DESIGN AND PRODUCTION OF A DISSIMILAR CHANNEL ANGULAR PRESSING SYSTEM TO OBTAIN HIGH STRENGTH ALUMINUM ALLOY SHEETS

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DESIGN AND PRODUCTION OF A DISSIMILAR CHANNEL ANGULAR PRESSING SYSTEM TO OBTAIN HIGH STRENGTH ALUMINUM ALLOY SHEETS

submitted by **GÖKTÜRK EMRE UZUNÇAKMAK** in partial fulfillment of the requirements for the degree of **Master of Science in Metallurgical and Materials Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ___________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Tayfur Öztürk ___________
Head of Department, **Metallurgical and Materials Engineering**

Prof. Dr. C. Hakan Gür ___________
Supervisor, **Metallurgical and Materials Engineering Dept., METU**

Prof. Dr. Bilgehan Ögel ___________
Co-Supervisor, **Metallurgical and Materials Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Tayfur Öztürk _______________
Metallurgical and Materials Engineering Dept., METU

Prof. Dr. C. Hakan Gür _______________
Metallurgical and Materials Engineering Dept., METU

Prof. Dr. Bilgehan Ögel _______________
Metallurgical and Materials Engineering Dept., METU

Prof. Dr. Vedat Akdeniz _______________
Metallurgical and Materials Engineering Dept., METU

Prof. Dr. A. Bülent Doyum _______________
Mechanical Engineering Dept., METU

Date: 15.06.2009

I hereby declare that all information in this document has been obtained and presented accordance with the academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name : Göktürk Emre Uzunçakmak

Signature :

ABSTRACT

DESIGN AND PRODUCTION OF A DISSIMILAR CHANNEL ANGULAR PRESSING SYSTEM TO OBTAIN HIGH STRENGTH ALUMINUM ALLOY SHEETS

Uzunçakmak, Göktürk Emre
M.S., Department of Metallurgical and Materials Engineering
Supervisor : Prof. Dr. C. Hakan Gür
Co-Supervisor : Prof. Dr. Bilgehan Ögel

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The aim of this thesis work is to design and manufacture a Dissimilar Channel Angular Pressing (DCAP) system for severe plastic deformation of aluminum alloy sheets in order to obtain ultra-fine grained structure. First, a DCAP system was designed by Finite Element Analysis and constructed after various optimization trials. Next, 6061-T0 aluminum alloy plates were severely deformed by various DCAP passes through the system. The samples were characterized by metallography, X-ray diffraction, tension and hardness tests. It has been observed that the yield strength was improved about 100 % after 2 DCAP passes, and 45 nm sub-grain size was obtained.

Keywords: Severe plastic deformation, Dissimilar Channel Angular Pressing, 6061 aluminum alloy, mechanical properties

ÖZ

YÜKSEK DAYANÇLI ALÜMİNYUM ALAŞIM PLAKALARI ELDE ETMEK İÇİN DEĞİŞİK KANALLI AÇISAL PRESLEME SİSTEMİNİN TASARIMI VE ÜRETİMİ

Uzunçakmak, Göktürk Emre
Yüksek Lisans, Metalurji ve Malzeme Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. C. Hakan Gür
Ortak Tez Yöneticisi : Prof. Dr. Bilgehan Ögel

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Bu tez çalışmasının amacı aşırı-ince taneli yapı elde etmek için alüminyum alaşım plakalarının aşırı plastik deformasyonunu sağlayacak bir Değişik Kanallı Açısal Presleme Sistemi tasarlamak ve üretmektir. İlk olarak, bir DCAP sistemi Sonlu Eleman Analizi ile tasarlanmış ve çeşitli optimizasyon denemeleri sonrası üretilmiştir. Daha sonra, 6061-T0 alüminyum alaşım plakaları, sistemden çeşitli DCAP geçişleri ile aşırı şekilde deforme edilmiştir. Numuneler metalografi, X-ışını kırınımı, çekme ve sertlik testleri karakterize edilmiştir. 2 DCAP pasosu sonra akma dayancının yaklaşık % 100 iyileştiği gözlemlenmiştir ve 45 nm tane boyutu elde edilmiştir.

Anahtar Kelimeler: Aşırı plastik deformasyon, Değişik Kanallı Açısal Presleme, 6061 alüminyum alaşımı, mekanik özellikler

To Fatma, Galip and
Merve Uzunçakmak,

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CHAPTER 1

INTRODUCTION

The materials with grain size ranging from 10 to 1000 nm are referred to as ultrafine grained (UFG) materials. Owing to the small grain size and large volume fraction of internal interfaces, UFG materials exhibit unique properties such as high strength, good ductility, high wear resistance and excellent plasticity.

In recent years, there has been a considerable interest in the field of UFG material fabrication. Researches have demonstrated that UFG structures can be produced by imparting high plastic strains to a material. Principally this method is based on application of severe plastic deformation (SPD) to the material. So called SPD techniques are equal channel angular pressing (ECAP) [1, 2], accumulative roll bonding [3].

Among SPD techniques, ECAP has gained a commercial significance in recent years because it is a relatively easy technique for producing UFG materials without changing their cross sectional area [2, 4, 5]. During ECAP process, a strain of approximately 1 can be introduced into the work piece at a single passage through the die with appropriate channel geometry [6-8]. Unlike other deformation techniques, the induced deformation in ECAP process is relatively uniform throughout the specimen [9-11]. Moreover a multipass operation is also possible in ECAP, since the cross sectional shape does not change significantly during processing [7, 12-14].

Despite its various advantages, ECAP process has two major drawbacks for wider commercial applications as stated below:

- Processing of long and thin work pieces is not possible with ECAP.

- ECAP is a discontinuous process due to the limitation regarding to work piece length.

In order to overcome these drawbacks, a novel ECAP based method which can introduce large shear deformation to a long and thin work piece was developed and named as Dissimilar Channel Angular Pressing (DCAP) [15].

DCAP is a unique shear-deforming process. In this process, the work piece is fed into the die by using rolls. The die has an inlet and outlet channels with dissimilar thicknesses; the thickness of the outlet channel is slightly larger than that of the inlet channel. A die configuration like this not only enables the multi-pass operation to take place in a continuous manner, but also allows the formation of various metallic strips into the desired final dimensions. DCAP has gained a commercial significance in recent years because it is as an alternative technique for the production of UFG materials via deformation without changing cross-sectional area.

Aims of this study were,

- To design and produce a DCAP system for the continuous deformation of sheet metals
- To investigate the effects of DCAP process on the mechanical properties of 6061 aluminum alloy sheets deformed through the DCAP system.

In the first part of the study a DCAP system was manufactured after designing the machine by using Finite Element Analysis method. During the manufacturing step, various modifications were made on the rolls and die of the machine to overcome the feeding problem during the process, to make higher number of passage through the system possible and to obtain products with better surface finish.

In the second part of the study, annealed 6061-T6 aluminum alloy sheets were deformed through the DCAP system. After the deformation process, hardness measurements and tensile testing were performed on the specimens to evaluate the mechanical properties. Microstructural examinations were also conducted on the DCAPed specimens to correlate the results of the mechanical tests with microstructural changes.

CHAPTER 2

LITERATURE SURVEY

2.1 Overview

Precipitation hardening is a well known process to obtain high strength in aluminum alloys. In addition to precipitation hardening, there are also many other thermomechanical processes for optimizing the mechanical properties of aluminum alloys. The basis for thermomechanical processes is the grain size control. In hot working this control is achieved by the addition of small amount of elements, which are not effective in precipitation hardening. Hence, during solutionizing ultrafine grained (UFG) structure obtained after hot working is preserved by the existence of those elements.

Unfortunately, production of aluminum alloys by this conventional treatment necessitates complicated establishments which require large amounts of investments. Moreover reduction in grain size is limited; minimum grain size attainable is 10 microns. Since it has known that properties can be improved by obtaining sub-micron level grain sizes, this limitation impedes obtaining aluminum alloys with better properties. In addition, thermomechanical processing parameters should be rearranged for different alloys [16].

In recent years, there has been a considerable interest in new production techniques for aluminum alloys. These interests focused on the producibility of high strength aluminum alloys at strip casting facilities and on the improvement of the material properties that is independent from strip casting and integrated production facilities. Researches are generally based on the severe plastic deformation (SPD) methods. SPD has been a promising method to produce ultrafine grained materials with attractive properties. Among SPD techniques, Equal Channel Angular Pressing

(ECAP) is the most practical method for the production of aluminum alloys. It was assumed that ECAP can take the place of complicated thermomechanical processes for the grain refinement of bulk aluminum alloys. However, ECAP is a discontinuous process and is not suitable for production of the sheet materials. Among SPD techniques for the sheet and strip production, Dissimilar Channel Angular Pressing (DCAP) was come into prominence [17].

2.2 Ultrafine Grained Materials

In common sense, UFG materials are the materials with a grain size of approximately 1 micron or with a grain size in sub micrometer level. Fabrication of UFG materials has been a considerable interest and extensive research work has been conducted to evaluate the characteristics of UFG materials. The increasing interest in UFG materials arises mainly from the strengthening of materials by grain refinement. It is known that in all metals the Hall-Petch effect contributes to the strengthening at room temperature according to the Equation 2.1 [18];

$$\sigma_e = \sigma_i + kd^{-m} \tag{2.1}$$

where σ_e : flow stress,

σ_i : stress characterizing the resistance to dislocation movement within the grain,

k : constant

d : grain size

m : exponent (approximately equals to 0.5 depending on the nature of the alloy)

Since strength is inversely proportional to grain size according to the Hall-Petch equation, UFG materials have higher strengths than that of coarse-grained materials.

2.3 Fabrication Methods of Ultrafine Grained Materials

In order to obtain UFG and nanocrystalline materials several methods have been developed. Traditionally, small grain sizes are attained using appropriate thermomechanical processing (TMP) methods, where a continuous recrystallization process named as geometric dynamic recrystallization (GDR) is usually observed [19].

Unfortunately, TMP methods can only produce materials with grain sizes in the range of 1 to 10 microns. Furthermore the refinement of grain sizes is achieved by specific processing route which involve specially designed heat treatments leading to an increase in the expense. Long duration for development and implementation of the method is another disadvantage. Consequently, the TMP methods are not suitable for the production of UFG materials.

Recently, severe plastic deformation (SPD) methods were introduced for the production of UFG materials [13, 20]. In order to have grain refinement, very high plastic strains are induced in a metal by SPD processes. Unlike conventional plastic deformation techniques like cold rolling and drawing, SPD methods can readily attain very fine microstructures at low temperatures with the application of high pressure. The structures after SPD processes consist of a large number of high angle boundary grains in the sub micrometer range which yields dramatic changes in properties. Moreover, methods of SPD are capable of producing bulk samples in a fully-dense condition, therefore showing a potential for use in industrial applications.

2.4 Severe Plastic Deformation (SPD) Processes

During well known deformation techniques, such as forging, extrusion and rolling large strains are imparted. However these techniques result in a product, which has a different shape from the starting billet. The characteristic feature of the new class of SPD processes is that the size and shape of the workpiece remains unchanged after processing.

The new SPD processes, are Equal Channel Angular Extrusion or Pressing (ECAE/P), ECAP-conform, High Pressure Torsion (HPT), Accumulative Roll Bonding (ARB), Con-Shearing and Dissimilar Channel Angular Pressing (DCAP). Among them, ECAE/P and HPT are used to introduce SPD on bulk materials and disc materials, respectively, while ARB, ECAP-conform, Con-Shearing and DCAP are applicable to sheet materials. Detailed information about these processes is provided below.

2.4.1 High Pressure Torsion (HPT)

SPD by HPT involves the deformation of discs by pure shear between two anvils: lower and upper anvils. During the process the former rotates while the latter holds the material as shown in Figure 2.1 [21, 22].

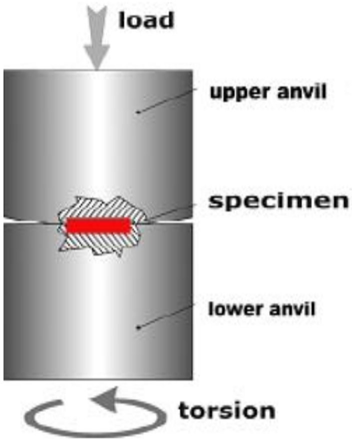


Figure 2.1 Schematic view of High Pressure Torsion [21].

This method is limited to small discs. During HPT the induced deformation is non uniform from the center to the outside diameter [21].

2.4.2 Accumulative Roll Bonding (ARB)

ARB involves the deformation of a stack of two sheets having equal thickness. After ARB 50 % reduction in thickness by plane strain rolling occurs. This amount of reduction usually yields the sheets to bond together. A schematic view of the ARB process is given in Figure 2.2.

