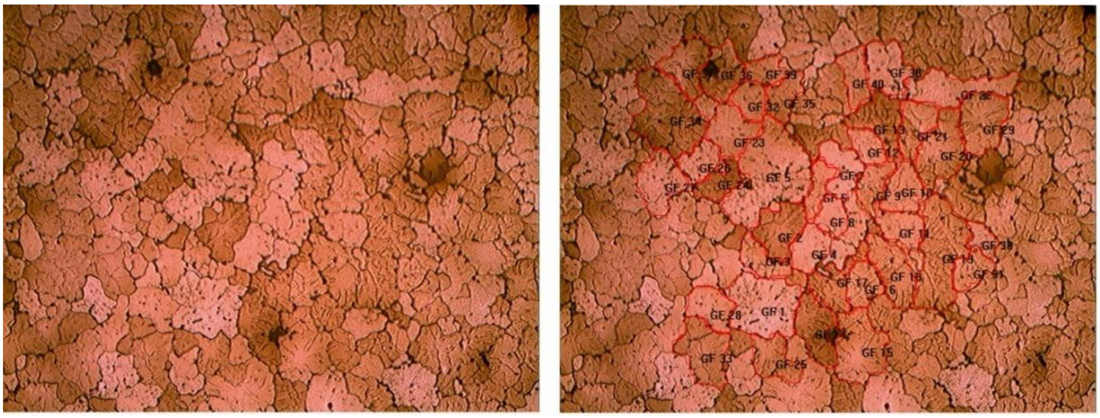
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	39220.98	175.15	1.50	38950.00
GF 2	9773.44	87.55	3.50	9730.00
GF 3	18060.27	123.80	2.50	19450.00
GF 4	58392.86	208.30	1.00	55050.00
GF 5	29922.99	147.25	2.00	27550.00
GF 6	43191.96	175.15	1.50	38950.00
GF 7	23226.56	147.25	2.00	27550.00
GF 8	34781.25	175.15	1.50	38950.00
GF 9	45458.71	175.15	1.50	38950.00
GF 10	15518.97	104.10	3.00	13750.00
GF 11	31838.17	147.25	2.00	27550.00
GF 12	36776.79	175.15	1.50	38950.00
GF 13	41906.25	175.15	1.50	38950.00
GF 14	12080.36	104.10	3.00	13750.00
GF 15	11183.04	87.55	3.50	9730.00
GF 16	29969.87	147.25	2.00	27550.00
GF 17	32236.61	147.25	2.00	27550.00
GF 18	24920.76	147.25	2.00	27550.00
GF 19	21207.59	123.80	2.50	19450.00
GF 20	11815.85	104.10	3.00	13750.00
Average	**28574.16**	**143.89**	**2.15**	**27683.00**

Figure B. 3. Microstructure and grain size measurement of squeeze cast 7075 aluminum alloy after solutionizing at 470^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours



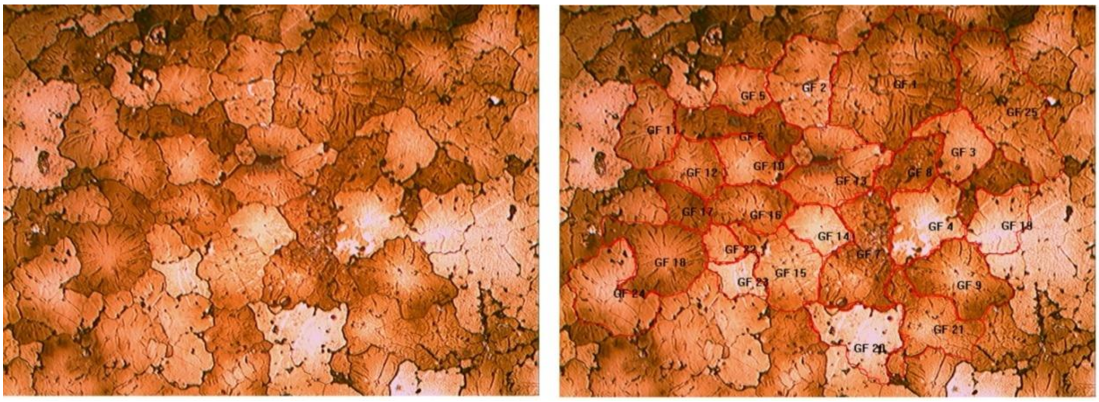
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	9830.36	87.55	3.50	9730.00
GF 2	7185.27	73.65	4.00	6880.00
GF 3	11169.64	87.55	3.50	9730.00
GF 4	7577.01	73.65	4.00	6880.00
GF 5	15478.79	104.10	3.00	13750.00
GF 6	4898.44	61.95	4.50	4865.00
GF 7	4797.99	61.95	4.50	4865.00
GF 8	7556.92	73.65	4.00	6880.00
GF 9	7895.09	73.65	4.00	6880.00
GF 10	6438.62	73.65	4.00	6880.00
GF 11	19443.08	123.80	2.50	19450.00
GF 12	8949.78	87.55	3.50	9730.00
GF 13	4888.39	61.95	4.50	4865.00
GF 14	11799.11	104.10	3.00	13750.00
GF 15	22553.57	123.80	2.50	19450.00
GF 16	16292.41	123.80	2.50	19450.00
GF 17	6967.63	73.65	4.00	6880.00
GF 18	5892.86	73.65	4.00	6880.00
GF 19	10228.79	87.55	3.50	9730.00
GF 20	16325.89	123.80	2.50	19450.00
GF 21	9281.25	87.55	3.50	9730.00
GF 22	4895.09	61.95	4.50	4865.00
GF 23	6334.82	73.65	4.00	6880.00
GF 24	15287.95	104.10	3.00	13750.00
GF 25	15525.67	104.10	3.00	13750.00
GF 26	18659.60	123.80	2.50	19450.00
GF 27	12418.53	104.10	3.00	13750.00
GF 28	5571.43	61.95	4.50	4865.00
GF 29	12947.54	104.10	3.00	13750.00
GF 30	17283.48	123.80	2.50	19450.00
GF 31	24160.71	147.25	2.00	27550.00
GF 32	12964.29	104.10	3.00	13750.00
GF 33	24950.89	147.25	2.00	27550.00
GF 34	9231.03	87.55	3.50	9730.00
GF 35	14313.62	104.10	3.00	13750.00
Average	**11714.16**	**94.12**	**3.39**	**11987.00**

Figure B. 4. Microstructure and grain size measurement of squeeze cast 7075 aluminum alloy after solutionizing at 475^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours



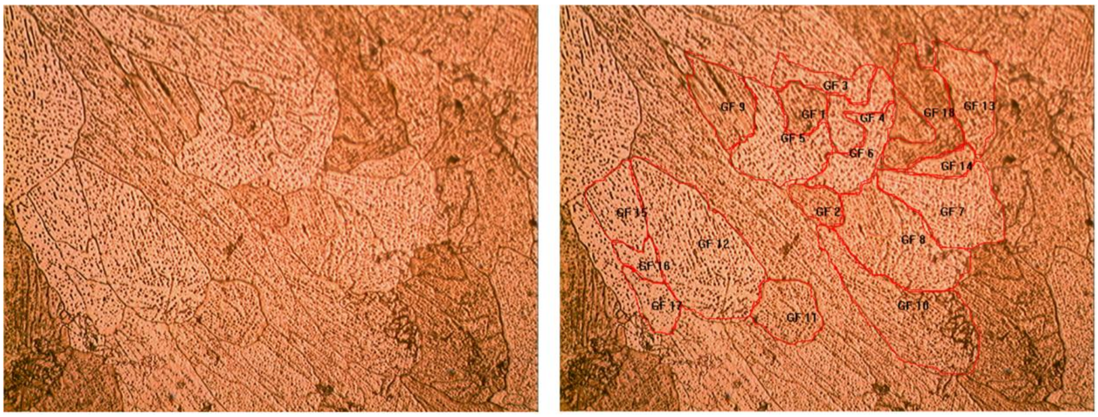
Field	Avrg. Intercept No (Micron)	Avrg. Dia.(Micron)	Avrg. Grain Area(Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	17614.96	123.80	2.50	19450.00
GF 2	9776.79	87.55	3.50	9730.00
GF 3	5886.16	73.65	4.00	6880.00
GF 4	6458.71	73.65	4.00	6880.00
GF 5	27210.94	147.25	2.00	27550.00
GF 6	4714.29	61.95	4.50	4865.00
GF 7	7376.12	73.65	4.00	6880.00
GF 8	4694.20	61.95	4.50	4865.00
GF 9	5792.41	73.65	4.00	6880.00
GF 10	7483.26	73.65	4.00	6880.00
GF 11	6793.53	73.65	4.00	6880.00
GF 12	4610.49	61.95	4.50	4865.00
GF 13	9870.54	87.55	3.50	9730.00
GF 14	9746.65	87.55	3.50	9730.00
GF 15	14099.33	104.10	3.00	13750.00
GF 16	6036.83	73.65	4.00	6880.00
GF 17	7787.95	73.65	4.00	6880.00
GF 18	9987.72	87.55	3.50	9730.00
GF 19	20330.36	123.80	2.50	19450.00
GF 20	12877.23	104.10	3.00	13750.00
GF 21	7895.09	73.65	4.00	6880.00
GF 22	12137.28	104.10	3.00	13750.00
GF 23	9324.78	87.55	3.50	9730.00
GF 24	5032.37	61.95	4.50	4865.00
GF 25	7530.13	73.65	4.00	6880.00
GF 26	5758.93	73.65	4.00	6880.00
GF 27	9897.32	87.55	3.50	9730.00
GF 28	7191.96	73.65	4.00	6880.00
GF 29	11534.60	104.10	3.00	13750.00
GF 30	3257.81	52.10	5.00	3440.00
GF 31	5236.61	61.95	4.50	4865.00
GF 32	5256.70	61.95	4.50	4865.00
GF 33	11959.82	104.10	3.00	13750.00
GF 34	20414.06	123.80	2.50	19450.00
GF 35	5698.66	61.95	4.50	4865.00
GF 36	8434.15	87.55	3.50	9730.00
GF 37	8872.77	87.55	3.50	9730.00
GF 38	9535.71	87.55	3.50	9730.00
GF 39	4202.01	61.95	4.50	4865.00
GF 40	5785.71	73.65	4.00	6880.00
Average	**9102.62**	**83.31**	**3.73**	**9350.50**

Figure B. 5. Microstructure and grain size measurement of squeeze cast 7075 aluminum alloy after solutionizing at 480^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours



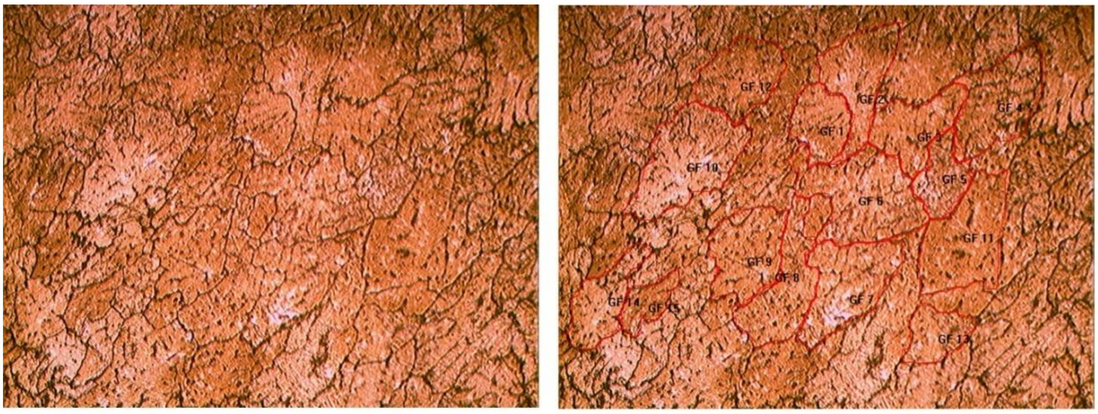
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	65193.08	247.30	0.50	77850.00
GF 2	24381.70	147.25	2.00	27550.00
GF 3	15924.11	104.10	3.00	13750.00
GF 4	22818.08	147.25	2.00	27550.00
GF 5	11219.87	87.55	3.50	9730.00
GF 6	18472.10	123.80	2.50	19450.00
GF 7	31587.05	147.25	2.00	27550.00
GF 8	12458.71	104.10	3.00	13750.00
GF 9	25145.09	147.25	2.00	27550.00
GF 10	14437.50	104.10	3.00	13750.00
GF 11	19329.24	123.80	2.50	19450.00
GF 12	14260.04	104.10	3.00	13750.00
GF 13	20514.51	123.80	2.50	19450.00
GF 14	11065.85	87.55	3.50	9730.00
GF 15	22918.53	147.25	2.00	27550.00
GF 16	16014.51	104.10	3.00	13750.00
GF 17	8668.53	87.55	3.50	9730.00
GF 18	26876.12	147.25	2.00	27550.00
GF 19	16422.99	123.80	2.50	19450.00
GF 20	23414.06	147.25	2.00	27550.00
GF 21	24411.83	147.25	2.00	27550.00
GF 22	5892.86	73.65	4.00	6880.00
GF 23	8049.11	73.65	4.00	6880.00
GF 24	26156.25	147.25	2.00	27550.00
GF 25	45060.27	175.15	1.50	38950.00
Agerage	**21227.68**	**126.93**	**2.54**	**22170.00**

Figure B. 6. Microstructure and grain size measurement of squeeze cast 7075 aluminum alloy after solutionizing at 485^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours



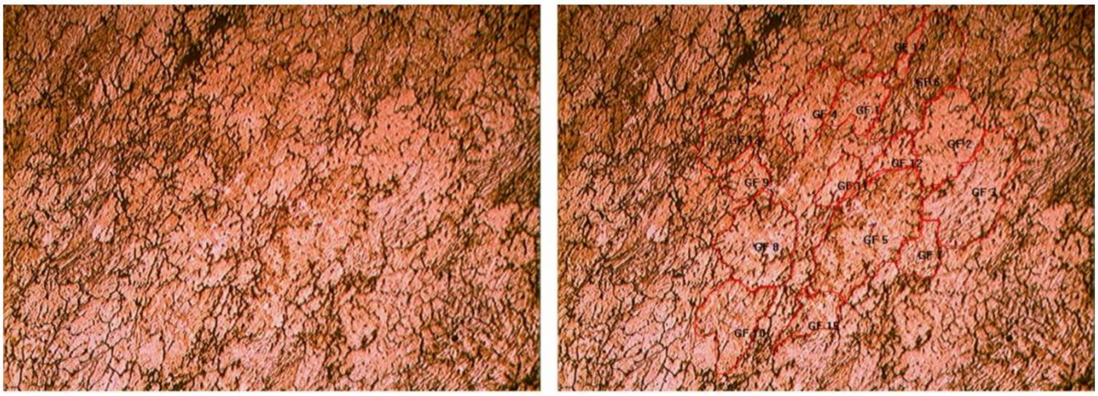
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	9110.49	87.55	3.50	9730.00
GF 2	7315.85	73.65	4.00	6880.00
GF 3	10714.29	87.55	3.50	9730.00
GF 4	12525.67	104.10	3.00	13750.00
GF 5	26805.80	147.25	2.00	27550.00
GF 6	16031.25	104.10	3.00	13750.00
GF 7	31453.13	147.25	2.00	27550.00
GF 8	40506.70	175.15	1.50	38950.00
GF 9	18810.27	123.80	2.50	19450.00
GF 10	45482.14	175.15	1.50	38950.00
GF 11	16084.82	104.10	3.00	13750.00
GF 12	56246.65	208.30	1.00	55050.00
GF 13	20896.21	123.80	2.50	19450.00
GF 14	6595.98	73.65	4.00	6880.00
GF 15	16406.25	123.80	2.50	19450.00
GF 16	6184.15	73.65	4.00	6880.00
GF 17	9739.96	87.55	3.50	9730.00
GF 18	23474.33	147.25	2.00	27550.00
Average	**20799.11**	**120.43**	**2.72**	**20279.44**

Figure B. 7. As cast microstructure and grain size measurement of squeeze cast 7085 aluminum alloy



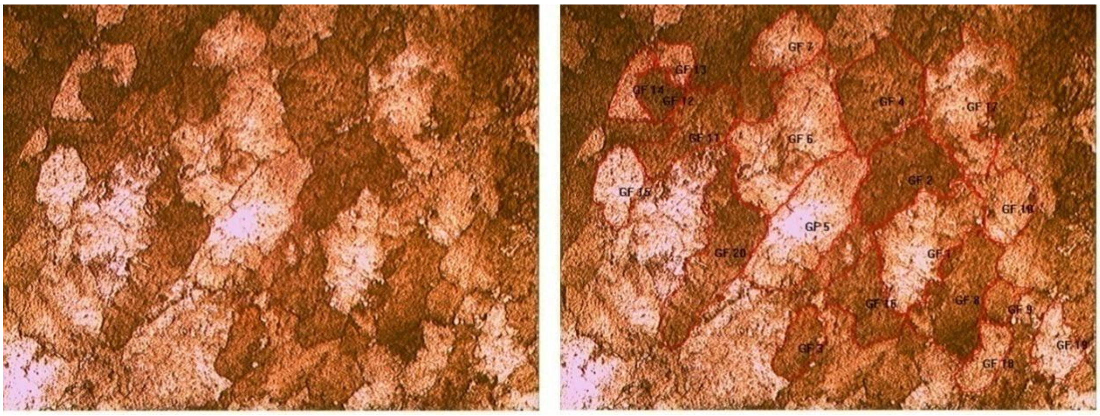
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	17219.87	123.80	2.50	19450.00
GF 2	26869.42	147.25	2.00	27550.00
GF 3	22597.10	123.80	2.50	19450.00
GF 4	30696.43	147.25	2.00	27550.00
GF 5	14578.13	104.10	3.00	13750.00
GF 6	41812.50	175.15	1.50	38950.00
GF 7	31560.27	147.25	2.00	27550.00
GF 8	27227.68	147.25	2.00	27550.00
GF 9	26779.02	147.25	2.00	27550.00
GF 10	38852.68	175.15	1.50	38950.00
GF 11	35095.98	175.15	1.50	38950.00
GF 12	24137.28	147.25	2.00	27550.00
GF 13	13399.55	104.10	3.00	13750.00
GF 14	18954.24	123.80	2.50	19450.00
GF 15	9143.97	87.55	3.50	9730.00
Average	**25261.61**	**138.41**	**2.23**	**25182.00**

Figure B. 8. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, with no recrystallization (top view)



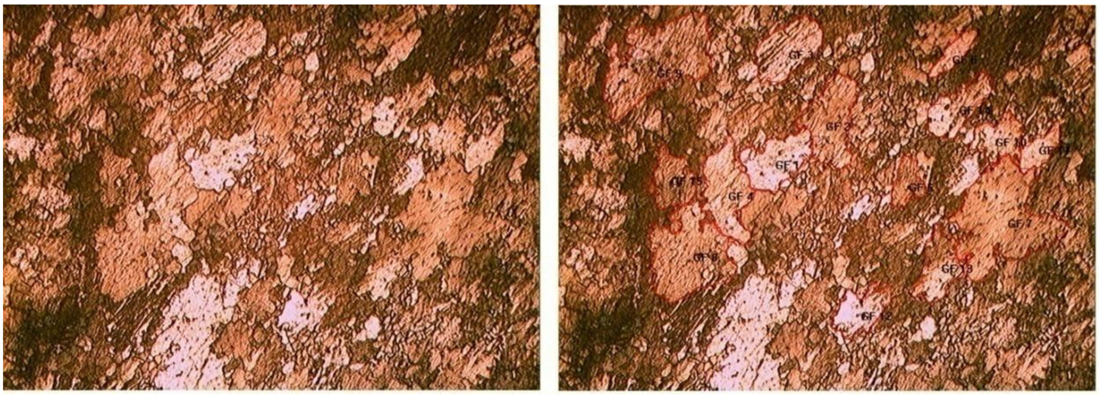
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	11718.75	104.10	3.00	13750.00
GF 2	24267.86	147.25	2.00	27550.00
GF 3	31640.63	147.25	2.00	27550.00
GF 4	15301.34	104.10	3.00	13750.00
GF 5	44002.23	175.15	1.50	38950.00
GF 6	28135.04	147.25	2.00	27550.00
GF 7	8862.72	87.55	3.50	9730.00
GF 8	27753.35	147.25	2.00	27550.00
GF 9	6609.38	73.65	4.00	6880.00
GF 10	20611.61	123.80	2.50	19450.00
GF 11	6391.74	73.65	4.00	6880.00
GF 12	6100.45	73.65	4.00	6880.00
GF 13	15103.79	104.10	3.00	13750.00
GF 14	12502.23	104.10	3.00	13750.00
GF 15	9502.23	87.55	3.50	9730.00
Average	**17900.22**	**113.36**	**2.87**	**17580.00**

Figure B. 9. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, with no recrystallization (front view)



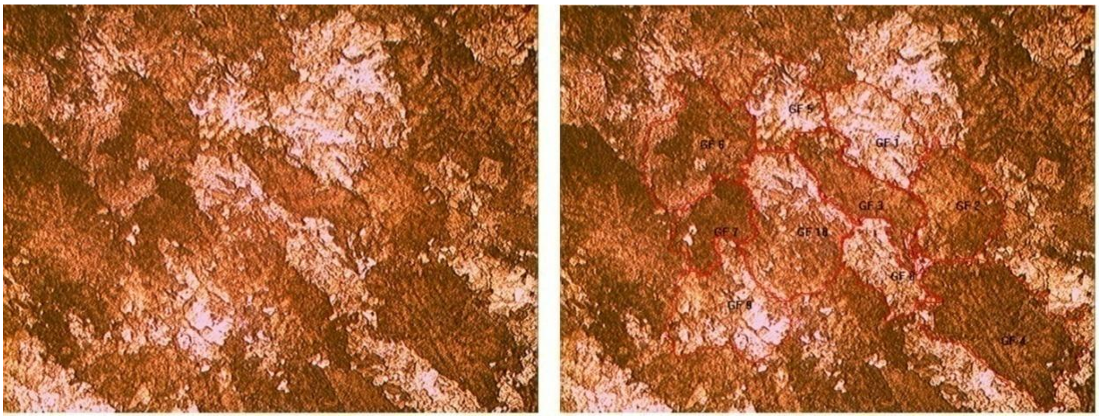
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	38316.96	175.15	1.50	38950.00
GF 2	30967.63	147.25	2.00	27550.00
GF 3	11005.58	87.55	3.50	9730.00
GF 4	33940.85	175.15	1.50	38950.00
GF 5	42505.58	175.15	1.50	38950.00
GF 6	50393.97	208.30	1.00	55050.00
GF 7	14547.99	104.10	3.00	13750.00
GF 8	33160.71	175.15	1.50	38950.00
GF 9	6030.13	73.65	4.00	6880.00
GF 10	16697.54	123.80	2.50	19450.00
GF 11	22379.46	123.80	2.50	19450.00
GF 12	8712.05	87.55	3.50	9730.00
GF 13	5618.30	61.95	4.50	4865.00
GF 14	7483.26	73.65	4.00	6880.00
GF 15	13566.96	104.10	3.00	13750.00
GF 16	19342.63	123.80	2.50	19450.00
GF 17	38132.81	175.15	1.50	38950.00
GF 18	10356.03	87.55	3.50	9730.00
GF 19	12820.31	104.10	3.00	13750.00
GF 20	38012.28	175.15	1.50	38950.00
Average	**22699.55**	**128.10**	**2.58**	**23185.75**

