M.MUTLU

APPLICATION OF THE CONTOUR METHOD IN COLD ROLLED ALUMINUM PLATES

MERT MUTLU

ATILIM UNIVERSITY 2019

JANUARY 2019

APPLICATION OF THE CONTOUR METHOD IN COLD ROLLED ALUMINUM PLATES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY

BY

MERT MUTLU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE/DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF MANUFACTURING ENGINEERING

JANUARY 2019

Approval of the Graduate School of Natural and Applied Sciences, Atılım University

____

Prof. Dr. Ali Kara

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of **Master of Science in Manufacturing Engineering, Atilim University.**

____

Prof. Dr. Sadık Engin Kılıç

Head of Department

This is to certify that we have read the thesis "Application of The Contour Method in Cold Rolled Aluminum Plates" submitted by "Mert Mutlu" and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

____

Assoc. Prof. Dr. Caner Şimşir

Supervisor

Examining Committee Members:

Assoc. Prof. Dr. Caner Şimşir _______________________

Assoc. Prof. Dr. Hakan Ahmet ARGEŞO _______________________

Asst. Prof. Dr. Omer Music _______________________

Date: *22/01/2019*

I hereby declare that all information in this document has been obtained and presented in accordance with 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: Mert MUTLU

Signature:

ABSTRACT

APPLICATION OF THE CONTOUR METHOD IN COLD ROLLED ALUMINUM PLATES

Mutlu, Mert
M.S., Manufacturing Engineering Department
Supervisor: Assoc. Prof. Dr. Caner Şimşir

January 2019, 65 pages

The recently popular contour method can measure residual stresses through cross section of any part. The contour method can give 2D stress map without any inverse calculation as other techniques do. It is cheap, simple and has many applications. Moreover, measurement depth is not limited by contrast with other techniques such as hole drilling and neutron diffraction.

This study presents an application of the contour method on a cold rolled aluminum plate. In this thesis, two AA 5083 specimens were used to determine the residual stresses by the contour method. The specimens were cut in two by using wire-Electric Discharge Machining (w-EDM) and then, the contours from the cut surfaces were measured by an optical surface profiler using the focus variation technique. The obtained data were processed by MATLAB software. After data processing, inverse of the measured contours were applied to a FE model and a 2D map of the residual stress was attained. The stress distribution profiles were compared to the results obtained from Slitting and Ring Core methods for verification and a good agreement with Slitting Method was achieved. Also, the stress distribution profile from the Contour Method was according to the expected stress distribution after a cold rolling process. Although there were some differences with Ring Core Method, similar trends were observed.

Keywords: Contour Method, Residual Stress, Colled Rolling, Aluminum

ÖZ

SOĞUK HADDELENMİŞ ALÜMİNYUM PLAKALARDA KONTUR METODUNUN UYGULAMASI

Mutlu, Mert

Yüksek Lisans, İmalat Mühendisliği Bölümü

Tez Yöneticisi: Doç. Dr. Caner Şimşir

Ocak 2019, 65 sayfa

Son zamanlarda popüler olan kontur metodu, herhangi bir parçanın enine kesitinden artık gerilmeleri ölçebilmektedir. Bu metot, diğer tekniklerde olduğu gibi herhangi bir tersinir hesaplamaya gerek duymadan 2 boyutlu gerilme haritasını verebilir. Kontur metodu ucuzdur, basittir ve birçok uygulama alanına sahiptir. Dahası, delik delme ve nötron kırınımı gibi tekniklere karşın ölçüm derinliği kontur metodu için kısıtlı değildir. Bu çalışma, soğuk haddelenmiş bir alüminyum plaka üzerinde kontur metodunun bir uygulamasını sunmaktadır. Bu tezde, kalıntı gerilmeleri kontur metodu yardımıyla belirlemek için iki adet AA 5083 numunesi kullanılmıştır. Numuneler, kıvılcımla malzeme işleme yöntemi ile ikiye kesilmiş ve daha sonra kesilen yüzeylerde bulunan konturlar odak değişimi tekniği kullanılarak optik yüzey ölçümü yapan bir makine tarafından ölçülmüştür. Elde edilen veriler MATLAB yazılımı kullanılarak işlemden geçirilmiştir. Veri işleme sonrasında ölçülen konturların tersleri sonlu elemanlar modeline uygulanmış ve kalıntı gerilmelerin iki boyutlu haritasına ulaşılmıştır. Elde edilen gerilme dağılımı profilleri, doğrulanması için dilme ve halka çekirdek yöntemlerinden elde edilen sonuçlarla karşılaştırılmış ve dilme yöntemi ile iyi bir uyum sağlanmıştır. Ayrıca, kontur metotu ile elde edilen gerilme dağılım profili, soğuk haddeleme işleminden sonra beklenen gerilme yapısına uygun olmuştur. Sonuçlar halka çekirdek metodu ile karşılaştırıldığında bazı farklılıklar ortaya çıksa da gerilme profillerinin benzer bir eğilim gösterdiği gözlemlenmiştir.

Anahtar Kelimeler: Kontur Metodu, Kalıntı Gerilmeler, Soğuk Haddeleme, Alüminyum

To My Lovely Parents

ACKNOWLEDGMENTS

First, the author would like to sincerely thank to his supervisor, Assoc. Prof. Dr. Caner ŞİMŞİR for his patience, support, guidance and friendship. Also, the author is thankful to Mr. ŞİMŞİR for giving a chance to work with him during this research.

The author is thankful to Yahya TUNÇ who is a research engineer in Metal Forming Center of Excellence (MFCE) for his contributions and guidance during this study. Also, the author would like to thank to Rasim Köksal ERTAN, Hasan Safa ÇAVUŞOĞLU, Serap YILMAZ and other members of Metal Forming Center of Excellence.

The author would like to thank to his workmate, Doğan Kıvanç AKSUNGUR for his support.

The author is thankful to Akif YALDIZ for his support and friendship.

The author performed most of the experimental studies at Metal Forming Center of Excellence facilities. Thus, the author would like to thank to Metal Forming Center of Excellence for allowing to use their facilities. In addition, the author is grateful to chairman of MFCE Asst. Prof. Dr. Besim BARANOĞLU.

Finally, the author is grateful and would like to thank to his parents, Hacer MUTLU and Hikmet Başol MUTLU for their patience, their support, their deepest love, their inspiration and their guidance through his life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
FEM	Finite Element Method
EDM	Electric Discharge Machine
FE	Finite Element
FEA	Finite Element Analysis
TIG	Tungsten Inert Gas
CMM	Coordinate Measuring Machine
GMAW	Gas Metal Arc Welding
CCD	Charge-Coupled Device
FSW	Friction Stir Welding
CAD	Computer Aided Design
ASTM	American Society for Testing and Materials
SAE	Society of Automotive Engineers
XRD	X-Ray Diffraction
ND	Neutron Diffraction
FOD	Foreign Object Damage
HSLA	High-Strength Low-Alloy
LED	Light Emitting Diode
BC	Boundary Condition
MFCE	Metal Forming Center of Excellence
HE	High Energy

NOMENCLATURE

σ	Normal Stress
$\sigma_{(x, y, z)}$	Normal Stress in x, y, or z directions
σ_x	Normal Stress in x direction
τ_{xy}	Shear Stress in x-y axis
τ_{xz}	Shear Stress in x-z axis
MPa	Megapascal (Pressure Unit)
°C	Centigrade (Temperature Unit)
p(z)	Polynomial Curve
z	Height
F_z	Amount of Focus
a, b, c	Coefficients
f(x)	Polynomial Curve
p1…10	Coefficients

CHAPTER 1

INTRODUCTION

This study presents application of the contour method to determine the cold rolling residual stresses on an aluminum alloy (AA 5083) plate. The calculated stress values were justified with results from the Slitting and Ring Core Methods/ which is predicted from Finite Element (FE) method.

The cold rolling process is a process that shape any metal using rolls **(Figure 1)** at temperature below recrystallization temperature. Since cold rolling process occurs at low temperatures, resistance of the material is high. The yield strength of the metal are increased by this process. Also, hardness of the material is risen because the grain is elongated through the direction of the rolling and it breaks. Thus, the material begins to harder and be brittle. Foil, sheet and plate are some of examples of the products after cold rolling [1]. In addition, this manufacturing method provides advantages such as good dimensional accuracy, tight tolerances possible, excellent surface finish and lubrication easier.

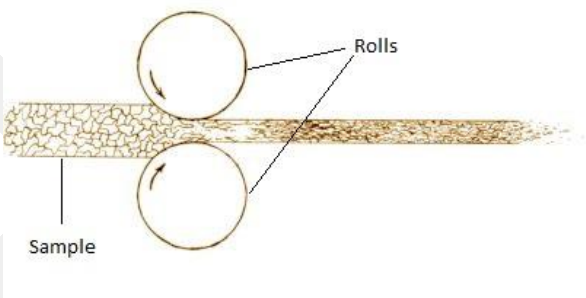


Figure 1: The cold rolling process

After an object becomes stable and reaches a state of equilibrium, stresses, which are self-equilibrated and found inside that object without any external loadings or influence can be defined as residual stresses [2], [3]. Those stresses may cause several material failures such as cracks **(Figure 2)**, fracture, corrosion, fatigue and distortion. These stresses have strong effect on the service life of the component. Engineering structures can occasionally be damaged due to these stresses which are not usually considered. However, measurement of residual stresses is a complicated problem. Although there exist many method to measure residual stresses, all of the available methods are limited or insufficient in certain terms. For example, neutron diffraction is a non-destructive, however; it is expensive, time consuming and it has limited specimen size [4], [5]. In following section of this chapter, these methods are explained briefly.

Figure 2: Cracks on a cast aluminum ingot due to excessive residual stresses [6]

The contour method, which is one of the ways to measure residual stresses, has been studied since 2000. It can be said that this method has a history of about two decades [4], [6], [7]. This method allows determination of 2D cross-sectional map of residual stresses along a plane of cut. In contour methods, a specimen is cut in two, which result the change of the contours of the cut surfaces due to elastic relaxation of residual stresses. Then, contours of surfaces are measured. Averaging the surface contours from both cut surfaces of two halves of the specimen is required to avoid irregulaties and eliminate errors due to possibility of shear stress existing during cut. Also, this operation makes the surface profiles be smoother [8].

The opposite of the measured contours are applied to Finite Element Model (FEM) in order to compute analytically original residual stresses normal to cut surfaces. As can be noted, the calculation does not involve any inverse method unlike most non-destructive measurement techniques [4].

The contour method has some advantages. It can be said that this method can give 2D map of residual stresses. Equipment for the contour method can be found in most laboratories. Moreover, the method has no limitations with regard to thickness of part or microstructure [9]. Although the contour method has various advantage as it was mentioned before, there are some disadvantages. These can be called as errors. Cutting process is very important for this method. Because the specimen can be affected due to cutting errors. For example, if the specimen is not clamped enough good, it can move and the stresses, which will be measured after FEM can be badly influenced. Accordingly, the specimen can deforms. Such a situation, which would be explained in next chapters was experienced in this study. Thus, using skim cut settings is efficient to get accurate results. These settings are very significant because the EDM cut width can be changed for different materials. This is considerable to prevent the skewed cut. In addition, the thermal equilibrium is needed to avoid thermal stresses during cutting [10], [11].

The contour method is suitable for determination of residual stresses in welding operations **(Figure 3)** such as Friction Stir Welding (FSW) [12]. However, it would be wrong to limit the contour method to any specific operation as it can be applied to any operation which produce volumetric residual stresses. For example, in this thesis, it is applied to cold rolling of an aluminum plate, which is a metal forming operation.

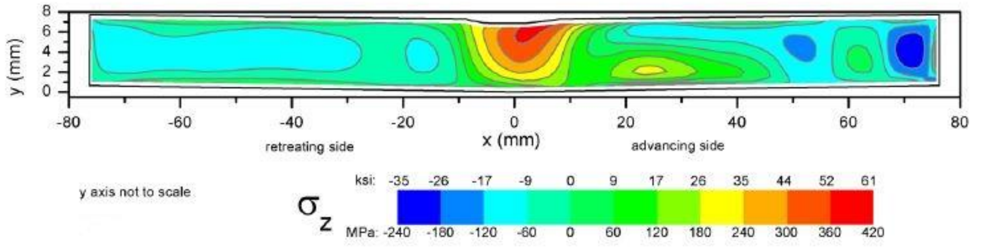


Figure 3: Longitudinal stress distribution using contour method after FSW [13]

In this thesis, an aluminum plate was selected because application areas of such these parts are diverse in several industries. To give an example, automotive, construction, aviation and more industries prefer aluminum due to light weight. Aluminum is ample in the earth and has a high resistance to corrosion and a good electrical conductivity. As it is mentioned in previous section, several processes such as cold rolling can be used to improve durability of improve mechanical properties of aluminum and its alloys/Pure aluminum is normally malleable and soft. However, aluminum is alloyed with some elements such as magnesium and copper to further improve their strength. In this thesis, an Al-Mg alloy (AA 5083) is used because its processing route involves cold rolling.

This study has two major contributions to the literature: The first is that an optical profiler using focus variation method was used to measure contours. The technique will be instead of CMM or laser profilometer. During surveys, this technique has never been applied in the residual stress measurements. Most studies use coordinate measuring machine (CMM) to measure the contours on surface of the specimen [8], [14], [15]. The second contribution is related to cold rolling process. When investigating most practices related to the contour method for residual stress measurement in the literature, it was seen that there is no study. In addition, the contributions of the cold rolling to the properties of the material was playing a big role to place in this thesis. All these factors led up arisen of this thesis.

1.1 Residual Stress Measurement Techniques

Residual stresses which can damage structure and strength of material are complex problems. Prediction about those stresses is usually difficult. Therefore, several techniques are used to measure such these stresses and obtain their distributions inside the component. The following part includes these techniques which may be divided into 2 main categorizes: destructive methods and non-destructive methods.