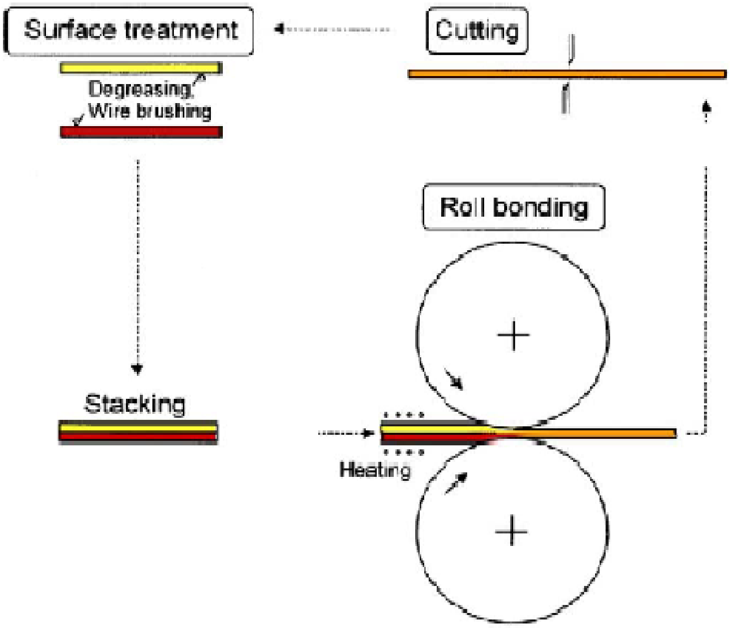


Figure 2.2 Schematic view of the Accumulative Roll Bonding process [3].

After the process the rolled sheet is cut in half and then stacked up to the initial thickness. Next it is rolled again to accumulate more strain. The sample dimensions do not change during the processing, allowing the accumulation of large plastic strains [3].

2.4.3 Con-Shearing Process

Con-Shearing process is a continuous pure shear deformation process. During the process, the sheet material is guided to an equal channel die by a large central roll, small satellite rolls, and guide shoe as shown in Figure 2.3. The material is subjected to pure shear deformation as it passes through the equal channel die [23].

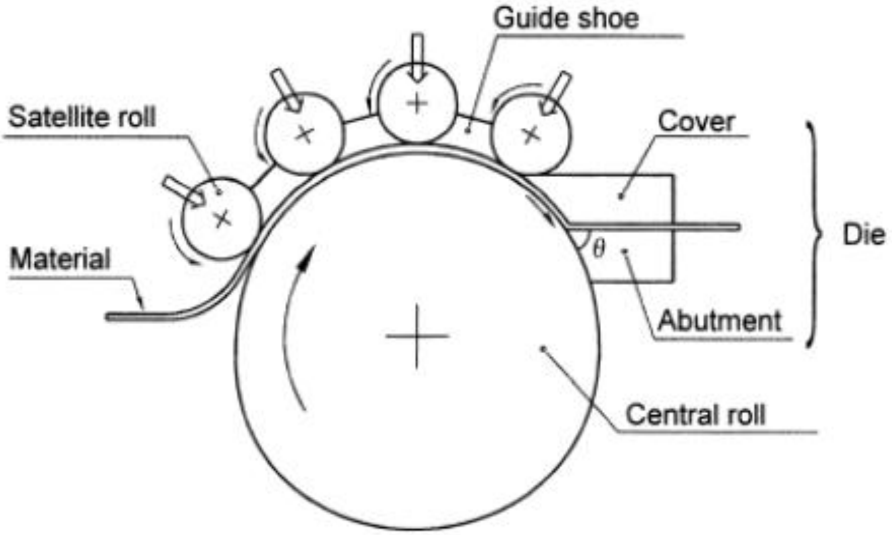


Figure 2.3 Schematic view of Con-Shearing process [23].

Since the die has equal channels, the thickness of the sheet remains same. This allows multiple passes to accumulate more stain in the material.

2.4.4 ECAP-Conform Process

Conform extrusion process was developed for the continuous extrusion of wire products almost thirty years ago. However, nowadays it has been combined with equal channel angular pressing in the ECAP-conform process. The ECAP-Conform setup is shown schematically in Figure 2.4.

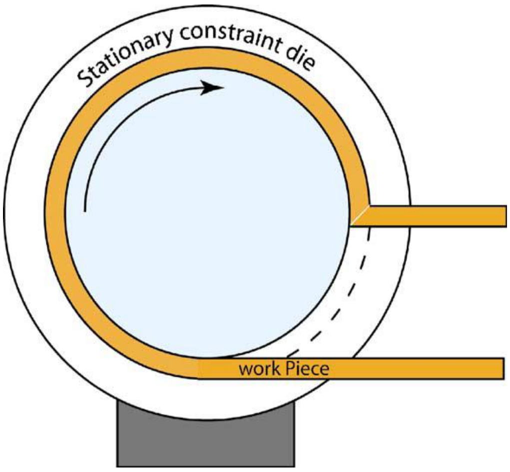


Figure 2.4 Schematic view of ECAP-Conform process [24].

As shown in the figure, in the center there is a rotating shaft containing a groove, into which the workpiece is fed. The workpiece moves forward by the frictional forces on the contact interfaces within the groove. During the process the workpiece rotates with the shaft.

The workpiece is constrained to the groove by a stationary constraint die. The stationary constraint die also stops the workpiece and forces it to turn an angle by shear just like a regular ECAP process. This set up effectively makes ECAP continuous [24].

2.4.5 ECAP Process

The principle of ECAP processing is schematically illustrated in Figure 2.5. During processing, a specimen is pressed through the die by the application of pressure via the ram of a hydraulic press. Specimen leaves the die without any change in the dimensions. The die is composed of two extrusion channels with identical cross sections. Channels intersect at a given angle.

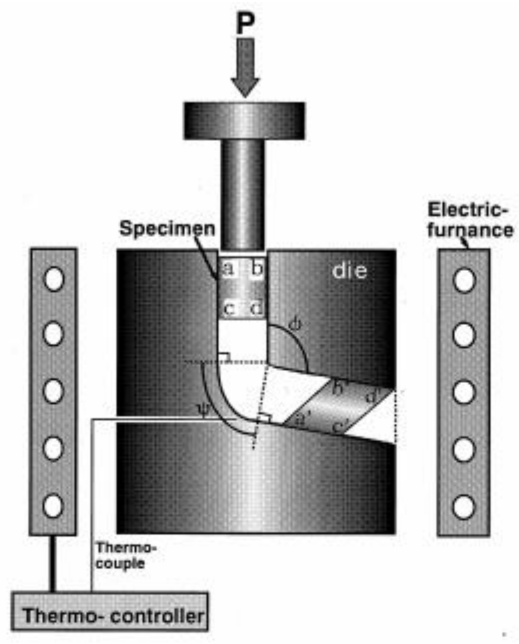


Figure 2.5 Principal illustration of the ECAP process [25].

Considerably high shear strains can be obtained by multiple passes through ECAP system. As a result, high levels of refinement of the microstructure down to the sub micrometer or even nanometer scale may be achieved [26].

2.5 Dissimilar Channel Angular Pressing (DCAP) Process

DCAP process is a unique shear-deformation technique and it is rather different from the conventional ECAP process. In DCAP process, the workpiece is fed into the die by the continuous revolution of a feeding roll, instead of pressure application by the ram of a hydraulic press. This kind of feeding not only makes continuous operation possible, but also allows the formation of various metallic strips into the desired final dimensions.

A schematic illustration of DCAP process is given in Figure 2.6 (a). In the first stage of the process, the strip is passed through the feeding and guide rolls. These rolls orient the strip into the forming die for shear deformation. The forming die is equipped with two channels having dissimilar thicknesses; the thickness of the outlet channel is slightly larger than that of the inlet channel. Such a die configuration enables the multipass operation to take place in a continuous manner [27].

Figure 2.6 (b) is an optical micrograph from the side surface of the strip processed by DCAP. As observed from the patterns, shear deformation is relatively uniform throughout the thickness direction except for those regions close to the bottom surface of the strip. Moreover, through the thickness direction textures determined from several surface layers, which are parallel to the surface of the strip, are very similar [15].

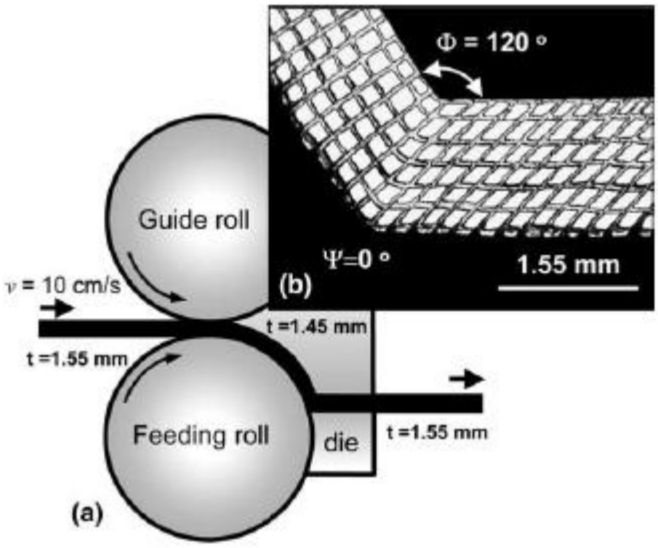


Figure 2.6 a) A schematic illustration of the DCAP machine used for continuous SPD production, **b)** Optical micrograph showing the shear deformation pattern recorded from the side surface of the specimen processed by DCAP [15].

2.5.1 Advantages of DCAP Process

The ECAP technique has some drawbacks due to its design as listed below;

i. In ECAP process, the length of the workpiece is limited by two factors:

   a. The aspect ratio (length: diameter) needs to be smaller than a critical value so that the workpiece will not bend during the pressing.
   b. The press ram has a constrained travel distance. This limitation makes ECAP a discontinuous process, with low production efficiency and high cost.

ii. A significant portion near both ends of the workpiece usually contains non-uniform microstructure or macro-cracks. These portions have to be discarded, which results in waste of material and increase in cost.

Consequently, production of UFG materials by ECAP process is expensive due to the discontinuous feature and material waste. Furthermore, its applications are limited to high valued markets, such as medical implants and devices, where the materials cost is not a major concern.

A DCAP process, on the other hand, was recently reported as an effective method for continuous processing of thin strips and sheets to produce UFG structures with low cost and high production efficiency [28]. Moreover, there is no shape change in the material during DCAP process. Owing to this advantage a material can pass through the system several times. As a result high levels of strain can be introduced to the material, which is another advantageous property of DCAP process when compared to traditional deformation techniques such as rolling or extrusion.

2.5.2 Parameters Affecting DCAP Process

The parameters that are affecting the resultant microstructure after DCAP process are channel angle, pressing speed and strain rate sensitivity. Detailed information about these parameters is provided in the following sections.

2.5.2.1 Channel Angle (Φ)

Importance of channel angle can be explained by describing the work of Lee et al. [28]. Lee et al. investigated the process conditions at which the UFG is obtained. In their study, aluminum strips were processed at the speed of approximately 5 m/min through the DCAP dies having channel angles of 120, 130, and 140°. Variations in the hardness of the specimens processed through the DCAP system with different channel angles is shown in Figure 2.7. As observed from the graph, in Region B curves has a negative slope. This implies that specimens DCAPed through the dies having different channel angles consist of ultrafine grains separated by boundaries with high angles of misorientation. Moreover, the generation of the UFG is directly related with the accumulative strain level and the strain per passage. The ultrafine grains can be attained only when both the accumulative strain and the strain per each passage imparted to the specimen go beyond certain values. The accumulative strain required to produce the UFG varies depending on the strain per each passage of DCAP, i.e. the channel angle.s

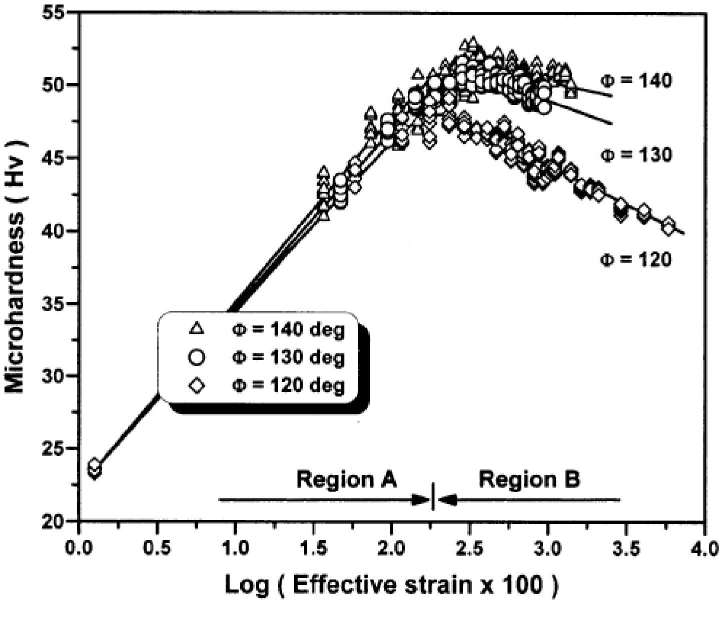


Figure 2.7 Variations in the hardness of the specimens processed with the DCAP dies having the channel angles of 120, 130, and 140°, showing how the trends in region B vary with various channel angles [28].

As the channel angle becomes larger, in other words as the strain imparted to the specimen per passage reduces, a higher level of the accumulative strain has to be imposed to the specimen to generate the UFG structure. By contrast, when the channel angle becomes smaller, the UFG structure can be produced even under the reduced total strain. It is also worthy to note that as the channel angle becomes smaller, the softening rates increases while the maximum hardness attainable by DCAP process decreases [28].

2.5.2.2 Pressing Speed

When pressing speed is low, recovery occurs more easily. As a result, more homogeneous microstructures are produced.

It is also obvious that the strength of the material only increases with increasing deformation by higher number of passes through the DCAP system, rather than increasing pressing speed. Moreover, in order to increase pressing speed, a high quality of the DCAP die is required and abrupt heating of the sample during pressing must be considered [29].