Figure B. 10. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 1 hour recrystallization (top view)



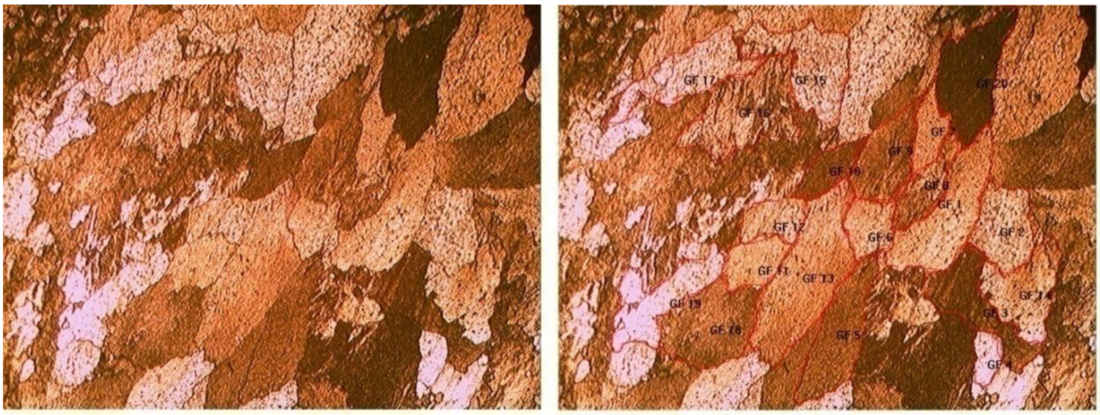
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	13891.74	104.10	3.00	13750.00
GF 2	17203.13	123.80	2.50	19450.00
GF 3	14253.35	104.10	3.00	13750.00
GF 4	16516.74	123.80	2.50	19450.00
GF 5	5303.57	61.95	4.50	4865.00
GF 6	4128.35	61.95	4.50	4865.00
GF 7	37443.08	175.15	1.50	38950.00
GF 8	27816.96	147.25	2.00	27550.00
GF 9	31412.95	147.25	2.00	27550.00
GF 10	8243.30	87.55	3.50	9730.00
GF 11	4560.27	61.95	4.50	4865.00
GF 12	9137.28	87.55	3.50	9730.00
GF 13	10948.66	87.55	3.50	9730.00
GF 14	10707.59	87.55	3.50	9730.00
GF 15	9210.94	87.55	3.50	9730.00
Average	**14718.53**	**103.27**	**3.17**	**14913.00**

Figure B. 11. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 1 hour recrystallization (front view)



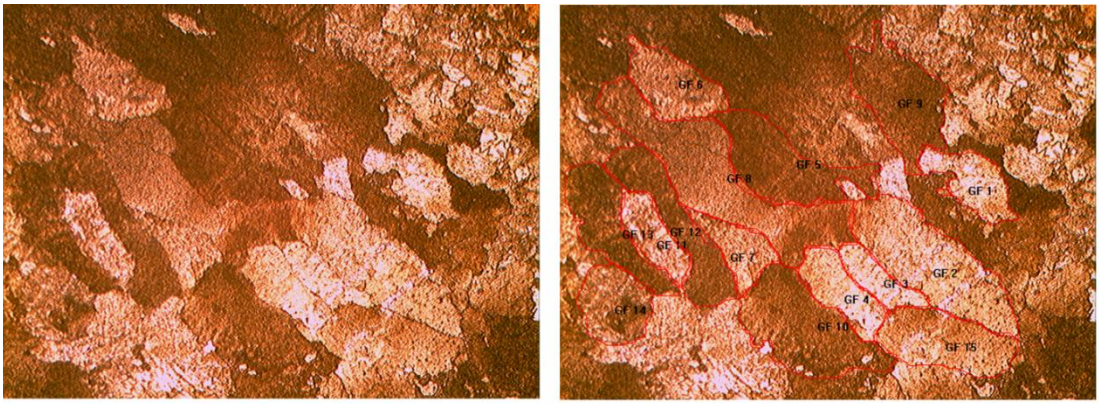
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	33599.33	175.15	1.50	38950.00
GF 2	36097.10	175.15	1.50	38950.00
GF 3	31854.91	147.25	2.00	27550.00
GF 4	67145.09	247.30	0.50	77850.00
GF 5	24703.13	147.25	2.00	27550.00
GF 6	47132.81	208.30	1.00	55050.00
GF 7	23075.89	147.25	2.00	27550.00
GF 8	22570.31	123.80	2.50	19450.00
GF 9	44129.46	175.15	1.50	38950.00
GF 10	54040.18	208.30	1.00	55050.00
Average	**38434.82**	**175.49**	**1.55**	**40690.00**

Figure B. 12. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 2 hours recrystallization (top view)



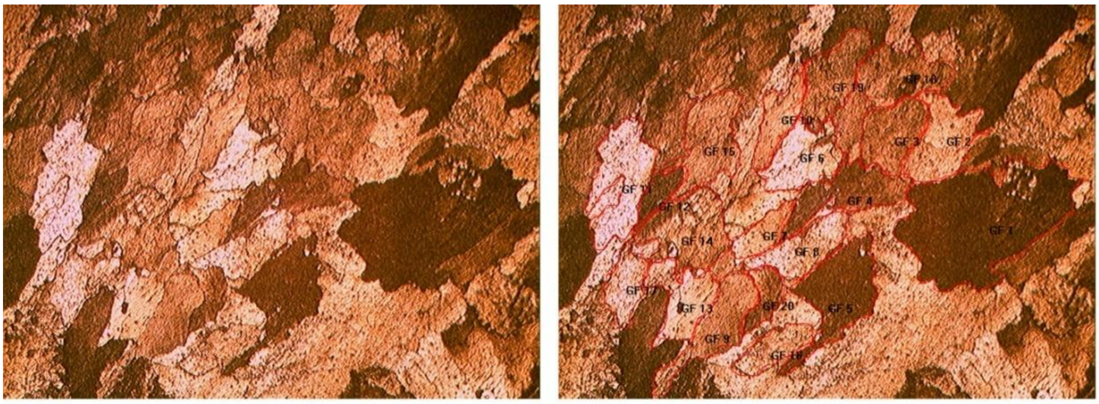
Field	Avrg. Intercept No (Micron)	Avrg. Dia.(Micron)	Avrg. Grain Area(Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	31098.21	147.25	2.00	27550.00
GF 2	20527.90	123.80	2.50	19450.00
GF 3	23199.78	147.25	2.00	27550.00
GF 4	5725.45	73.65	4.00	6880.00
GF 5	26363.84	147.25	2.00	27550.00
GF 6	11621.65	104.10	3.00	13750.00
GF 7	9197.54	87.55	3.50	9730.00
GF 8	12897.32	104.10	3.00	13750.00
GF 9	19915.18	123.80	2.50	19450.00
GF 10	9626.12	87.55	3.50	9730.00
GF 11	11845.98	104.10	3.00	13750.00
GF 12	10660.71	87.55	3.50	9730.00
GF 13	45391.74	175.15	1.50	38950.00
GF 14	22958.71	147.25	2.00	27550.00
GF 15	28784.60	147.25	2.00	27550.00
GF 16	34603.79	175.15	1.50	38950.00
GF 17	25309.15	147.25	2.00	27550.00
GF 18	28891.74	147.25	2.00	27550.00
GF 19	24097.10	147.25	2.00	27550.00
GF 20	31580.36	147.25	2.00	27550.00
Average	**21714.84**	**128.59**	**2.48**	**22103.50**

Figure B. 13. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 2 hours recrystallization (front view)



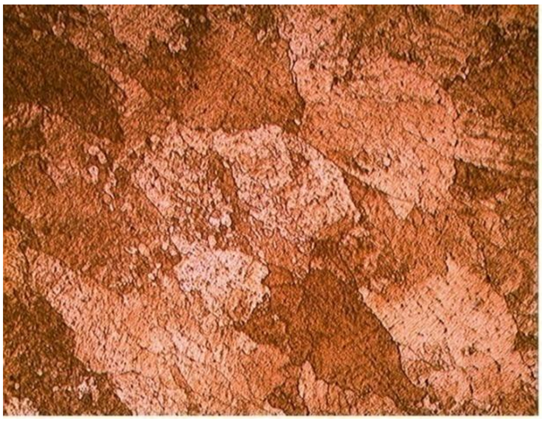
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	18415.18	123.80	2.50	19450.00
GF 2	52804.69	208.30	1.00	55050.00
GF 3	12696.43	104.10	3.00	13750.00
GF 4	19443.08	123.80	2.50	19450.00
GF 5	37165.18	175.15	1.50	38950.00
GF 6	23795.76	147.25	2.00	27550.00
GF 7	14996.65	104.10	3.00	13750.00
GF 8	69659.60	247.30	0.50	77850.00
GF 9	37510.04	175.15	1.50	38950.00
GF 10	46426.34	208.30	1.00	55050.00
GF 11	16114.96	123.80	2.50	19450.00
GF 12	31590.40	147.25	2.00	27550.00
GF 13	29159.60	147.25	2.00	27550.00
GF 14	22489.96	123.80	2.50	19450.00
GF 15	32457.59	175.15	1.50	38950.00
Average	**30981.70**	**155.63**	**1.93**	**32850.00**

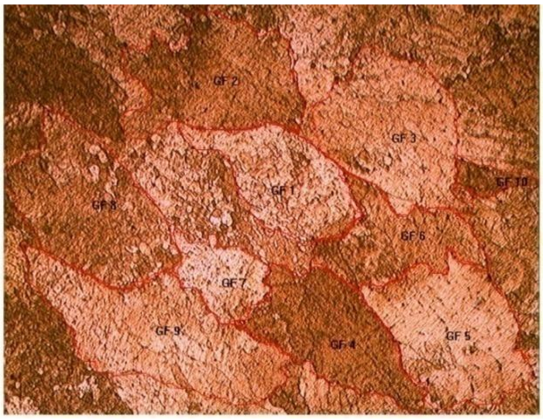
Figure B. 14. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 3 hours recrystallization (top view)



Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	75140.63	247.30	0.50	77850.00
GF 2	20199.78	123.80	2.50	19450.00
GF 3	17621.65	123.80	2.50	19450.00
GF 4	21066.96	123.80	2.50	19450.00
GF 5	27220.98	147.25	2.00	27550.00
GF 6	18696.43	123.80	2.50	19450.00
GF 7	7657.37	73.65	4.00	6880.00
GF 8	16125.00	123.80	2.50	19450.00
GF 9	19553.57	123.80	2.50	19450.00
GF 10	12515.63	104.10	3.00	13750.00
GF 11	25335.94	147.25	2.00	27550.00
GF 12	6890.63	73.65	4.00	6880.00
GF 13	16443.08	123.80	2.50	19450.00
GF 14	25660.71	147.25	2.00	27550.00
GF 15	22757.81	123.80	2.50	19450.00
GF 16	10473.21	87.55	3.50	9730.00
GF 17	10938.62	87.55	3.50	9730.00
GF 18	20116.07	123.80	2.50	19450.00
GF 19	19831.47	123.80	2.50	19450.00
GF 20	7677.46	73.65	4.00	6880.00
Average	**20096.15**	**121.36**	**2.68**	**20442.50**

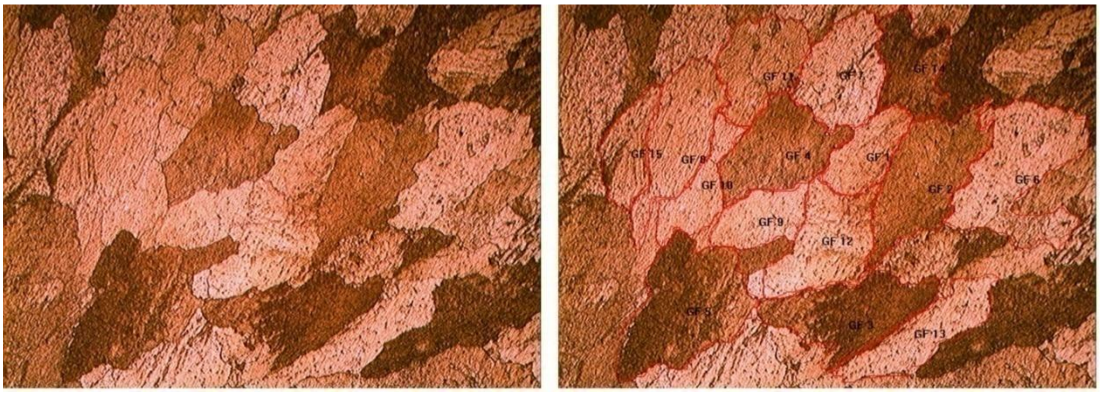
Figure B. 15. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 3 hours recrystallization (front view)





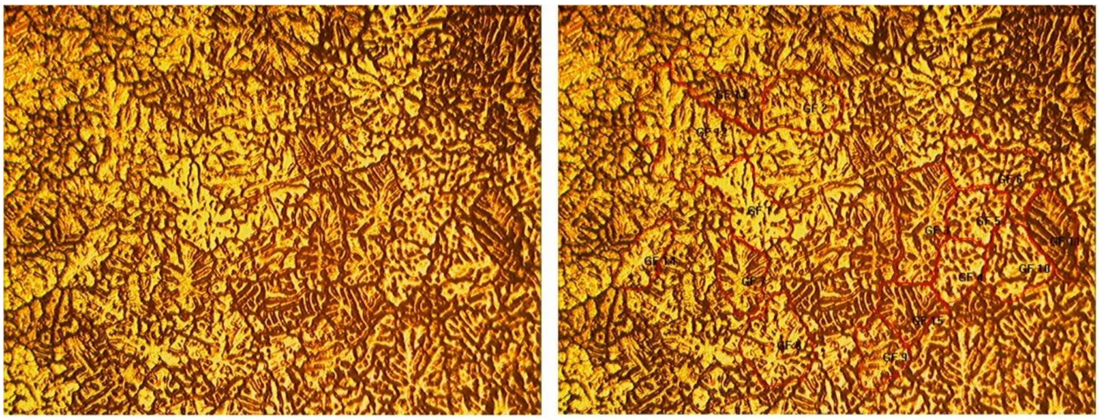
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	53976.56	208.30	1.00	55050.00
GF 2	74795.76	247.30	0.50	77850.00
GF 3	79212.05	247.30	0.50	77850.00
GF 4	63324.78	208.30	1.00	55050.00
GF 5	76811.38	247.30	0.50	77850.00
GF 6	46995.54	208.30	1.00	55050.00
GF 7	25309.15	147.25	2.00	27550.00
GF 8	82831.47	247.30	0.50	77850.00
GF 9	94720.98	294.00	0.00	110100.00
GF 10	8343.75	87.55	3.50	9730.00
Average	**60632.14**	**214.29**	**1.05**	**62393.00**

Figure B. 16. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 4 hours recrystallization (top view)



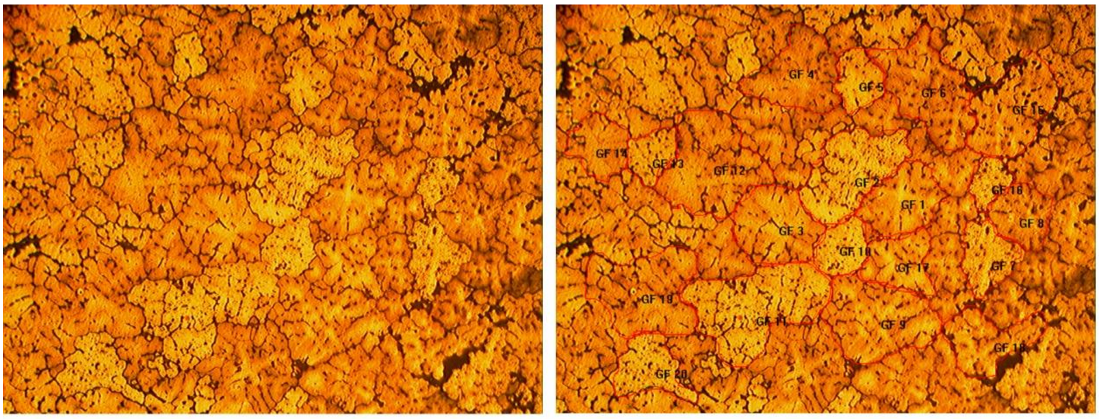
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg. Grain Area (Micron Sqr.)	Avrg. Grain No (Micron)
GF 1	21646.21	123.80	2.50	19450.00
GF 2	50203.13	208.30	1.00	55050.00
GF 3	45388.39	175.15	1.50	38950.00
GF 4	40905.13	175.15	1.50	38950.00
GF 5	61577.01	208.30	1.00	55050.00
GF 6	60837.05	208.30	1.00	55050.00
GF 7	37429.69	175.15	1.50	38950.00
GF 8	40667.41	175.15	1.50	38950.00
GF 9	21672.99	123.80	2.50	19450.00
GF 10	20702.01	123.80	2.50	19450.00
GF 11	34429.69	175.15	1.50	38950.00
GF 12	40617.19	175.15	1.50	38950.00
GF 13	33006.70	175.15	1.50	38950.00
GF 14	28386.16	147.25	2.00	27550.00
GF 15	21585.94	123.80	2.50	19450.00
Average	**37270.31**	**166.23**	**1.70**	**36210.00**

Figure B. 17. Microstructure and grain size measurement of hot rolled 7085 aluminum sheet, which was produced by permanent mold casting, after 4 hours recrystallization (front view)



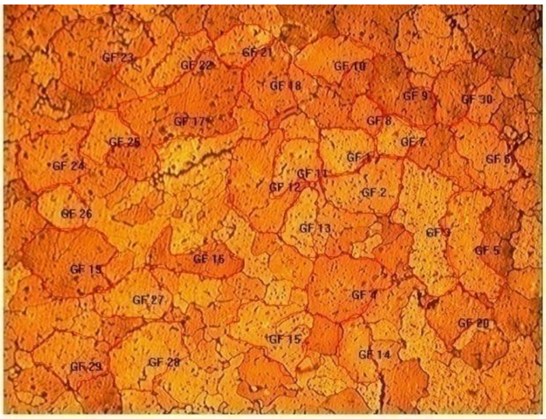
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (MicronSqr.)	Avrg Grain No (Micron)
GF 1	18830.36	123.80	2.50	19450.00
GF 2	19155.13	123.80	2.50	19450.00
GF 3	25292.41	147.25	2.00	27550.00
GF 4	12445.31	104.10	3.00	13750.00
GF 5	13031.25	104.10	3.00	13750.00
GF 6	21813.62	123.80	2.50	19450.00
GF 7	13168.53	104.10	3.00	13750.00
GF 8	21358.26	123.80	2.50	19450.00
GF 9	12739.96	104.10	3.00	13750.00
GF 10	17025.67	123.80	2.50	19450.00
GF 11	15013.39	104.10	3.00	13750.00
GF 12	36867.19	175.15	1.50	38950.00
GF 13	17728.79	123.80	2.50	19450.00
GF 14	10928.57	87.55	3.50	9730.00
GF 15	13590.40	104.10	3.00	13750.00
Average	**17932.59**	**118.49**	**2.67**	**18362.00**

Figure B. 18. Microstructure and grain size measurement of as cast 7075 aluminum sheet, which was produced by permanent mold casting



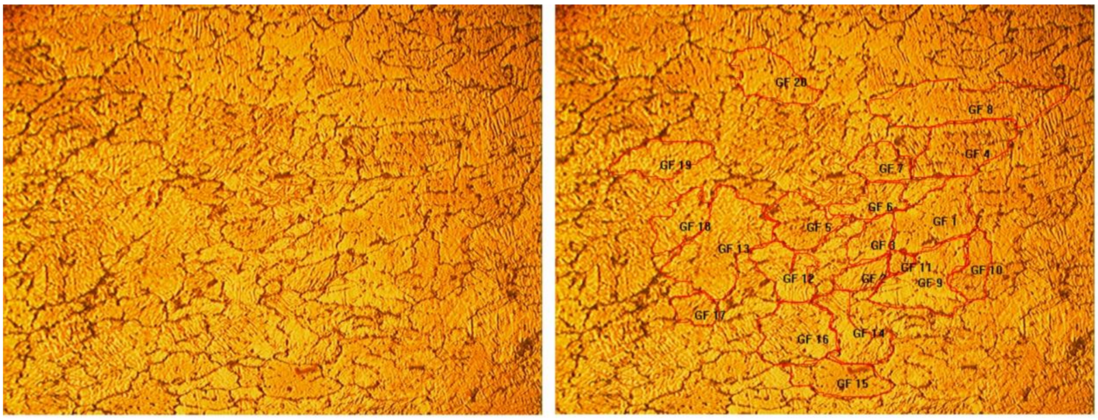
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	20246.65	123.80	2.50	19450.00
GF 2	29969.87	147.25	2.00	27550.00
GF 3	25928.57	147.25	2.00	27550.00
GF 4	25178.57	147.25	2.00	27550.00
GF 5	10945.31	87.55	3.50	9730.00
GF 6	31376.12	147.25	2.00	27550.00
GF 7	13828.13	104.10	3.00	13750.00
GF 8	14216.52	104.10	3.00	13750.00
GF 9	33760.04	175.15	1.50	38950.00
GF 10	11142.86	87.55	3.50	9730.00
GF 11	42063.62	175.15	1.50	38950.00
GF 12	37774.55	175.15	1.50	38950.00
GF 13	9780.13	87.55	3.50	9730.00
GF 14	13751.12	104.10	3.00	13750.00
GF 15	28938.62	147.25	2.00	27550.00
GF 16	7111.61	73.65	4.00	6880.00
GF 17	15220.98	104.10	3.00	13750.00
GF 18	19161.83	123.80	2.50	19450.00
GF 19	34453.13	175.15	1.50	38950.00
GF 20	15689.73	104.10	3.00	13750.00
Average	**22026.90**	**127.06**	**2.53**	**21863.50**

Figure B. 19. Microstructure and grain size measurement of 7075 aluminum sheet, which was produced by permanent mold casting, after first T6 heat treatment with 475^{o}C solutionizing temperature