1.1.1 Destructive Methods

In those methods, structural changes occur on the sample. Those methods depend on 'Strain Release Principle'. The sample is cut to make the stresses relax and then, measurement is taken over the damaged part. After measurement, residual stresses are inversely calculated via the obtained values. Hole drilling and slitting are some examples of this method [2]. The contour method, studied in this thesis, also belongs to this category.

1.1.1.1. Hole Drilling

In this method, there is a mini hole which is drilled in surface of the specimen. The deformations of surrounding surface are measured by using the strain gauges or optical techniques **(Figure 4)**. The hole drilling method has some advantages such as safe and fast results for several specimen types. Thus, this method is popular in many implementations [6]. This method may be called as 'semi-destructive' because the material quantity removed from the specimen is quite small [2]. Moreover, this method is standardized in ASTM E837 [2], [6], [16].

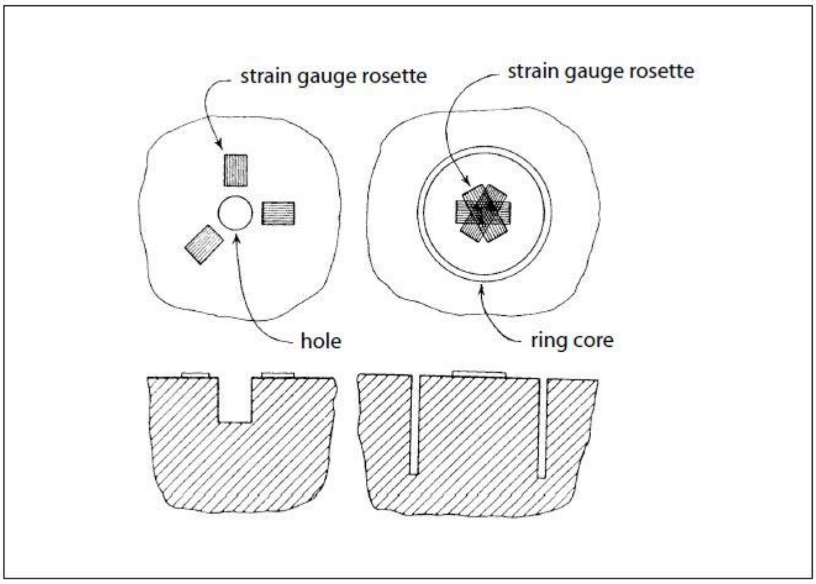


Figure 4: Schematics of Hole Drilling (Left) and Ring Core (Right) [2]

1.1.1.2. Slitting

Another name of this method which has similar principles to hole drilling method is crack compliance method [2], [6], [16]. This method includes that relief strain is measured by using strain gauges which positioned on front or back or both surface of specimen **(Figure 5)** when depth of slit is gradually increased via wire-EDM or miling cutter [6].

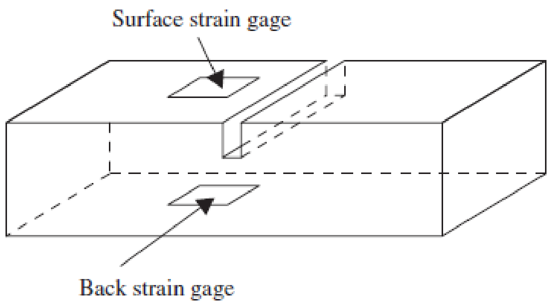


Figure 5: Schematic of Slitting Method [6]

Moreover, pieces of the material can taken away by electro-chemical techniques [17]. The slitting method has more flexibility than other methods such as ring core. For example, contraints of the geometry are less tight. On the other hand, this method has no standard compared to hole drilling method [2].

1.1.1.3. Ring Core Method

This method is a variation of hole drilling method. After the strain gauges are attached the specimen, the base positioned around the gauges is formed by drilling **(Figure 4).** Although this method has an advantage of larger information depth due to larger strains, there is a important difficulty. For every drilling, the strain gauges are removed from surface of specimen and then reattached [2], [6].

1.1.1.4. Deep Hole Drilling

The deep hole drilling method combines the hole drilling and ring core methods. This method uses the different members of other methods **(Figure 6)**. Firstly, a hole is drilled into the specimen. Following step, the residual stresses are determined by measuring change of the hole diameter using an air probe. This process is done through the hole depth. Measuring the stresses which stay within the specimen is principal characteristic of this method. This method is available for the specimens with rather scale and weights such as aluminum or steel castings [2], [6], [18].

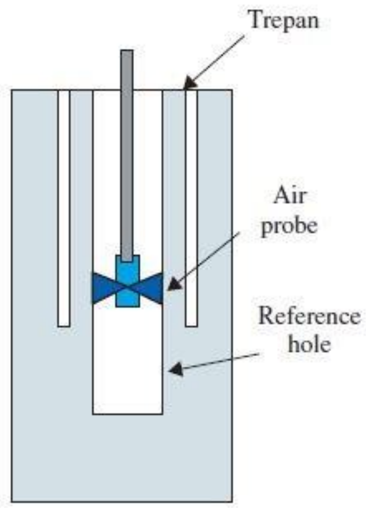


Figure 6: Schematic of Deep Hole Drilling [6]

1.1.1.5. Contour Method

This is the method used in this thesis. The contour method is an improved technology which can give 2D map of the residual stresses through cross-section of the material. The method includes cutting the specimen using wire-EDM, and measuring displacements on the cut surfaces using a CMM or a laser profilometer. The original residual stresses normal to cut surfaces of the specimen are calculated by using a Finite Element Model. The measurements from both cut surfaces are averaged to prevent asymmetric effects. The contour method is effective because it can provide full map of the residual stress measurements. **Figure 7** shows 3D FE model to calculate residual stresses [6], [7], [19], [20]. The details of the theory of contour method is provided in Chapter 3.

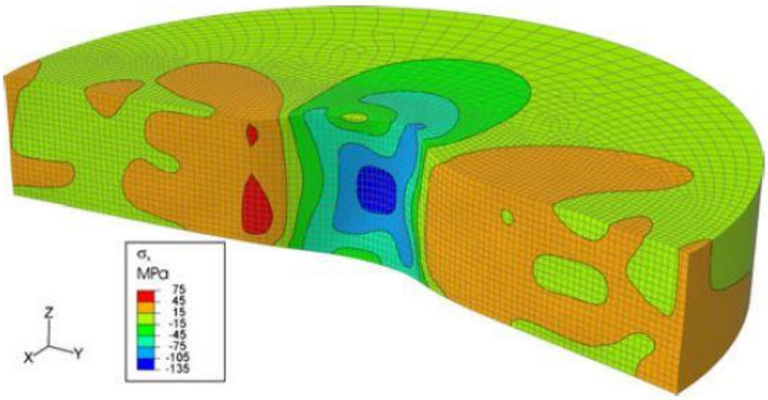


Figure 7: 3D FE Model for Contour Method [20]

1.1.1.6. Sectioning

The sectioning uses some steps of other methods to measure residual stresses. After cutting the specimen rankly, the relaxation strain is measured by strain gauge or diffraction measurements. The obtained data is used to find magnitude and position of the residual stresses. This method involves inverse calculation. Therefore, the sectioning method can spend different time to calculate stresses on complicated geometries [2], [6]. The sectioning method is shown in **Figure 8** [21].

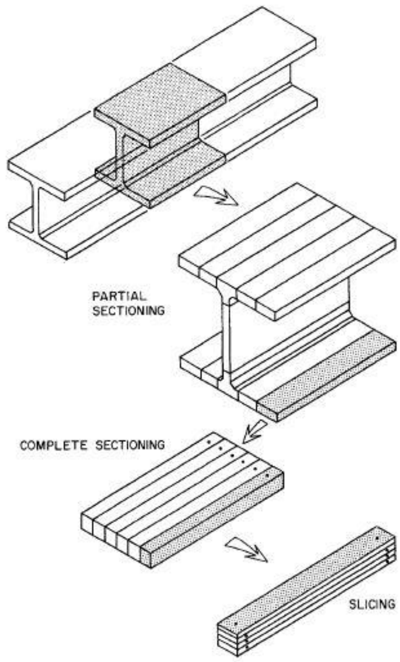


Figure 8: The Sectioning Method [21]

1.1.2. Non-desructive Methods

1.1.2.1. X-Ray Diffraction Method

X-ray diffraction (XRD) method is a non-destructive method which can measure the strain caused by the residual stresses in crystallatice and calculate the associated stresses [22]. This method is applicable only for crystalline and polycrystalline materials [23]. X-rays from standard XRD equipment cannot deeply penetrate into the materials and their depth range is o n the order of microns. Because of that. XRD is usually used to obtain surface residual stresses. Furthermore, there is a good handbook about XRD stress measurement which has been published by the SAE International [24]. Recently, the instruments used for the XRD residual stress measurements were developed rapidly , and now are in a better position than the traditional instruments [6].

1.1.2.2. Synchrotron (HE-XRD) Method

The Synchrotron method or High Energy XRD (HE-XRD) works using high energy X-rays which are stronger and have much intense energy. Due to higher energy, these rays can penetrate up to several milimeters of the material. The source which is called as synchroton radiation facilities produces X-rays. The strain affects the diffracted energy and that energy changes in lattice gap. The variations are measured via X-ray detector [6].

1.1.2.3. Neutron Diffraction Method

The neutron diffraction (ND) is a method that can measure strain caused by changes which exist in the lattice gap as XRD does. In other words, ND has similar principles comparing X-ray diffraction. Nevertheless, ND has better penetration depth comparing X-rays because the neutrons are uncharged and capability of their penetration is well. Therefore, the neutrons may penetrate through inside of the material. This permits that the bulk stresses can be analyzed. The source of neutrons for ND method can be spallation, fission or a nuclear reactor. There is no necessary to prepare the specimen. Also, there is no geometric shape limitation. However, cost and time consuming for measurements are disadvantages of ND. This method can be applied on many different parts such as rolled rods or weldments [2], [6], [25], [26].

CHAPTER 2

LITERATURE SURVEY

The contour method is a method for residual stress measurements and has become popular since 2000 [10]. This method is usually more effective than existing techniques such as neutron diffraction, sectioning and hole drilling to measure residual stresses. When traditional methods give discrete value of stresses, the contour method gives continuous stress map. Also, the contour method is quite simple and relatively inexpensive. This section includes several studies about the contour method from past until now in literature.

Prime [5], explained theory of the contour method, its advantages against other traditional techniques such as synchrotron diffraction and experimental mechanics of the method in this work. It was mentioned that the full 2D stress maps can be calculated without need to inverse calculation as other conventional methods. The experimental steps of the contour method were clarified in this paper as other literature papers. These are cutting process, measurement, data reduction and Finite Element Analysis (FEA). The importance of cutting process for relaxing the stresses were explained. Moreover, it was emphasized that describing a pre-existing surface for other traditional methods such as hole drilling was important and also, the contour method uses a shape measurement. This subject was referred much more than several articles in this paper. It was expressed that one of the advantages of the contour method was measuring a continuous data map. Therefore, it was said that the limited number of points taken was removed. Additionally, it was mentioned that the assumptions could be needed in this study. Thus, it was told that they can cause new errors. However, it was indicated that these challenges would be contribution to development of the contour method. This paper is very effective for understanding the fundamentals of this new approach.

Prime and Gonzales [4], studied on a steel specimen to show the accuracy of the contour method in this paper. The results of the contour method and the bending test were compared. Also, differences of the contour method than other existing methods such as neutron diffraction and hole drilling were mentioned. In this work, a used specimen was a beam with 30x10 mm cross section and its material was forged 21Cr-6Ni-9Mn austenitic stainless steel. The plastic deformations as bending type occurred on the specimen was analyzed after heating and cooling processes. After measuring contours on cut surfaces, the obtained data was transferred to FEM to get a full 2D stress map. The results from post-processing were compared to analytical solution. It was seen that the results are similar. At the end of this work, it was seen that the contour method can measure the correct residual stresses without simplifying stress assumptions. This paper is very useful for beginner researchers. This paper is similar in some sections to other papers in literature. For example, theory of the Bueckner's superposition principle, stress of the contour method and FE application are similar.

Prime and Newborn et al. [11], studied the residual stresses due to the quenched-induced stresses which could not be relaxed enough by a cold-compression stress relief process in high strength aerospace aluminum products. The contour method was applied to measure residual stresses and the results were compared each other. In this study, two specimens, AA 7050-T74 and AA 7050-T7452 hand forgings, were used. The dimensions of 7050-T74 were 107x158x718 mm and others were 107x158x359 mm. These specimens were investigated after quenching and cold compression processes. Steps of the contour method were applied to measure residual stresses. Three cuts were applied to 7050-T7452 for axial and transverse stresses. For 7050-T74, the only cut was one for just axial stresses. Four different types' 3D models were used to simulate the material processes such as thermal, mechanical, cold-work stress relief and cutting. Three structural analysis were performed due to properties of the used specimen. The results from measured residual stresses and FEM prediction for axial stresses in 7050-T74 forging were very close. However, the peak tensile stresses in measurements were a bit lower than in FEM prediction. Furthermore, the results for cut 2 and 3 in 7050-T7452 forging showed appropriate similarities. However, comparing the results from cut 1 for axial stresses in 7050-T7452 were not available because the stresses varied with position along the length. According to this study, the contour method is simple to map the stresses precisely compared to other methods. In addition, this work was the first in the literature for the application of contour method in quenched aluminum alloys.