2.5.2.3 Strain Rate Sensitivity

Strain rate sensitivity plays an important role in clarifying the enhanced ductility of aluminum alloys. Elevated strain rate sensitivity prevents necking and therefore increases the ductility. As reported by Wei et al. [30] FCC metals UFG structure exhibit an elevated strain rate sensitivity with respect to their conventional grain size counterparts.

2.5.3 Previous Studies on SPD and DCAP Process

In the study of Zhu et al. [31] production of UFG materials by different processing methods was investigated. It was mentioned that UFG materials produced by SPD techniques are contamination-free and porosity-free so that they usually have high strength and good ductility.

A study examining the effect of SPD on the mechanical properties was performed by Horita et al. [32]. They stated that according to the conventional deformation processes such as rolling, drawing and extrusion, SPD techniques cause decrease in the ductility of the material to a smaller extent.

The mechanism of grain refinement in aluminum alloys during SPD was studied by Kaibyshev et al. [33] In the study, analysis was performed on AA2219 aluminum alloy, containing Al_3Zr nanoscale particles and Al-3% Cu alloy. It was shown that the mechanism of grain refinement in AA219 alloys is continuous dynamic recrystallization (CDRX) comprising two main elementary processes. The first one is the formation of three dimensional arrays of low-angle boundaries (LABs), whereas the second one is straining occurrence of high-angle boundaries (HABs). The grain refinement mechanism at Al-Cu alloys was geometric recrystallization (GRX) which occurs with formation of deformation bands outlined by HABs.

Han et al. [34] studied the effects of the deformation history and initial textures on the texture evolution in aluminum alloys. In their work, it was stated that DCAP process can be used to control the textures. This is because <111>//ND textures, such as {111}<110> and {111}<112> are effective for improving the deep drawability and the reducing planar anisotropy of the metallic sheets having a FCC structure [35]. In order to understand the combined effect of the initial texture and deformation history, specimens having various initial textures were prepared prior to DCAP by using different thermomechanical routes as shown in Figure 2.8.

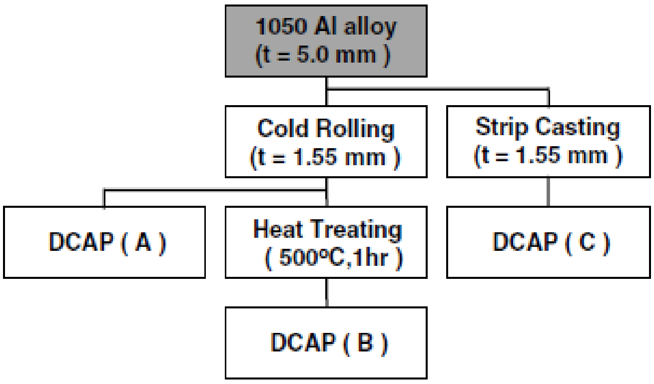


Figure 2.8 Various thermomechanical routes to prepare the 1050 Al alloy sheets having different textures [34].

Texture evolutions and major texture types of the specimens before and after DCAP process are summarized in Table 2.1.

Table 2.1 Summary showing how the textures are evolved due to DCAP process under the given texture components [34].

Specimens	Before DCAP		After DCAP	
	Major	Minor	Major	Minor
Cold rolled	{112}{111}	{110}{112}	{001}{110}	{111}{112}
Heat treated	{001}{100}	{112}{111}	{001}{110} {110}{110}	{111}{112}
Strip-cast	{112}{111} {110}{112} {110}{001}	{001}{100}	{001}{110} {111}{112}	

Regardless of the initial texture in the aluminum alloy, the <111>//ND textures and the {001}<110> rotated cube texture were developed as a result of DCAP Process. Initial and stable orientations are listed in Table 2.2. However, the intensities of these textures after DCAP were strongly affected by the initial texture prior to DCAP.

Table 2.2 Summary showing the initial orientations and the stable orientations before and after the simple shear deformation, respectively [34].

Initial Orientation	**Stable Orientation**
{112}<111>	<111> // ND
<111> // ND	<111> // ND
{110}<100>	<111> // ND
{123}<634>	{001}<110>
{001}<110>	{001}<110>
{110}<112>	{112}<110>
{015}<051>	{110}<110>
{043}<034>	{001}<110>
{001}<100>	{012}<021>

In the study, it was concluded that the texture produced after DCAP process is effective for improving the deep drawability and reducing the planar anisotropy of the metallic sheets having a FCC structure.

The strengthening behavior of the 1050 Al-alloy processed by DCAP was studied by Lee et al. [28]. The results were then compared with the cold rolled specimens. In their study, at first a specimen was deformed by DCAP. Next an identical specimen was cold rolled unidirectionally up to 94% of reduction in thickness. Annealing was not applied to the cold rolled specimen. Hardness and microstructures of differently processed specimens were then compared. The variation in the hardness of the DCAPed specimen is given in Figure 2.9. Figure 2.10 reveals the variations in the hardness of the cold rolled specimen.

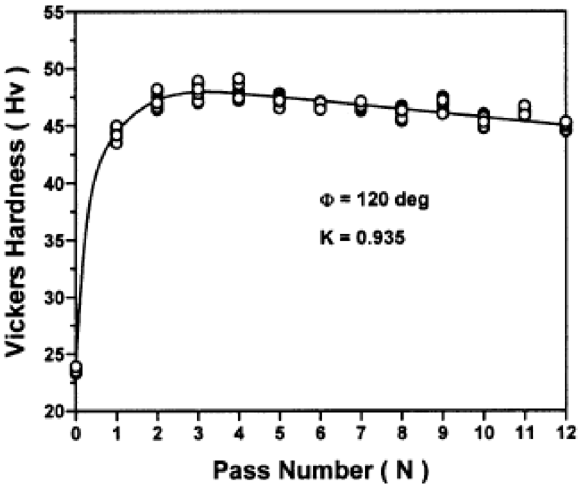


Figure 2.9 Variation in the hardness of the DCAPed 1050-Al alloy sheet as a function of the pass number [28].

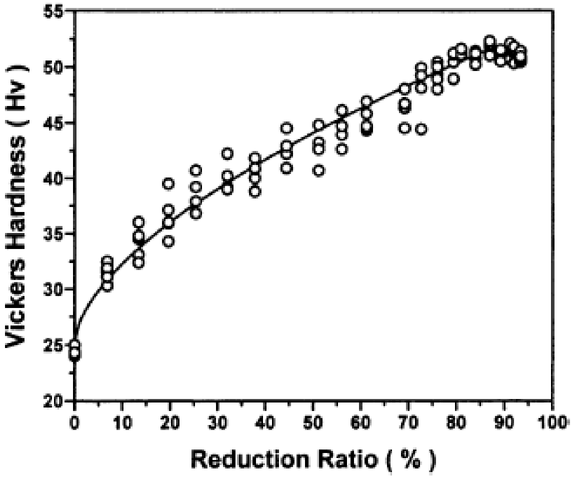


Figure 2.10 Variation in the hardness of the cold rolled 1050 Al-alloy sheet as a function of reduction ratio [28].

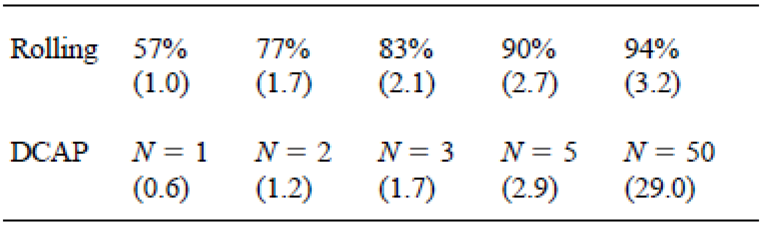
As seen from the figures, graphs have different axes. So, to make the comparison between two processing methods, effective strain (ε) was calculated from Equations 2.2 and 2.3 by using the data in the graphs;

$$\varepsilon = \frac{2N}{\sqrt{3}} \cdot K^2 \cot\left(\frac{\Phi}{2}\right) \quad \ldots \text{ for DCAP} \qquad (2.2)$$

$$\varepsilon = \frac{2}{\sqrt{3}} \cdot \left| \ln(1 - R) \right| \quad \text{... for cold rolling} \tag{2.3}$$

Effective strain data with respect to reduction ratio for cold rolled specimens and with respect to pass number for DCAPed specimens is provided in Table 2.3.

Table 2.3 Reduction ratio of rolling and pass number of DCAP to obtain the required amount of the strain indicated within the parenthesis [28].



Rolling	57% (1.0)	77% (1.7)	83% (2.1)	90% (2.7)	94% (3.2)
DCAP	$N = 1$ (0.6)	$N = 2$ (1.2)	$N = 3$ (1.7)	$N = 5$ (2.9)	$N = 50$ (29.0)

As observed clearly from the table, the strain imposed to the specimen after 5 DCAP pass can only be obtained by cold rolling when reduction in thickness is about 90 %. Thus, it was concluded that cold rolling is not an efficient technique as a strengthening mechanism when compared to DCAP.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 General

In the present study, a DCAP system was constructed for the shear deformation of aluminum alloy sheets. The design and production details for the DCAP system were provided in this chapter. After DCAP process, samples were characterized by metallography, X-ray diffraction, tension and hardness tests.

Steps of experimental procedure are given in Figure 3.1.

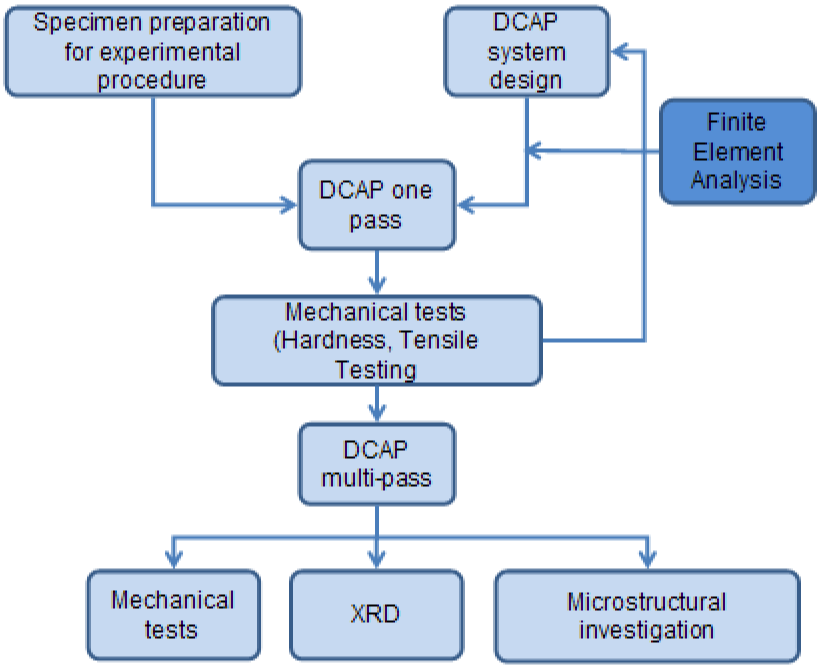


Figure 3.1 Steps of experimental procedure.

3.2 Preparation of Aluminum Specimens

For the present work, 6061-T6 series aluminum alloy sheet metals were supplied from Turkish Aerospace Industry, TAI. Chemical composition of the alloy is given in Table 3.1.

Table 3.1 Composition of 6061 series aluminum alloy.

Component	**Amount (wt. %)**
Aluminum	95.8-98.6 (Balance)
Magnesium	0.8-1.2
Silicon	0.4 – 0.8
Iron	≤ 0.7
Copper	0.15-0.40
Zinc	≤ 0.25
Titanium	≤ 0.15
Manganese	≤ 0.15
Chromium	0.04-0.35
Others each	0.05
Others total	≤ 015

As received aluminum sheets were in the size of 1000 x 600 x 2 mm. So, prior to process, 300 x 110 x 2 mm plates were cut by using guillotine. Next, two different heat treatment was applied to the aluminum plates: *annealing* and *solutionizing*. Details of the treatments were provided below:

- In solutionizing, as received aluminum plates were heated up to 530 ºC in a furnace. Specimens were then quenched in water. Unfortunately buckling of these plates occurred after quenching. This problem hindered the passage of plates through DCAP system. When solutionizing was applied to aluminum alloy strips with the dimensions of 170 x 27.5 x 2 mm, buckling was not observed. Consequently solutionized samples were only deformed in the form of strips.

- In annealing, as received aluminum plates and strips were heated up to 450 ºC in a furnace and kept at this temperature for 16 hours. Next, specimens were cooled to room temperature in the furnace. The purpose of annealing process was to obtain 6061-T0 aluminum alloy series from as received 6061-T6. Throughout this thesis annealed aluminum plates was also referred to as 6061-T0 plates.

After the treatment processes, specimens were deformed by utilizing the DCAP system.

3.3 Construction of DCAP System

3.3.1 Design of DCAP System

First stage in the experimental procedure of the present thesis was the construction of a DCAP system having a proper design for the deformation of flat products. During the design of a severe plastic deformation system for the continuous deformation of aluminum plates, it was necessary to apply alterations to the principles of ECAP system.

Flat products like plates cannot pass through a die with the application of compressive forces since they have tendency to bend as their length: thickness ratio increases. In a similar manner if tensile forces are used, neck formation, excessive reduction in thickness of the plate and even tearing is observed. These problems can only be solved if deformation takes place with the application of shear forces. The basic method to apply shear forces to a material is the employment of friction forces. In the present work, this principle was used in the design of the DCAP system.