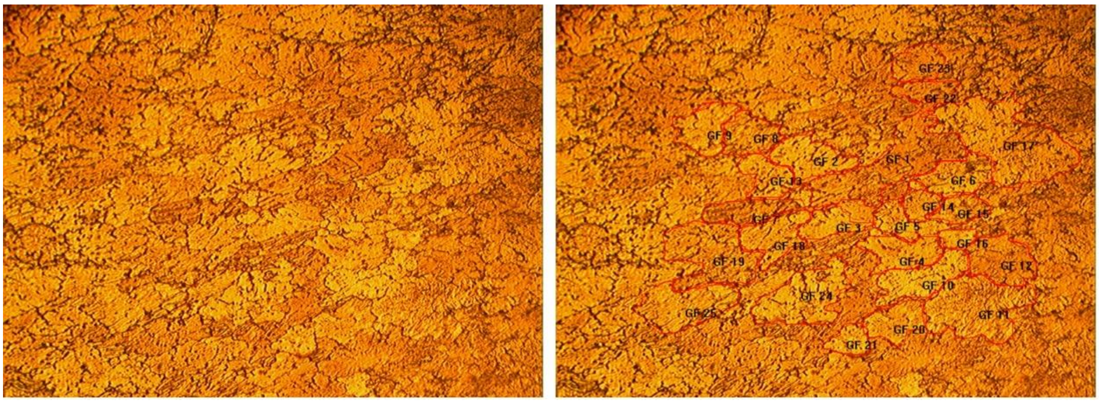
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	10168.53	87.55	3.50	9730.00
GF 2	15954.24	104.10	3.00	13750.00
GF 3	25851.56	147.25	2.00	27550.00
GF 4	19486.61	123.80	2.50	19450.00
GF 5	18415.18	123.80	2.50	19450.00
GF 6	14738.84	104.10	3.00	13750.00
GF 7	6646.21	73.65	4.00	6880.00
GF 8	4556.92	61.95	4.50	4865.00
GF 9	13654.02	104.10	3.00	13750.00
GF 10	11655.13	104.10	3.00	13750.00
GF 11	9455.36	87.55	3.50	9730.00
GF 12	20625.00	123.80	2.50	19450.00
GF 13	8424.11	87.55	3.50	9730.00
GF 14	9070.31	87.55	3.50	9730.00
GF 15	16724.33	123.80	2.50	19450.00
GF 16	11213.17	87.55	3.50	9730.00
GF 17	39341.52	175.15	1.50	38950.00
GF 18	13292.41	104.10	3.00	13750.00
GF 19	23658.48	147.25	2.00	27550.00
GF 20	10707.59	87.55	3.50	9730.00
GF 21	8025.67	73.65	4.00	6880.00
GF 22	8327.01	87.55	3.50	9730.00
GF 23	26404.02	147.25	2.00	27550.00
GF 24	15328.13	104.10	3.00	13750.00
GF 25	8484.38	87.55	3.50	9730.00
GF 26	8337.05	87.55	3.50	9730.00
GF 27	13017.86	104.10	3.00	13750.00
GF 28	17320.31	123.80	2.50	19450.00
GF 29	13784.60	104.10	3.00	13750.00
GF 30	11531.25	104.10	3.00	13750.00
Average	**14473.33**	**105.67**	**3.03**	**14959.83**

Figure B. 20. Microstructure and grain size measurement of 7075 aluminum sheet, which was produced by permanent mold casting, after <u>second</u> T6 heat treatment with 475^{o}C solutionizing temperature



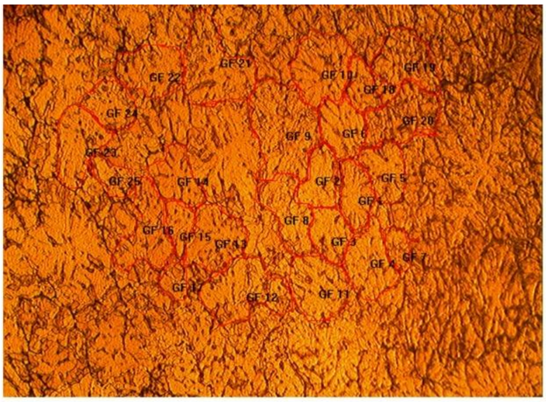
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	18656.25	123.80	2.50	19450.00
GF 2	5835.94	73.65	4.00	6880.00
GF 3	7175.22	73.65	4.00	6880.00
GF 4	19747.77	123.80	2.50	19450.00
GF 5	13078.13	104.10	3.00	13750.00
GF 6	7952.01	73.65	4.00	6880.00
GF 7	8005.58	73.65	4.00	6880.00
GF 8	30127.23	147.25	2.00	27550.00
GF 9	19597.10	123.80	2.50	19450.00
GF 10	7848.21	73.65	4.00	6880.00
GF 11	2330.36	43.80	5.50	2435.00
GF 12	11959.82	104.10	3.00	13750.00
GF 13	28767.86	147.25	2.00	27550.00
GF 14	12485.49	104.10	3.00	13750.00
GF 15	12743.30	104.10	3.00	13750.00
GF 16	18592.63	123.80	2.50	19450.00
GF 17	5454.24	61.95	4.50	4865.00
GF 18	10429.69	87.55	3.50	9730.00
GF 19	12140.63	104.10	3.00	13750.00
GF 20	14189.73	104.10	3.00	13750.00
Average	**13355.86**	**98.79**	**3.28**	**13341.50**

Figure B. 21. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, with no recrystallization (top view)



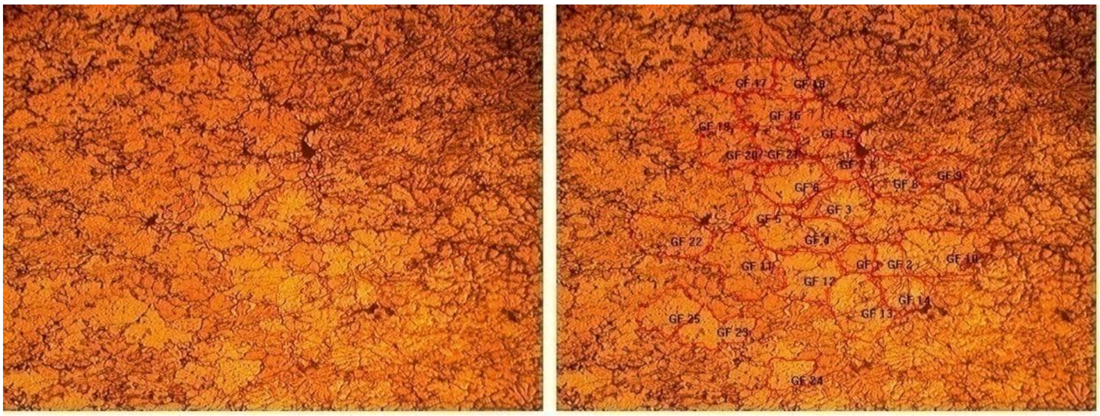
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	29052.46	147.25	2.00	27550.00
GF 2	11487.72	104.10	3.00	13750.00
GF 3	6827.01	73.65	4.00	6880.00
GF 4	10684.15	87.55	3.50	9730.00
GF 5	5845.98	73.65	4.00	6880.00
GF 6	11444.20	104.10	3.00	13750.00
GF 7	8939.73	87.55	3.50	9730.00
GF 8	9251.12	87.55	3.50	9730.00
GF 9	10674.11	87.55	3.50	9730.00
GF 10	12947.54	104.10	3.00	13750.00
GF 11	24776.79	147.25	2.00	27550.00
GF 12	12944.20	104.10	3.00	13750.00
GF 13	8166.29	87.55	3.50	9730.00
GF 14	5273.44	61.95	4.50	4865.00
GF 15	6117.19	73.65	4.00	6880.00
GF 16	3113.84	52.10	5.00	3440.00
GF 17	36190.85	175.15	1.50	38950.00
GF 18	11209.82	87.55	3.50	9730.00
GF 19	21703.13	123.80	2.50	19450.00
GF 20	8943.08	87.55	3.50	9730.00
GF 21	5039.06	61.95	4.50	4865.00
GF 22	5414.06	61.95	4.50	4865.00
GF 23	7530.13	73.65	4.00	6880.00
GF 24	19412.95	123.80	2.50	19450.00
GF 25	16526.79	123.80	2.50	19450.00
Average	**12380.63**	**96.11**	**3.36**	**12842.60**

Figure B. 22. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, with no recrystallization (front view)



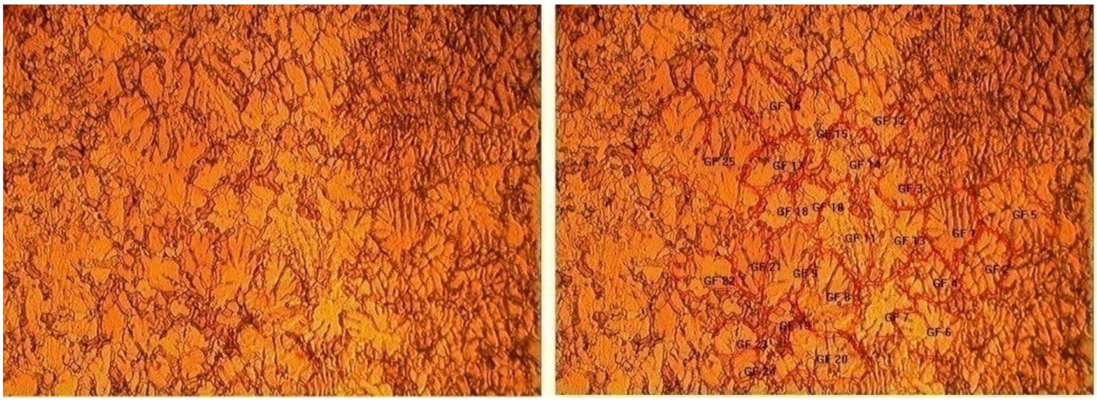
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	8809.15	87.55	3.50	9730.00
GF 2	9210.94	87.55	3.50	9730.00
GF 3	8889.51	87.55	3.50	9730.00
GF 4	13680.80	104.10	3.00	13750.00
GF 5	10094.87	87.55	3.50	9730.00
GF 6	10436.38	87.55	3.50	9730.00
GF 7	4352.68	61.95	4.50	4865.00
GF 8	13178.57	104.10	3.00	13750.00
GF 9	25694.20	147.25	2.00	27550.00
GF 10	17059.15	123.80	2.50	19450.00
GF 11	14866.07	104.10	3.00	13750.00
GF 12	19198.66	123.80	2.50	19450.00
GF 13	14514.51	104.10	3.00	13750.00
GF 14	10680.80	87.55	3.50	9730.00
GF 15	5460.94	61.95	4.50	4865.00
GF 16	14825.89	104.10	3.00	13750.00
GF 17	3940.85	52.10	5.00	3440.00
GF 18	6696.43	73.65	4.00	6880.00
GF 19	13888.39	104.10	3.00	13750.00
GF 20	15204.24	104.10	3.00	13750.00
GF 21	21318.08	123.80	2.50	19450.00
GF 22	13674.11	104.10	3.00	13750.00
GF 23	14290.18	104.10	3.00	13750.00
GF 24	9679.69	87.55	3.50	9730.00
GF 25	5544.64	61.95	4.50	4865.00
Average	**12207.59**	**95.20**	**3.34**	**12107.00**

Figure B. 23. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 1 hour recrystallization (top view)



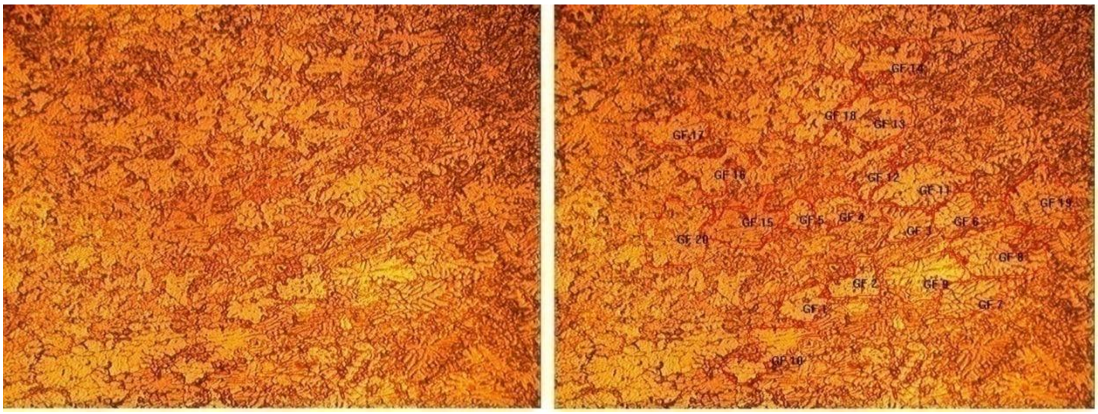
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	4714.29	61.95	4.50	4865.00
GF 2	3910.71	52.10	5.00	3440.00
GF 3	10677.46	87.55	3.50	9730.00
GF 4	13175.22	104.10	3.00	13750.00
GF 5	4332.59	61.95	4.50	4865.00
GF 6	10851.56	87.55	3.50	9730.00
GF 7	6107.14	73.65	4.00	6880.00
GF 8	9324.78	87.55	3.50	9730.00
GF 9	6843.75	73.65	4.00	6880.00
GF 10	16871.65	123.80	2.50	19450.00
GF 11	16577.01	123.80	2.50	19450.00
GF 12	13084.82	104.10	3.00	13750.00
GF 13	14815.85	104.10	3.00	13750.00
GF 14	6532.37	73.65	4.00	6880.00
GF 15	11695.31	104.10	3.00	13750.00
GF 16	8129.46	87.55	3.50	9730.00
GF 17	9672.99	87.55	3.50	9730.00
GF 18	5832.59	73.65	4.00	6880.00
GF 19	15512.28	104.10	3.00	13750.00
GF 20	9746.65	87.55	3.50	9730.00
GF 21	7359.38	73.65	4.00	6880.00
GF 22	13312.50	104.10	3.00	13750.00
GF 23	9944.20	87.55	3.50	9730.00
GF 24	5236.61	61.95	4.50	4865.00
GF 25	9518.97	87.55	3.50	9730.00
Average	**9751.21**	**87.15**	**3.58**	**10067.00**

Figure B. 24. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 1 hour recrystallization (front view)



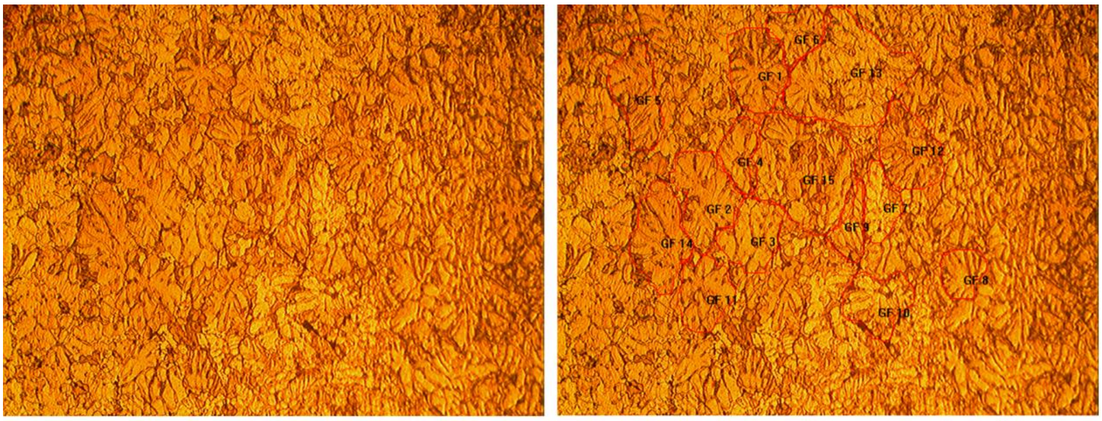
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (MicronSqr.)	Avrg Grain No (Micron)
GF 1	14266.74	104.10	3.00	13750.00
GF 2	13071.43	104.10	3.00	13750.00
GF 3	6827.01	73.65	4.00	6880.00
GF 4	9816.96	87.55	3.50	9730.00
GF 5	21087.05	123.80	2.50	19450.00
GF 6	13058.04	104.10	3.00	13750.00
GF 7	13248.89	104.10	3.00	13750.00
GF 8	17434.15	123.80	2.50	19450.00
GF 9	15458.71	104.10	3.00	13750.00
GF 10	5705.36	73.65	4.00	6880.00
GF 11	16158.48	123.80	2.50	19450.00
GF 12	11373.89	87.55	3.50	9730.00
GF 13	17226.56	123.80	2.50	19450.00
GF 14	12960.94	104.10	3.00	13750.00
GF 15	11986.61	104.10	3.00	13750.00
GF 16	14387.28	104.10	3.00	13750.00
GF 17	11588.17	104.10	3.00	13750.00
GF 18	6850.45	73.65	4.00	6880.00
GF 19	4389.51	61.95	4.50	4865.00
GF 20	18529.02	123.80	2.50	19450.00
GF 21	8283.48	87.55	3.50	9730.00
GF 22	10151.79	87.55	3.50	9730.00
GF 23	5802.46	73.65	4.00	6880.00
GF 24	3612.72	52.10	5.00	3440.00
GF 25	46761.16	208.30	1.00	55050.00
Average	**13201.47**	**100.92**	**3.20**	**14031.80**

Figure B. 25. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 2 hours recrystallization (top view)



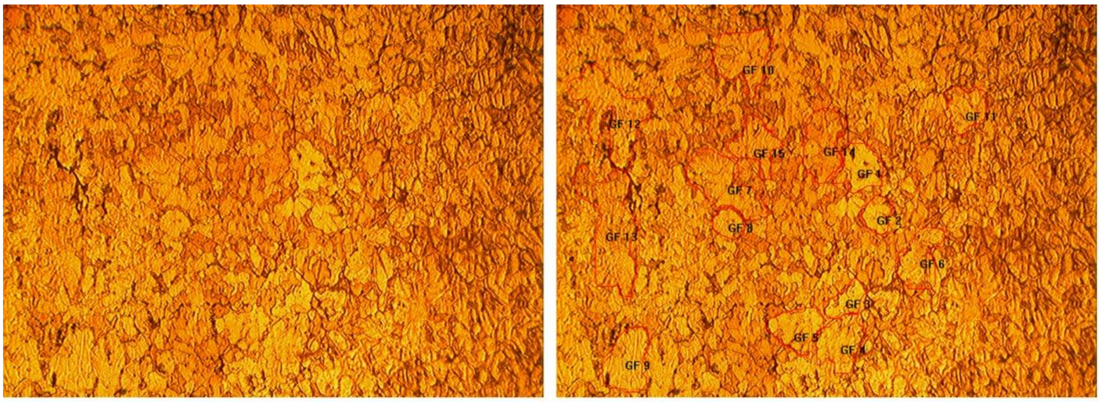
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area(Micron Sqr.)	Avrg Grain No (Micron)
GF 1	6344.87	73.65	4.00	6880.00
GF 2	6405.13	73.65	4.00	6880.00
GF 3	6177.46	73.65	4.00	6880.00
GF 4	5427.46	61.95	4.50	4865.00
GF 5	3595.98	52.10	5.00	3440.00
GF 6	6277.90	73.65	4.00	6880.00
GF 7	10459.82	87.55	3.50	9730.00
GF 8	15743.30	104.10	3.00	13750.00
GF 9	12813.62	104.10	3.00	13750.00
GF 10	11611.61	104.10	3.00	13750.00
GF 11	15358.26	104.10	3.00	13750.00
GF 12	9411.83	87.55	3.50	9730.00
GF 13	12515.63	104.10	3.00	13750.00
GF 14	10553.57	87.55	3.50	9730.00
GF 15	12234.38	104.10	3.00	13750.00
GF 16	9358.26	87.55	3.50	9730.00
GF 17	8906.25	87.55	3.50	9730.00
GF 18	14092.63	104.10	3.00	13750.00
GF 19	15512.28	104.10	3.00	13750.00
GF 20	16935.27	123.80	2.50	19450.00
Average	**10486.77**	**90.15**	**3.48**	**10696.25**

Figure B. 26. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 2 hours recrystallization (front view)



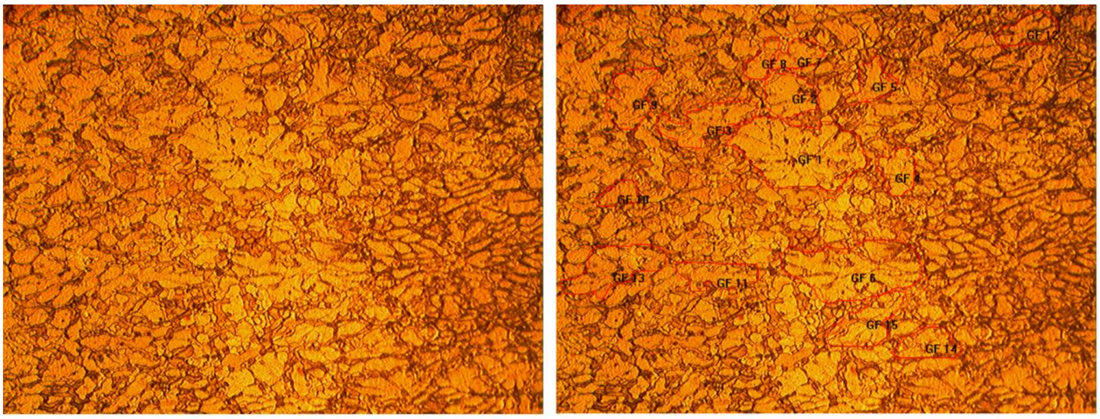
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	19024.55	123.80	2.50	19450.00
GF 2	21753.35	123.80	2.50	19450.00
GF 3	15676.34	104.10	3.00	13750.00
GF 4	10767.86	87.55	3.50	9730.00
GF 5	17233.26	123.80	2.50	19450.00
GF 6	10858.26	87.55	3.50	9730.00
GF 7	9505.58	87.55	3.50	9730.00
GF 8	8239.96	87.55	3.50	9730.00
GF 9	8236.61	87.55	3.50	9730.00
GF 10	15133.93	104.10	3.00	13750.00
GF 11	14296.88	104.10	3.00	13750.00
GF 12	18900.67	123.80	2.50	19450.00
GF 13	45220.98	175.15	1.50	38950.00
GF 14	20641.74	123.80	2.50	19450.00
GF 15	45488.84	175.15	1.50	38950.00
Average	**18731.92**	**114.62**	**2.80**	**17670.00**

Figure B. 27. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting , after 3 hours recrystallization (top view)



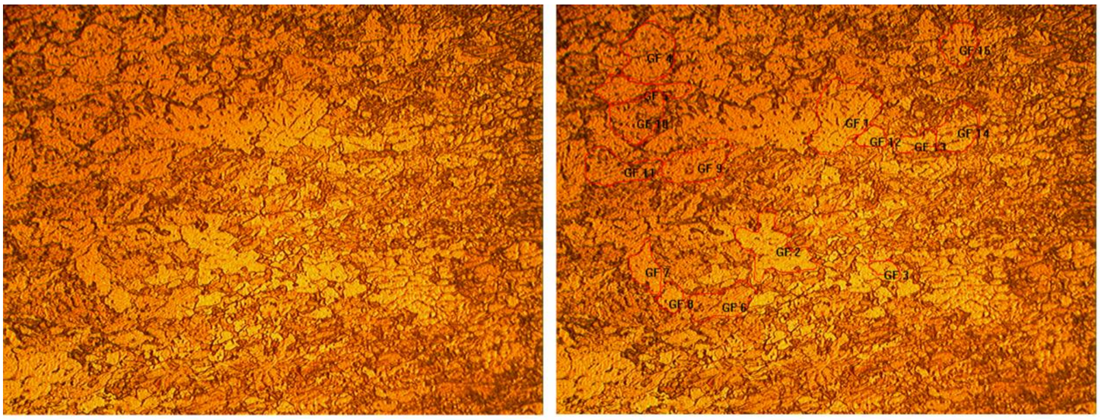
Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	8162.95	87.55	3.50	9730.00
GF 2	4245.54	61.95	4.50	4865.00
GF 3	4600.45	61.95	4.50	4865.00
GF 4	9676.34	87.55	3.50	9730.00
GF 5	8618.30	87.55	3.50	9730.00
GF 6	9180.80	87.55	3.50	9730.00
GF 7	14357.14	104.10	3.00	13750.00
GF 8	3783.48	52.10	5.00	3440.00
GF 9	10617.19	87.55	3.50	9730.00
GF 10	12428.57	104.10	3.00	13750.00
GF 11	7007.81	73.65	4.00	6880.00
GF 12	18636.16	123.80	2.50	19450.00
GF 13	22476.56	123.80	2.50	19450.00
GF 14	11189.73	87.55	3.50	9730.00
GF 15	8029.02	73.65	4.00	6880.00
Average	**10200.67**	**86.96**	**3.60**	**10114.00**