Turski and Edwards [14], studied to determine transverse residual stresses along a longitudinal cross section of steel bead-on- plate specimen. In experiment of this work, the weld beam on the plate specimens were used. The material of plates was heat treated 316L austenitic stainless steel. The initial geometry of plate was 600x150x50 mm. Then, 180x120x17 mm base plates machined from the initial shape. The residual stresses after welding process which was Tungsten Inert Gas (TIG) was evaluated using the contour method. The specimen was cut in two via wire electro-discharge machining (EDM). Then, contours of both sides of the new surfaces after the cut were measured by using coordinate measuring machine (CMM). Next, data reduction was done by averaging surface contours. This operation is important because of removing effects of shear stress and any defects in the cut. Also, smoothing via curve fitting was implied on variations in the surface contour due to roughness of EDM cut. Then, residual stresses normal to cut plane were calculated using Finite Element Model. The analysis was linear elastic. In results of this study, the distribution of transverse residual stresses were shown graphically. It was indicated that the peak stresses were close to welded surface and also, it was said that the magnitude of these stresses decreased through bottom of the specimen. The points of the largest peak stresses which were at the weld start and stop positions were shown. Moreover, it was mentioned that the contour method should not be applied in single with regard to accuracy and uncertainty due to no analytical equation which transforms surface contour to stress map. Therefore, it was emphasized that doing an error analysis was not possible. Nevertheless, it was said that the results were so close and the agreement was good by comparison with neutron diffraction method. In addition, this study included information which was about benefits of the contour method for validating measurement based on diffraction compared to other papers. It means that the contour method is seen as an auxiliary method. This is because the contour method is not sensitive enough in local microstructure variations in welded samples. This study is beneficial for extracting information about the contour method and its relations to other methods.

Traoré and Hosseinzadeh [27], made a study about development of potential plasticity during cutting process and its effects on residual stress calculation by contour method. For this work, 2D Finite Element Model (FEM) was used to predict effect of plasticity on the calculated stresses. The dimension of the plate used in experiment was 150 mm wide and 300 mm long. Three sections such as A, B and C were created within 300 mm long. Regions of A and C were identical, B was different. Cooling to 20 °C from 1000 °C was implemented on the plate to generate the residual stress. Then, cutting was implemented through the middle of 300 mm long. For simulation, asymmetric and symmetric plane conditions were specified. Also, two yield stress cases which consisted of 500 MPa and 1500 MPa were counted in. During simulation of contour cuts, distribution of plastic strain were observed according to the specified conditions. The results were compared. Furthermore, transverse residual stresses measured by the contour method were compared with the results from neutron diffraction and slitting methods. It was mentioned that the plasticity can occur when the residual stresses approach to the yield stress of the material where the measurement is taken from. It means that the residual stress measurement can be affected. It is important due to the contour method based on theory of elasticity and also, superposition principle. It was said that the plasticity effect depends on how the cut face is restraint for opening and closure. In addition, it was indicated that the plasticity does not effect on the measured results when peak residual stresses are less than approximately thirty percent (30%) of the yield strength of the material. This paper is important for understanding how the plasticity occurs during cutting operation although the theory of elasticity exists on the contour method. Moreover, this study is valuable in terms of investigating possible plasticity effect together with the residual stress measurements.

Prime and Hughes [28], studied about the performance of the contour method on welded plate to measure cross-sectional residual stresses and explained comparisons between the contour method results and neutron diffraction measurements. The principle and application procedure of the contour method were introduced in this paper as other studies related to same subject. In experiment, the welded plate was investigated. The material of this plate was ferritic steel BS 4360 grade 50D. Also, its geometry was 1000 x 150 x 12.5 mm before welding process. Tungsten Inert Gas (TIG) weld was made. The U-shaped groove which 6 mm wide and 8.5 mm depth was machined in the middle of the plate and it was welded. Then, all steps were applied on the specimen for contour method and neutron diffraction measurements. Two cross-sectional maps of residual stresses were compared and it was indicated that the agreement between them was perfect. The similar results were obtained. There were some uncertainties. This is because that the continuous data was acquired by the contour method and individual measurement points were acquired by the neutron diffraction. It was emphasized that the contour method has an important contribution to other existing techniques. Moreover, hole drilling method, XRD method, their advantages and disadvantages were mentioned in this study. In addition, it was remarked that the contour method has wide application range although it was destructive. It was said that the contour method is simple and cheap. This study is good in terms of showing abilities of contour method comparing with another technique which is neutron diffraction to measure residual stress.

Bouchard and Ledgard et al. [9], had a study to find out how best cutting process which can be used for contour residual stress measurement will be. Several criteria were used for the assessment. These were about complexity of geometry of specimen and wire breakage caused by length of the specimen. The experiments involved blind wire cutting trials. Three wire electro-discharge machines (EDMs) which were supplied from three different manufacturers (A, B and C) were used for the experiment. Two test specimens were used for each machines. One of these specimens were 60 mm thick, 240 mm wide austenitic stainless steel plate. It had weld defects. Other specimen were made from stainless steel and it had complex structure and included two manual metal arc welds. According to the specifications for trials, the cutting processes were applied to the test components. It was said that these EDMs had close results of operation about surface roughness levels. However, it was seen that EDM A and B were not enough about cutting long length. The wires were broken during operation. Also, ledges occurred on specimens after trials using EDM A and B. It was mentioned that EDM C predominated in terms of preventing wire breakage and minimizing defects caused by cutting. Moreover, it was indicated that EDM C was the best proper device to perform for residual stress measurement. In addition, this study focuses more on importance of the quality of cutting process for the contour method comparing to other papers. Also, this paper gives similar information about the contour method. For example, advantages of the method are that the method can be easily implemented and it gives 2D residual stress map on the cut surface.

Prime and Martineau [29], studied the residual stresses by the dynamic effect on steel plate. It was called as 'Foreign Object Damage (FOD)' residual stress. The material of specimen tested in the experiment was a low carbon, copper precipitation Hardened, High-Strength Low-Alloy steel (HSLA-100). The dimensions were 51 mm thick, 148 mm wide and 457 mm long were used to measure residual stress. Testing process was done after a sphere with 2.2 km/sec speed hit the specimen. The range of the speed was controlled using a pair of light screens during testing. The material of the sphere as a projectile was tungsten carbide and its diameter was 6.4 mm. The crater with 10 mm diameter and 12 mm deep occurred on 148 mm wide and 457 mm long surface of the plate. The residual stresses from impact events were measured by the contour method. The cutting step of the contour method was applied on surface with 51 thick and 148 mm wide. 'Skim cut' settings were used as other studies. Also, the finite element model was used to predict both size of crater and resulting residual stress. The software was LS-DYNA. The agreement between 3D model and the measurement was good. Especially, peak compressive stresses were very similar, 1100 MPa predicted from model and approximately 900 MPa in measurements. It was indicated that the results were very close although there were dynamic conditions. Moreover, it was said that the comparisons between the prediction and measurements could not be proper for other stress map. Because the model was not done and the steel plate had initial stress. Therefore, the plate before impact was measured to evaluate initial residual stress. The similar results as 51 mm thick plate which was used in impact test were obtained. Additionally, it was mentioned that thermal stress relief was not allowed due to that potential loss of strength could be on this used material. This reason is that the stresses existed by the impact exceeded yield strength. Furthermore, it was stated that comparing with other technique such as neutron diffraction could not be due to size of the plate. Also, it was mentioned that the stress was over-predicted in region of penetration and magnitudes of residual stress. However, the model could be developed if considering initial stresses. The main difference of this paper than other studies is to measure the residual stress by impact event. This study is very beneficial to understand the residual stress measurements from foreign object damage.

Prime et al. [15] studied on several weldments to measure residual stresses using the contour method. It can be said that making an analysis on several types of weldments are different than other studies. For this study, a laser system was used in first time for measurement process. This was also a difference comparing other most studies. The different tests were performed. For first test, the specimen was a ferritic steel BS 4360 grade 50D and its dimensions were 1000x150x12.5 mm. The U-groove with 6 mm wide and 8.5 mm depth was machined in the middle of the plate. Then, tungsten inert gas welding (TIG) was applied. After cutting using EDM, surface contours were measure by CMM. The residual stresses were calculated using 3D FEM. Moreover, the results were compared to ND. The agreement between two techniques were good. It was said that peak residual stress in the middle of welding region was tensile and could exceed yield due to the thermo-mechanical cycle of welding process. For second test, specimens were two plates of pressure vessel steel. Their dimensions were 37 mm thick, 105 mm wide and 700 mm long. These plates were welded using submerged-arc welding. Also, it was said that a different section was taken near center of weld length for measurement. Dimensions of this section were 250 mm weld direction, 215 mm transverse and 37 mm thickness before measurement. After cutting process, new surfaces were measured by using two different CMMs because of obtaining correct data from only one of cut surfaces. Then, measurement data were smoothing and were transferred to FEM in order to map residual stresses. It was emphasized that stress near edges of plate in map were affected and discarded because of problems during cutting process. In third test, two different specimen were used. These were 12.7 mm diameter 316L stainless steel rod and an 1100 aluminum rod with the same diameter. Two specimens were welded to each other using inertia friction welding. It was indicated that epoxy was used to prevent movement of weldment during cutting. Then, the contours of two cut surfaces were measured using a high accuracy laser. It was said that there were some challenges in dissimilar material combination during measurement. That was wider cut effect on aluminum. Therefore, shifting data was done to avoid that effect. After averaging and smoothing data, FE simulation was implemented to calculate hoop residual stresses. It was said that the stresses in weld region were tensile and also, stress on steel side was higher than on aluminum side. Furthermore, it was indicated that curvature shape occurred at the end of steel rod. This was because axial stresses which were existing after cutting were not in equilibrium. These axial stresses were tensile near the surface and compressive near the axis. In addition, it was mentioned that axial stresses could be observed on manufacturing of rod, especially for cold-drawn and cold-extruded rods. According to three different weld application, the contour method was able to map residual stress. This study is beneficial in terms of examining several different weldments for residual stress measurements.

Murugan and Narayanan [8], explained 3D thermo-mechanical simulation model to determine residual stress and compared the simulated results and the experimental results by the contour method. For simulation, temperature dependent thermal and mechanical properties were considered due to welding was a heat process. A welded Tee-joint specimen was used in the experiment. The material of parts of the specimen was carbon steel plate. These parts were welded to each other by using Gas Metal Arc Welding (GMAW). The dimensions were not introduced. After welding process, the cutting and contour measurement steps were done. For these steps, wire cut electrical discharge machine (EDM) and coordinate measuring machine (CMM) were used. Both the vertical and horizontal planes of the welded Tee-joint were measured. The software, MATLAB, was used to map surfaces. The surface roughness and uncertainties after cutting removed by smoothing. Then, averaging contours of two halves of weldment was applied to prevent errors propagation for both horizontal and vertical plates due to presence of shear stresses. Also, finite element model was developed to measure residual stress according to elastic conditions. Because the contour method is based on Bueckner's superposition principle. After experiment and simulation, similar results were obtained. The peak values of stress were very close. It was indicated that there were tensile stresses at middle of the horizontal plate of Tee-joint (weld zone) and compressive stresses through edges of plate. Furthermore, it was mentioned that compressive and tensile stresses balanced each other. The agreement between simulation and contour method was good. It was emphasized that the stress curve in regions of compressive stress were smoother than FEM. This is because the coarse element was used to reduce calculation time. It was said that the contour method is very effective to find distributions of residual stress after cut process. This is similar as other studies about welding. Using MATLAB software can be seen as difference than other most papers.

Prime et al. [13] studied longitudinal stress distribution and also, compared this distribution to microstructure of several welding areas. A 50-micron diameter wire was used to cut. This diameter was bigger than general wire diameter in most studies. Another difference in this work was using a laser scan to measure surface contours after cutting process. Also, examining microstructure was seen as a difference. The material was titanium alloy, Ti-6Al-4V. The residual stresses after friction stir welding (FSW) were observed. The dimensions of the specimen or weldment used in experiment was not presented. After 3D elastic finite element model, full stress map over a transverse cross-section of stress component was calculated. Moreover, microstructure on same area was shown and microhardness on several welding areas was determined. The longitudinal stress distribution was demonstrated. It was indicated that residual tensile stress was on stir zone and a peak tensile stress stayed mildly below surface. It was said that the stresses were asymmetric comparing to higher stresses advancing side of weld. High compressive stresses were seen at the edge of plate because of machining effect. Additionally, microhardness increased with respect to data.

Prime [30], reported measurements of residual stress over cross-section of quenched steel plate. In experiment, a low carbon, copper precipitation-hardened, HSLA-100 was used. It was emphasized that the quenching stresses could be observed in this material due to potential of loss of strength. The dimensions of plate tested in this work were 60.75 mm thick, 151.6 mm wide and 305 mm long. EDM with 150 μm diameter brass wire was used for cutting. Then, a section with 151.6 mm long and 60.75 mm wide was measured for residual stresses. It was said that the stresses in the center of cut plane were in tension and other stresses at top and bottom were in compression as typical quenching stresses. Peak tensile stress was about 200 MPa and peak compressive stress was about 165 MPa. Also, it was mentioned that stresses at each 20 mm region of lateral edges were some different compared to stresses in the center. It was said that this could be because elastic relaxation could affect edge regions when the test specimen was removed from larger plate. It was indicated that the magnitudes of these stresses were bit lower than expected in general quenching steel. However, it was stated that these stresses were explicit to affect damaging performance such as fatigue. In general, it was remarked that residual stress than 10 % of yield strength of material could be problem with regard to fracture performance. After simulation, it was indicated that agreement between measurements by contour method and results from 3D finite element model was perfect although there were uncertainties and assumptions during measurement. It was confirmed that the contour method gave a successful stress map. Moreover, comparisons between simple measurement methods such as crack compliance was done. It was said that those simple methods had some deficient such as remaining unresolved about edge effects.