First design is the one in which plate was fed into the die with the usage of friction forces by 270° revolution of the roll, as given in Figure 3.2 [24].

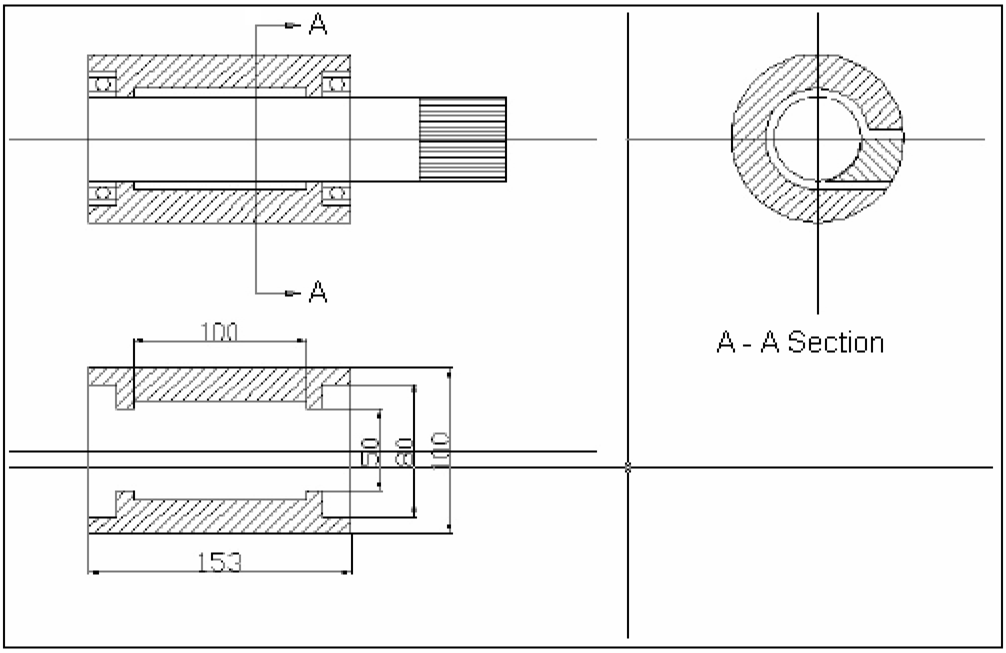


Figure 3.2 ECAP based first design for continuous production [24].

In order to observe the processing of plates with various thicknesses through this system, modeling studies was performed by Finite Element Analysis. Analysis revealed that this process is applicable only for very thin plates (1 mm or less) and only when excessive friction coefficient is applied.

Due to difficulties in applying this design for practical applications, an alternative design, as given in Figure 3.3, was considered. However, modeling studies revealed the fact that the new design was not suitable for continuous deformation of flat products.

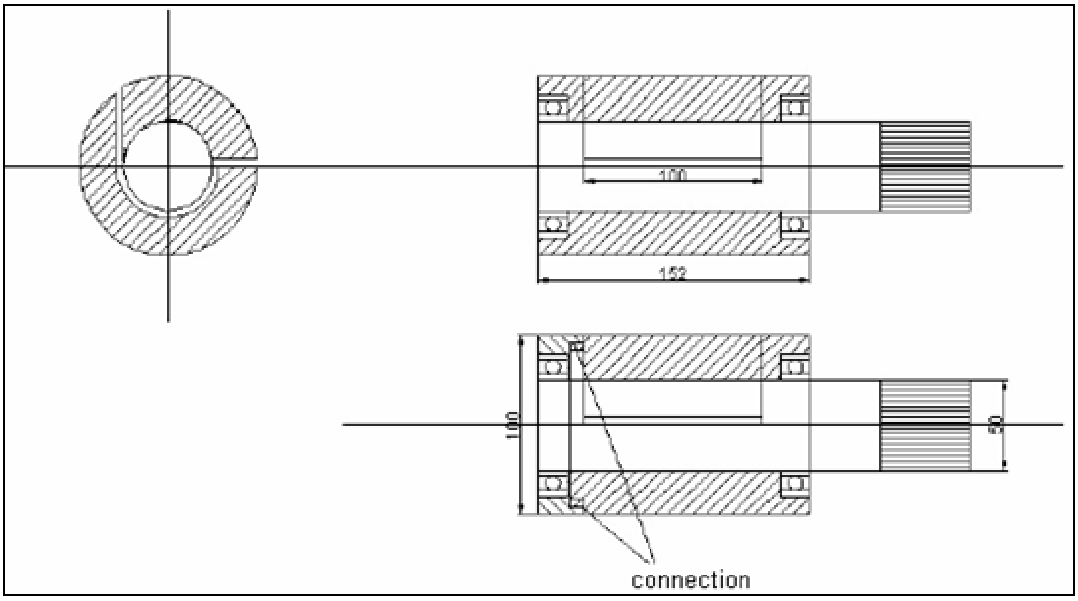


Figure 3.3 ECAP based second design for continuous production.

Evaluation of the problems occurred during design stage revealed that the main problem is using friction forces ineffectively. After various studies on the design of the systems for continuous deformation of aluminum sheets, a design similar to the one described in the work of Lee et al. [15] was selected for the present DCAP system. The drawing of the final system is shown in Figure 3.4.

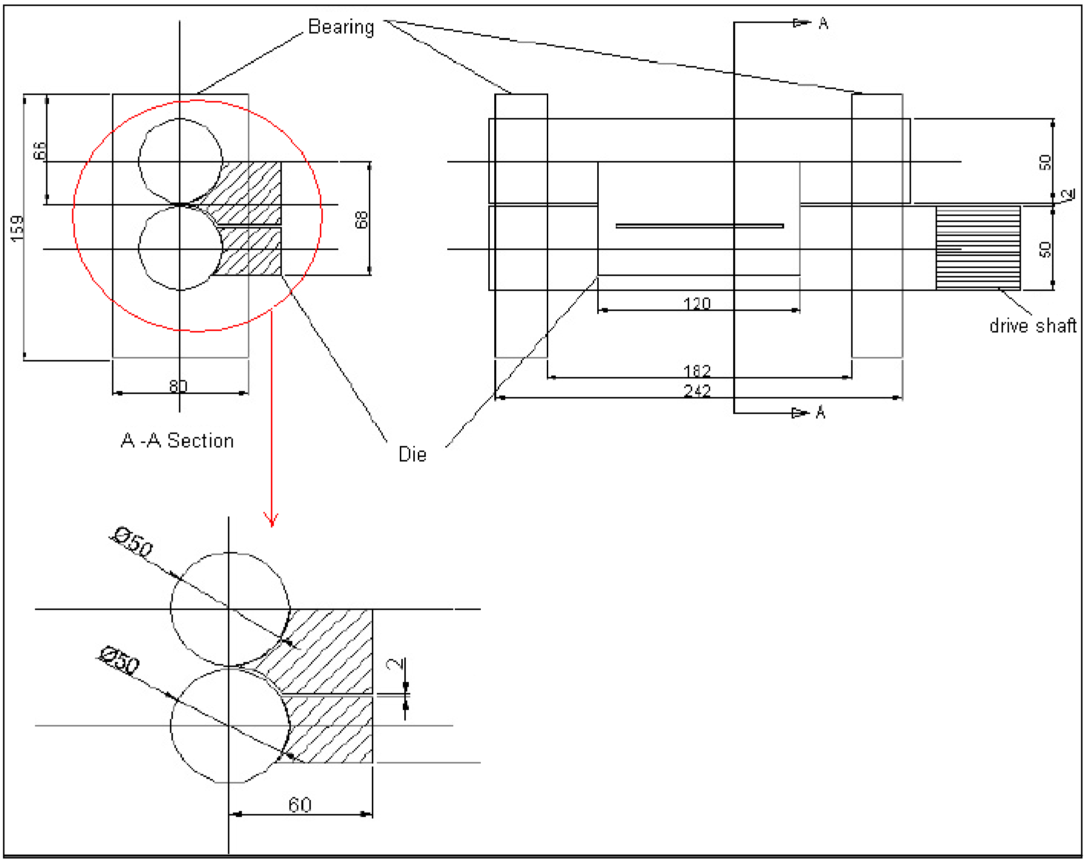


Figure 3.4 DCAP system design for continuous deformation process.

3.3.2 Modeling Studies

Homogeneous deformation is an important parameter in severe plastic deformation processes since homogenity of strain distribution gives uniform grain size and shape to the material together with uniform mechanical properties. Absence of strain distribution homogenity gives rise to process design problems. Nonhomogeneous deformation causes buckling and high residual stresses in materials.

Buckling and residual stresses are not acceptable for post-manufacturing processes. Thus, homogeneous horizontal and verticle plastic strain distributions should be obtained through the material. To provide these properties to the material, die and process design are accepted as important factors.

Beside material properties, die geometry and friction coefficient affect deformation homogeneity during DCAP process. Hence, various die geometries and friction coefficients together with simulation studies were used for optimization of die geometry and friction coefficient.

In the present study, simulation of DCAP process was performed by Msc.Marc Finite Element Modeling Program. For the simulation,

- Plane strain condition was assumed.
- The process was assumed to be isothermal.
- Strain rate effects were neglected.
- The die and the rolls are assumed to be rigid.
- Shear type of friction with Arc-tangent method was assumed.

DCAP of a sheet metal having dimensions 150 x 2 mm was simulated. Since the plain strain condition was used, a plain passing through the center of the rolls and the sheet was simulated. The sheet was meshed into 7740 finite elements with average edge length of 0.2 mm. An automatic time stepping procedure based on plastic strain increment was used. Global remeshing was employed when element distortion, strains and rotations reached a critical value. No damage criterion was considered.

Material data was directly taken from Msc.Marc's database. Following was assumed;

- Material shows elasto-plastic deformation behavior.
- Elasto-plastic behavior is determined by Von Mises yield interface.
- Plastic yield vector is determined by relative yield rule.
- Associated flow rule (Prandtl-Reuss).
- Material hardening occurs according to piecewise-linear hardening rule.

As process candidates 4 different process designs were considered and simulated which were:

- C-ECAP with one roll and 270^o rotation of the plate
- C-ECAP with one roll and 180^o rotation of the plate
- C-ECAP with two rolls and 60^o rotation of the plate
- C-DCAP with two rolls and 60^o rotation of the plate

The results of the simulations are presented in the following chapter.

3.3.3 Production of DCAP System

DCAP system for the continuous deformation of 6061 aluminum sheets was constructed by Yeter Makine Kalıp ve Döküm San. Tic. Ltd. Şti./OSTİM, according to the design drawings provided by the author.

DCAP system was composed of an engine, guide and feeding rolls, lower and upper dies. The material of guide and feeding rolls together with upper and lower dies was selected as tool steel AISI H13. Carburizing treatment was applied to rolls and dies until their hardness reached to 65 HRC. The diameter and length of rolls was 50 mm and 120 mm, respectively. Polyamide was used in the part for specimen passage toward rolls. The engine was connected to the gears that are attached to the guide and feeding rolls. The revolution velocity of the rolls was 20 cm/min. Lower die was fixed to the main body whereas upper die was movable to arrange the distance between rolls and die. Surface of the dies were smooth whereas the surface of rolls was channeled in order to facilitate feeding process. The photograph of the constructed DCAP system is shown in Figure 3.5. A closer image to the channeled guide roll of the system is provided in Figure 3.6.

Figure 3.5 DCAP system.

Figure 3.6 The image of channeled roll.

Aluminum sheets were deformed by two passages through this system. The image of aluminum sheets after one and two passes through DCAP process is given in Figure 3.7. As seen from the image, patterns on the surface of specimens occurred due to the existence of channels on the rolls. Moreover, surface cracks were also observed on the induced patterns. Existence of cracks hindered tensile testing. In addition, the distance between “guide roll - lower die” and “lower die – upper die” were not fixed precisely which ended up unreliable hardness measurements. In this

DCAP system, deformation of the aluminum sheets was possible only up to two passes due to feeding problems.

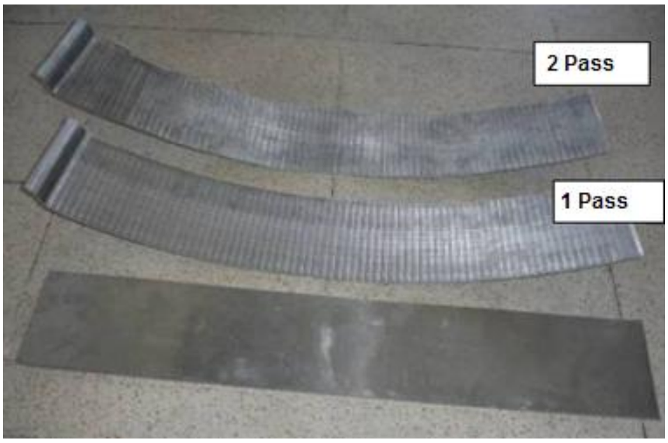


Figure 3.7 The image of the aluminum sheets after one and two passes.

In order to overcome these problems, alternative guide and feeding rolls were constructed and assembled to the DCAP system. The new rolls had a patterned surface, as shown in Figure 3.8.