Figure B. 28. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 3 hours recrystallization (front view)



Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	33030.13	175.15	1.50	38950.00
GF 2	9311.38	87.55	3.50	9730.00
GF 3	11584.82	104.10	3.00	13750.00
GF 4	5939.73	73.65	4.00	6880.00
GF 5	5943.08	73.65	4.00	6880.00
GF 6	29260.04	147.25	2.00	27550.00
GF 7	5025.67	61.95	4.50	4865.00
GF 8	3649.55	61.95	5.00	3440.00
GF 9	10101.56	61.95	3.50	9730.00
GF 10	3569.20	61.95	5.00	3440.00
GF 11	8055.80	61.95	4.00	6880.00
GF 12	6683.04	61.95	4.00	6880.00
GF 13	14420.76	61.95	3.00	13750.00
GF 14	7064.73	61.95	4.00	6880.00
GF 15	11079.24	61.95	3.50	9730.00
Average	**10981.25**	**81.26**	**3.63**	**11289.00**

Figure B. 29. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 4 hours recrystallization (top view)



Field	Avrg. Intercept No (Micron)	Avrg. Dia. (Micron)	Avrg Grain Area (Micron Sqr.)	Avrg Grain No (Micron)
GF 1	16071.43	104.10	3.00	13750.00
GF 2	12287.95	104.10	3.00	13750.00
GF 3	1747.77	36.80	6.00	1725.00
GF 4	11859.38	104.10	3.00	13750.00
GF 5	6847.10	73.65	4.00	6880.00
GF 6	7844.87	73.65	4.00	6880.00
GF 7	4781.25	61.95	4.50	4865.00
GF 8	2665.18	43.80	5.50	2435.00
GF 9	9194.20	87.55	3.50	9730.00
GF 10	9301.34	87.55	3.50	9730.00
GF 11	8547.99	87.55	3.50	9730.00
GF 12	2397.32	43.80	5.50	2435.00
GF 13	2872.77	52.10	5.00	3440.00
GF 14	7295.76	73.65	4.00	6880.00
GF 15	5547.99	61.95	4.50	4865.00
Average	**7284.15**	**73.09**	**4.17**	**7389.67**

Figure B. 30. Microstructure and grain size measurement of hot rolled 7075 aluminum sheet, which was produced by permanent mold casting, after 4 hours recrystallization (front view)

C. SEM EXAMINATION

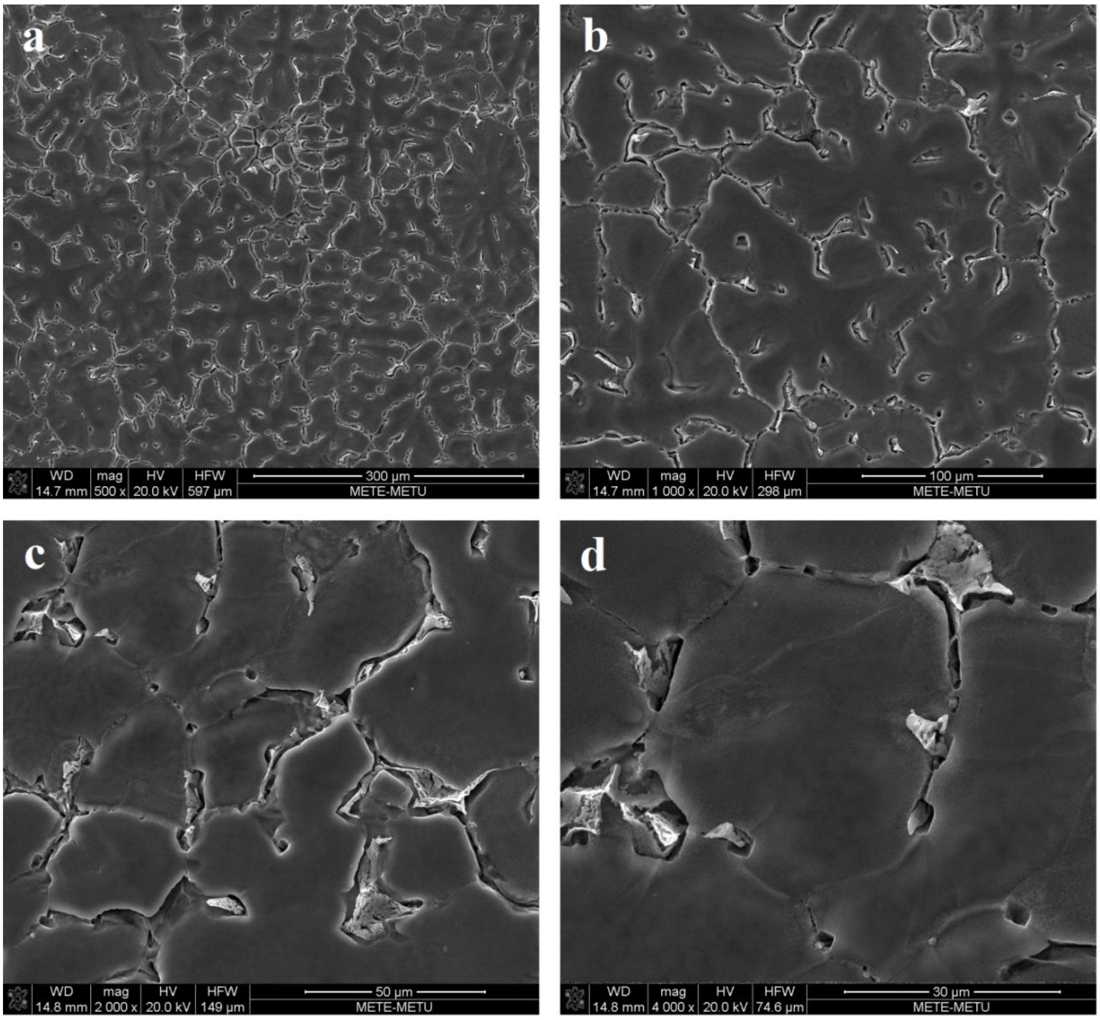


Figure C. 1. SEM images of as cast 7075 aluminum alloy that was produced by squeeze casting process with various magnifications

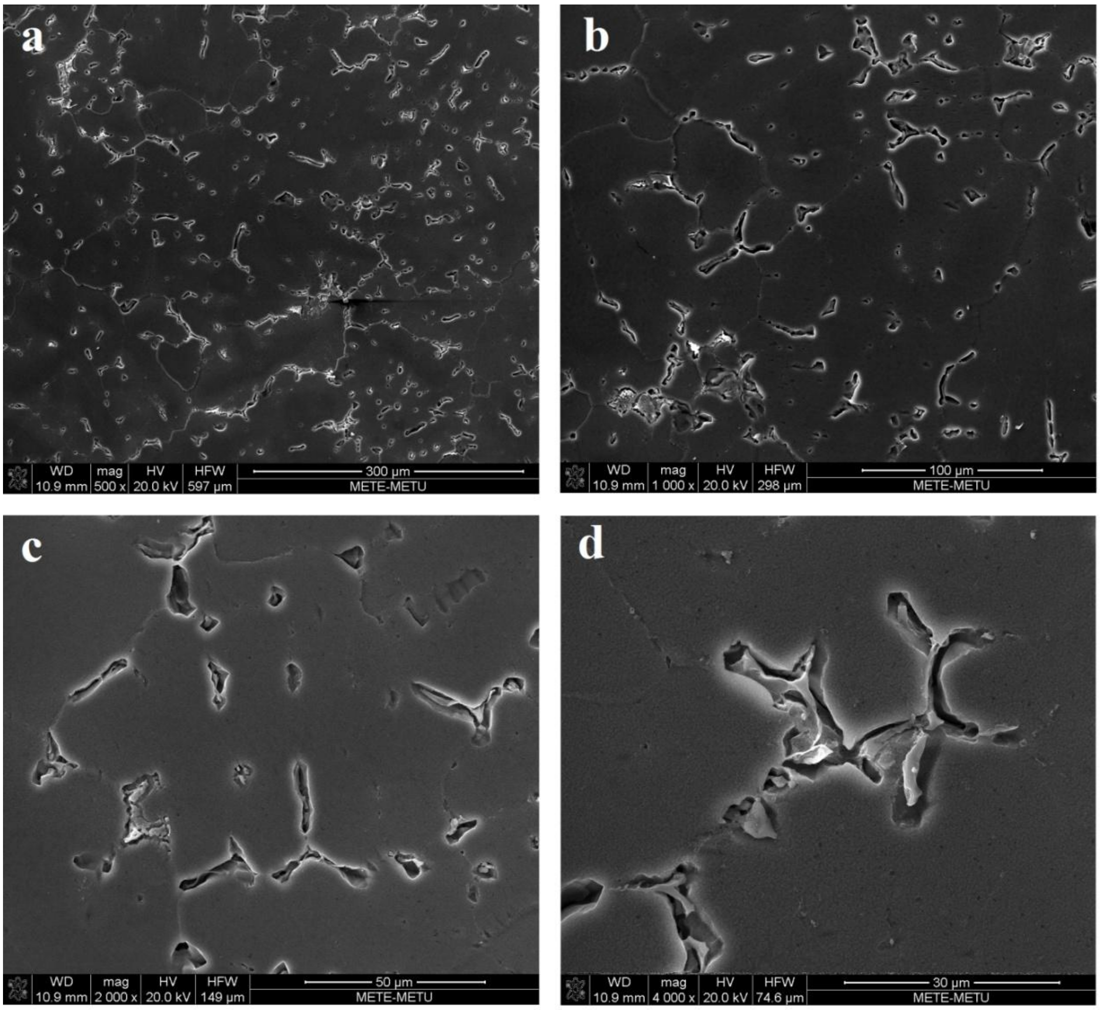


Figure C. 2. SEM images of squeeze cast 7075 aluminum alloy after solutionizing at 465°C/90 minutes, quenching in the water and aging at 120°C/24 hours with various magnifications

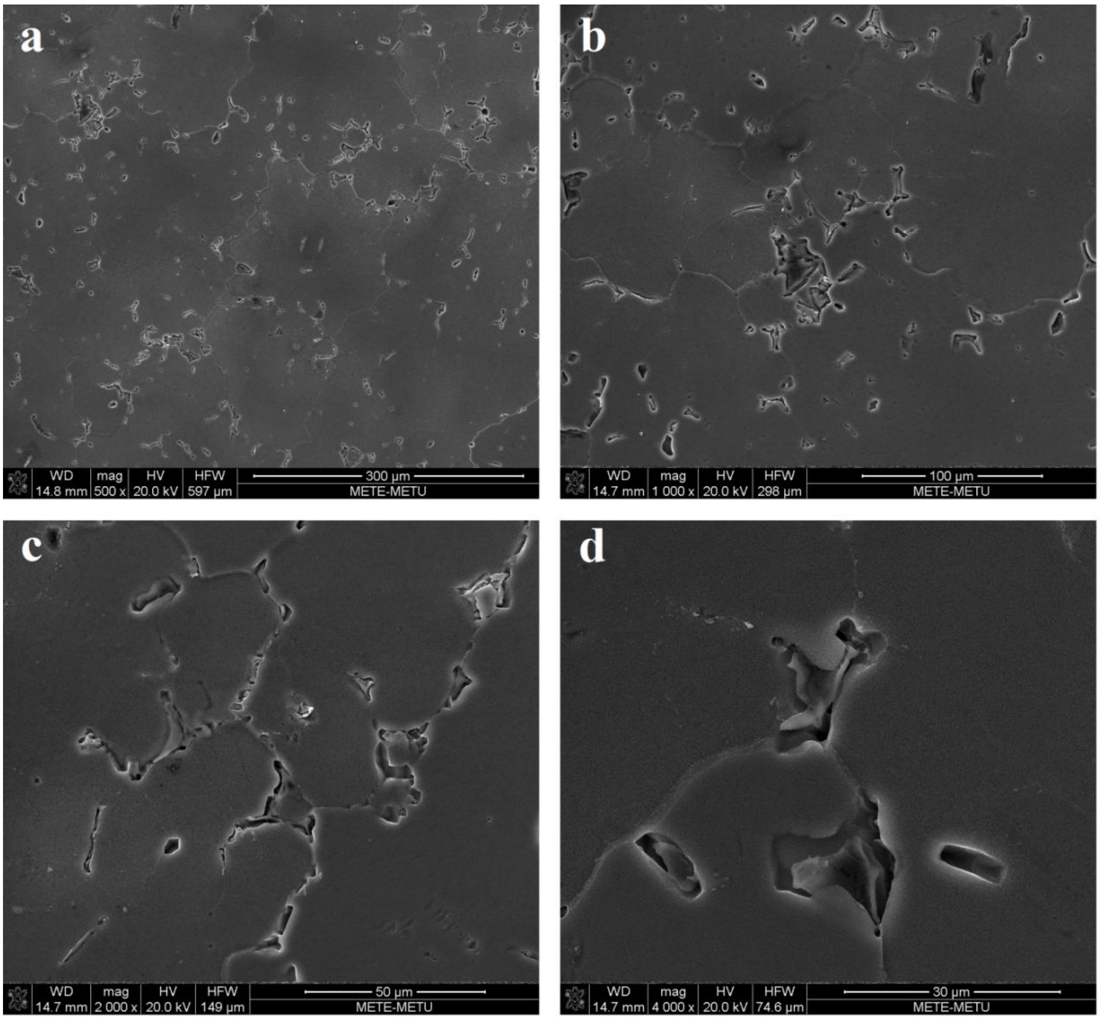


Figure C. 3. SEM images of squeeze cast 7075 aluminum alloy after solutionizing at 470^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

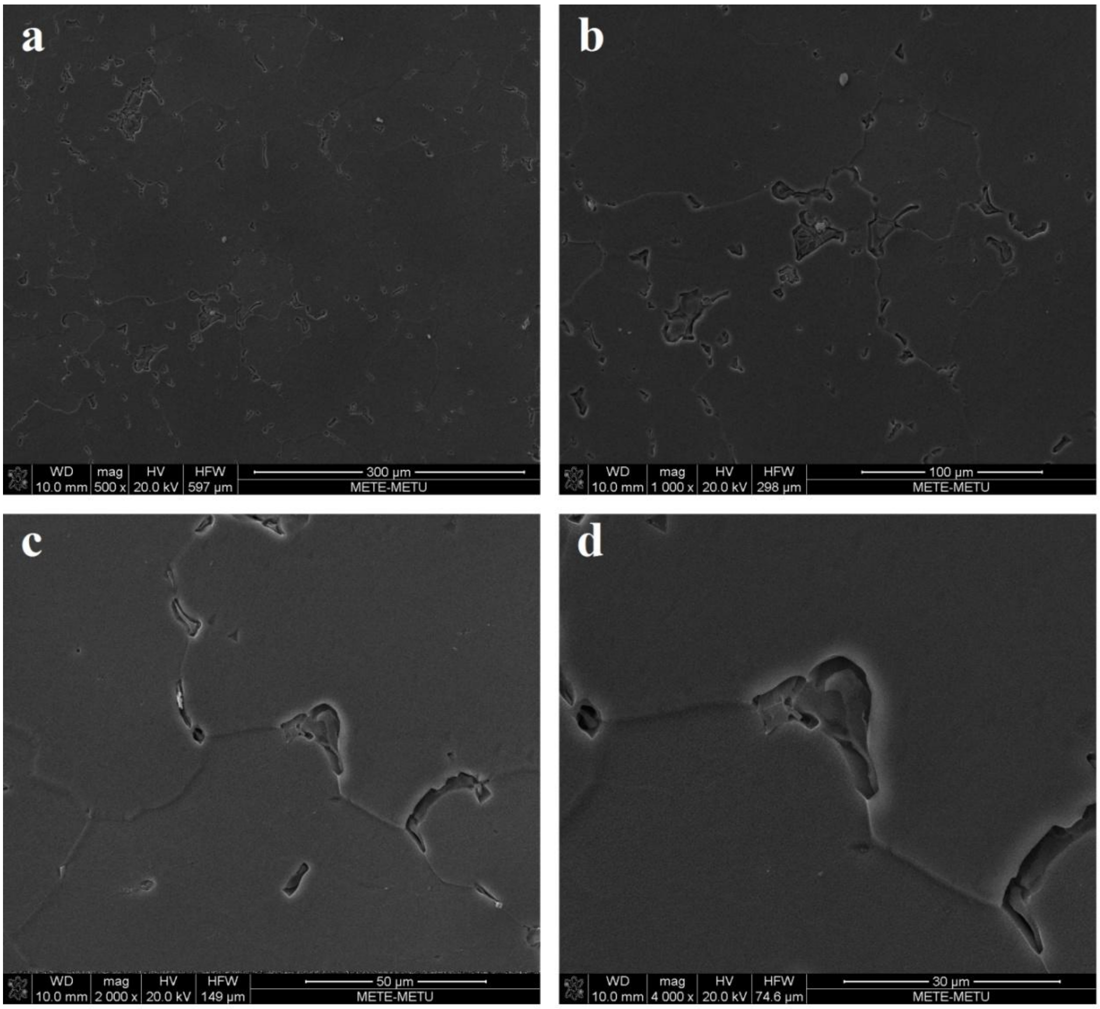


Figure C. 4. SEM images of squeeze cast 7075 aluminum alloy after solutionizing at 475^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

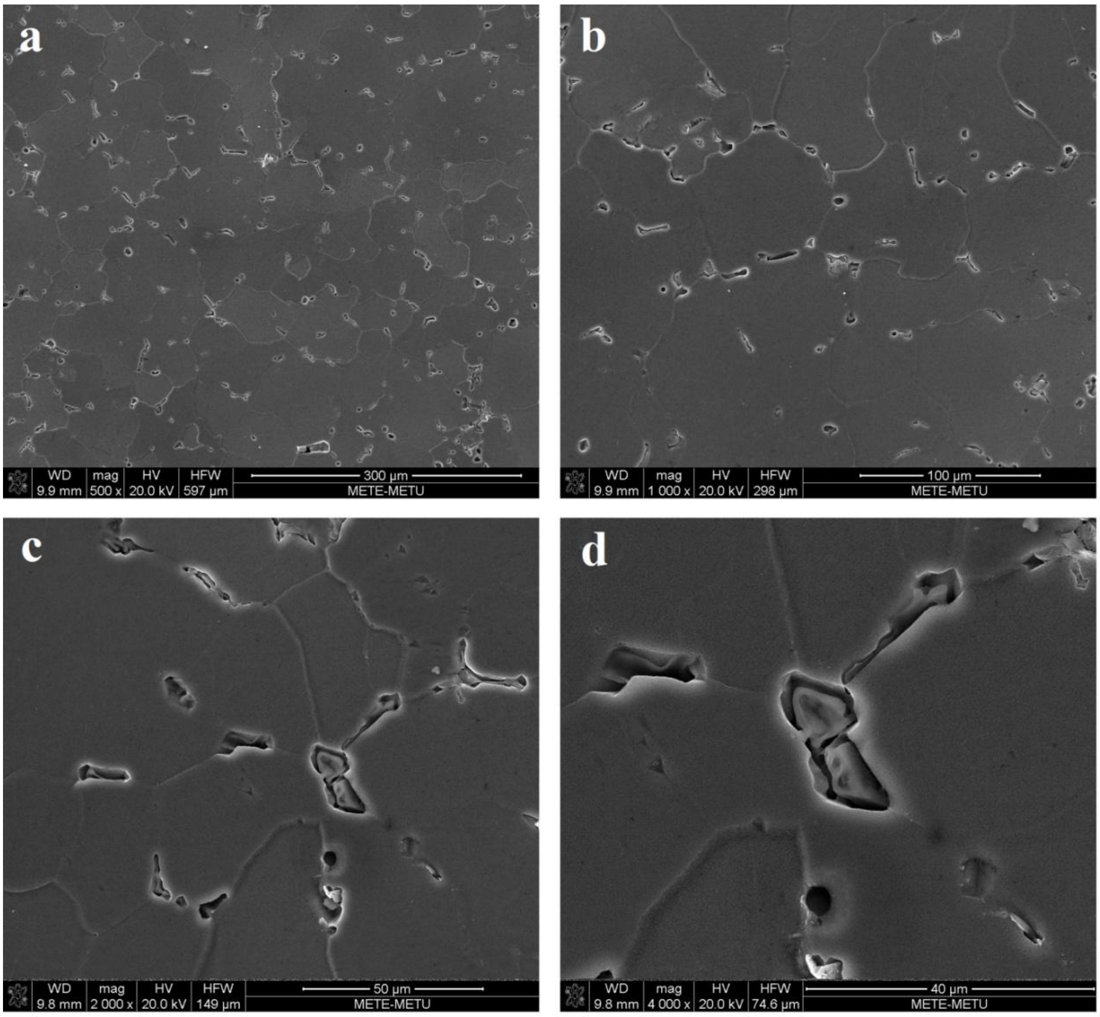


Figure C. 5. SEM images of squeeze cast 7075 aluminum alloy after solutionizing at 480^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