Chuan Liu and Xiang Yi [31], studied the longitudinal residual stress measurement by using the contour method in different thickness friction stir welded specimens. The stresses were investigated after friction stir welding process. Two different specimen were used for this study. The material of these specimens were AA6061-T6 aluminum alloy. One of these specimens was a plate which had dimensions of 250 mm long, 270 mm wide and 8 mm thick. Dimensions of other plate were 300 mm long, 206 mm wide and 4 mm thick. Due to different dimensions, parameters of welding processes were changed for both plates. Then, steps of the contour method were implemented. For cutting, wire-EDM was used to cut for both plates. Ideal cutting condition were created to prevent thermal stresses. After the cutting, coordinate measuring machine (CMM) was used to measure surface contours from both cut sides of 4 mm and 8 mm thick plates. The obtained data were filtered and processed to remove imperfections. Also, data from both cut sides were averaged to be smooth. Next, the smoothed data were applied to finite element model. For FE analysis, ANSYS was used to obtain 2D stress map. It was said that there were tensile stresses near weld areas for two specimens. Moreover, it was indicated that stresses in advancing sides were higher than in the retreating sides. The peak tensile stresses were observed close to advancing side for 4 and 8 mm thick plates. Furthermore, stresses at top, middle and bottom of surfaces were compared and it was told that the magnitude of stresses in the middle line was larger than others. In addition, it was expressed that longitudinal stress distribution was not uniform and also, was not M-shaped as many previous works in literature. According to other works in literature, similar results were also acquired in this study. It was indicated that the contour method could be useful method to determine residual stresses.

2.1 Original Contribution and the Structure of the Thesis

In this thesis, there are two contributions for the literature. First is about cold rolling process. As it was mentioned in previous sections, there are no studies for residual stress measurement by the contour method. Second contribution is about measurement process which is one of steps of the contour method. When researching in the literature, focus variation method was not used to measure surface contours over the specimen.

In most studies, it was found that CMM was used for measurement. With this study, it was aimed to add innovation to literature by using the focus variation method.

This thesis includes 6 chapters. First chapter where this section exists is introduction. This chapter involves short information about the residual stresses and techniques for measuring these stresses. The second chapter is literature survey. Review of most studies about related subject exist here. Theory of the contour method is located in third chapter. Experimental procedure and its steps during this research are presented in forth chapter. The fifth chapter presents the results and discussion of this study. Finally, the sixth chapter summarizes this thesis.

CHAPTER 3

THEORY OF CONTOUR METHOD

The section explains the fundamental of the contour method shows differences from other methods.

The method which is a variation of elastic superposition principle (Bueckner's Principle) is based on solid mechanics [4], [10]. This principle is shown in **Figure 9** below:

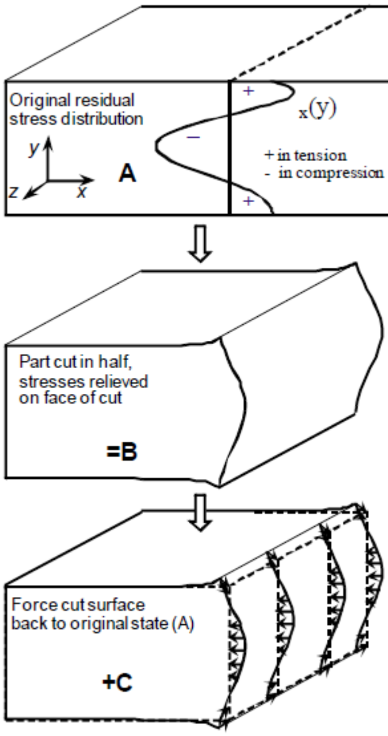


Figure 9: The Superposition Principle for Traditional Contour Method [5]

In step A, the part stays in the undisturbed condition which involves that the residual stresses to be determined. In step B, the part is cut in two and has deformed due to the residual stresses were set free by the cutting process. In step C, there is the new deformed surface by the cut and it is forced back to its original shape. Supposing elasticity conditions, when adding the stress state which was relaxed partially in step B to the change in stress from step C, this operation gives original stress over the part [12].The formulation is shown below:

$$\sigma^{(A)}(x,y,z) = \sigma^{(B)}(x,y,z) + \sigma^{(C)}(x,y,z) \tag{3.1}$$

Where σ without any subscripts indicates stress tensor.

In superposition principle, there are some assumptions that material behaves purely elastic when residual stresses relax and the cutting process does not create any apparent stresses which affect the measured contour [4], [5], [10]. If applications of the superposition principle are appropriate, the residual stresses through the plane of the cut can be determined experimentally. The contour of free surface in step B is measured after the cutting and the surface of a stress-free model is analytically forced to original state as step C by using opposite of the measured contour since the stresses in step B are unknown. It means that the original stresses along the part body cannot be obtained. Nevertheless, shear and normal stresses on the free surface in step B must be zero. Thus, C by itself would give the original stresses through the plane of the cut.

$$\sigma_x^{(A)} = \sigma_x^{(C)} \tag{3.2}$$

$$\tau_{xy}^{(A)} = \tau_{xy}^{(C)} \tag{3.3}$$

$$\tau_{xz}^{(A)} = \tau_{xz}^{(C)} \tag{3.4}$$

Efficaciously, the normal stress component (σ_x) can be empirically identified. There is information about displacements in the normal (x) direction during measurement of the surface contour. The contour method does not include information about transverse direction. In step C, surface is forced back to the original condition in only x direction. Displacements in transverse direction is unconstrained. Therefore, the normal stresses can be determined by the contour method. However, the shear stresses (τ_{xy} and τ_{xz})

cannot be determined. This is because the free surface conditions are automatically enforced in Finite Element Analysis if displacements in transverse direction are left unconstraint [4], [5], [10], [12].

An arbitrary plane exists in the contour method measurement. There are three arbitrary rigid body motions in the described plane. One of these motions is in 2D and others are in 3D: force in x direction and moment in y and z axes. These motions can be determined by the need for the residual stresses in order to get equilibrium conditions for force and moment. If appropriate conditions are applied, a Finite Element Model which is used to solve the stresses will automatically account for the arbitrary motions considering the equilibrium conditions [4], [5].

The steps of the contour method are shown simply at **Figure 10** in below. Firstly, the specimen is cut in two by using wire-EDM. Then, the contours on both cut surfaces of the specimen are measured using any proper machine such as a coordinate measuring machine (CMM) in most studies of literature or an optical machine as in this study. Later, the data processing which is an important step of the contour method is done to obtain appropriate measurements. This process involves filtering noise, removing errors and averaging the measured contours from both cut surfaces. The cutting process can cause that noise occurs and roughness exists on the new surfaces. When FE calculations, undesirable results can be arisen. Therefore, filtering process should be performed to avoid and remove errors.

Averaging is a significant step to prevent effects from the cutting. Because there are some problems during the cutting. For example, the specimen can move or the wire which is component of cutting machine can swan around [6]. After the inverse of the measured contours are taken, the proper values are transferred to any Finite Element Model to calculate the residual stresses. For this step, building suitable boundary conditions is very important. Finally, FE results are post processed to get 2D map of the stresses.

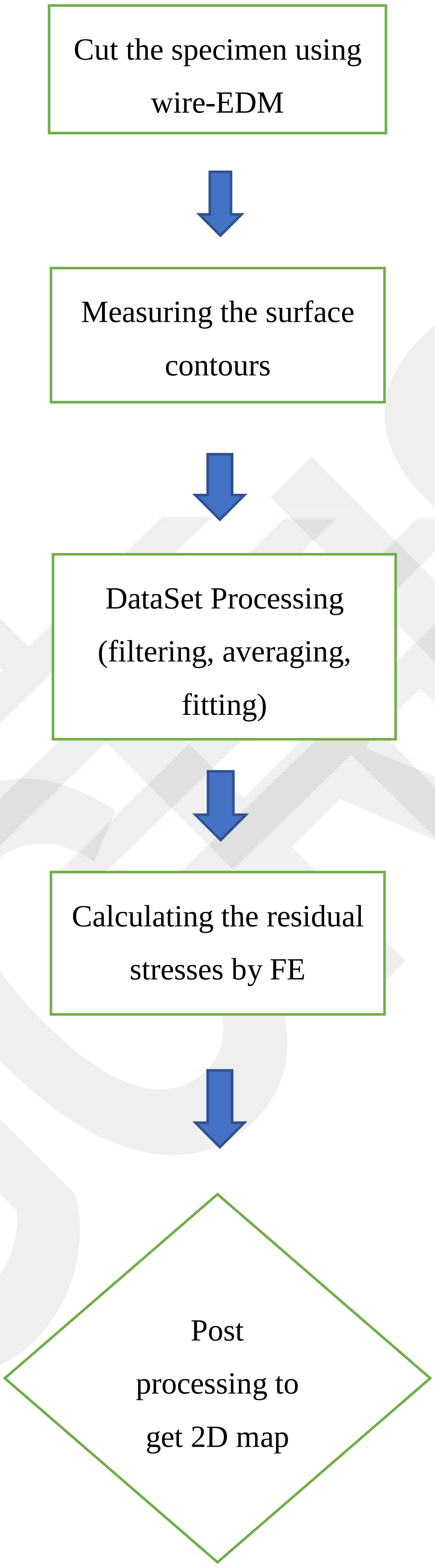


Figure 10: The Flow Chart of Steps of Contour Method

The contour method is relatively simple and inexpensive. This method gives a full 2D map of residual stresses through cross section of component by just using the measured contour on cut surface of specimen. There are no inverse calculations or assumptions about variations of the stresses. Moreover, this method cannot include extra instruments such as strain gages or other during experimental procedure. The required equipment during experiments can easily found in almost laboratories and machine shops. These are advantages in comparison with other measurement methods [4].

CHAPTER 4

EXPERIMENTAL PROCEDURE

This section involves experimental implementation of contour method. All steps from cutting to construction of Finite Element (FE) were explained in detail here.

4.1 Material and Manufacturing History

In this thesis, AA 5083 alloy was used as a specimen. Dimensions of the specimen are 100x60x20 mm (**Figure 11**). The specimen was prepared from a 5083 aluminum plate with 400x400x20 mm dimensions. Those plate was manufactured by the cold rolling process **(Figure 1)**. The specimen used for this thesis was prepared from 400x400x20 mm plates using wire-EDM.

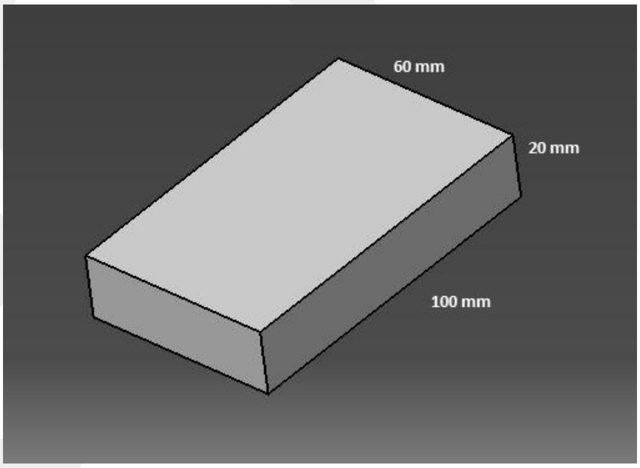


Figure 11: 3D Model of Specimen

When searched the literature, the chemical composition of the AA 5083 alloy and the elements were shown at **Table 1**.

Table 1: The Chemical Composition of AA 5083 (weight percent) [32]

Mg	Fe	Cu	Ti	Si	Zn	Mn	Cr	Al
4.0-4.9	0.40	0.10	0.10	0.40	0.25	0.4-1.0	0.05-0.25	Balance

In addition, the results taken from the spectral analysis and the Vickers hardness values were shown at **Table 2** and **Table 3**. All tests were done at the laboratories of MFCE.

Table 2: Weight Percent of Element after Spectral Analysis

Element	%	Element	%	Element	%
Si	0.230	**B**	0.013	**Mo**	0.018
Fe	0.320	**Ba**	0.0012	**Na**	0.0024
Cu	0.037	**Be**	0.0012	**P**	0.0021
Mn	0.578	**Bi**	0.049	**Pb**	0.014
Mg	5.676	**Ca**	0.0012	**Sn**	0.021
Cr	0.119	**Cd**	0.0019	**Sr**	<0.0010
Ni	<0.0020	**Co**	0.011	**V**	0.049
Zn	0.170	**Ga**	0.024	**Zr**	0.0069
Ti	0.029	**In**	<0.0020	**Sb**	0.056
Ag	0.0024	**Li**	<0.00002	**Hg**	0.096
Al	92.460				

When comparing weight percent of element from the literature and the tests, it is seen that the most of values match the range.

Table 3: The Vickers Hardness

Nr	d_h	d_v	d	HV 0.2
	micrometer			
1	63,32	61,54	62,43	95
2	61,56	62,42	61,99	96
3	60,68	62,42	61,55	98
4	63,32	63,74	63,53	92
5	64,20	64,62	64,41	89
6	63,76	62,42	63,09	93
7	61,12	63,30	62,21	96
8	62,44	60,22	61,33	99
9	62,88	63,74	63,31	93
10	60,24	62,42	61,33	99
11	64,20	65,06	64,63	89
12	62,00	61,98	61,99	96
13	61,12	62,42	61,77	97
14	63,32	62,42	62,87	94
15	62,00	63,74	62,87	94

4.2 Cutting the Specimen

Making the cut is one of the important steps of the contour method. It is very critical process due to deformations on material especially affecting the residual stresses. There should be no plasticity, zero width and no stresses in ideal cutting. Thus, wire Electric Discharge Machining (EDM) is the most suitable method for contour method because of introducing low stress [5].

Making a straight cut is possible using EDM. Therefore, low surface roughness and high quality can be achieved easily [9]. During cutting, ‘skim cut’ settings were used to minimize residual stresses due to cutting. The used parameters during cutting were explained in next section. The specimen was clamped using a special designed a clamping tool to prevent extra deformation on the specimen [12]. Temperature of water in the EDM tank is a sufficient factor when cut process performs. Thus, thermal equilibrium and good conditions are needed to measure main residual stresses [33].