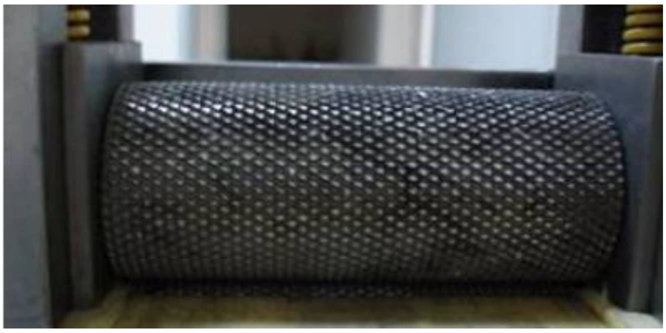


Figure 3.8 The image of patterned roll.

In order to arrange the distance between lower and upper dies, a metal frame, given in Figure 3.9, was used.

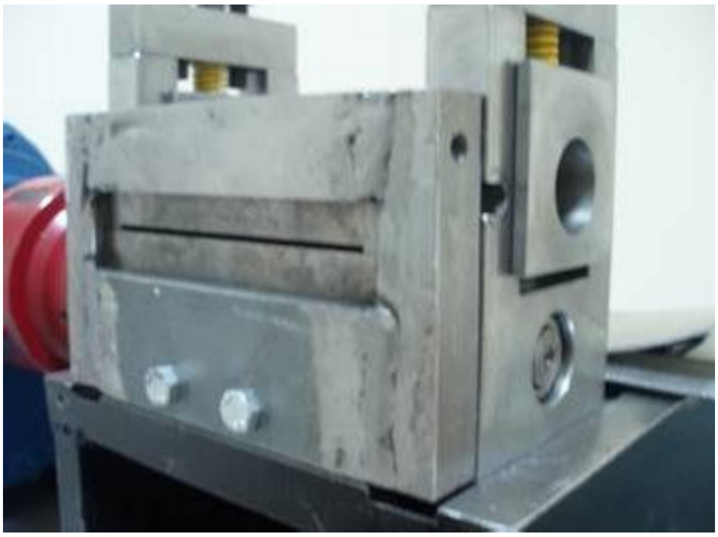


Figure 3.9 Metal frame used to fix upper and lower dies.

The new roll system helped to overcome the feeding problems during the DCAP process. Solutionized aluminum strips and 6061-T0 plates were easily passed through the system. However rolls caused surface patterns (spots). The spots made the tensile test performed on the specimen after deformation unreliable, as will be mentioned in the next chapter. Patterned rolls increased the number of passage during the DCAP process, unfortunately after deformation specimens were not suitable for mechanical testing.

The trials on the DCAP system with different rolls revealed that the surface of rolls should be patterned for feeding the specimen into the system and should be smooth as well in order not to leave traces on specimen surface. Moreover the problem in fixing the distance between rolls and dies shall be solved. The eventual DCAP system constructed according to these criteria is shown in Figure 3.10. In this system for precise adjustment of the space between upper and lower rolls, pressure gauge was used. Mechanical testing after deformation was performed on the samples obtained from the smooth part of the specimen. The patterned parts were discarded.

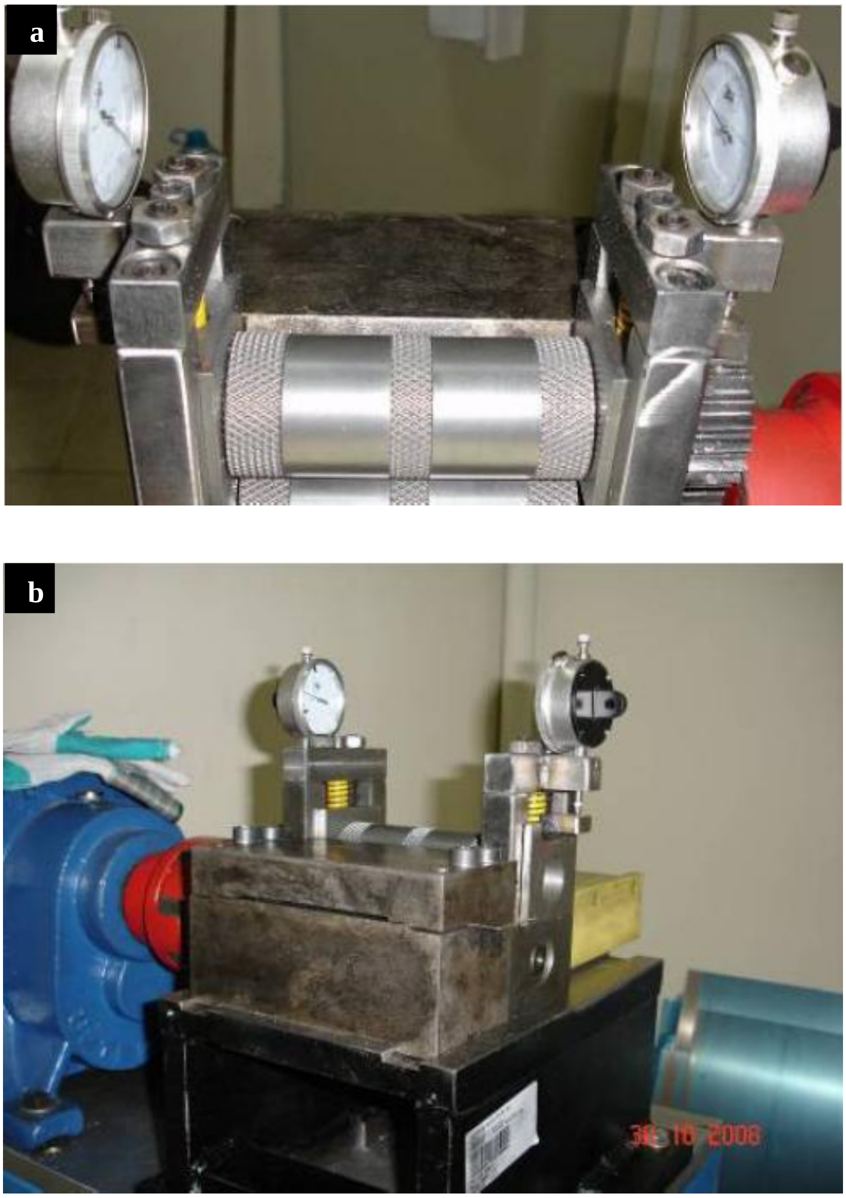


Figure 3.10 a) The image of partially patterned rolls, **b)** The eventual DCAP system used in the present study.

For the comparison of the roll surface, the images of aluminum sheets after DCAP process by utilizing channeled, patterned and partially patterned rolls are provided in Figure 3.11 a, b and c, respectively.

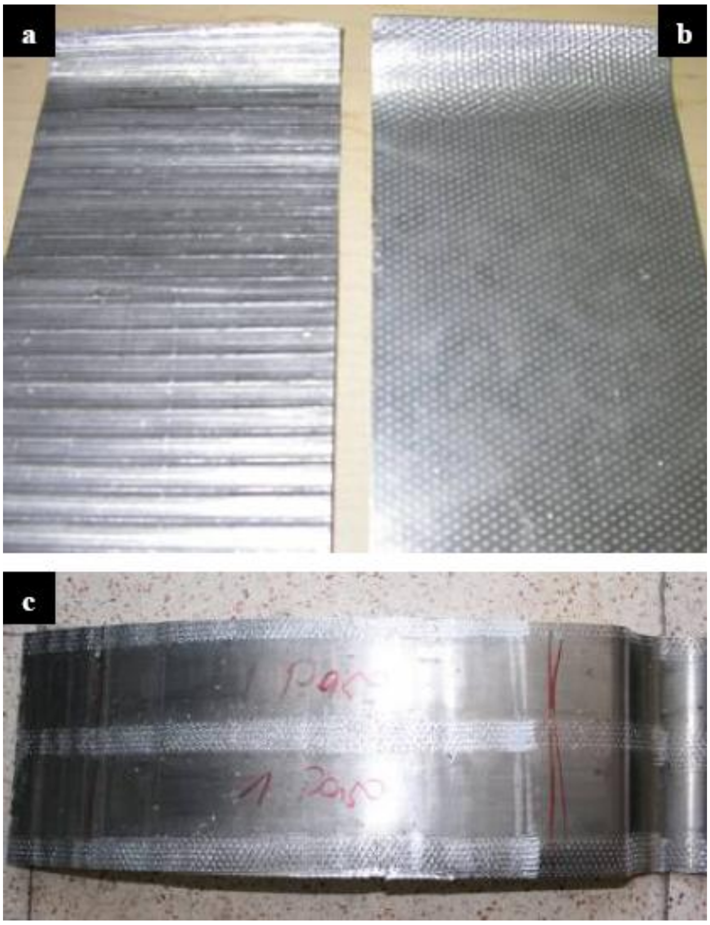


Figure 3.11 Specimens deformed through DCAP system having **a)** channeled roll, **b)** patterned roll, and **c)** partially patterned roll.

3.4 DCAP Process

The eventual DCAP system with partially patterned rolls was suitable only for the deformation of plates. As a result, solutionized aluminum specimens, which were in the form of thin strips, were not deformed through this system. Only 6061-T0 plates were passed through the DCAP system.

For each experiment two specimens were deformed through DCAP process. The number of passage was limited to two for all specimens owing to the fracturing of samples with increased hardness and feeding problems occurred in the system.

3.5 Characterization of Specimens

3.5.1 Microstructural Examinations

Microstructural features of the aluminum samples after DCAP process were analyzed by examining the polished and etched surfaces under optical microscope and Scanning Electron Microscope (SEM). For this purpose a JEOL JSM 6400 SEM equipped with a Semafor Digitizer was employed. In order to observe change in size and shape of grains after DCAP process, cross sectional area which is parallel to the direction of deformation was inspected.

The procedure for the preparation of samples prior to examination is as follows: a small sample was cut from the deformed DCAPed plate first. Next the sample was embedded in bakelite for easier handling. Embedded sample was then polished by using 1 μ and 0.3 μ alumina powder one after the other. After polishing, the sample was etched in an acidic solution having the composition given in Table 3.2 for 20 seconds.

Table 3.2 Composition of the etchant used for aluminum samples.

Chemical	Volume
Methanol	25 ml
Hydrochloric Acid	25 ml
Nitric Acid	25 ml
Hydrofluoric Acid	1 drop

An image of samples employed in microstructural examination is provided in Figure 3.12.

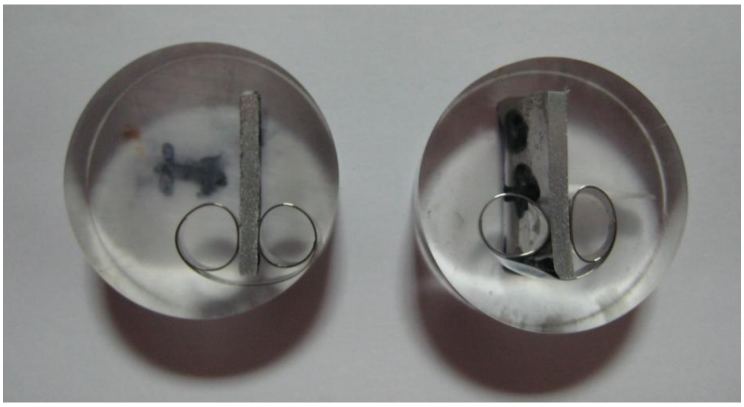


Figure 3.12 Samples used in microstructural examination.

3.5.2 Tensile Tests

In order to evaluate effect of deformation on the mechanical properties such as yield strength, ultimate tensile strength and ductility, tensile tests were performed on the aluminum samples after DCAP process. For tensile test measurements, specimens were prepared in accordance with the standard of ASTM B557M-02a "Standard Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products [Metric]". Gauge length and width of the specimens were 45 mm and 12.5 mm, respectively.

Specimens were tested by using Schimadzu digital tensile equipment system having 10 kN load capacity, at a rate of 0.5 mm/min. Stress-strain data was attained after tensile testing of the specimens. Yield stress (σ_Y) of the aluminum specimens were determined by using 0.2% offset method.

3.5.3 Hardness Measurements

EMCO Universal Digital apparatus was used for the evaluation of Vickers hardness of the samples. Applied load was selected as 30 kg in measurements.

In each experiment, hardness was measured from four different points on the sample surface. The average of these four values was taken as representative data.

3.5.4 X-Ray Diffraction (XRD)

In order to determine the sub-grain size, XRD line-broadening of the DCAPed samples were investigated. X-Ray diffractogrammes were obtained by employing a Rigaku D/Max 2200/PC model X-Ray Diffractometer with Cu-K_α radiation. The generator settings were selected as 40 kV and 35 mA. The diffraction data were collected over a 2θ range of 37.5° to 40° from (111) plane, with a step width of 0.02° and a counting time of 5 s per step (FT method). The width of the peak measured at half of the maximum intensity is related to the cell or sub-grain size according to Equation 3.1.

$$t = \frac{0.9\lambda}{B_S \cdot \cos\theta_B} \tag{3.1}$$

where B_S: structural broadening

λ: wavelength of the radiation used (λ=1.54183 Å)

θ_B: Bragg's angle of the peak

B_S is determined from Equation 3.2.

$$B_S^2 = B_D^2 - B_R^2 \tag{3.2}$$

where B_D: width measured from peak of DCAPed specimen. It includes structural and instrumental broadening

B_R: measured from the peak of reference or standard specimen. It includes only the instrumental broadening.