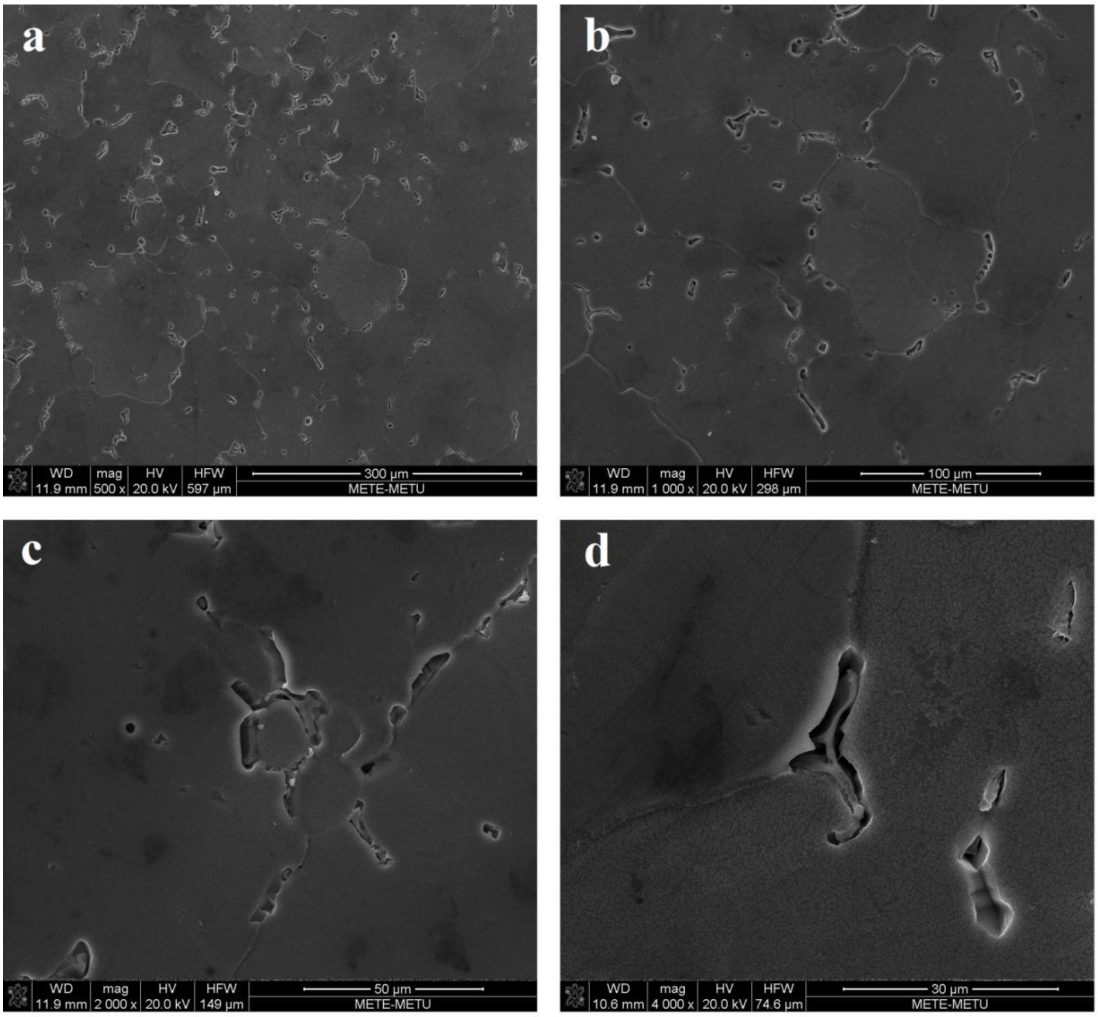


Figure C. 6. SEM images of squeeze cast 7075 aluminum alloy after solutionizing at 485^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

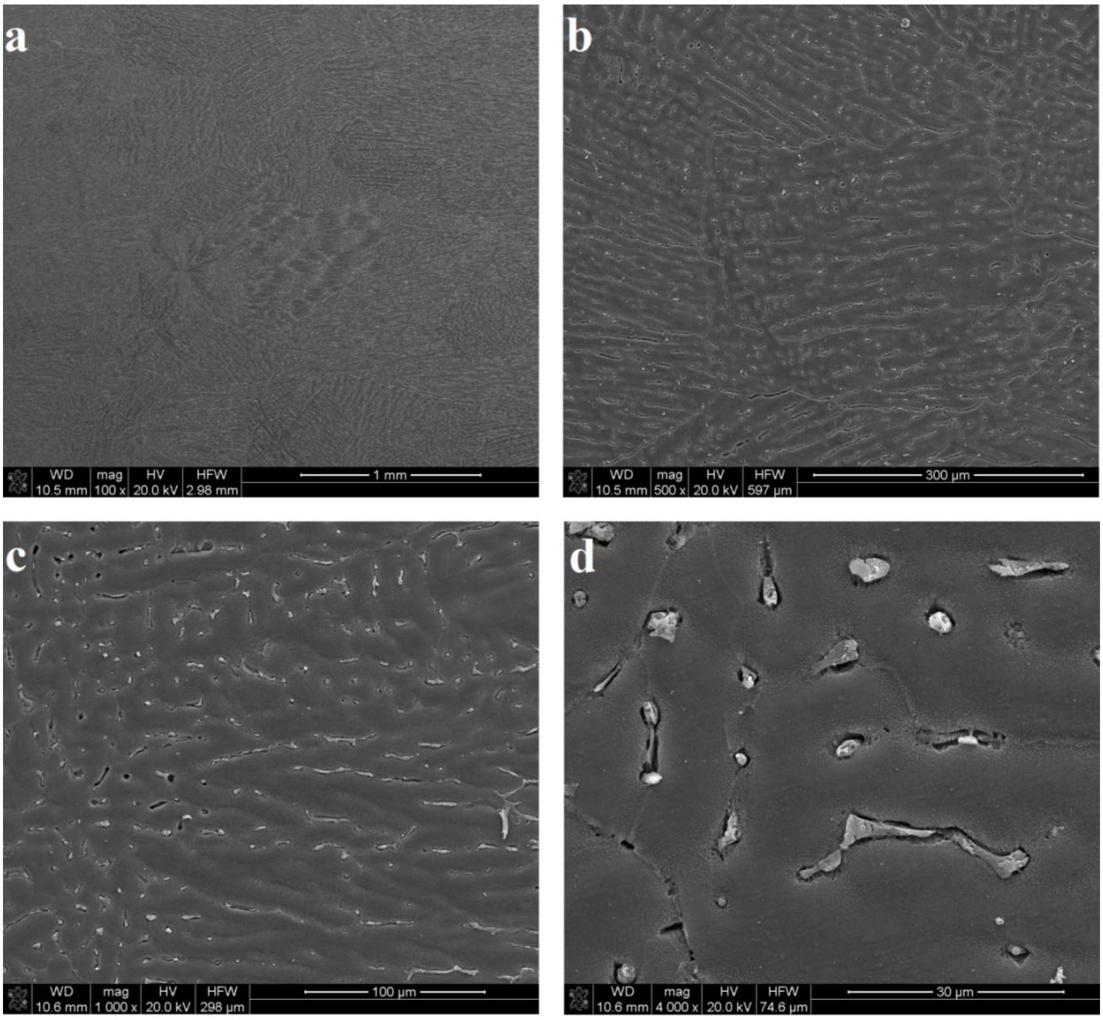


Figure C. 7. SEM images of as cast 7085 aluminum alloy that was produced by squeeze casting process with various magnifications

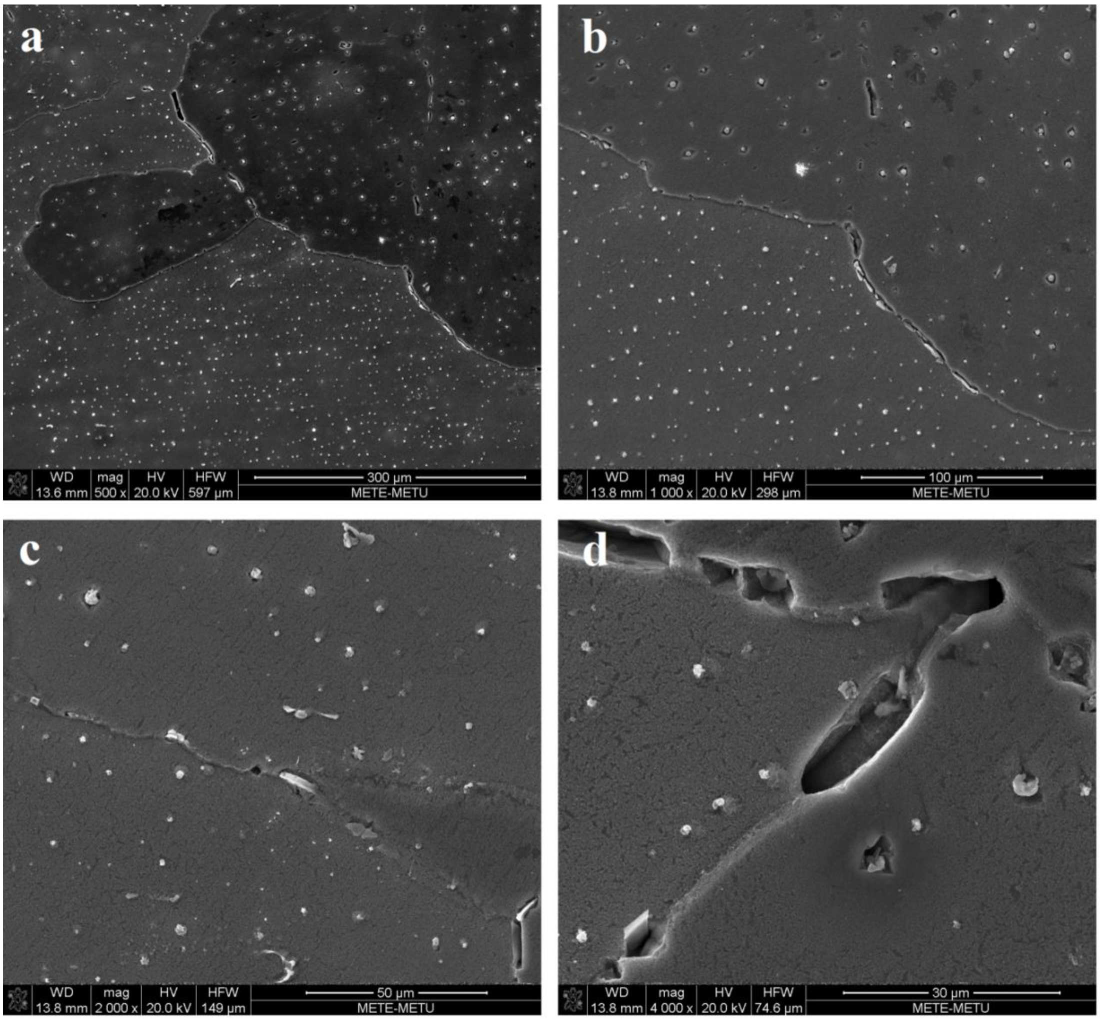


Figure C. 8. SEM images of squeeze cast 7085 aluminum alloy after solutionizing at 460^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

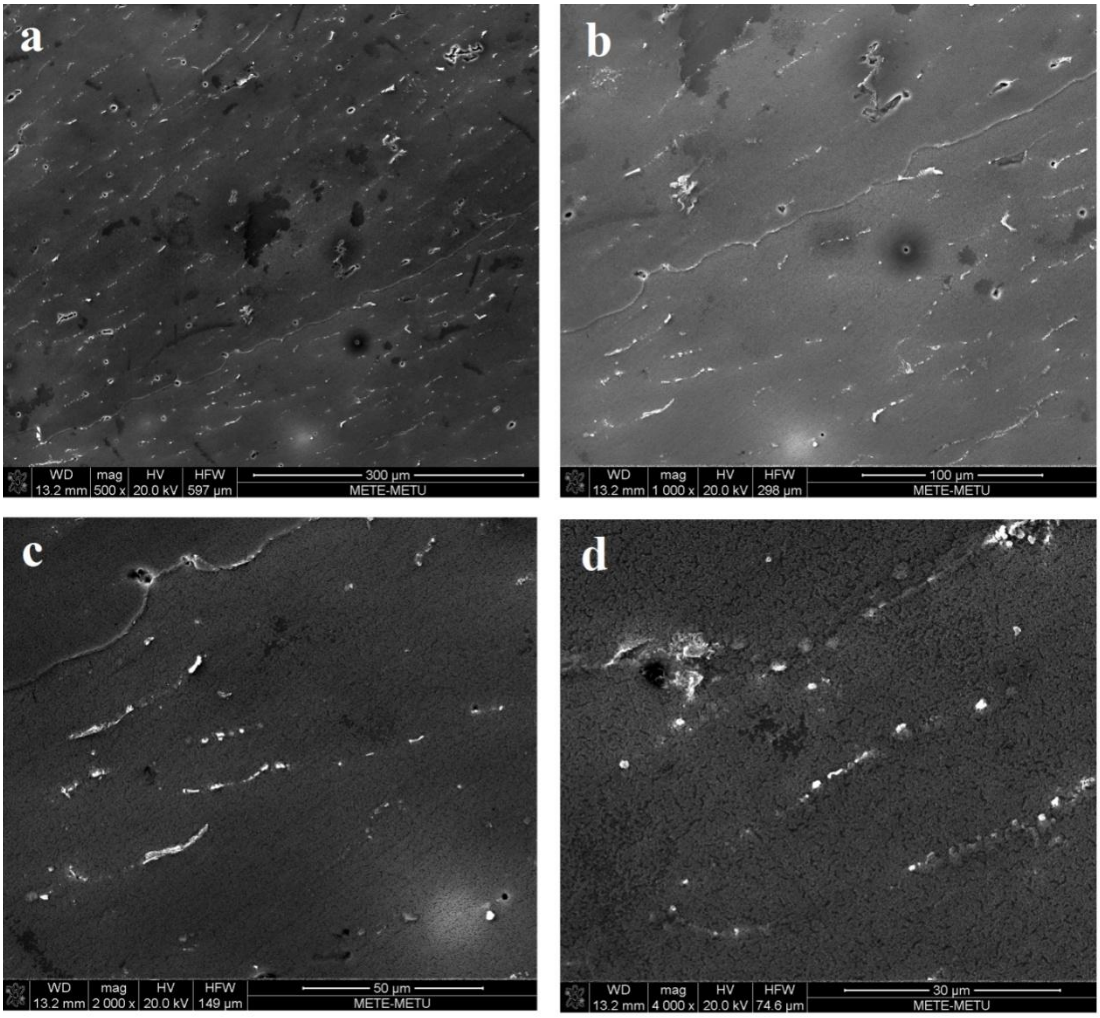


Figure C. 9. SEM images of squeeze cast 7085 aluminum alloy after solutionizing at 465^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

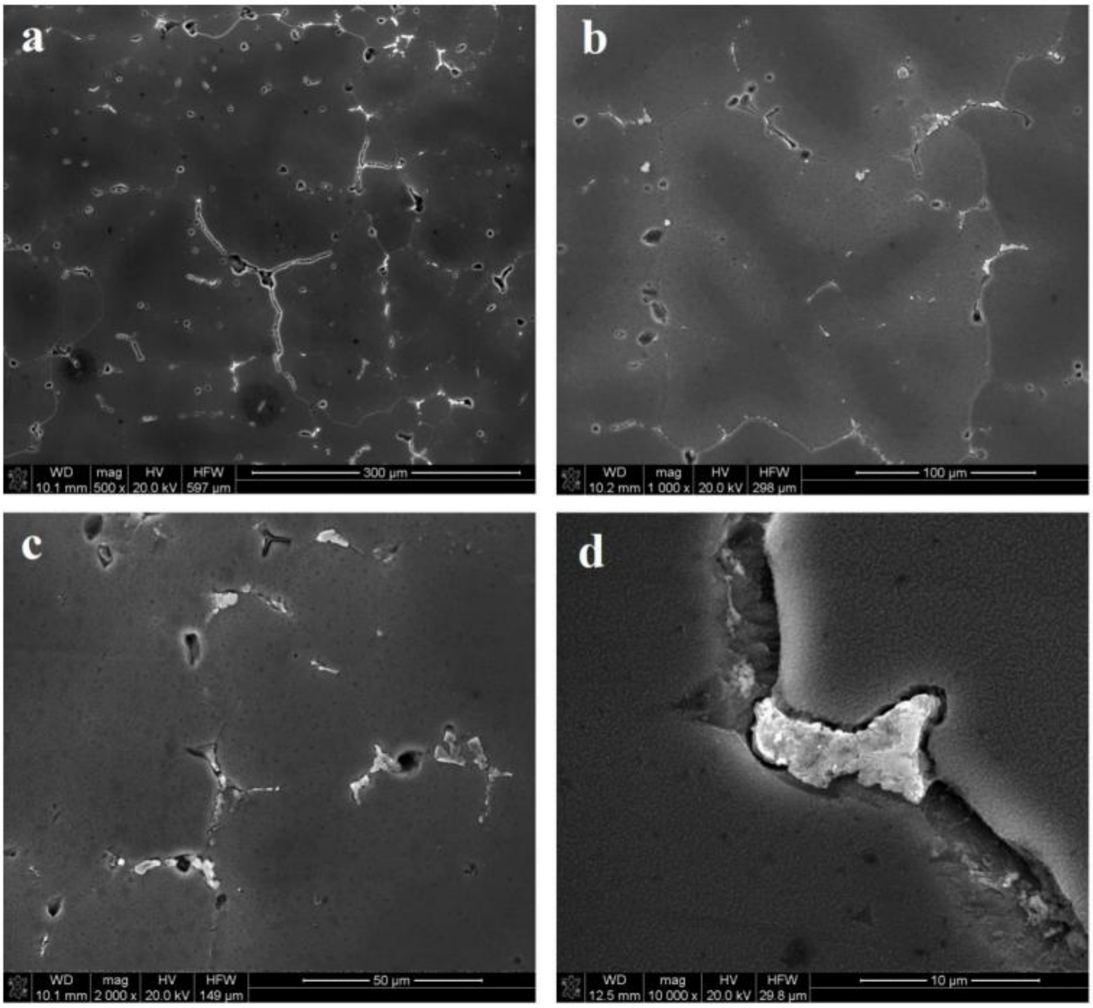


Figure C. 10. SEM images of squeeze cast 7085 aluminum alloy after solutionizing at 470^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

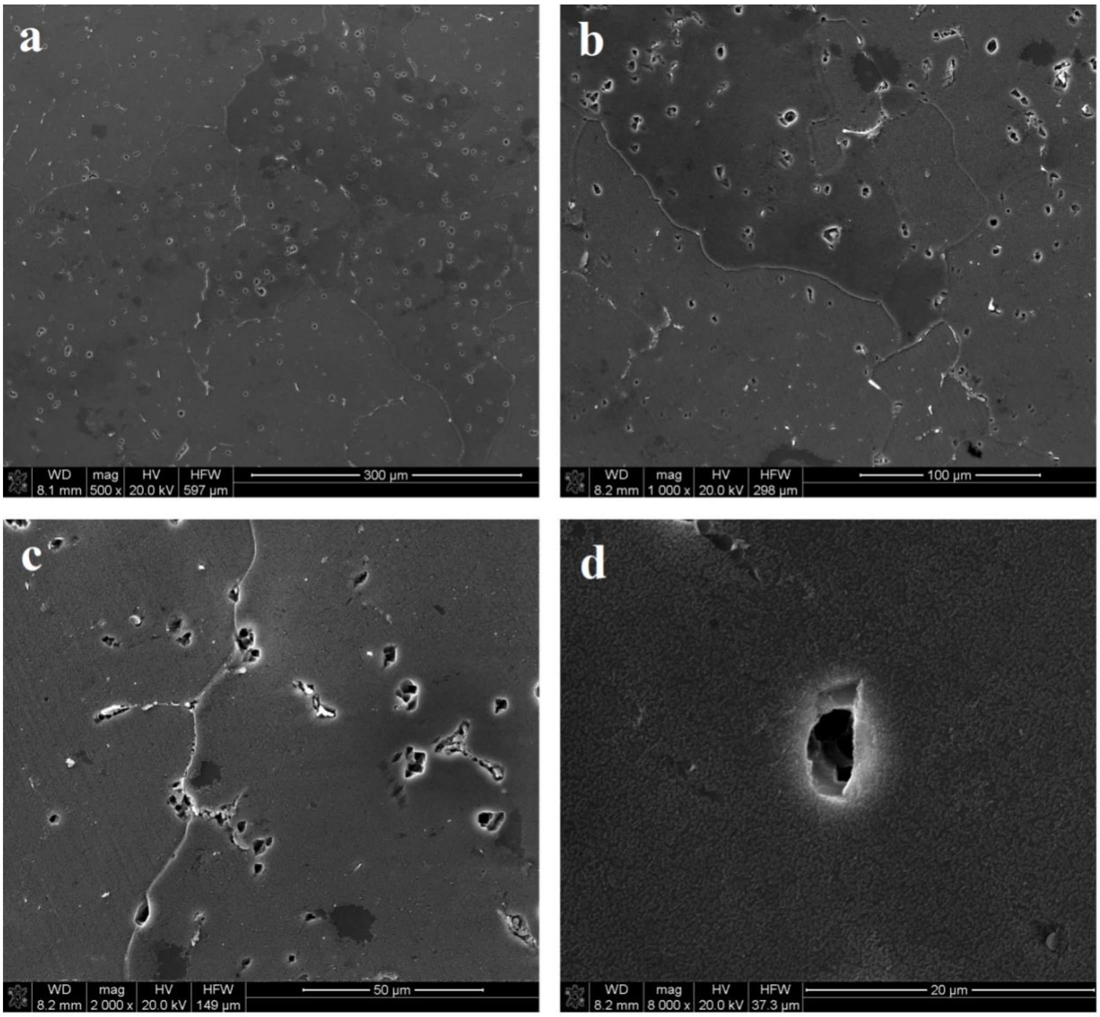


Figure C. 11. SEM images of squeeze cast 7085 aluminum alloy after solutionizing at 480°C/90 minutes, quenching in the water and aging at 120°C/24 hours with various magnifications

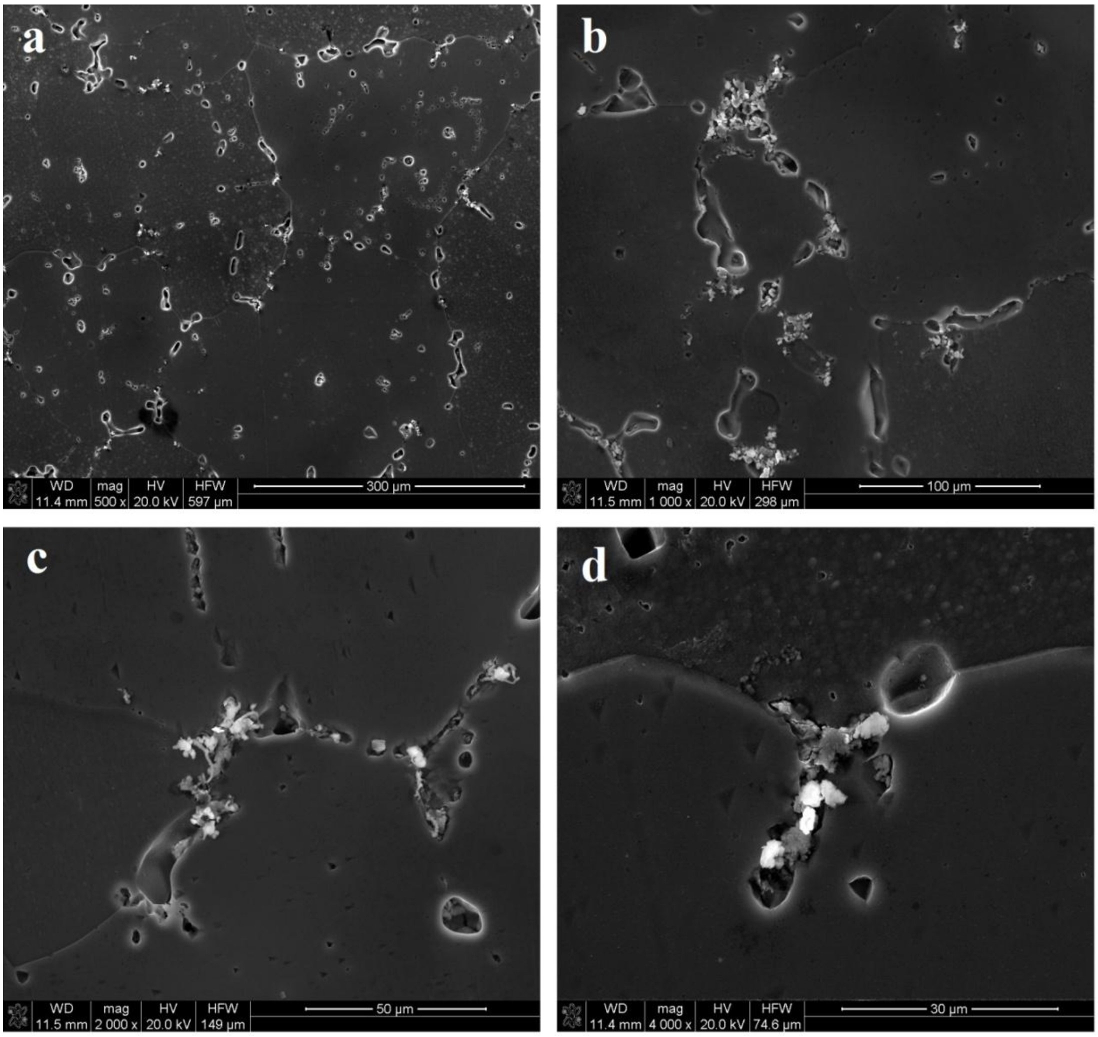


Figure C. 12. SEM images of squeeze cast 7085 aluminum alloy after solutionizing at 490^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours with various magnifications