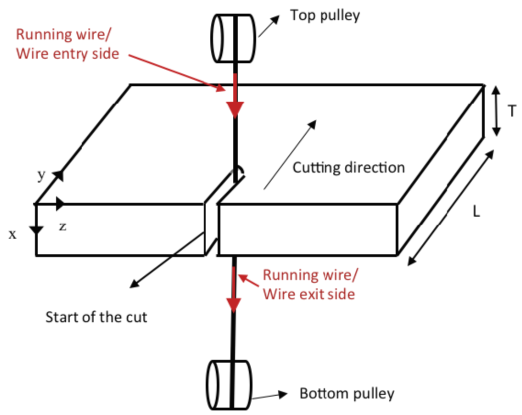


Figure 12: Cutting Specimen via EDM [9]

For this study, the specimen is a cold rolled AA 5083 aluminum plate. For the cutting process, Sodick Premium AQ537L machine was used and zinc-coated wire was 250 micrometer in diameter. Only a single cut was applied on the specimen to prevent any extra stresses to occur. During the cutting process, the special designed clamping tool was used for positioning the specimen. The CAD model of clamping tool and setup position of the specimen can be seen in **Figure 13**. Then, The remainders of the electrolyte was cleaned to avoid the rust formation.

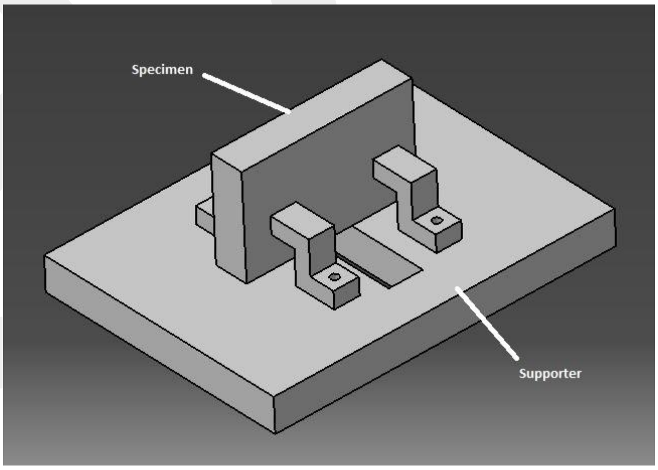


Figure 13: CAD Model of the Clamping Tool and Setup Position of the Specimen

4.2.1 EDM Cutting Parameters

In this section, the parameters used while the specimen was cutting were shown at **Table 4** and they were explaind briefly.

Table 4: EDM Cutting Parameters

Parameters	ON	OFF	IP	MAO	SV	V (Voltage)	SF (mm/min)	WK	WT (g)	WS (m/min)	WP (Hz)
Value	002	118	2215	280	+060.0	8.0	0005	025	110	070	050

ON: Voltage is transferred to wire and specimen when on time.

OFF: Voltage is not tranferred to wire and specimen.

IP (_ _ _ _) : The two values from the right side show maximum value of the current used via machine.

MAO: It is important for stabilization of EDM.

- M controls voltage.
- A controls OFF time.
- O controls ON time.

SV: It controls feed and backflow of wire.

V: It shows supply voltage between specimen and wire. It can be valued from 0 to 9.

SF: It shows maximum servo speed.

WK: It shows material and diameter of wire. The two values form the right side show dia of the wire and third value shows material.

0-Hard Brass, 1-Soft Brass, 2-AP, 3-Tungsten and 4-Molybdenum.

WT: It shows maximum wire tension.

WS: It shows speed of wire.

WP: It shows water pressure which controlled by flush pump.

4.3 Measurement

Measuring the surface contours on cut planes is a critical process to reach correct values of residual stresses. Therefore, a machine which has high level precision should be chosen. In general, Coordinate Measurement Machine (CMM) is commonly used and appropriate for desired purpose [10]. Also, laser scanners can be used to obtain the similar measurement results as CMM [5]. However, a metrological machine more sensitive than CMM was preferred in this study. It is called as **ALICONA InfiniteFocus (Figure 14)** which can do a 3D micro measurement. A software works with ALICONA was used. It is GOM Inspect. This software has many functions such as CAD import, inspection of surface defects, curvature-based inspection and GD&T analysis. Thus, this machine was preferred to make this study be easier and faster.

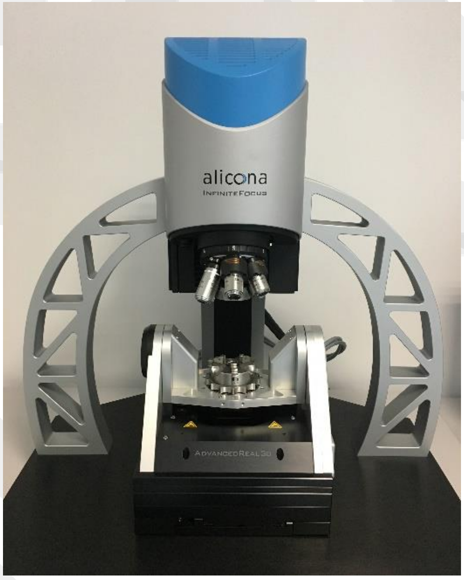


Figure 14: The Optical Metrology Machine (ALICONA)

During experiment, some measurements were made via lenses with different magnification and were compared each other. For this study, 5X magnification lenses were used. Although there are some disadvantages for big parts (time consuming due to large area and too much data) and very small parts, ALICONA is the best choice to this study.

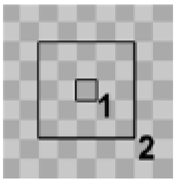
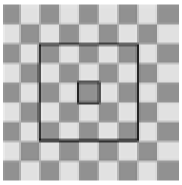
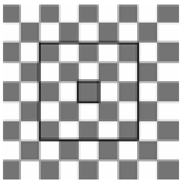
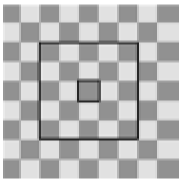
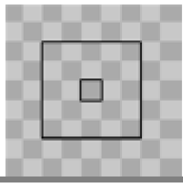
4.3.1 Focus Variation

The focus variation is a method that uses optics to measure surface topography in limited depth of area. This method has existed since 1924. However, it is recent for measuring surface texture when compared to other methods. The application area of this method is wide. Focus variation uses the best positions of the optical element from the specimen to measure surface during scanning laterally. There are four main components of focus variation instrument. These are an optical system, light source, a CCD (charge-coupled device) sensor and a driving unit [34].

During measurement, light is not reflected directly to sample surface because of variations. Therefore, the light is captured by the objective in different directions and then, pictured to semi-transparent mirror and tube lens to a CCD sensor. The light is reflected in various degrees over a CCD sensor depending on vertical position of the specimen. When the degree of focus is diversified by moving the specimen, contrast on the CCD sensor is changed. The position of sample on focus is specified via analyzation of contrast change. The surface topography is obtained with every lateral measurement. Also, the color of sample can be identified on this way.

The small regions which stay around pixel position must be kept in mind when measuring contrast change. Because they are important in resolution. The standard deviation of grey values of small region is calculated by one of methods which measure contrast in the image of CCD sensor. The grey values are almost same and their standard deviation will be low when focusing level is low **(See Table 5).** In otherwise, the grey values are very clear. Thus, high level values will be obtained in focus measurement.

Table 5: The Grey Values Level of Specimen and Their Standard Deviation in Different Positions [34]

Scan position	Surface image	Standard deviation
Out of focus		10
Almost in focus		20
In focus		50
Almost in focus		20
Out of focus		10

The following step in focus variation method is to calculate focus curve and its maximum value. There is a peak **(See Figure 15)** equal to the most focused place in focus curve. This peak point can be determined by using three different methods. These methods are maximum point, polynomial curve fitting and point spread function curve fitting.

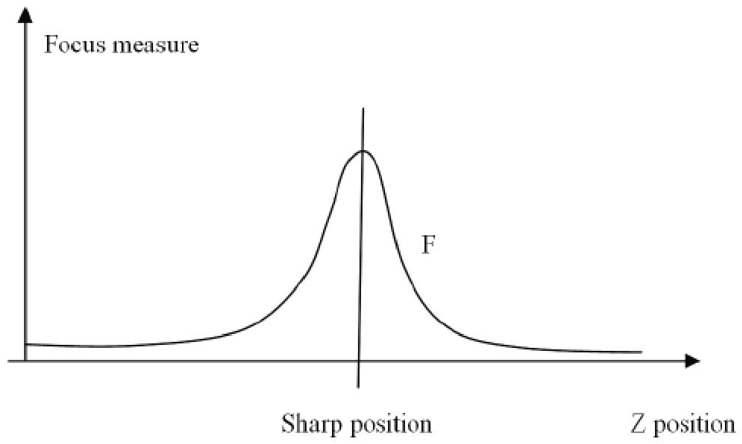


Figure 15: The Changes of Focus vs. Z axis Position [34]

In maximum point method, the depth value is calculated in out of rank of the largest focus information by using equation 5.1. This method is very fast but its accuracy is the lowest.

$$depth = \arg(maxF_z) \quad for \quad z_1 \leq z \leq z_z \tag{4.1}$$

In polynomial curve fitting method (equation (5.2)), a polynomial curve, p(z) is fitted by using the left and right points around maximum focused point via the least square technique (equations (5.3), (5.4) and (5.5)). Higher resolution of depth value is advantage for this method.

$$p(z) = az^2 + bz + c \tag{4.2}$$

$$min_{a,b,c} \sum_{z_1 \leq z \leq z_z} (F_z + [az^2 + bz + c])^2 \tag{4.3}$$

$$p'(z) = 2az + b = 0 \tag{4.4}$$

$$z_{maximum} = -\frac{b}{2a} \tag{4.5}$$

F_z is amount of focus and z is height.

In point spread function curve fitting method, the measured focus values are benefited to fit function. The depth values are obtained by calculating maximum of the function. This method is the slowest but very accurate. The depth map will be getable when maximum detection is implemented for all lateral positions of CDD sensor.

The post-processing should be performed because there are non-ideal focus and other effects. There are several steps in post-processing procedure. Deleting non-ideal depth values is important step. There are two criterions for deletion. First might be the quality of curve in polynomial fitting. Second might be colour information. After deletion, the holes can stay in depth map. Filling algorithm is a good way that uses height information of the nearest valid neighbour points. Generally, the points around the hole are used with spline or NURBS interpolation. However, such these interpolation steps are not good when the resulting dataset is used for the determination of surface texture.

After measured points deleted using post-processing, this information must be protected for calculations. This could performed by using a valid map or certain depth values. Also, values can be not a number. It should be careful that invalid depth maps symbolize a single point or an area for texture calculations. Handling invalid points is very important issue. Therefore, there are two steps for this implementation. First is filtering using a convolution of depth values. Second step is integration of depth values. If there are invalid points in depth map, boundary of integration is equivalent to boundary of valid points.

When the focus variation method is compared to other two methods which are imaging confocal microscopy and point auto focusing techniques, there are several differences. For imaging confocal microscopy, there are two important differences. One of these is width of the curve to calculate maximum sharpness. Although confocal microscopy has poor quality in vertical resolution, it gets larger range than the focus variation. Second difference is that confocal microscopy use coaxial illumination. This can provide a result for limited slope angle. In case that the focus variation compares to point auto focusing techniques, there are two main differences. The first difference is that point auto focusing uses a single point. There is a need to move a specimen laterally. In the focus variation method, many points are measured in a specific area. Other difference is that focus variation works in way as vertical scanning.

4.3.1.1 Apparatus

Previously, the components of focus variation method were mentioned briefly. Now, these components will be explained in this section. Firstly, the components of focus variation method are shown below:

- Optical system
- Light source
- a CCD sensor
- microscope objective
- driving unit
- and PC with software.

Optical system is very important part. Because the focus variation works by determining the depth positions. The maximized contrast information is needed. Therefore, detecting path of the optics, maximizing the optical transfer function and minimizing stray light are required. Moreover, the basic lenses are not satisfactory due to that the focus variation uses colour information.

CCD sensor can detect the light from the specimen. In order to obtain high contrast, the characteristic of the sensor must be high radiometric resolution or high spatial resolution. A high radiometric resolution is necessary for calculation of focus in low contrast specimen and the sensor can be a colour sensor in this case. A high spatial resolution is necessary for minimizing region during focus calculation and the sensor can be a monochrome sensor.

The light source is important for focus variation method. The material and geometry can affect the measurement. The light is reflected in order to create an image on CCD sensor. Because this method uses contrast on the image. The features below is needed for light sources to get high measurement quality. These are;

- ✓ Spectrum of the light source
- ✓ Polarization of the light and
- ✓ Direction of illumination.

Polarized light is efficient for metallic sample. Direction of light source is important to obtain high quality contrast. For focus variation, there are 5 different variety light sources. These are coaxial illumination (a), ring light (b), dark field illumination (c), diffuse illumination (d) and point light (e) (**See Figure 16**).

The spectrum of light source is significant for sample and CCD sensor. Therefore, a white light source can used. The LED light is beneficial due to stability and long lifetime.

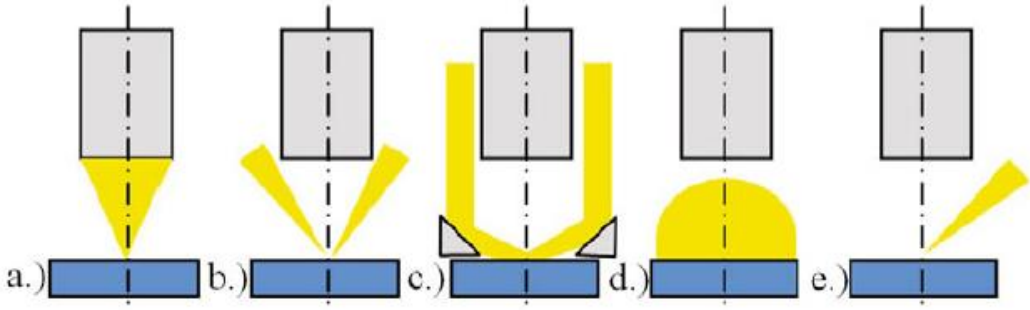


Figure 16: Individual types of illumination [34]

It is beneficial that microscope objective with high numerical aperture is used in order to achieve a high resolution for focus variation.