B_R^2 is subtracted to eliminate the instrumental broadening.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

After deformation of 6061 aluminum alloy sheets through the DCAP system, mechanical tests were performed. Results of tensile testing and hardness measurements together with microstructural evaluations are presented in this chapter. Modeling studies during system design are also included in the following sections.

4.2 Modeling Studies

As mentioned in the previous chapter, first design for continuous deformation of sheet metals was based on an ECAP system. Scenes from Finite Element Modeling (FEM) of this design are provided in Figure 4.1.

As observed from the images, the plate is fed into the groove in Scene 1 and high amount of strain is applied to it when it enters the outlet channel in Scene 2. Although the design seemed to be adequate for high strain application, it had two drawbacks:

- This process was applicable only for very thin plates having thickness of 1 mm or less.
- The process necessitates excessive friction coefficients to run.

Consequently, this design was evaluated as not suitable for practical applications.

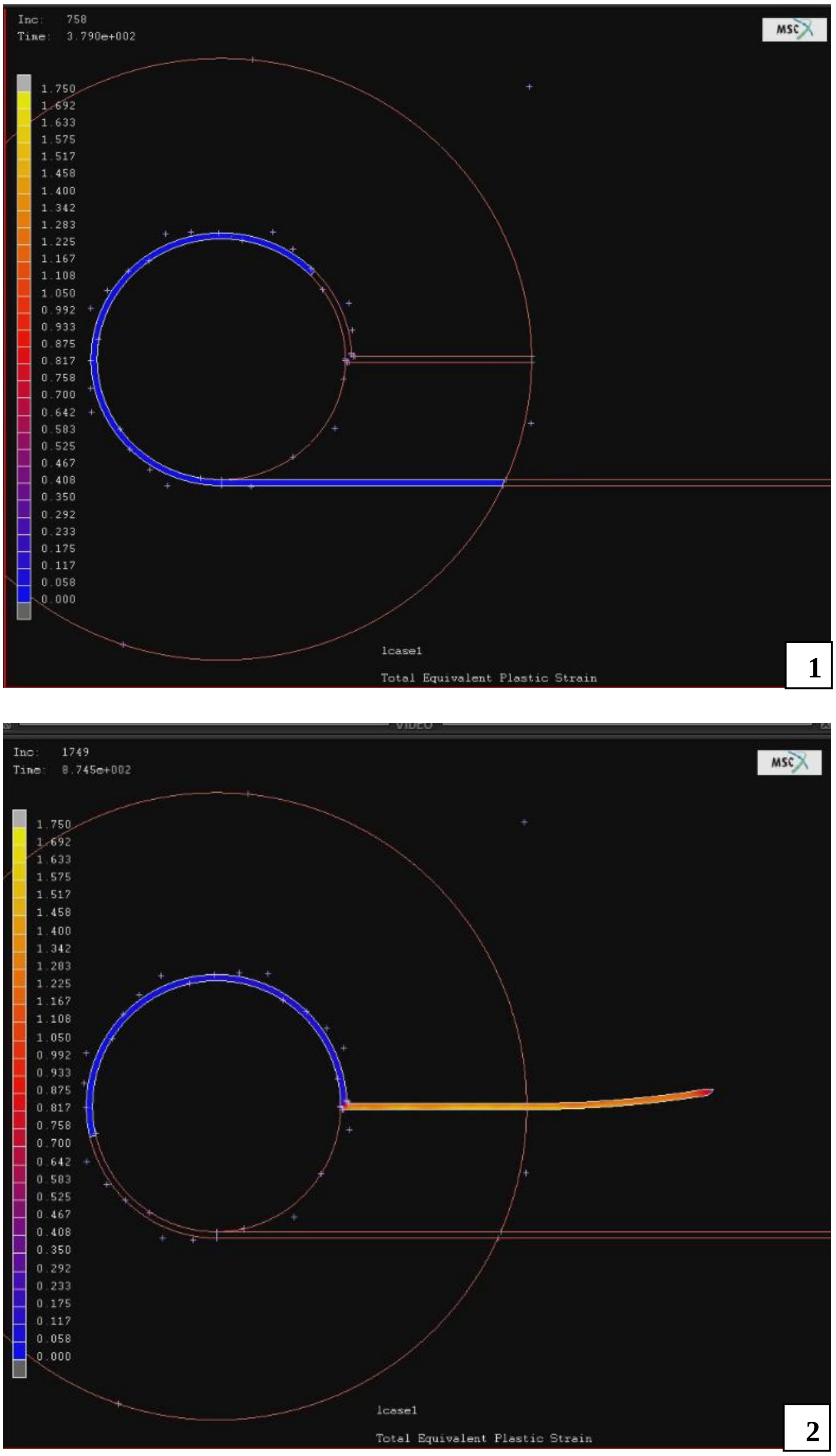


Figure 4.1 FEM Scenes of ECAP based first design for continuous deformation.

Scenes from FEM studies for the second ECAP based design are given in Figure 4.2. Although this design seemed to be adequate for high strain applications, usage of friction forces was less efficient when compared to previous design. Hence second design was also accepted as unsuitable for continuous production.

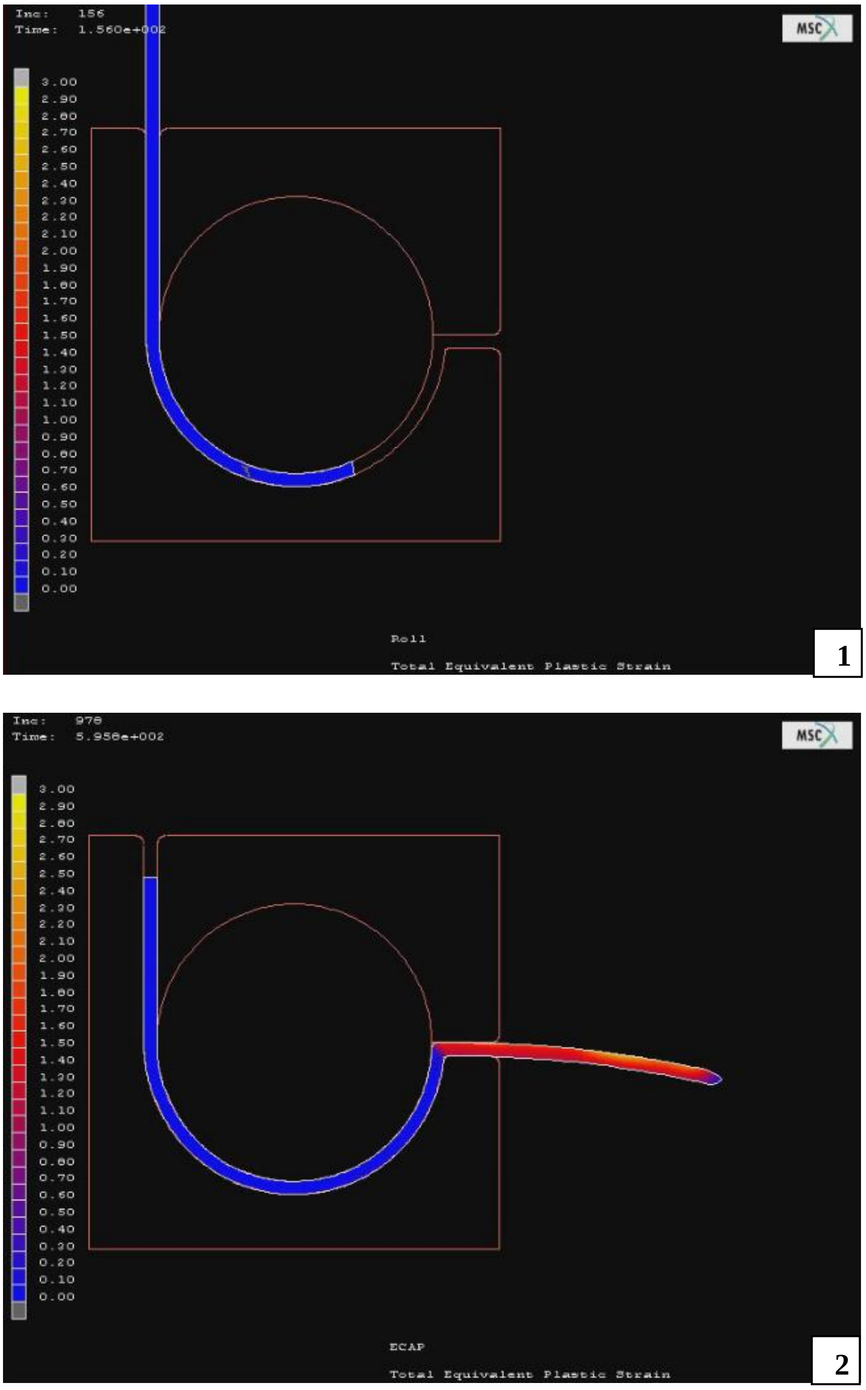


Figure 4.2 FEM Scenes of ECAP based second design for continuous deformation.

After further evaluations on FEM results for the first system design, it was decided that the basic problems are ineffective usage of the friction forces, limitations at the plate thickness and feeding some part of the sheet material into the die by hand until the clutching of the sheet by feeding roll. To overcome these problems, an alternative system for continuous severe plastic deformation of sheet metals was designed based on the work of Lee et al. [15]. The FEM Scenes from the analysis performed for the design are seen from Figure 4.3.

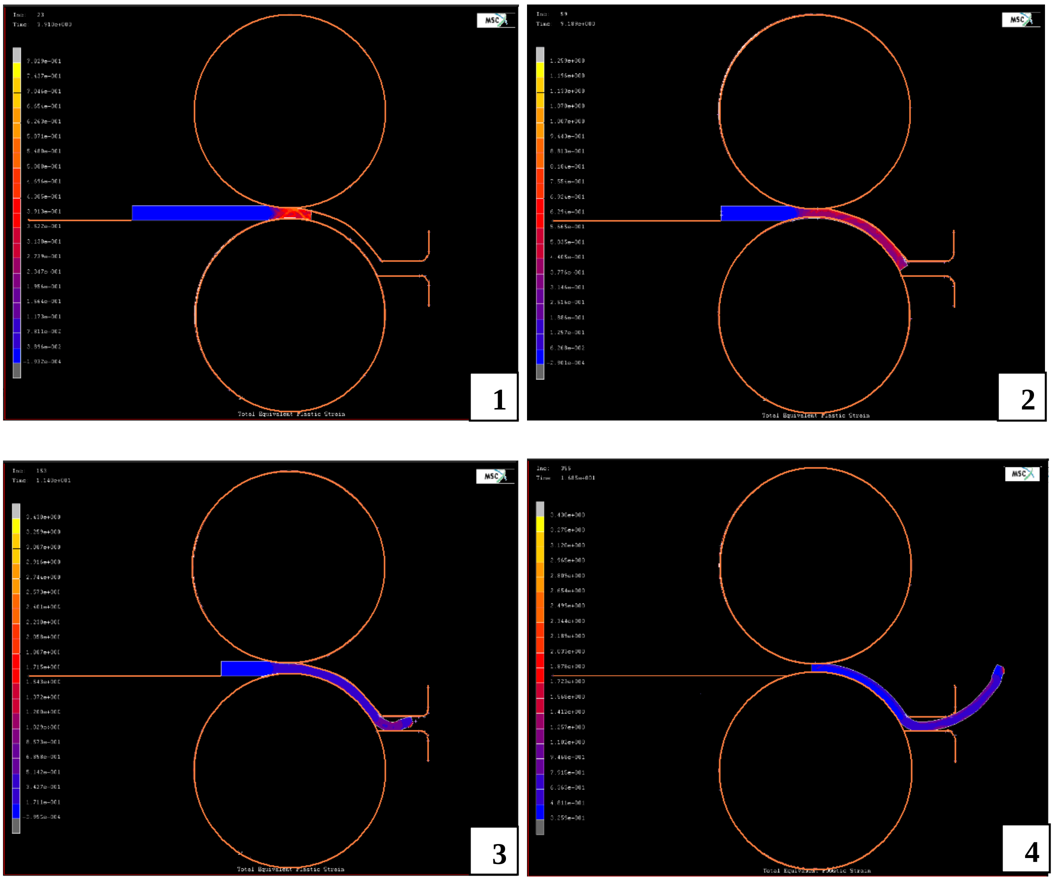


Figure 4.3 The FEM Scenes of initial DCAP system design.

In the design outlet channel thickness of the die had the same value with the thickness of sheet metal in order not to have shape change after DCAP process. According to FEM analysis, 20 % reduction in thickness was applied to sheet metal by normal forces via feeding rolls, initially. Since the friction forces of the system were proportional to the normal forces, high friction forces were obtained at low friction coefficients due to elastic response of the material. Thus, ineffective usage of the friction forces and clutching problems occurred in the previous design were solved in this design. Other critical limitations realized during analysis are as follows:

- Due to high amount of deformation at the entry side of the system by the feeding rolls, outlet channel of the die can not be filled by sheet metal. As a result, metal bended within the outlet channel as seen from Scene 3.
- In Scene 4, it was observed that neither shear deformation nor high levels of strains was introduced to sheet material which is against the principle of severe plastic deformation.

These results revealed that the amount of applied deformation by the feeding rolls is an important parameter for the DCAP system design.