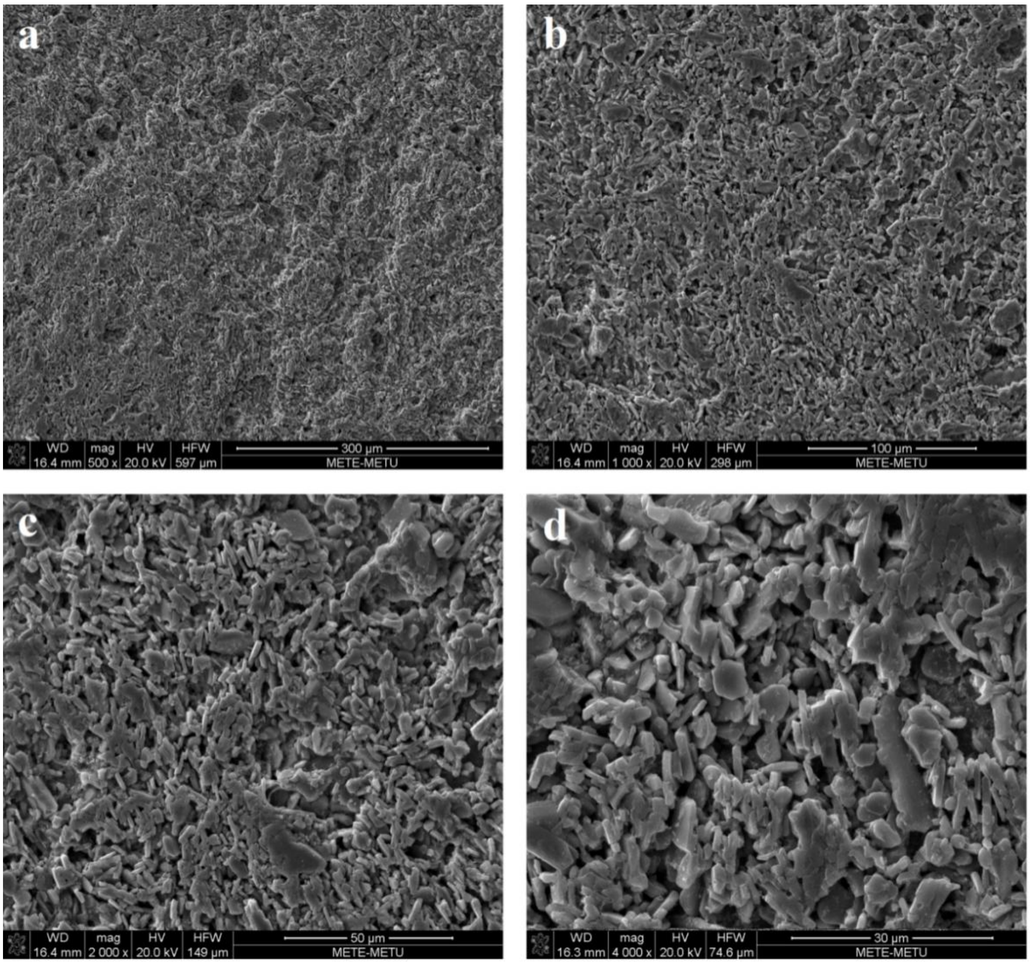


Figure C. 13. Microstructures of Alumina – 7085 Aluminum alloy composite with various magnifications for 1300^{o}C alumina preform sintering temperature (second group)

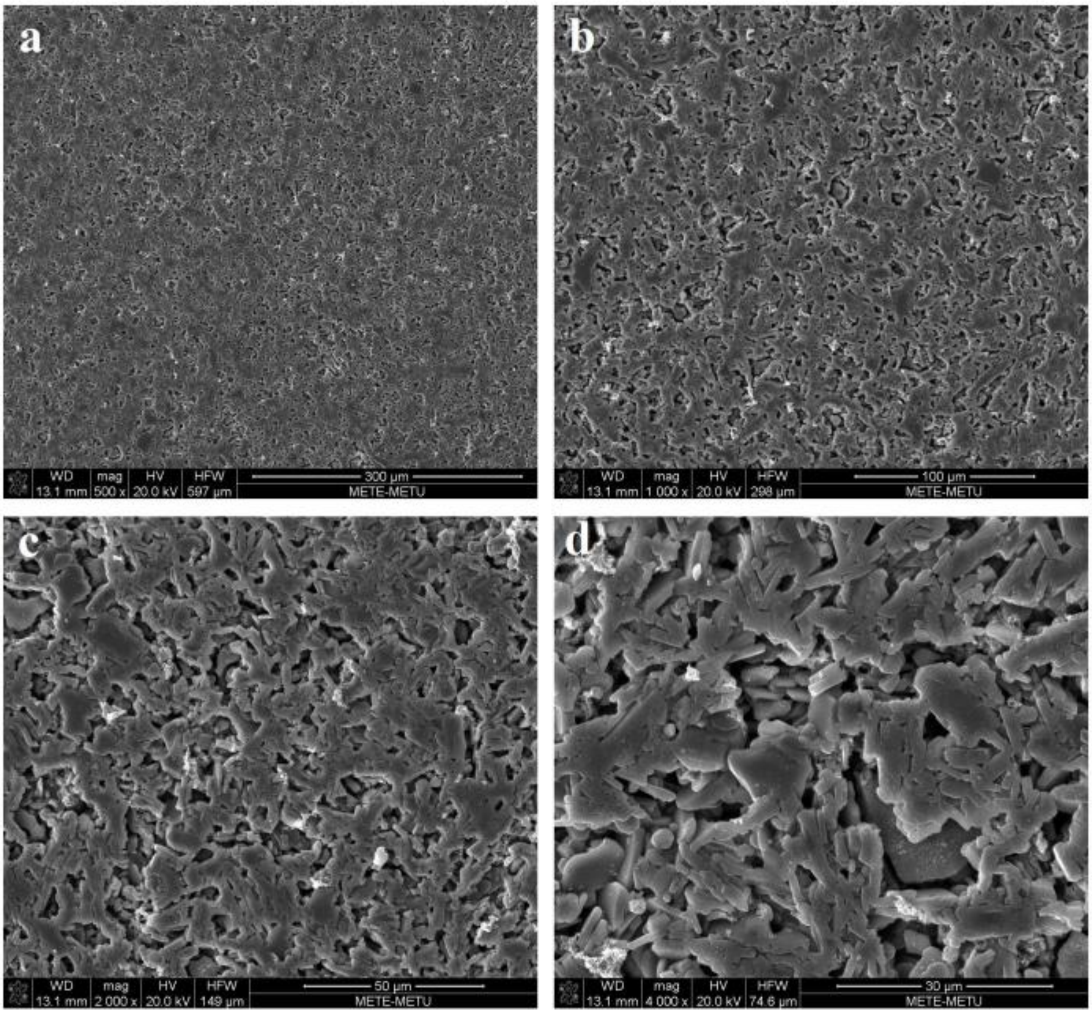


Figure C. 14. Microstructures of Alumina – 7085 Aluminum alloy composite with various magnifications for 1450^{o}C alumina preform sintering temperature (second group)

D. X-RAY DIFFRACTION MEASUREMENT

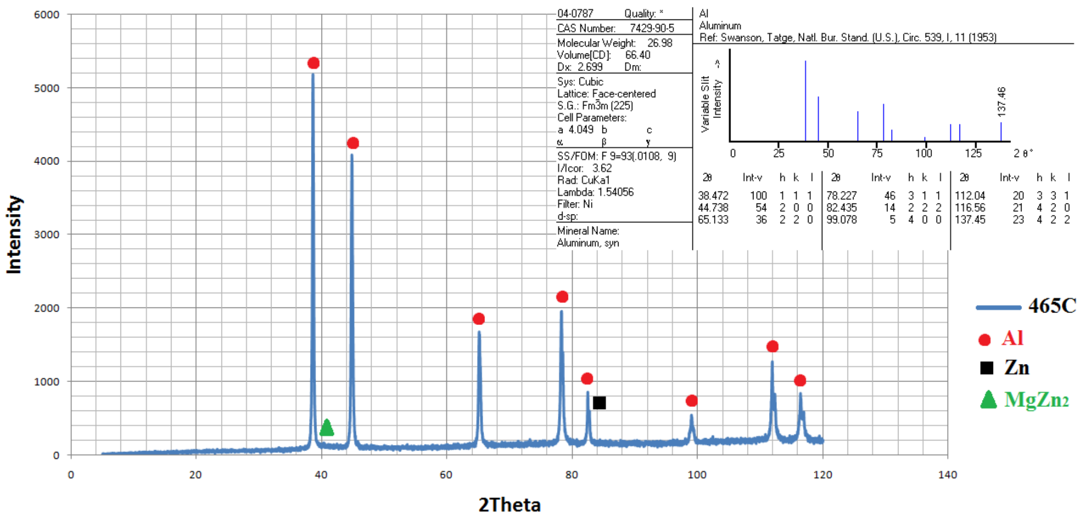


Figure D. 1. XRD pattern of squeeze cast 7075 aluminum alloy after solutionizing at 465°C/90 minutes, quenching in the water and aging at 120°C/24 hours

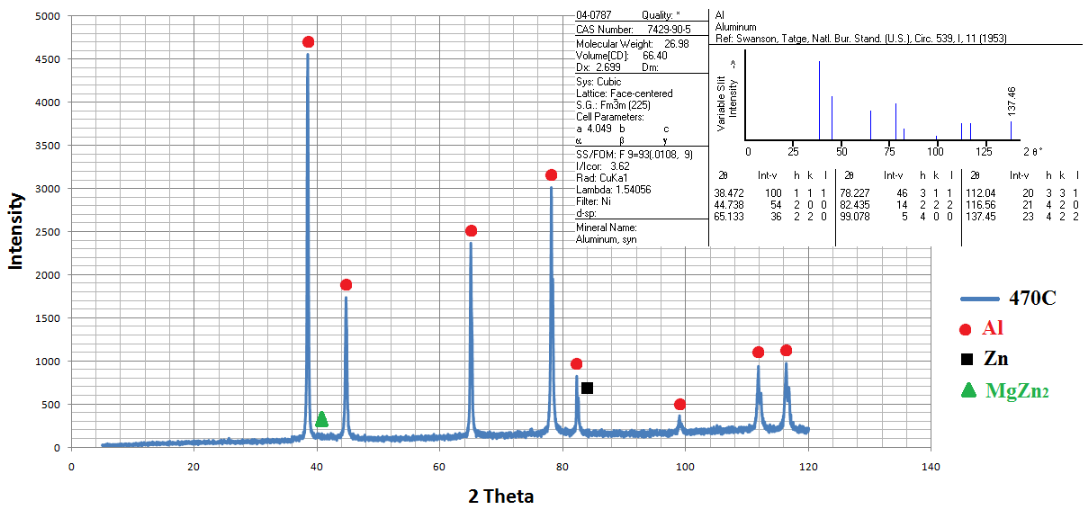


Figure D. 2. XRD pattern of squeeze cast 7075 aluminum alloy after solutionizing at 470°C/90 minutes, quenching in the water and aging at 120°C/24 hours

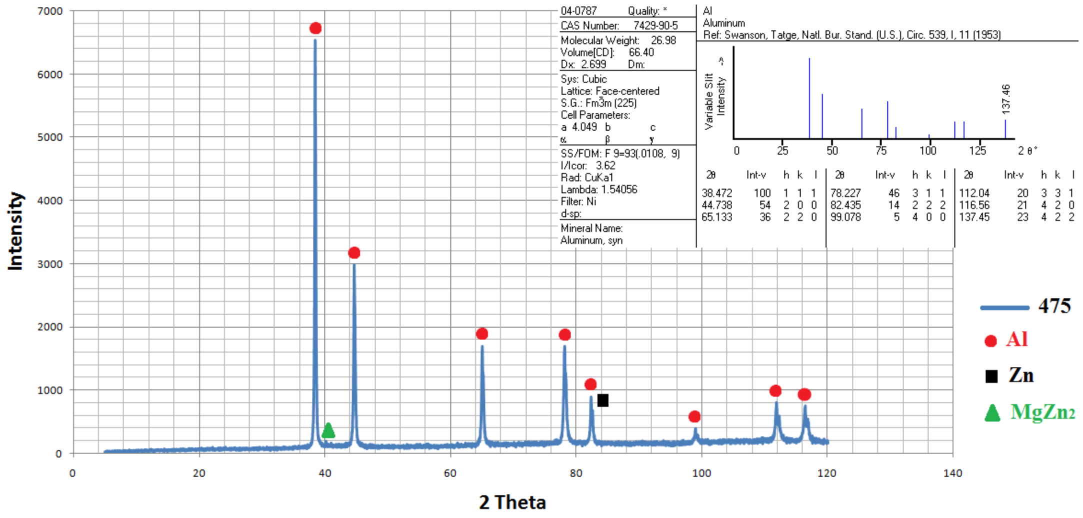


Figure D. 3. XRD pattern of squeeze cast 7075 aluminum alloy after solutionizing at 475^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours

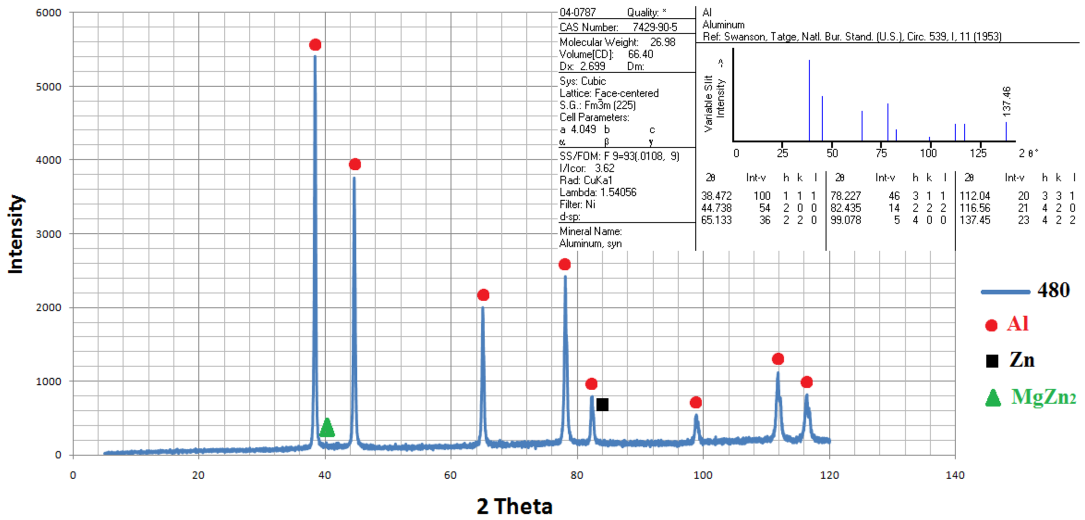


Figure D. 4. XRD pattern of squeeze cast 7075 aluminum alloy after solutionizing at 475^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours

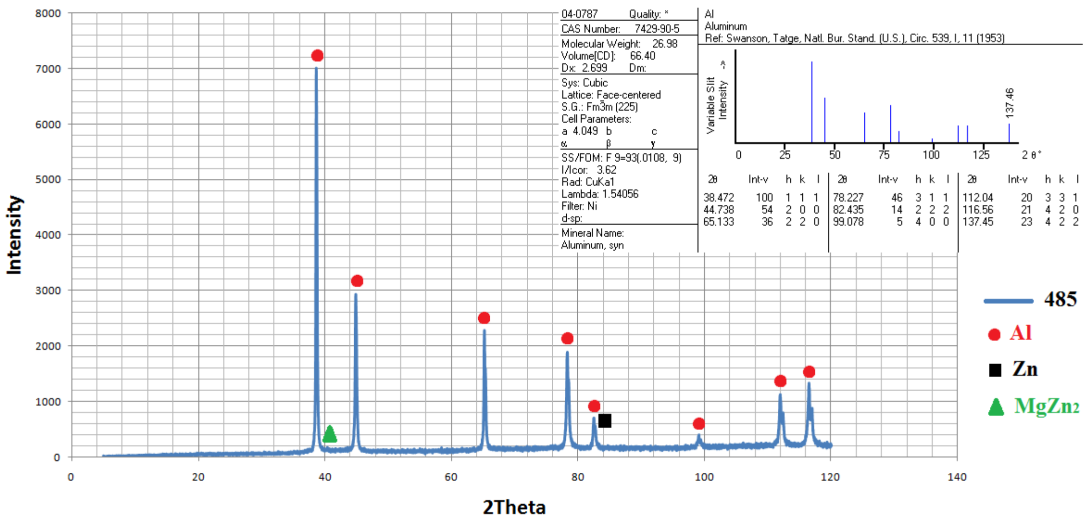


Figure D. 5. XRD pattern of squeeze cast 7075 aluminum alloy after solutionizing at 485°C/90 minutes, quenching in the water and aging at 120°C/24 hours

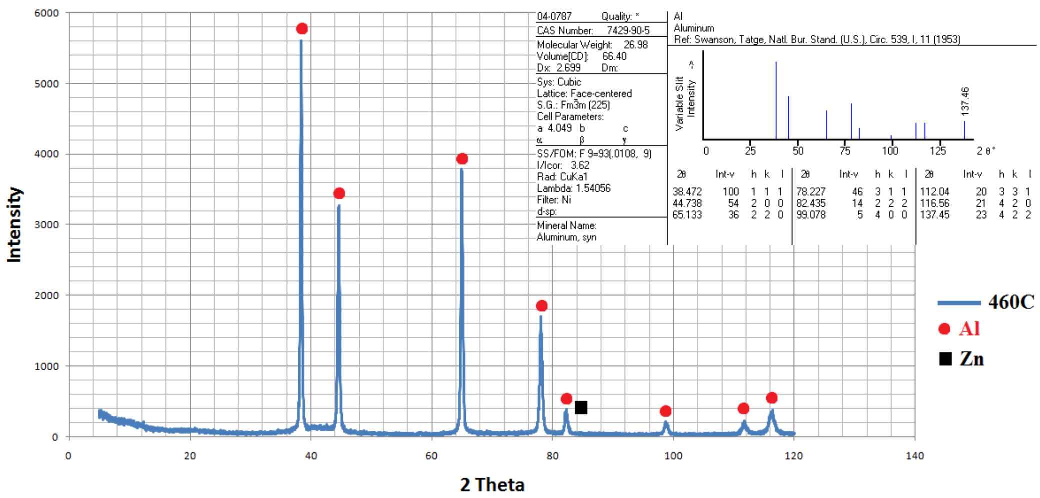


Figure D. 6. XRD pattern of squeeze cast 7085 aluminum alloy after solutionizing at 460°C/90 minutes, quenching in the water and aging at 120°C/24 hours

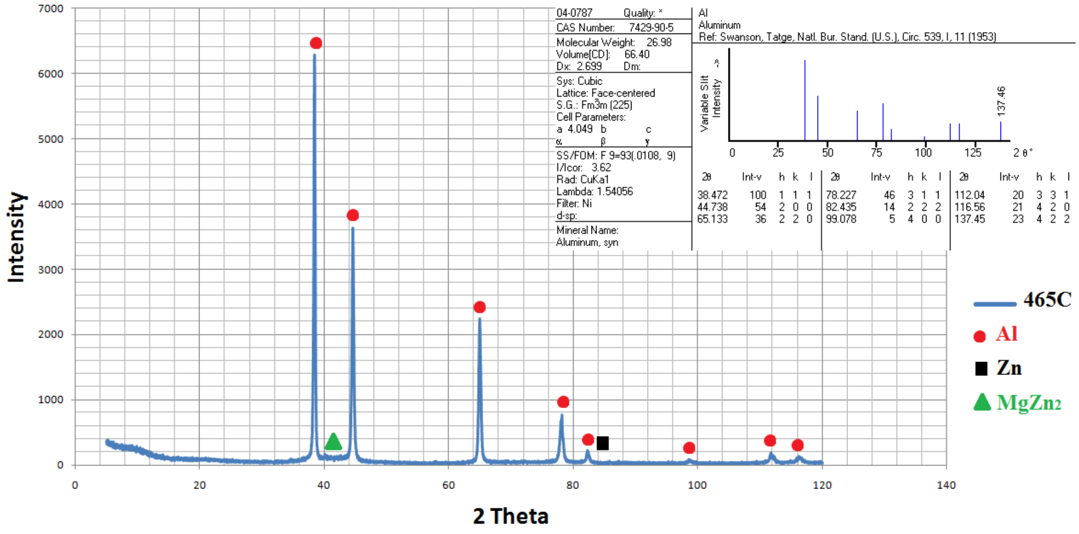


Figure D. 7. XRD pattern of squeeze cast 7085 aluminum alloy after solutionizing at $465^{o}C$/90 minutes, quenching in the water and aging at $120^{o}C$/24 hours