For focus variation, the driving unit is very important component to obtain good speed of measurement and gain good accuracy. There are several types of driving unit. One of them is direct drives. This type is good at the highest speed. However, using in vertical direction is hard. Other type is piezo-electric drives. This type consists high resolution. Though, it has got limited range. Third type is spindle drives which have high resolution, large range and ability of driving a high load.

In order to obtain a higher quality results, choosing the right parameters and settings is very important process during surface texture measurement. Choosing correct lenses with high resolution, using the correct light source, adjusting the settings of sensor, arranging the scan range and adjusting resolution in vertical and lateral direction should be optimized for a good application.

The focus variation method has some limitations as with other methods. Using translucent materials are complicated to measure. Also, there should be a measurable surfaces because the focus variation runs a range of focus values to map surface topography. For this, the contrast is needed. The light source, sample surface and optical system identify contrast amount. For creating contrast, there is two way. These are material change effect and topography variations effect.

For complex problems or applications, there are some extensions in focus variation principle. These are repeatability information, high radiometric data acquisition, 2D alignment and 3D alignment. Flexibility is advantage of optical metrology. However, uneducated users can reach incorrect results due to this flexibility. In repeatability information which is one of the extensions, a mathematical model is fitted into focus point. There can be linear of non-linear optimization model in math model. It was mentioned that focus variation method works by using contrast in previous section. Sometimes, there could be areas with low brightness due to different on flat or steep **(Figure 17)**. High radiometric data acquisition includes a solution that varies amount of lightning or pose of image on the CCD sensor to create one image. The steps of the solution is respectively shown below:

1. Specify the necessary pose range for CCD sensor
2. Make several images in pose
3. Reunite images to one image

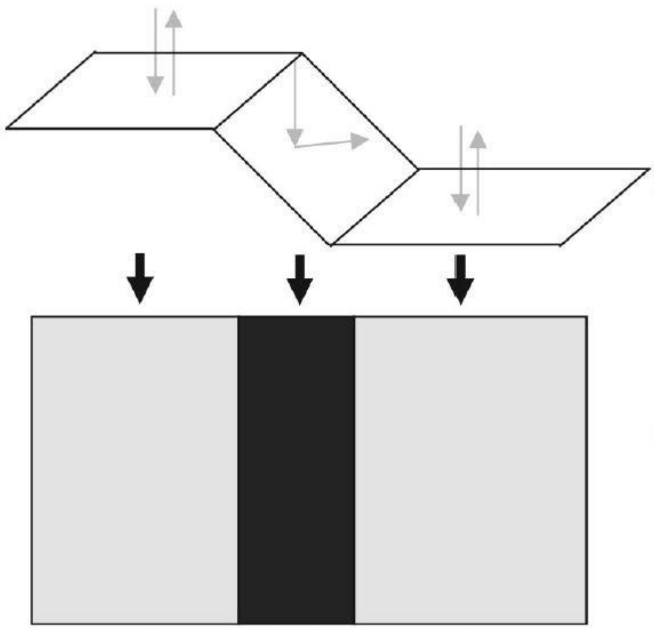


Figure 17: The different brightness resulted on the CCD sensor due to the light reflected from the flat area and the steep area [34]

2D and 3D alignments are two ways that can ensure better accuracy from measurement datasets. In 2D alignment, there are some steps below to increases accuracy of the fine alignment from dataset.

1. Achieve individual datasets with overlap at positions of the x-y stage.
2. Refine the positions of datasets by using information in the overlap region of neighbor datasets.
3. Reunite the individual datasets at the positions which were purified.

In 3D alignment, the rotation unit which has three translations and three rotations is used to ensure a high accurate 3D datasets. This procedure includes similar steps as 2D alignment [34].

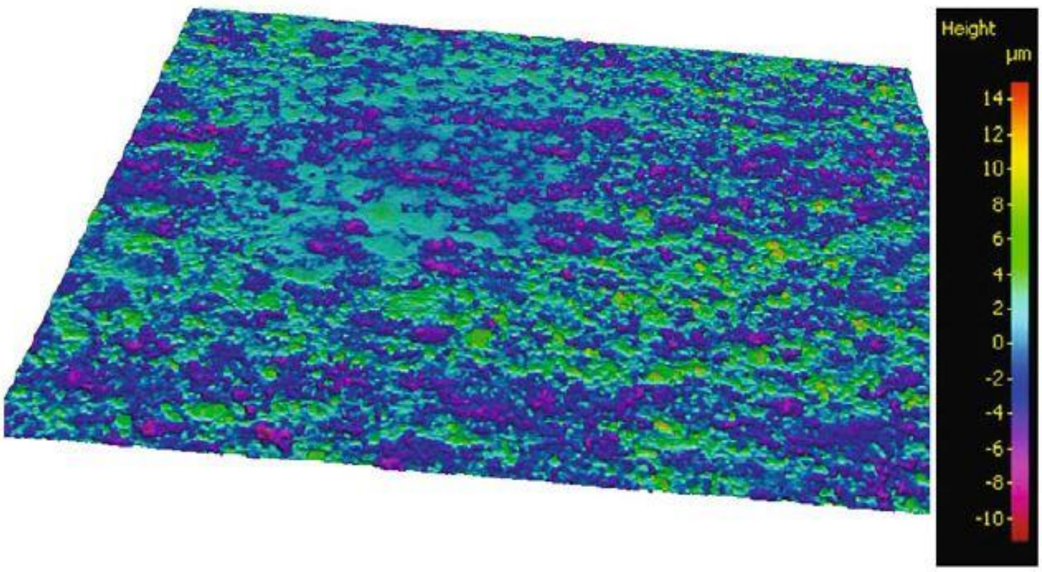


Figure 18: 3D colored measurement image [34]

4.3.2 Processing Data from Measured Surfaces

In this section, measurements taken via different lenses were compared. These lenses are 5X and 10X. The resolution of them are different. For 5X lens, vertical resolution range is from 410 nm to 4.5µm and lateral resolution range is from 3.52 µm to 22.5µm. For 10X lens, vertical resolution range is between 200 nm and 1 µm, lateral resolution range is between 1.9 µm and 10 µm. Data from each sides of specimen cut surfaces was processed using a software, which the optical profiler has. It is called as GOM

Inspect. This software is used to analyse 3D data obtained via CMMs, laser scanners or optical profilers such as used in this research. During this step, data is filtered from surface roughness and became clean from the noise caused by physical process of measurment. Also, averaging the measured contours occurs when both cut surfaces after cutting are placed on different planes and overlapped each other. After the 3D data was fixed to a determinated plane, data corresponding to a certain axis was left constant. The coordinates of the data corresponding to other axes were read. The transformation from 3D to 2D was procured in that way.

In addition, there were parameters depending a person who uses the software. The determination of the area to be taken for measurement may be from such parameters. For this thesis, the red line, which was drawn in the middle of the cut surfaces of both specimens gave the data to calculate the residual stresses. Since only elastic deformation occurs on the specimen, line can be specified on the desired direction such as **Figure 19**.

Figure 19: The Data were taken along the Red Line

As it was mentioned above, the measurement includes surface roughness and noise. These were filtered using GOM Inspect software before data processing in MATLAB. Thus, the data became smoother for next steps such as curve fitting process. Using ALICONA InfiniteFocus was beneficial to get the best data in order to reach residual stresses inside the specimen. Then, the 2D graphs were plotted in MATLAB. They were compared each other. According to the data obtained from both cut surfaces and depending on the principles of the contour method, it was observed that the surfaces exhibited an inverse character to reset each other.

Moreover, according to the graphs **(Figure 21 ve 23)** , similarities between lenses (5X and 10X) are very close. Therefore, any lenses can be used. It may differ depend on aim of the study, lots of data and desired resolution.

The graphs plotted in MATLAB can be shown below. For **Figure 21**, the specimen C1 was cut in direction as **Figure 20.** For **Figure 23**, the specimen B5 was cut in direction as **Figure 22.** The blue and red lines were plotted by using the surface contours which were measured via 5X lens. The green and magenta lines were plotted by using data measured via 10X lens. Moreover, the blue and green lines express left sides of both specimens. Other colors express right sides of both specimens.

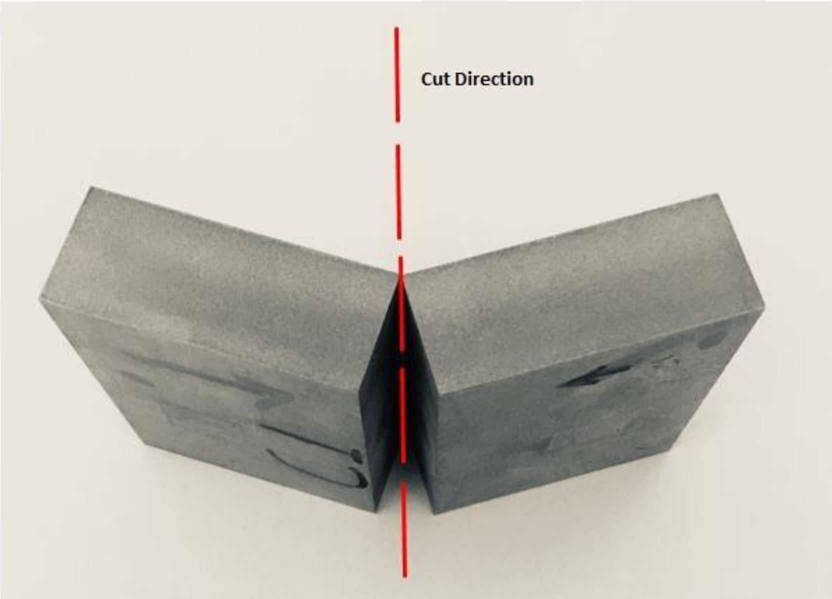


Figure 20: Specimen C1 Cut Direction

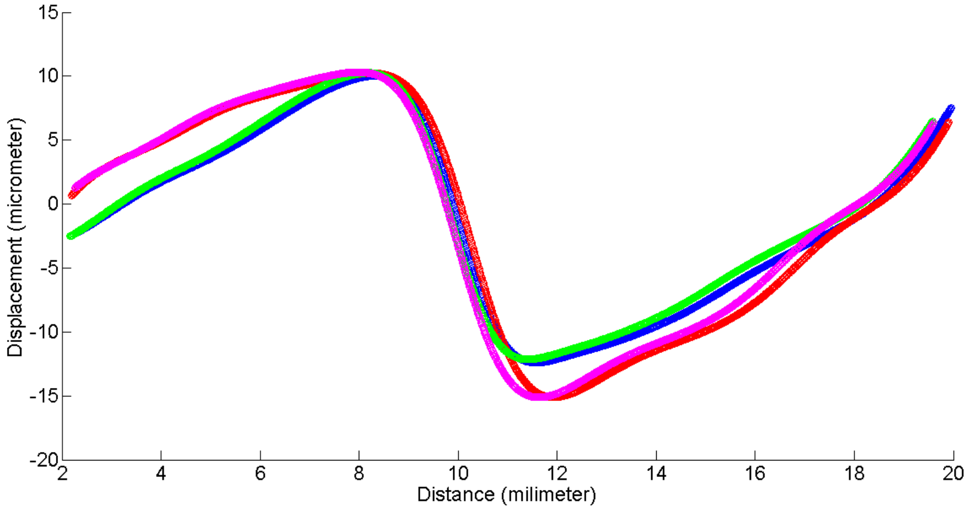


Figure 21: The Displacement Profile in Left Side (Blue, Green) versus in Right Side (Red, Magenta) in 2D for Specimen C1

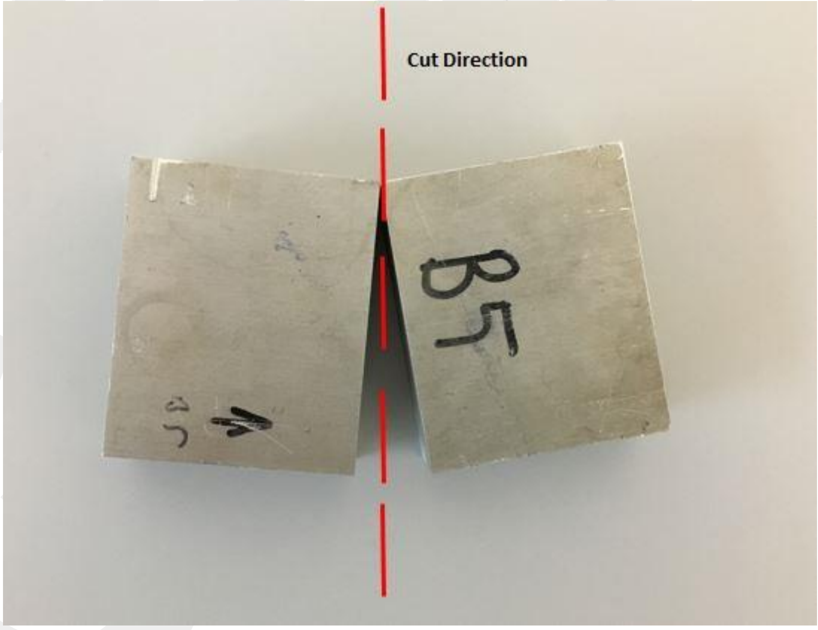


Figure 22: Specimen B5 Cut Direction

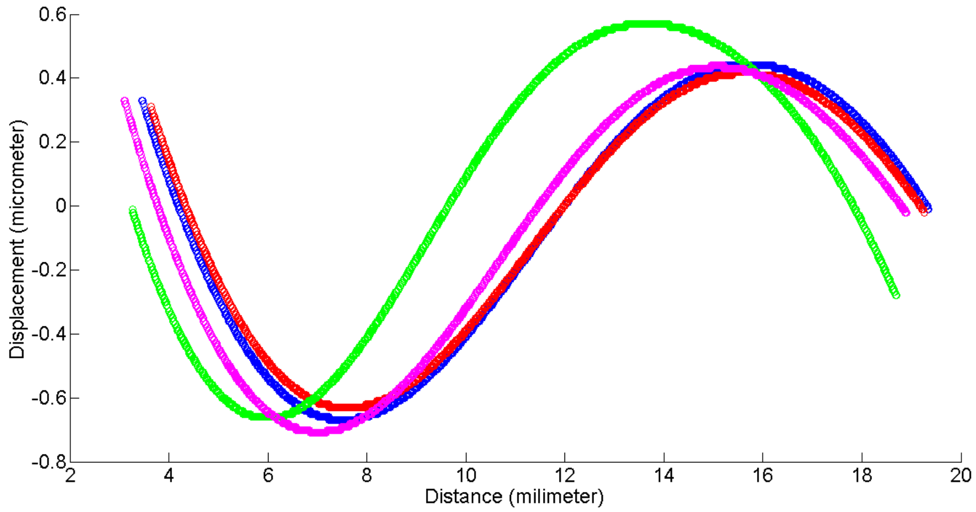


Figure 23: The Displacement Profile in Left Side (Blue, Green) versus in Right Side (Red, Magenta) in 2D for Specimen B5

4.3.3 Curve Fitting Tool

In this section, the measured contours from the cut surfaces of both specimens B5 and C1 were processed to be applicable for FE analysis. Therefore, the Curve Fitting which is one of application tools of MATLAB was applied on the measured contours plotted by using MATLAB. Then, the obtained formula by using that tool was used to spread the measured contour data uniformly to surface of the specimen in order to calculate the residual stress. The curve fitting applications for two specimens C1 and B5 were shown at **Figure 24 and Figure 25**. The fitting curves on the plotted contour values were shown with helping red arrow.