Further evaluations and analysis were performed to identify the deformation limit that could be applied by the feeding roll. It was found that the amount of reduction in thickness should not exceed the limit of 8 %. By the reduction levels below 8 %, outlet channel was filled with sheet material. In Figure 4.4, FEM study of the eventual DCAP system is given showing adequate amount of applied shear deformation and imposed high levels of strain on the sheet material.

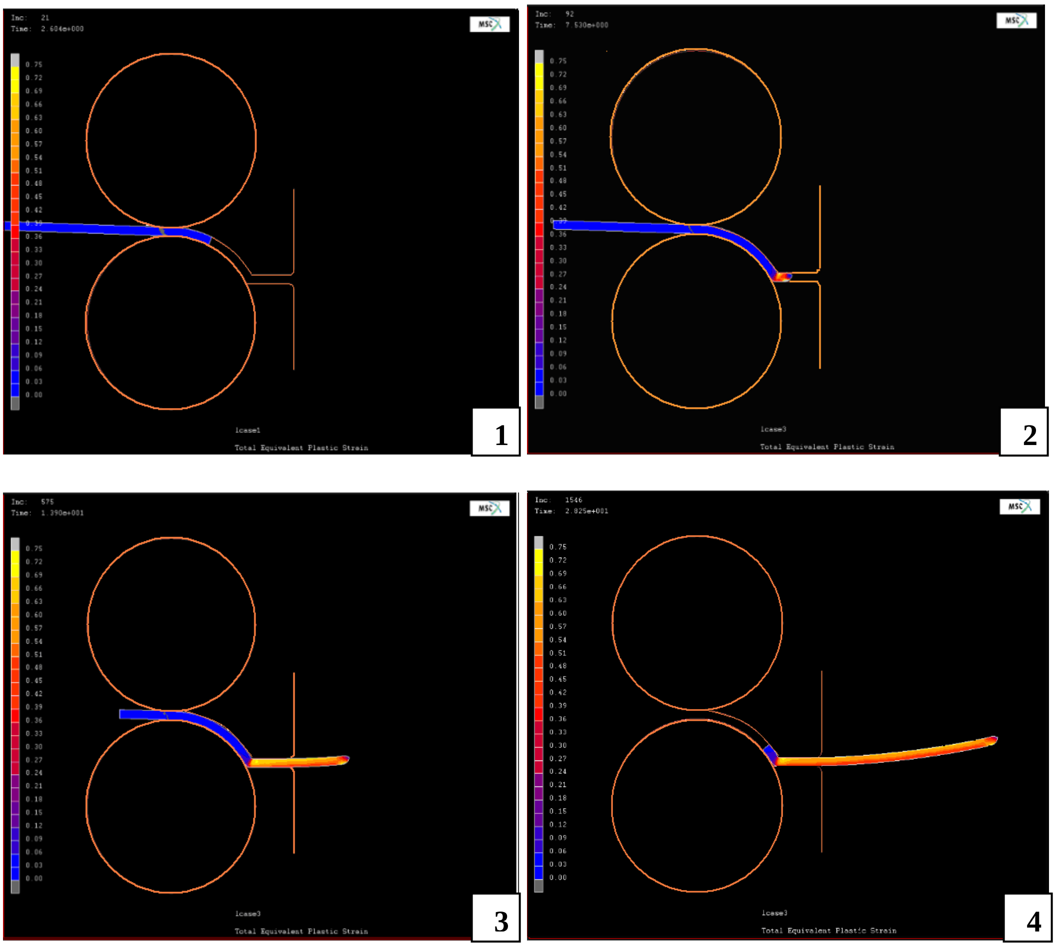


Figure 4.4 The FEM Scenes of eventual DCAP system design.

4.3 Mechanical Tests

In order to discuss the strengthening behavior of 6061 aluminum alloys associated with DCAP process, mechanical tests were performed. Work hardening, work softening and change in ductility after DCAP process was evaluated by means of tensile tests and hardness tests.

4.3.1 Tensile Test

Tensile tests were performed on solutionized strips and annealed plates of 6061 aluminum alloy. Solutionized aluminum strips were deformed through the DCAP system with patterned roll. These rolls induced spots on the surface of the strips after DCAP process. Existence of spots yielded notch effect during tensile testing. As a result, specimens fractured without showing plastic deformation. Solutionized specimens before and after tensile testing are shown in Figure 4.5.

Figure 4.5 Solutionized aluminum tensile test specimen deformed through patterned portion of the roll.

The results obtained from tensile tests of solutionized strips were evaluated as unreliable, and thus they were not reported.

Tensile tests were performed on 6061-T0 plates after first and second deformation through the DCAP system. The data on yield strength (σ_Y), ultimate tensile strength (σ_{UTS}) and % elongation before and after DCAP are tabulated in Table 4.1. Engineering stress-strain curves of annealed 6061 aluminum alloy plates before and after DCAP is presented in Figure 4.6.

Table 4.1 Mechanical test results of 6061-T0 plates before and after DCAP process.

Strength and elongation values of 6061-T0 plates			
# DCAP Pass	**σ_Y (MPa)**	**σ_{UTS} (MPa)**	**Elongation (%)**
0	60	134	36
1	85	137	16
2	118	145	12

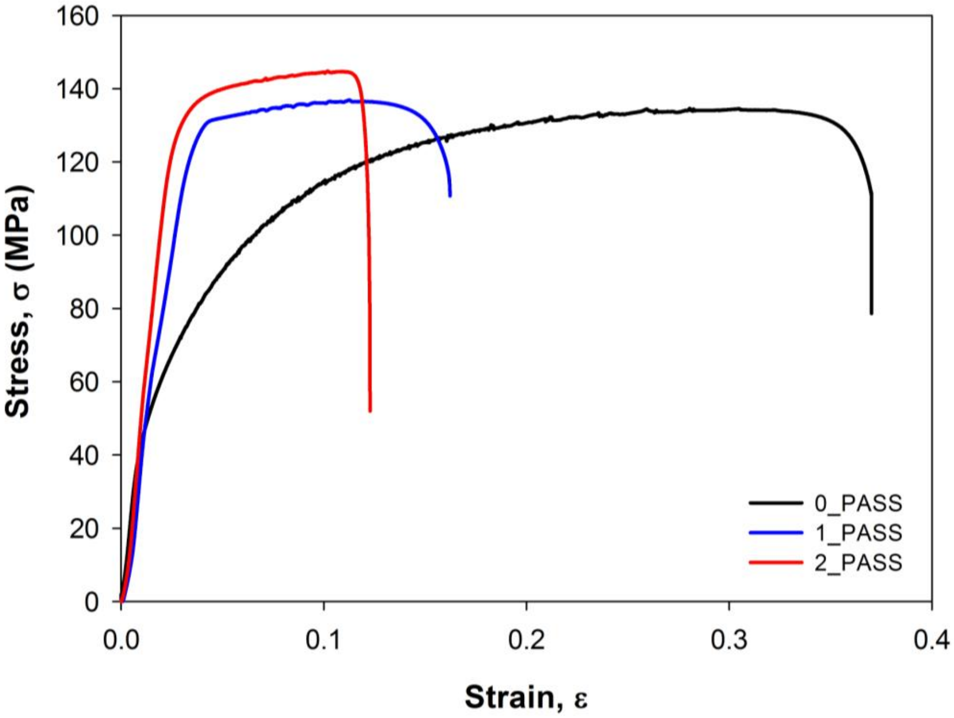


Figure 4.6 Engineering stress-strain curves of 6061-T0 plates before and after DCAP process.

Improvement in yield and ultimate tensile strength values are evident after DCAP process. However, in spite of the increase in σ_Y and UTS values, 6061 aluminum alloys exhibited little work hardening. This was apparent from the appearance of the stress peaks at very low strain values. This result indicated that density of dislocations saturated at a very small strain due to the fast dynamic recovery rate. Dynamic recovery rate increases with the increase in dislocation density since the probability of a dynamic recovery increases with dislocation saturation [36].

The strength of aluminum alloys changed depending on the DCAP pass number. The change is illustrated in Figure 4.7. As observed from the figure the enhancement in the yield strength of the plates was pronounced. σ_Y of DCAPed specimens increased from 60 MPa to 85 MPa and to 118 MPa when they were deformed through the system once and twice, respectively. According to the values, σ_Y increased 41 % after 1 pass and almost 100 % after 2 passes when compared to the unDCAPed plates.

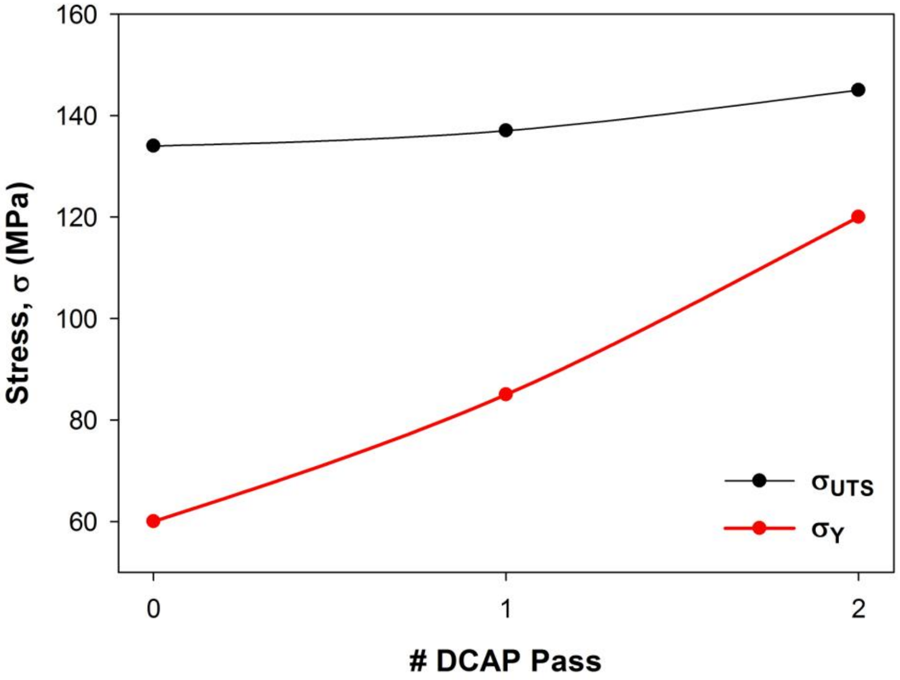


Figure 4.7 Variation in σ_Y and UTS values as a function of pass number.

On the other hand, the UTS values increased from 134 MPa to 137 MPa and to 145 MPa when plates were deformed through the system once and twice, respectively. Increase in the UTS values were 2 % and 8 % after 1 and 2 passes through the DCAP system, respectively.

Elongation of DCAPed specimens decreased with the increase in DCAP pass number. As the aluminum plates strengthened, they became less ductile.

4.3.2 Hardness Tests

Hardness measurements were applied after DCAP processing of both solutionized and annealed specimens in order to state the different strengthening capability of separately heat treated alloys after DCAP process. The variation in the hardness of the annealed and solutionized specimens after DCAP process is tabulated in Table 4.2. Graphical representation of the variation in hardness as a function of pass number is given in Figure 4.8.

Table 4.2 Hardness test results of 6061-T0 plates before and after DCAP process.

Vickers Hardness (HV30) of Aluminum Specimens		
# DCAP Pass	**Solutionized**	**Annealed**
0	42	39
1	61	43
2	69	44

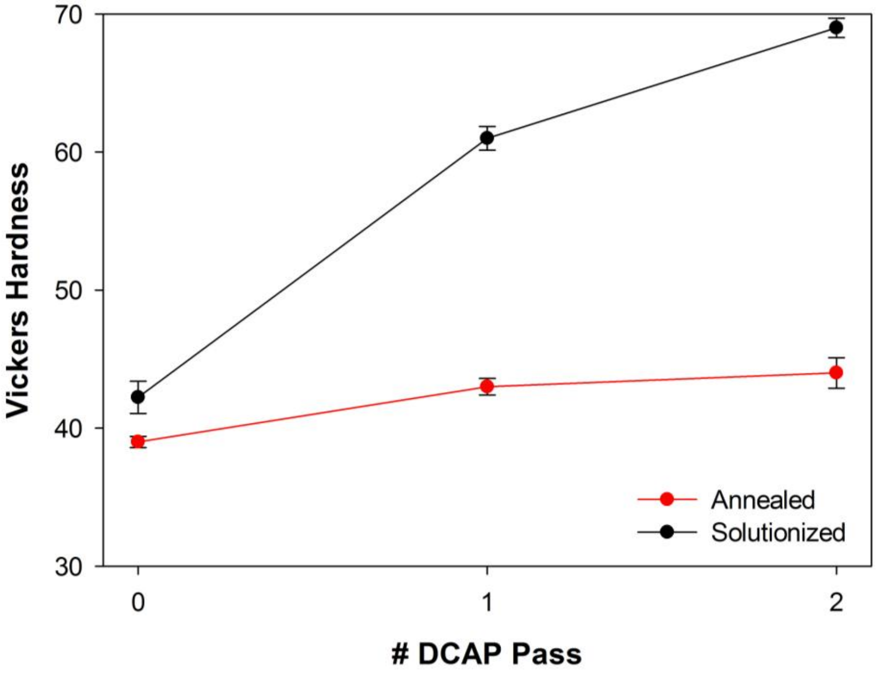


Figure 4.8 Variation in hardness as a function of pass number.

As observed from the data plastic deformation enhanced the hardness of aluminum alloys. Increase in the hardness of solutionized strips was 45 % and 64 % after 1 and 2 passes through the DCAP system, respectively, whereas it was 10 % after both passes in the annealed plates.