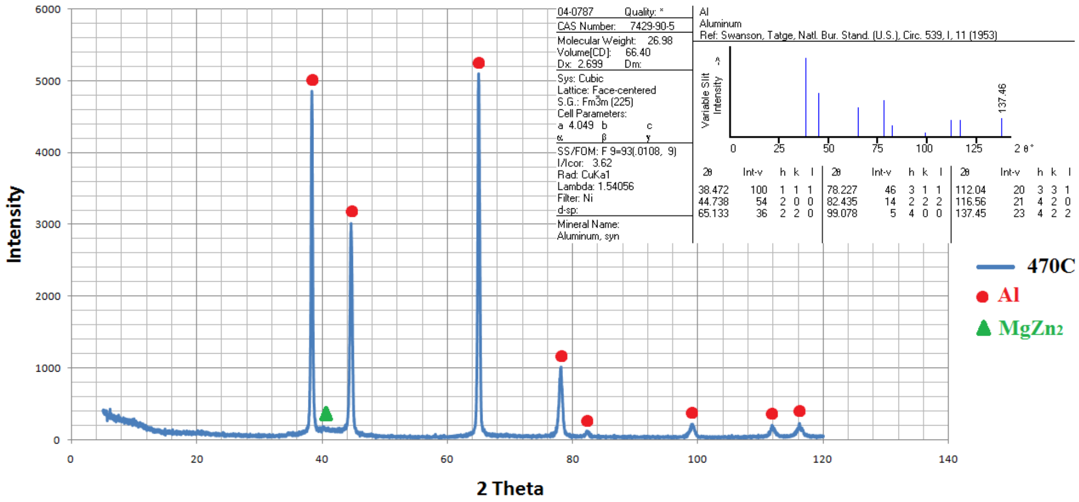


Figure D. 8. XRD pattern of squeeze cast 7085 aluminum alloy after solutionizing at $470^{o}C$/90 minutes, quenching in the water and aging at $120^{o}C$/24 hours

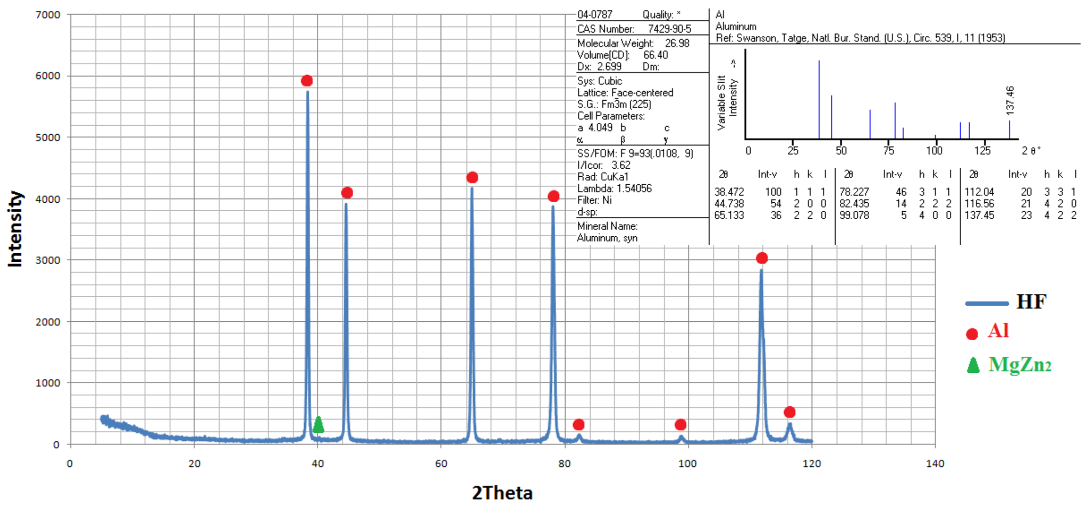


Figure D. 9. XRD pattern of squeeze cast 7085 aluminum alloy after T6 heat treatment, hot forging at 260°C, recrystallization at 516°C during 20 hours and quenching

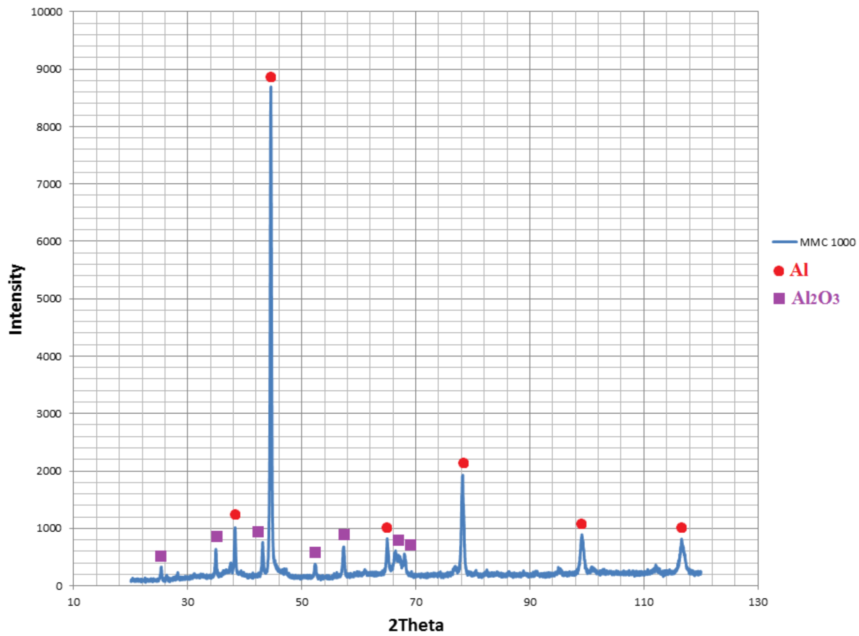


Figure D. 10. XRD pattern of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1000°C

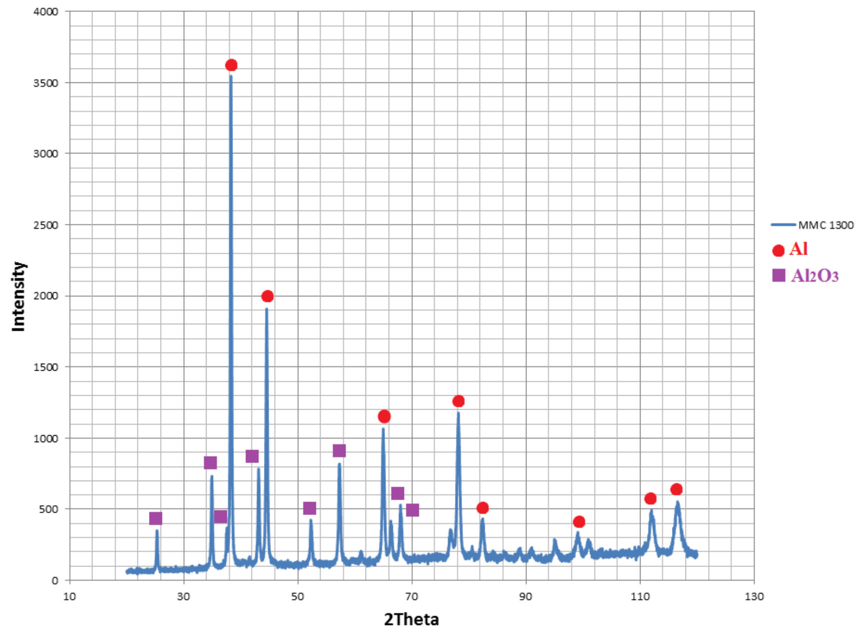
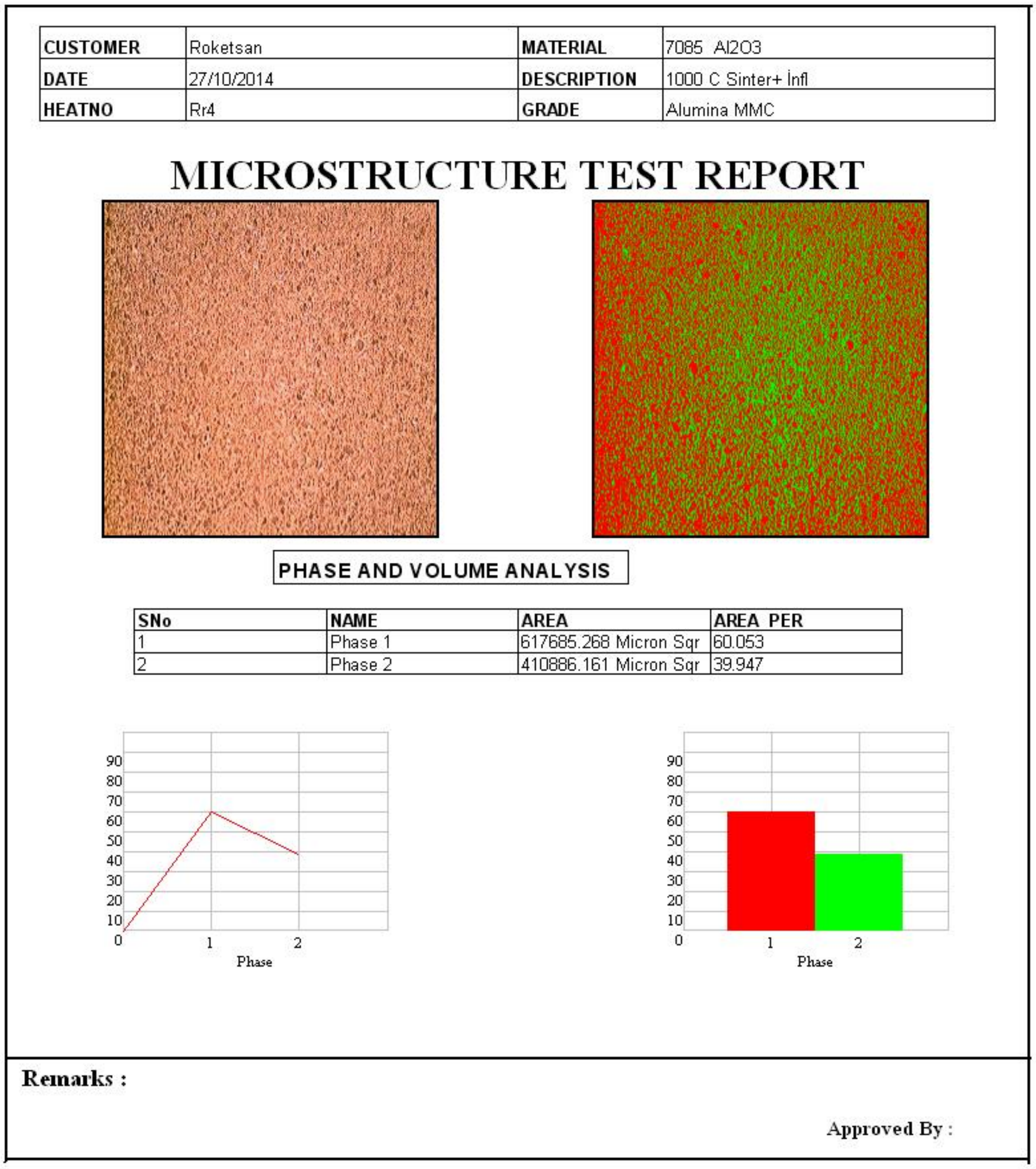


Figure D. 11. XRD pattern of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1300°C

E. PHASE ANALYSIS



CUSTOMER	Roketsan	MATERIAL	7085 Al2O3
DATE	27/10/2014	DESCRIPTION	1000 C Sinter+ İnfl
HEATNO	Rr4	GRADE	Alumina MMC

MICROSTRUCTURE TEST REPORT

PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA PER
1	Phase 1	617685.268 Micron Sqr	60.053
2	Phase 2	410886.161 Micron Sqr	39.947

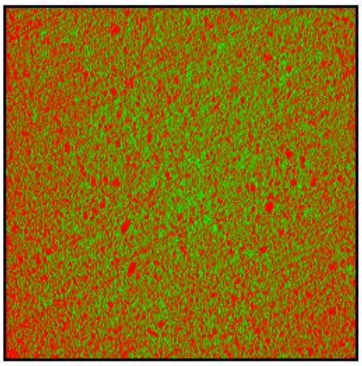
Remarks :

Approved By :

Figure E. 1. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1000^{o}C (first group)

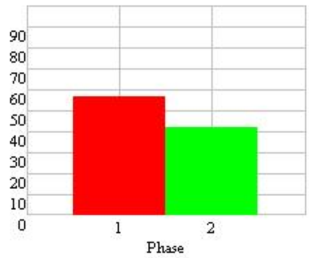
CUSTOMER	Roketsan	**MATERIAL**	7085 MMC
DATE	16/10/2014	**DESCRIPTION**	1100 C sinter+infl
HEATNO	R3	**GRADE**	Alumina MMC

MICROSTRUCTURE TEST REPORT



PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA PER
1	Phase 1	589680.804 Micron Sqr	57.330
2	Phase 2	438890.625 Micron Sqr	42.670



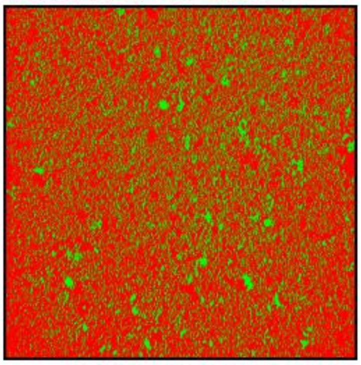
Remarks :

Approved By :

Figure E. 2. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1100^{o}C (first group)

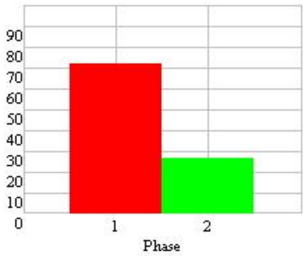
CUSTOMER	Roketsan	**MATERIAL**	7085 Al2O3
DATE	14/10/2014	**DESCRIPTION**	1200 C Sinter +inf
HEATNO	R2 x100	**GRADE**	Alumina MMC

MICROSTRUCTURE TEST REPORT



PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA PER
1	Phase 1	183619.835 Micron Sqr	72.324
2	Phase 2	70264.463 Micron Sqr	27.676



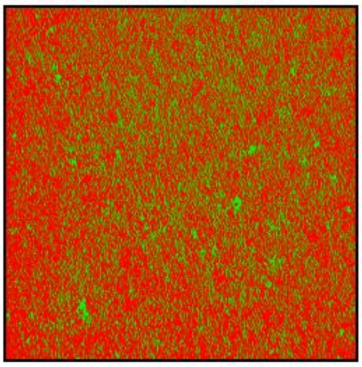
Remarks :

Approved By :

Figure E. 3. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1200^{o}C (first group)

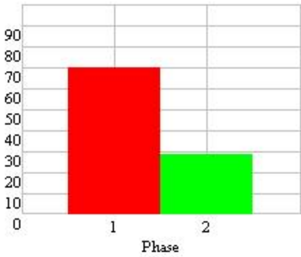
CUSTOMER	Roketsan	MATERIAL	7085 Al2O3
DATE	9/10/2014	DESCRIPTION	1300 C sinter+ infl
HEATNO	R1 x100	GRADE	Alumina MMC

MICROSTRUCTURE TEST REPORT



PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA PER
1	Phase 1	723837.054 Micron Sqr	70.373
2	Phase 2	304734.375 Micron Sqr	29.627



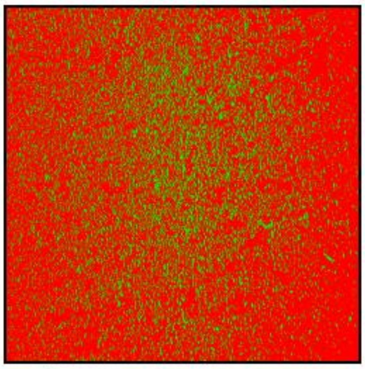
Remarks :

Approved By :

Figure E. 4. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1300^{o}C (first group)

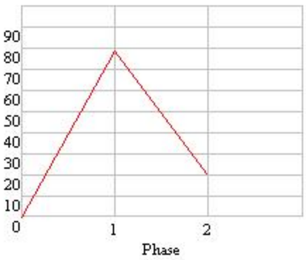
CUSTOMER	Roketsan	**MATERIAL**	7085 Al2O3
DATE	3/3/2015	**DESCRIPTION**	1300 C Sinter+infl
HEATNO	R3x100	**GRADE**	Alumina MMC

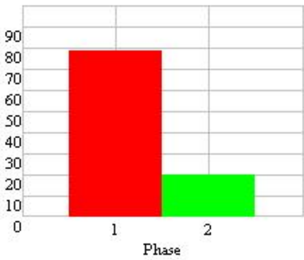
MICROSTRUCTURE TEST REPORT



PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA_PER
1	Phase 1	-1.#IO Micron Sqr	79.817
2	Phase 2	-1.#IO Micron Sqr	20.183





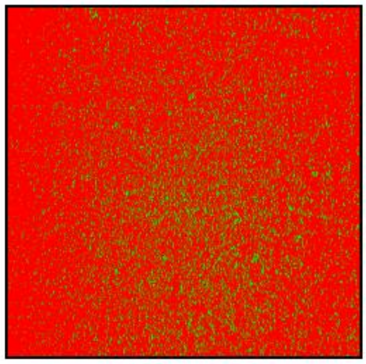
Remarks :

Approved By :

Figure E. 5. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1300^{o}C (second group)

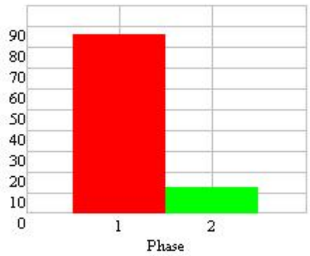
CUSTOMER	Roketsan	MATERIAL	7085 Al2O3
DATE	4/3/2015	DESCRIPTION	1400 C Sinter+İnfl
HEATNO	R3 x100	GRADE	Alumina MMC

MICROSTRUCTURE TEST REPORT



PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA PER
1	Phase 1	892158.482 Micron Sqr	86.738
2	Phase 2	136412.946 Micron Sqr	13.262



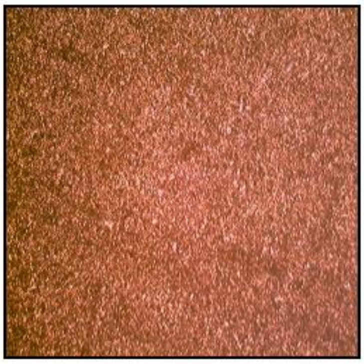
Remarks :

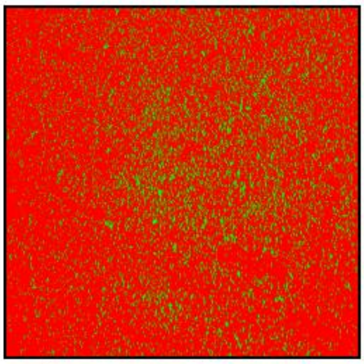
Approved By :

Figure E. 6. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1400°C (second group)

CUSTOMER	Roketsan	MATERIAL	7085 Al2O3
DATE	4/3/2015	DESCRIPTION	1450 C Sint+İnfl
HEATNO	R3x100_2	GRADE	Alumina MMC

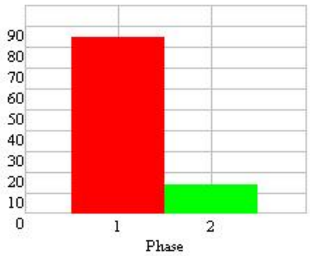
MICROSTRUCTURE TEST REPORT





PHASE AND VOLUME ANALYSIS

SNo	NAME	AREA	AREA_PER
1	Phase 1	874550.223 Micron Sqr	85.026
2	Phase 2	154021.205 Micron Sqr	14.974



Remarks :

Approved By :

Figure E. 7. Phase analysis of Alumina – 7085 Aluminum alloy composite whose alumina preform was sintered at 1450°C (second group)

F. MECHANICAL TESTING

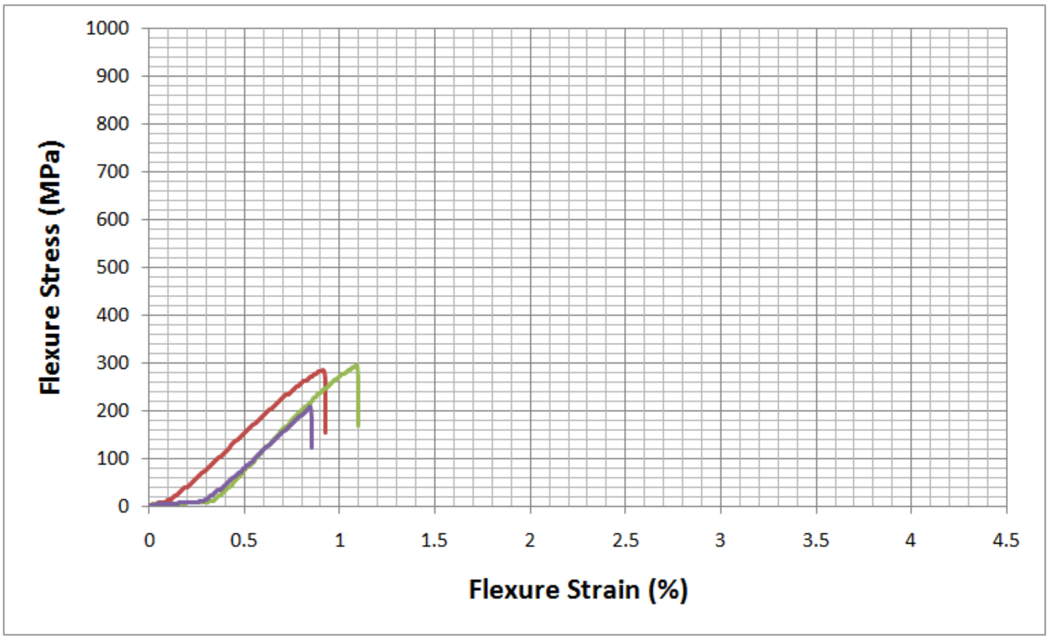


Figure F. 1. Three point bending test results of squeeze cast 7075 aluminum specimens before heat treatment (as cast)

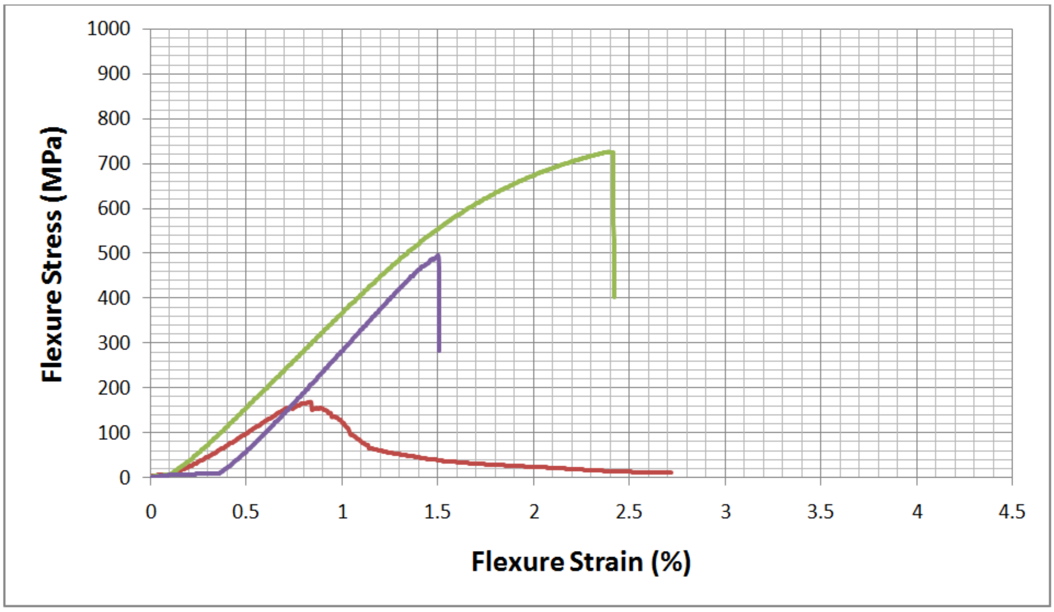


Figure F. 2. Three point bending test results of squeeze cast 7075 aluminum specimens after solutionizing at 465°C/90 minutes, quenching in the water and aging at 120°C/24 hours