The obtained formulas for specimens C1 and B5 are 9^{th} (ninth) degree. They were used to fit the measured contours from the cut surfaces of the specimens. Also, the equations with high degree were important to get the smooth transition between data. General equation was shown below. Also, coefficents of the equation exists at **Table 6**. The coefficients and the equation were used to calculate the displacement value applied to specimen during FEA. Also, they were auxiliary factors to find the stress values.

$$f(x) = p1 * x^9 + p2 * x^8 + p3 * x^7 + p4 * x^6 + p5 * x^5 + p6 * x^4 + p7 * x^3 + p8 * x^2 + p9 * x + p10 \quad (4.6)$$

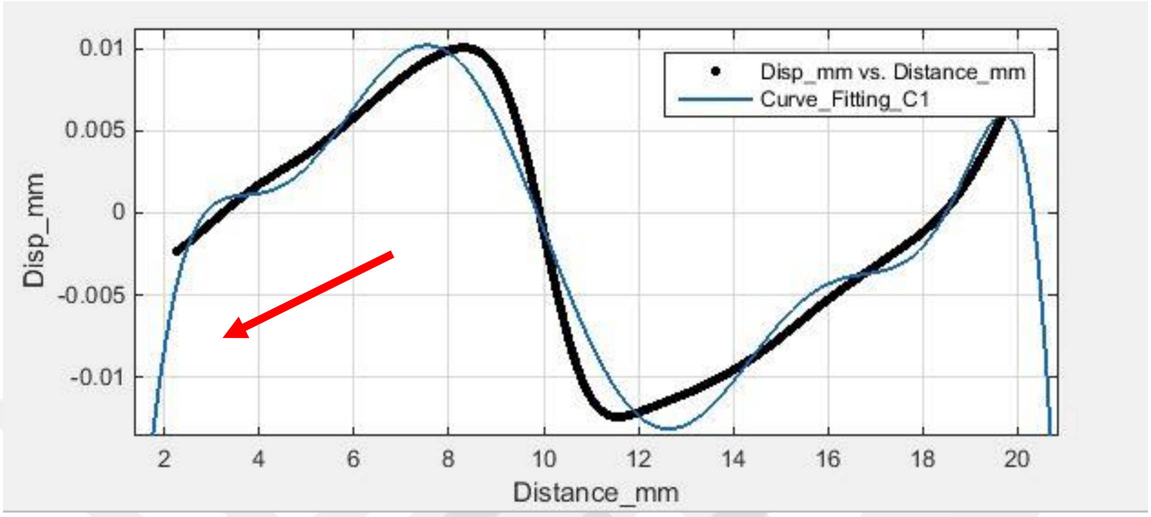


Figure 24: The Curve Fitting Application for Measured Contours from Specimen C1

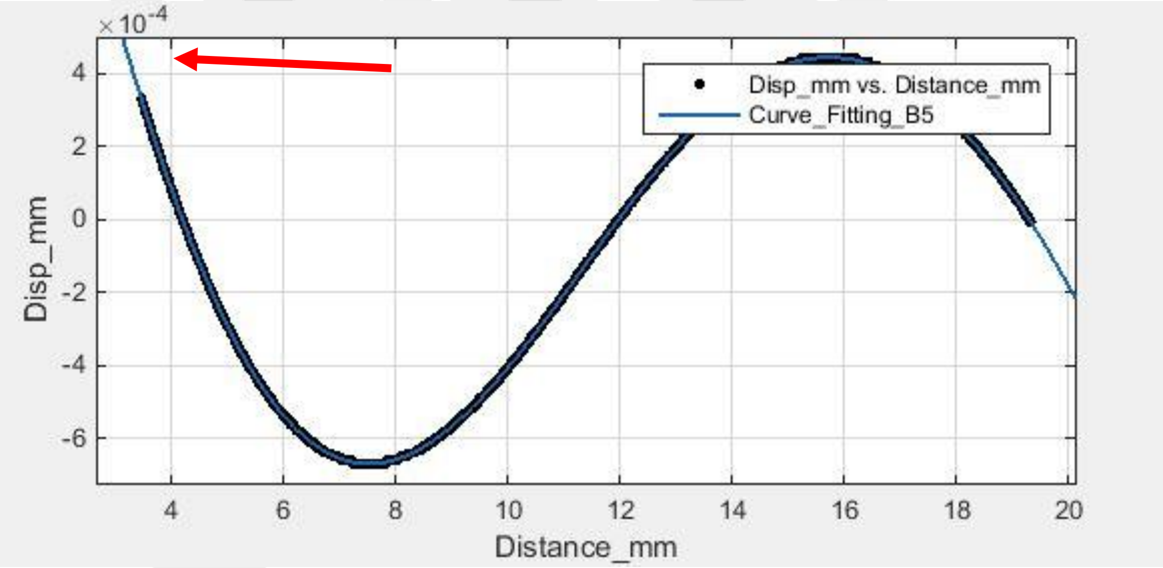


Figure 25: The Curve Fitting Application for Measured Contours from Specimen B5

Table 6: Coefficients after Curve Fitting Tool

Coefficients	Specimen C1	Specimen B5
P1	-5.0400E-10	1.6600E-12
P2	4.3690E-08	-1.7410E-10
P3	-1.5310E-06	7.8050E-09
P4	2.7280E-05	-1.9620E-07
P5	-2.4720E-04	3.0660E-06
P6	7.8910E-04	-3.1260E-05
P7	4.0690E-03	2.0800E-04
P8	-4.2160E-02	-7.9780E-04
P9	1.2770E-01	1.0480E-03
P10	-1.3390E-01	8.9440E-04

4.4 FEM and Calculation Residual Stresses

This section includes description of modelling in FE, how to apply the measured contours from cut surfaces to FEM and calculation of residual stress on the cold rolled aluminum plate. As it was mentioned in previous chapters, the contour method has no inverse calculation. This makes the contour method be simple.

After measurement step, the obtained data were processed. This process was mentioned in detail in previous sections. Data process is important about filtering noise, averaging the measured contours and fitting data. Averaging data is a significant step to prevent asymmetric effects as it was explained in previous sections. Then, the obtained steady data were used for FEM application.

Before FE analysis, direction of inverse of the measured contours and boundary conditions for fixed dipslacement were identified. The aim is to reach an analysis as similar as experimental conditions. By this means, the expected stress values and profiles can be found easily. For this study, MSC Marc Mentat Software was used for

FEA. After cutting process, the dimensions of the specimens were changed. During FE analysis, the applied boundary conditions (BCs), dimensions and load case can be found in **Figure 26**. These conditions were applied for 2D and 3D simulations. Adding z axis for 3D analysis was only difference.

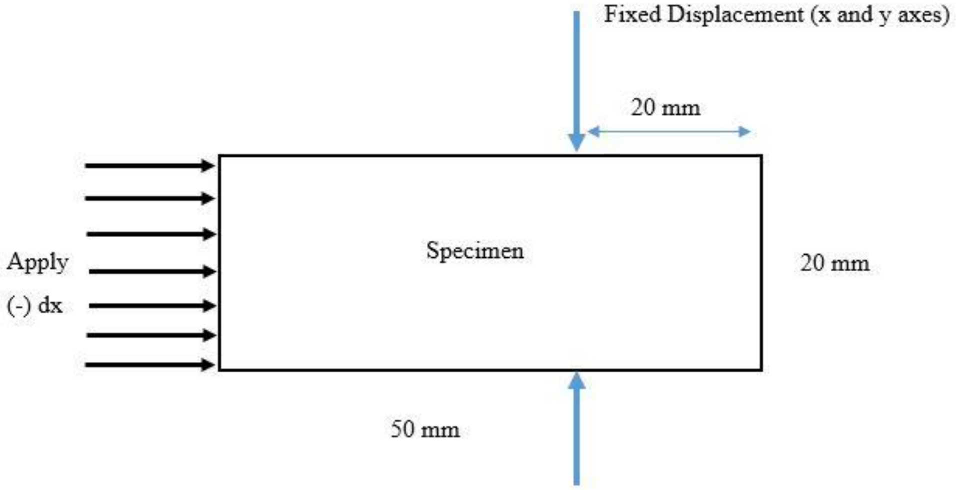


Figure 26: BCs, Dimensions and Load Case for FE Analysis

Depending on analysis type, the used elements and their numbers were changed. This is important to get the best results. Thus, the used element types were shown in **Figure 27**. The full integration was preferred in this thesis. For 2D analysis with plane strain assumption, quadratic element (quad 8) was chosen. Also, hex 8 element was chosen for 3D analysis.

Plane strain assumption was used to make the analysis be simple. In plane strain, it is assumed that dimensions in z directions are larger than dimensions in x and y direcitions. It means that the important and considerable loads apper in xy plane since the specimen is infinite in z-diection. In other words, there is no change in z-direction. Displacement values was used because of plane strain. In the plane stress assumption, there is no change in displacement along z-direction since the specimen is very thin. Additionally, no stresses exist in z-direction. Thus, plane strain assumption was used for 2D analysis.

The problem was initailly defined in 2D conditions. This provided simplicity to pass to 3D conditions as it was mentioned above. The small strain approach was used due to depending on principles of the contour method. This is because it was assumed that only elastic deformation on the specimen occurred.

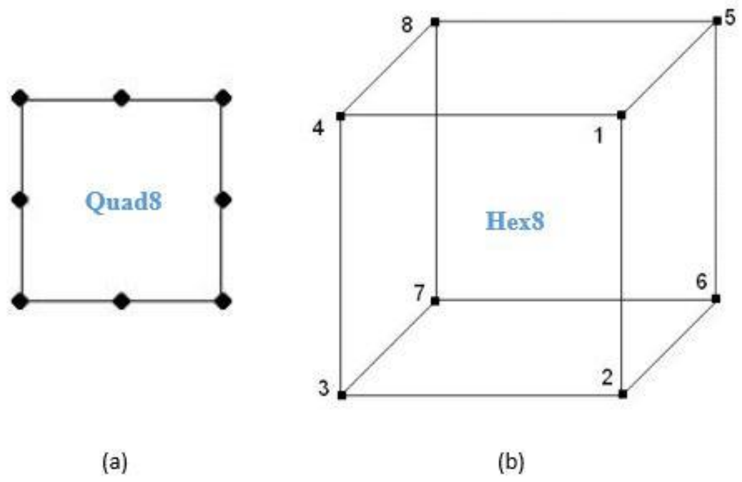


Figure 27: Element Types a) Quad 8, b) Hex 8

After analysis, stress distributions on both specimens C1 and B5 were shown below. Specimens C1 and B5 were divided in 100 elements through x direction and in 50 elements through y direction. According to several trials, the increase in the number of elements did not cause very large changes. However, if more sensitive results are wanted, number of elements can be increased.

Figure 28: Stress Distribution on Specimen B5 (2D)

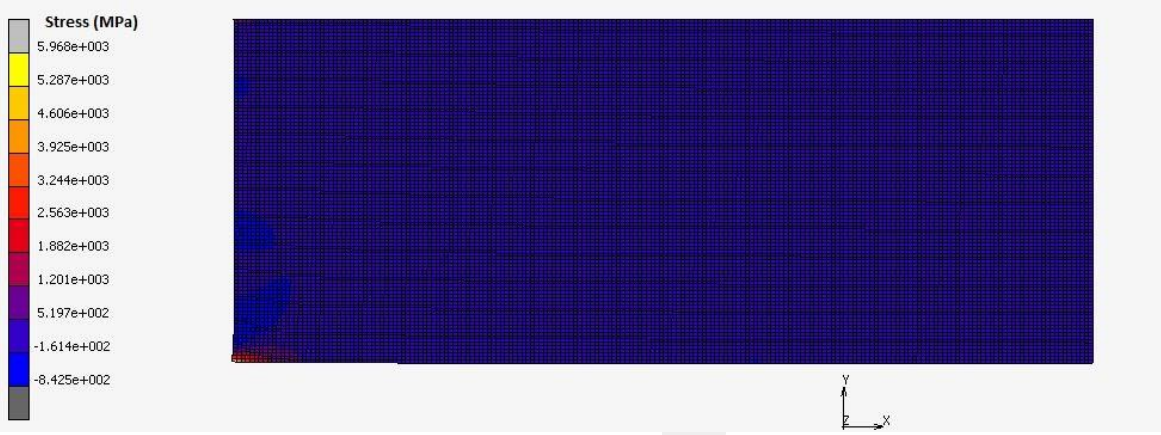


Figure 29: Stress Distribution on Specimen C1 (2D)

When looking at stress values of specimen C1, it was specified that there was a mistake. It was observed that 10-fold difference existed in between values of diplacement of both specimens. Although measurements were iterated, no different results were obtained. For this reason, it was decided that specimen B5 would be kept using for 3D analysis. Firstly, 60000 elements were used to calculate stress. Then, 240000 elements were used to reach finer results. Negative displacements were applied on related surface of 3D model. In order to get homogeneous distribution, formulation obtained from curve fitting tool was used. **In Figure 30 and 31**, stress distribution on specimen B5 can be seen.