It was obvious that the hardening capability of solutionized specimens after DCAP process was higher than that of annealed plates. It is known that a high content of solute in the matrix can decrease the dynamic recovery rate and hence increase the dislocation accumulation rate [37]. Since solutionized aluminum samples had higher solute content than annealed plates, they showed higher strengthening effect as expected.

The little increase in the hardness value of the annealed plates was attributed to the high dynamic recovery rate after DCAP process and low strain hardening capability [37].

4.4 Microstructural Examination

Optical microscope images of undeformed and 2 pass DCAPed samples are provided in Figures 4.9 and 4.10. These images were obtained by examining the surface of the specimens that it parallel to the direction of deformation.

In the optical micrographs, microstructural features such as grain size and grain boundaries were not clear as seen from Figures 4.9 and 4.10. Hence, observation of grain refinement from optical micrographs was not possible. According to Figure 4.10, grains were assumed to be elongated along the direction of deformation after DCAP process.

SEM image of annealed aluminum samples after 2 DCAP passes is given in Figure 4.11. Just like the optical micrographs, grains cannot be observed clearly from the SEM image due to the high deformation and high dislocation density on the surface of the specimens.

Microstructural examinations via optical microscope and SEM revealed that the examination of the ultrafine grain structure of DCAPed 6061 aluminum alloy sheets would be possible by Transmission Electron Microscope (TEM).

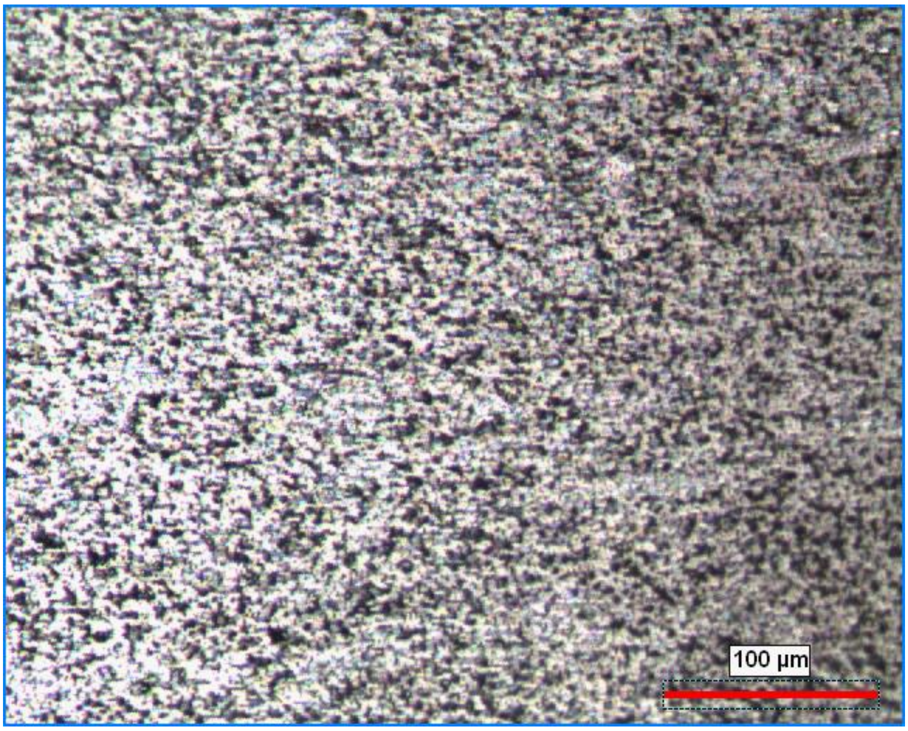


Figure 4.9 Optical microscope image of annealed specimen before DCAP process at 300X magnification.

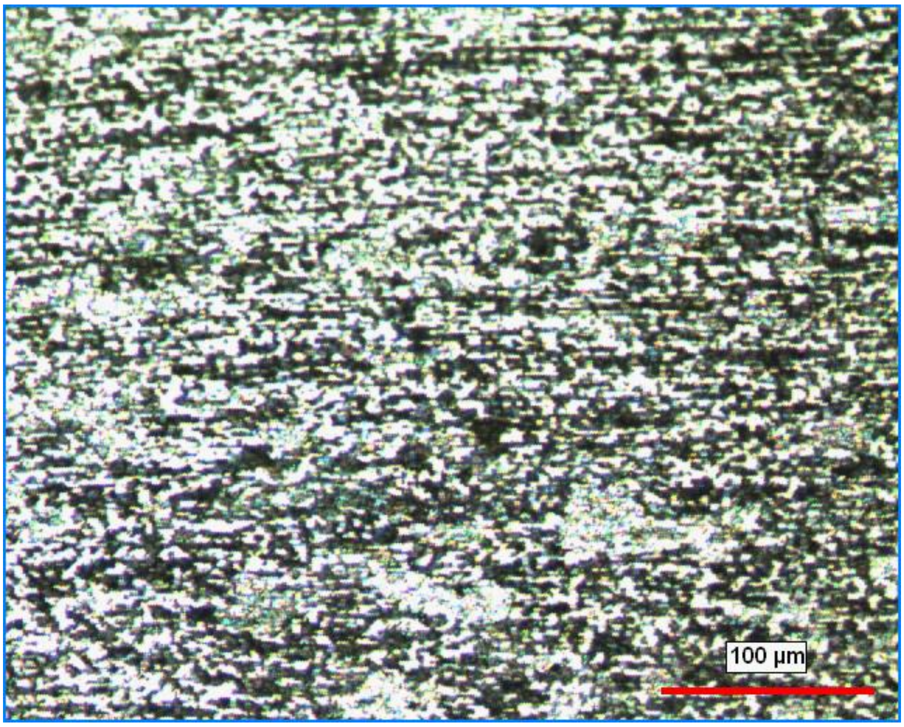


Figure 4.10 Optical microscope image of annealed specimen after 2 passes through the DCAP system at 300X magnification.

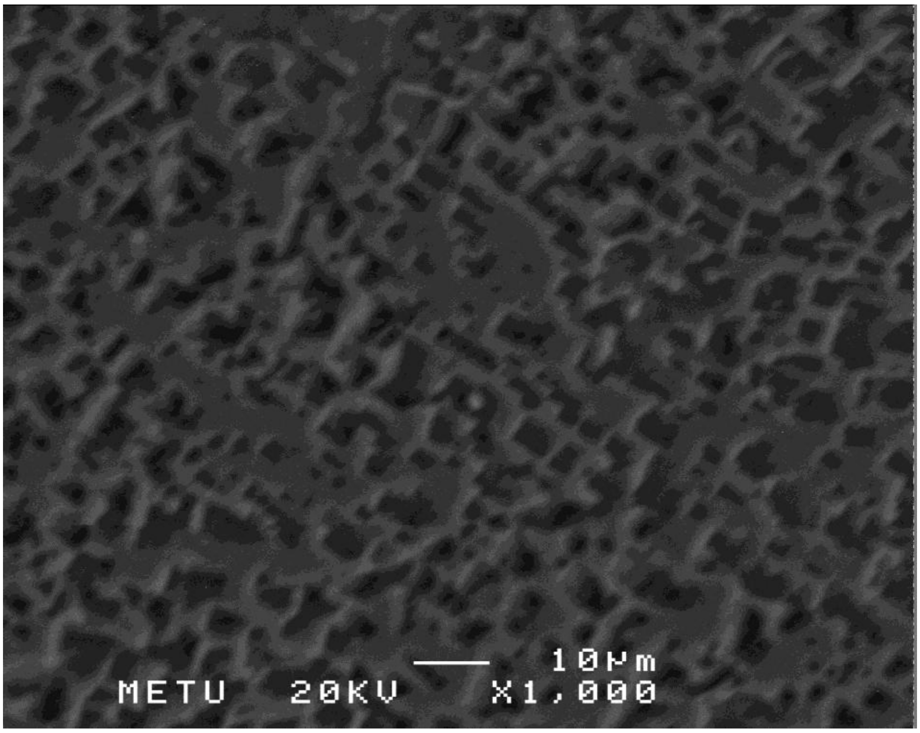


Figure 4.11 SEM image of annealed specimen after 2 passes through the DCAP system.

4.5 X-Ray Diffraction

Annealed and 2 pass DCAP aluminum samples were examined via XRD. The X-Ray diffractogrammes for the peak of (111) plane of 6061 aluminum alloy specimens in annealed and 2 DCAP passes conditions are given in Figure 4.12. After determining the broadening of the DCAPed specimen's peak (B_D) and that of the reference specimen (B_R) at the annealed condition by using Equations 3.1 and 3.2, the sub-grain (cell) size of the DCAPed specimen was calculated as about 45 nm. After 2 DCAP passes X-Ray line broadening was detected.

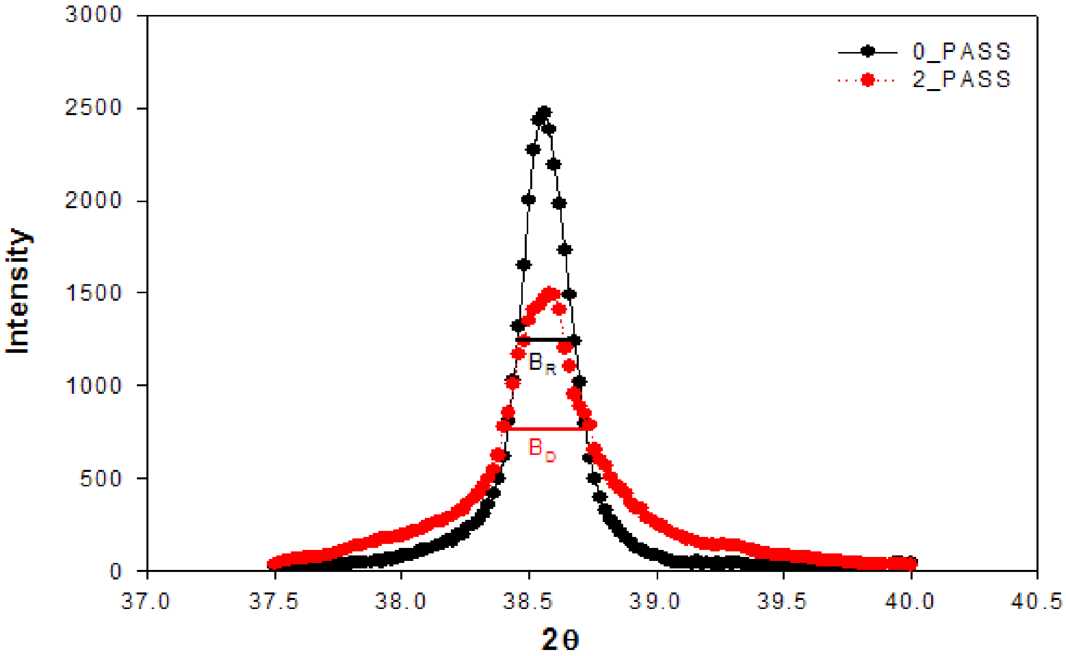


Figure 4.12 X-Ray diffraction peaks of (111) plane for annealed and 2 pass DCAPed conditions.

CHAPTER 5

CONCLUSIONS

A DCAP system was constructed for severe plastic deformation of 6061 aluminum alloy sheets by using the FEM simulation results. In order to obtain an effective DCAP system, various modifications were applied to its components during construction. After completion of the DCAP system, 6061-T0 aluminum alloy sheets were deformed by 2 DCAP passes. The following conclusions were drawn from this study:

1. Channeled and patterned rolls induced cracks and spots on the specimen surface which resulted in unreliable mechanical testing. By various trials, the DCAP system with partially patterned rolls was developed for the deformation of 2 mm thick plates.
2. The amount of reduction at thickness of the specimen which applied by the rolls at the entry side, should not exceed the limit of 8 % for complete filling of the outlet channel by the sheet metal.
3. Solutionized specimens exhibited higher hardening capability with respect to annealed specimens as a result of DCAP process.
4. Remarkable improvement in the yield strength was obtained. However, a slight increase in ultimate tensile strength, which is an indication of low strain hardening capability, was observed.
5. Decrease in ductility is acceptable compared to the remarkable improvement in the yield strength after DCAP passes.
6. DCAP is a promising method to improve mechanical properties of aluminum alloy sheets.
7. Due to etching problems of 6061 aluminum alloy samples, grain refinement cannot be observed from optical micrographs and SEM images. Only

elongation of grains along the direction of shearing after DCAP process could be seen.

8. The sub-grain size about 45 nm was calculated based on the XRD peak-broadening of the DCAPed samples.

5.1 Recommendations for Further Studies

Followings are recommended for the further studies;

- TEM examinations shall be performed for microstructural investigations. By these analyses ultra-fine grained structure can be observed. Moreover texture analyses may be conducted as well.
- DCAP system modifications shall be performed so that higher number of passes through the system may be possible. A modified system would also make the mechanical property examination of solutionized specimens possible.
- DCAP of age hardened specimens may be investigated.
- Fatigue properties of the specimens after DCAP process may be investigated.
- Fracture toughness of the specimens after DCAP process may be investigated.
- Beside 6061 aluminum alloy sheets, aluminum alloys from different series or another metal shall be deformed through the system.
- In order to observe the hot deformation behavior, a furnace system may be established on the specimen passage part of the system.

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