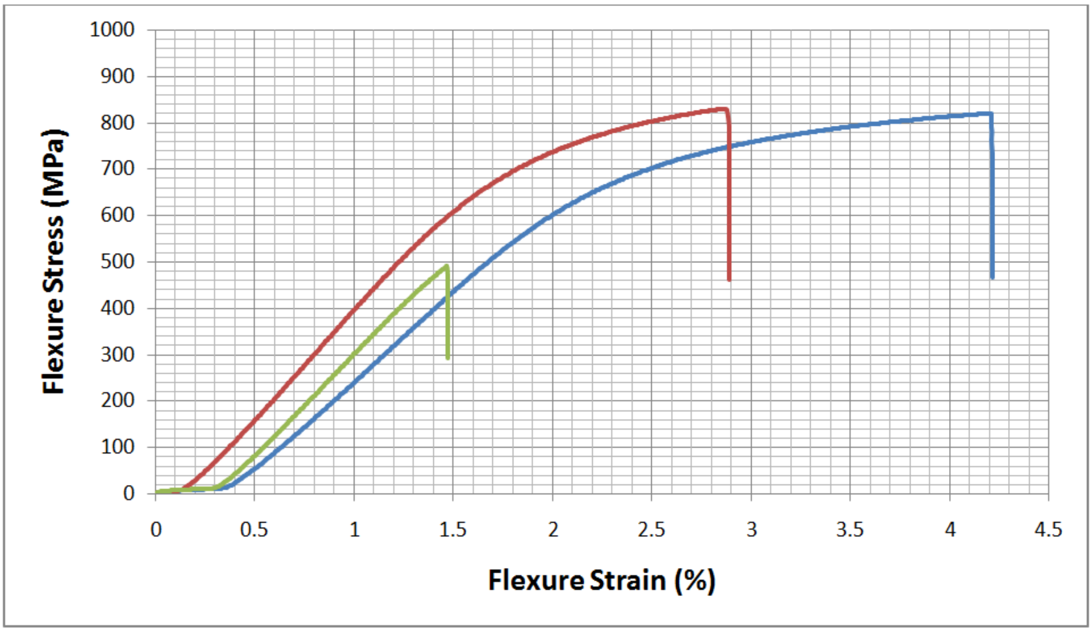


Figure F. 3. Three point bending test results of squeeze cast 7075 aluminum specimens after solutionizing at 470°C/90 minutes, quenching in the water and aging at 120°C/24 hours

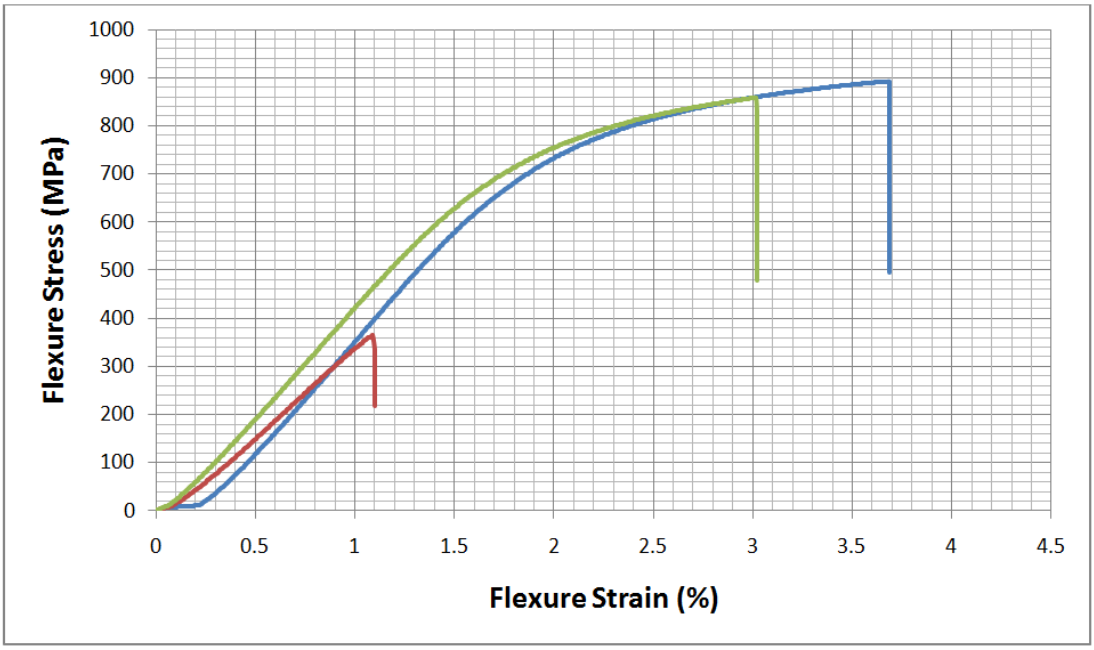


Figure F. 4. Three point bending test results of squeeze cast 7075 aluminum specimens after solutionizing at 475°C/90 minutes, quenching in the water and aging at 120°C/24 hours

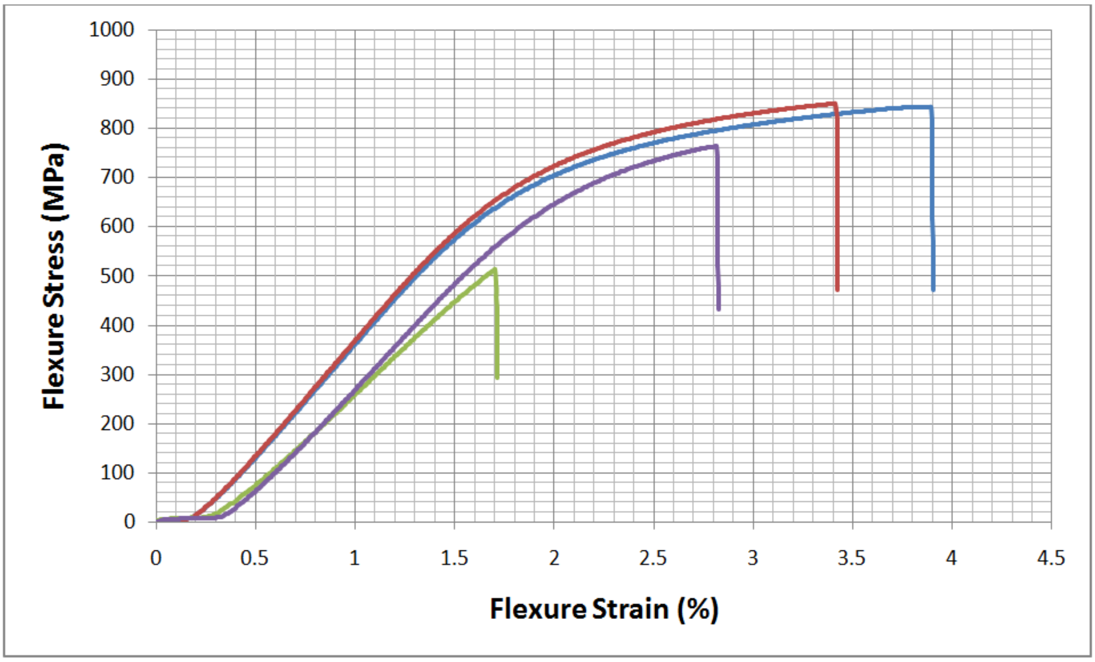


Figure F. 5. Three point bending test results of squeeze cast 7075 aluminum specimens after solutionizing at 480°C/90 minutes, quenching in the water and aging at 120°C/24 hours

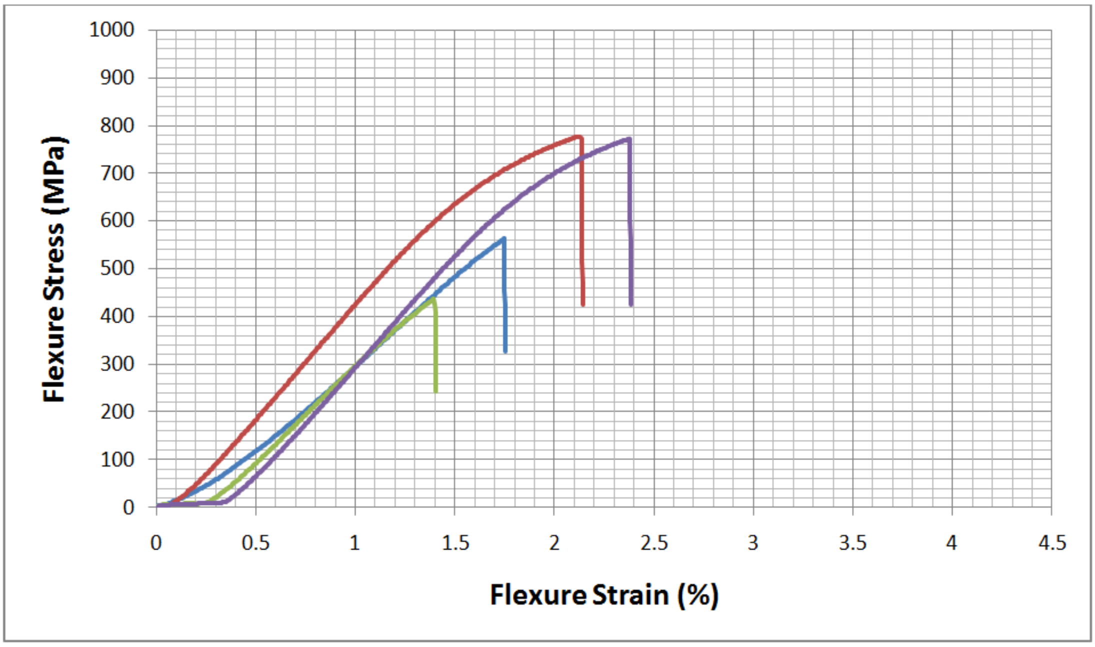


Figure F. 6. Three point bending test results of squeeze cast 7075 aluminum specimens after solutionizing at 485°C/90 minutes, quenching in the water and aging at 120°C/24 hours

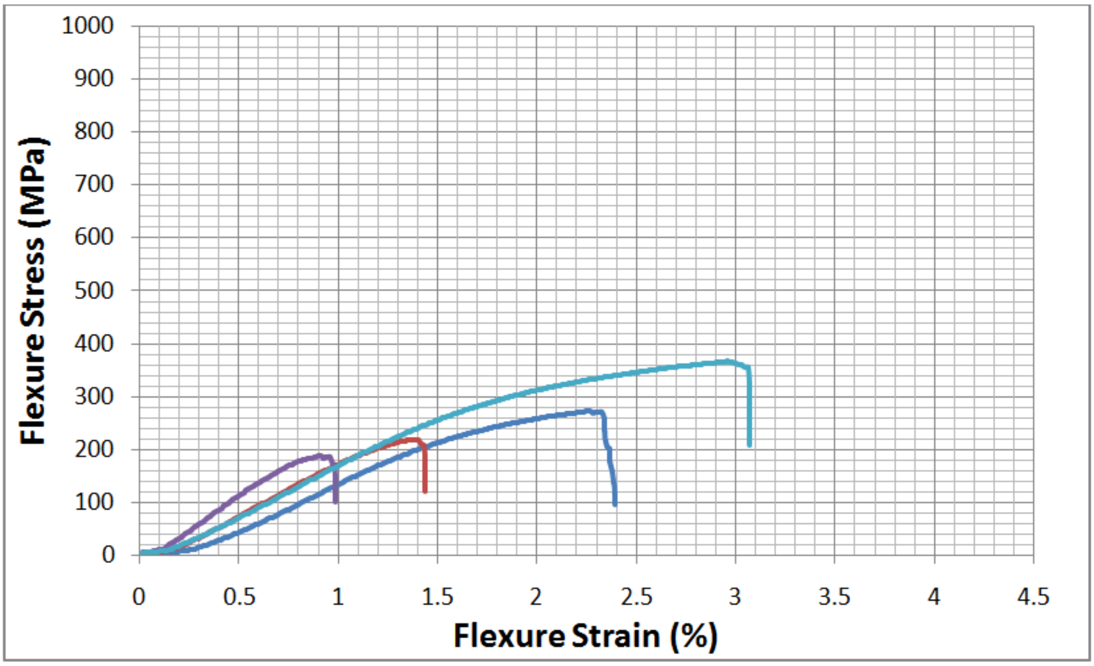


Figure F. 7. Three point bending test results of squeeze cast 7085 aluminum specimens before heat treatment (as cast)

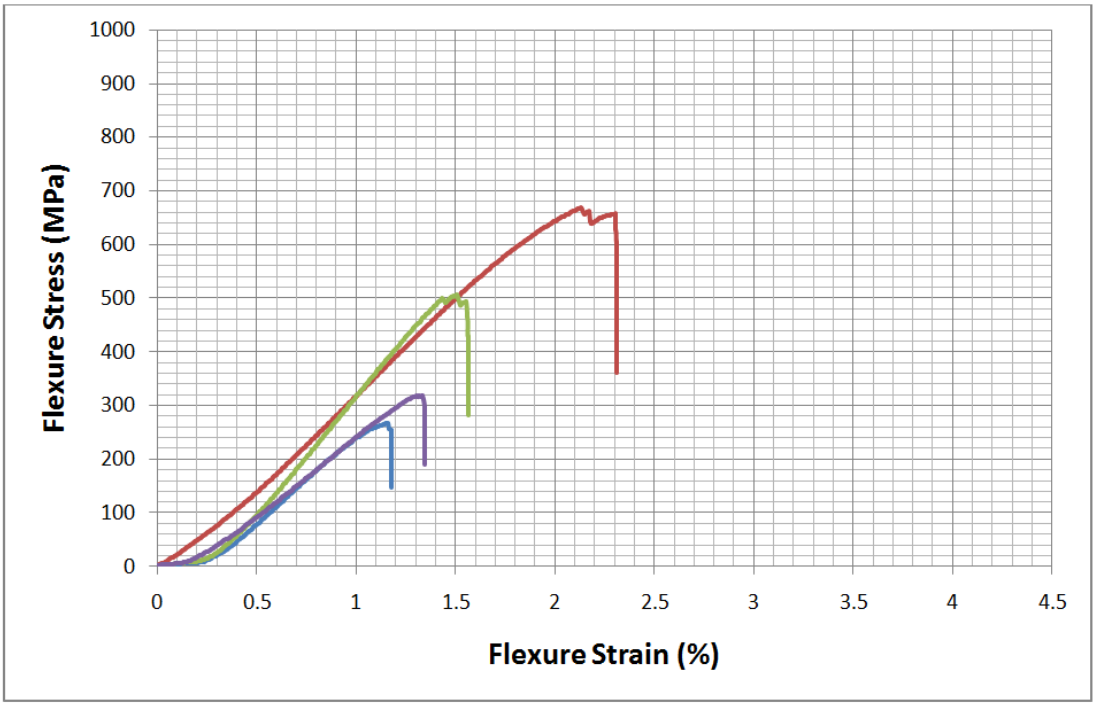


Figure F. 8. Three point bending test results of squeeze cast 7085 aluminum specimens after solutionizing at 460^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours

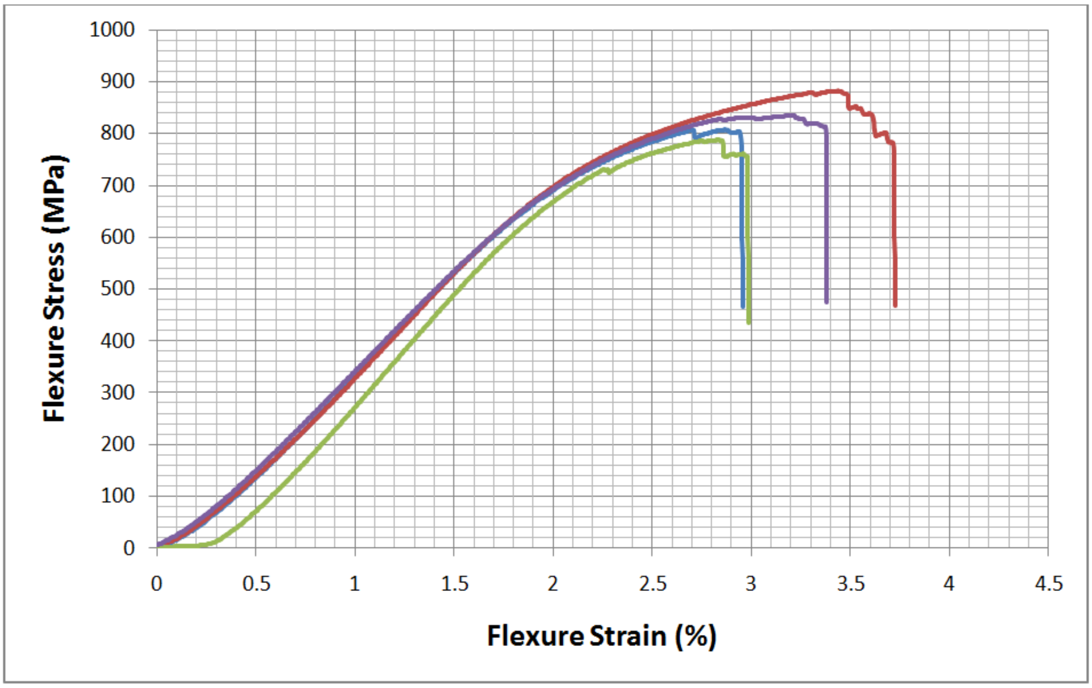


Figure F. 9. Three point bending test results of squeeze cast 7085 aluminum specimens after solutionizing at 465^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours

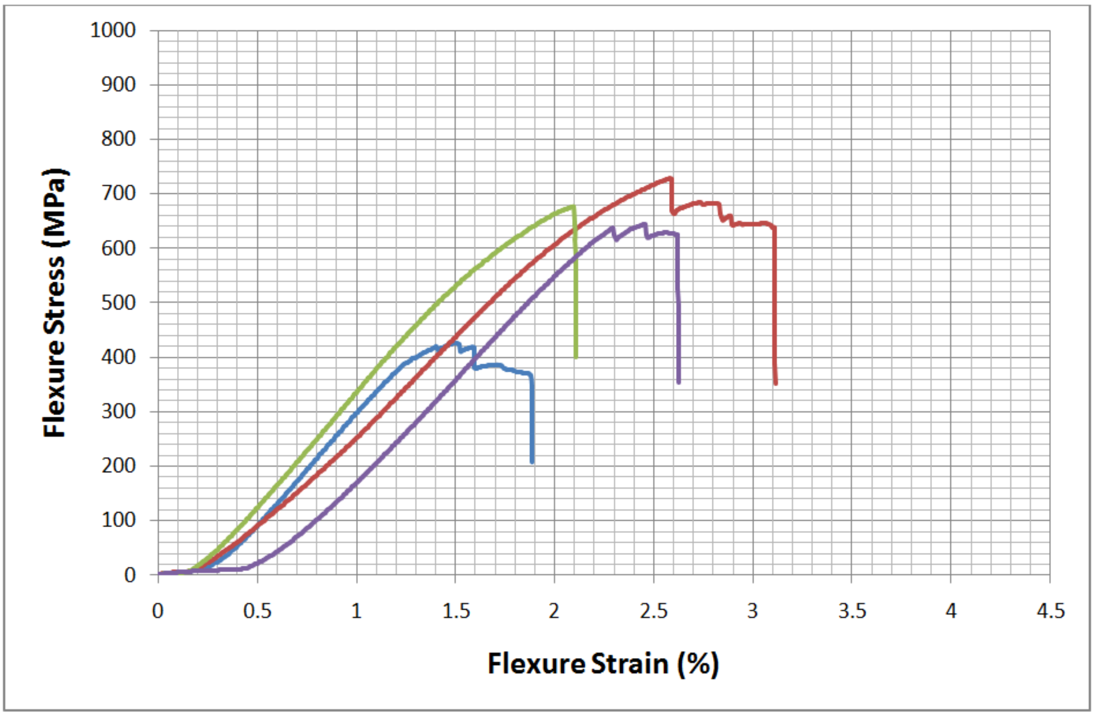


Figure F. 10. Three point bending test results of squeeze cast 7085 aluminum specimens after solutionizing at 470^{o}C/90 minutes, quenching in the water and aging at 120^{o}C/24 hours

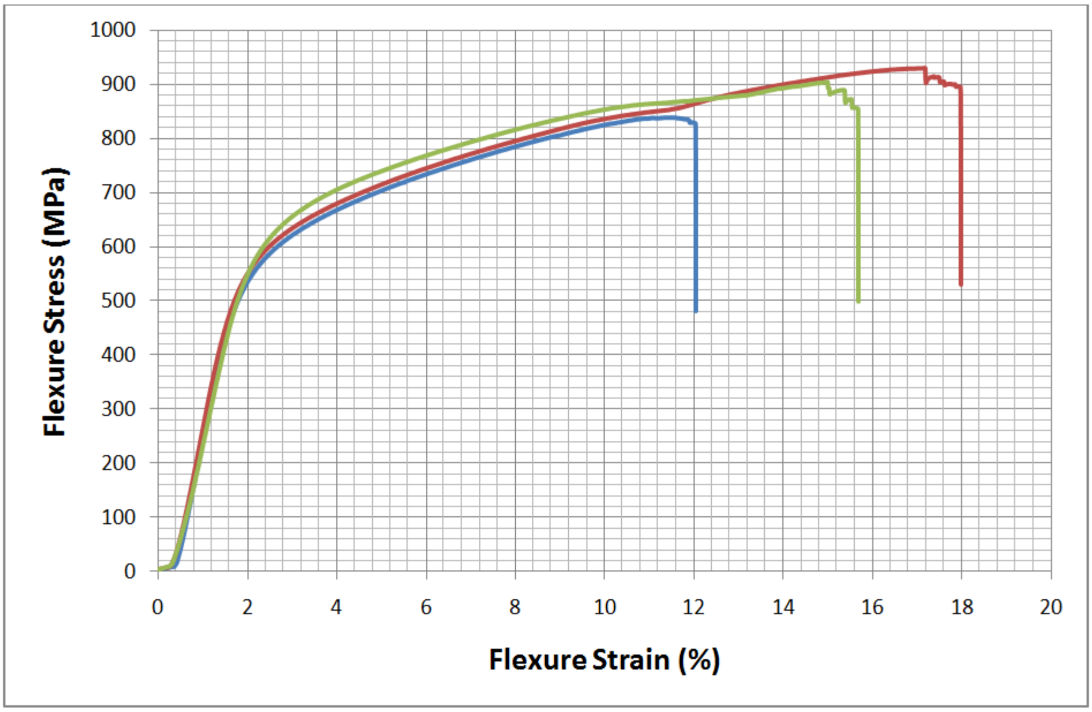


Figure F. 11. Three point bending test results of squeeze cast 7085 aluminum specimens after T6 heat treatment, hot forged at 260°C and recrystallization at 516°C during 20 hours