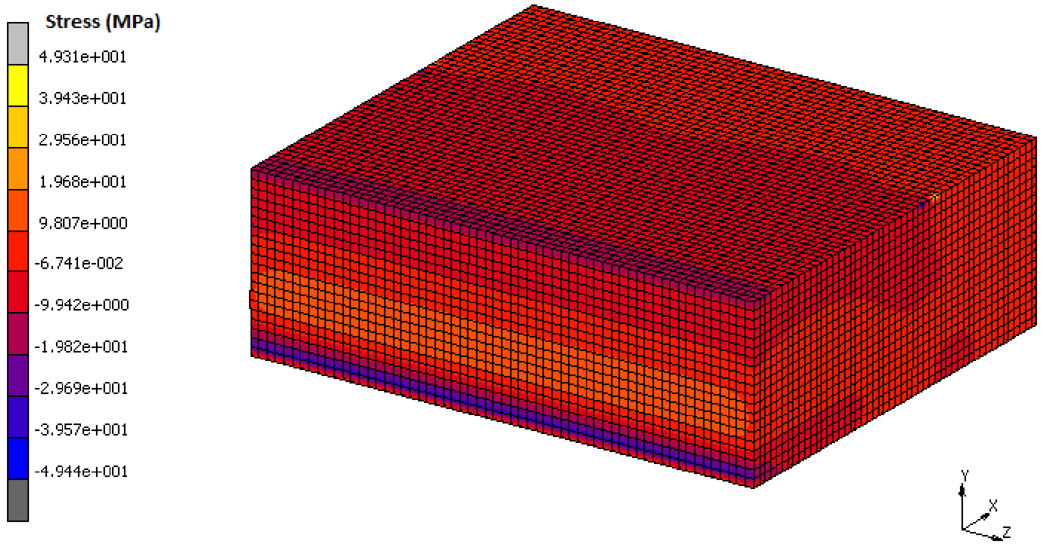


Figure 30: Stress Distribution on Specimen B5 (60000 elements, 3D)

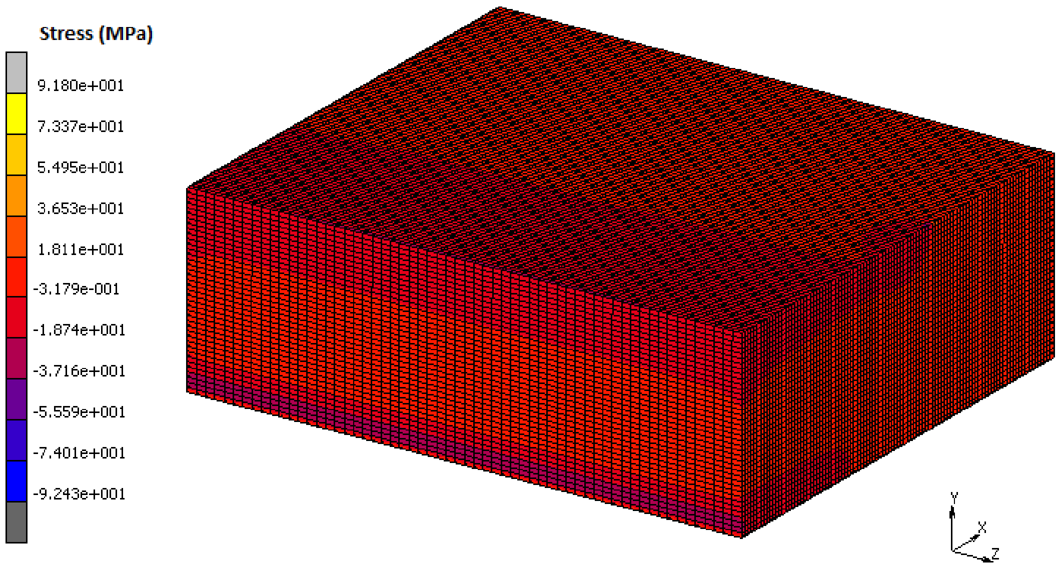


Figure 31: Stress Distribution on Specimen B5 (240000 elements, 3D)

CHAPTER 5

RESULTS & DISCUSSION

This section includes results ofthe contour method and comparisons with slitting and ring core measurements. MARC Mentat which is a FE analysis program was used to calculate residual stresses on the specimen. FE application is last step of the contour method. The measured contours from the cut surfaces of the two (C1 and B5) specimens were used to determine residual stresses by FE after dataset processing. Both 2D and 3D analysis were done. Plane strain model was chosen for 2D analysis. Firstly, models of the specimens were built. As it was mentioned in previous chapters, dimensions of the specimen were 100x60x20 mm. After cutting step, lengths of the specimens were dropped to 50 mm **(Figure 32)**.

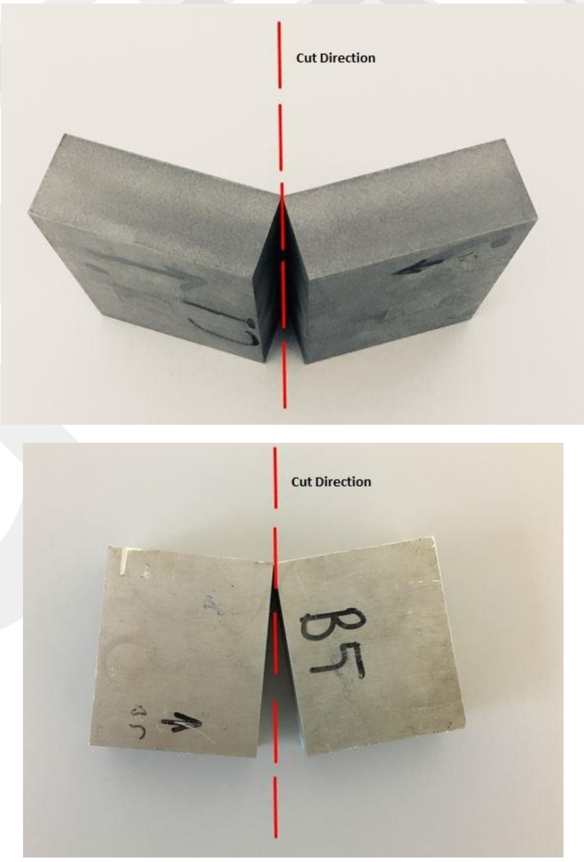


Figure 32: The Two Specimens from Same Material after Cut

Moreover, results calculated by using the contour method were compared to results obtained via the slitting method and ring core method. In following sections, models set in FE, results and comparions can be seen.

After the surface contours measured from cut surfaces of the specimen C1 were applied to FEM, residual stresses were obtained. Then, these stresses were plotted through the arc length. Arc length is a distance that is between bottom and top of cut surface. 2D model was used and plane strain was choosen. 2D stress map over the cross-sectional area was shown below **(Figure 33)**.

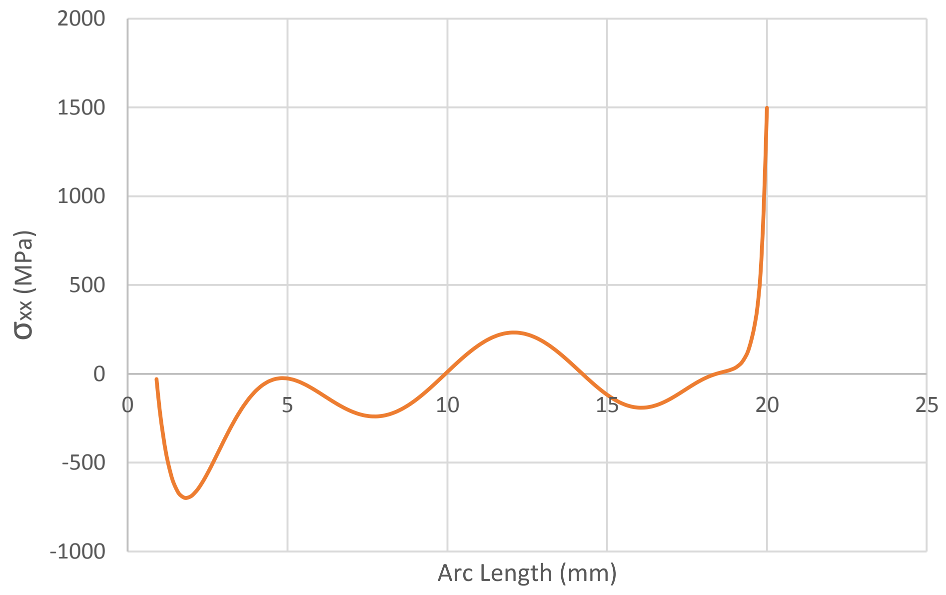


Figure 33: Residual Stresses on Cut Surface of Left Side of C1 by Contour Method

According to **Figure 33**, values of the residual stresses were bigger than expected. There may be several reasons for the undesirable situations. These may be plastic deformation on the specimen and it is still continuing. Thus, evaluation of the results related the specimen C1 was stopped.

When looking at cut surfaces of specimen C1, it can be seen easily that an unexpected fault happened **(Figure 34)**. A line caused by cutting process was occured in middle of the cut surfaces. This could be cause that displacement differences through cross-sectional surface took place. Furthermore, the specimen C1 might have moved during cutting and it might have been freed from the clamping tool. This might have caused plasticity and the displacement values might have been affected. for this reason, stress distribution within the specimen C1 was observed higher than expected. For applications of the contour method, the test sample can be clamped enough rigidly as possible to minimize the cutting plasticity [35].

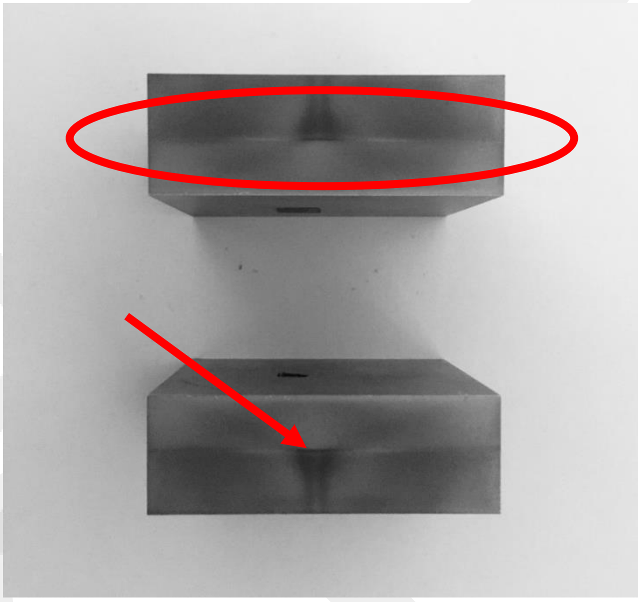


Figure 34: Specimen C1 after Cut

Although there were some problems for specimen C1 as it was mentioned above, an expected trend was observed for specimen B5 **(Figure 35)**. The stress distribution on the material produced by cold rolled process occured as expected profile. Compression was seen on location close to surface of the specimen. In middle of the specimen, it was observed that a transition from tension to light compression existed. This research has the characteristics of continuing the Slitting method. The Slitting method is a technique that is generally used for residual stress measurement on the material with high thichness. The results obtained from the slitting method were given a part in this study. Measurements were performed by slitting method on the specimen used in thesis. In **Figure 36**, the stress distribution obtained via slitting method on the specimen can be seen easily [36].

The results were quite similar when looking at **Figure 35 and Figure 36**. There is a small difference. This is a range of the arc length. The values of arc length were choosen between -10 an 10 milimeters for the slitting method and were selected in between 0 and 20 milimeters for the contour method. The reason for this can be due to the differences in implementation in both methods.

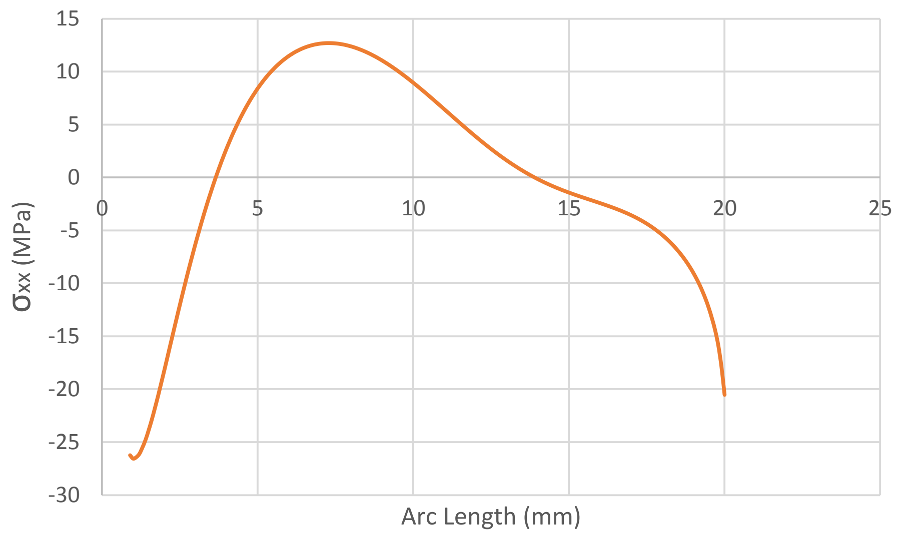


Figure 35: Residual Stress Profile on Cut Surface of Left Side of B5 by Contour Method

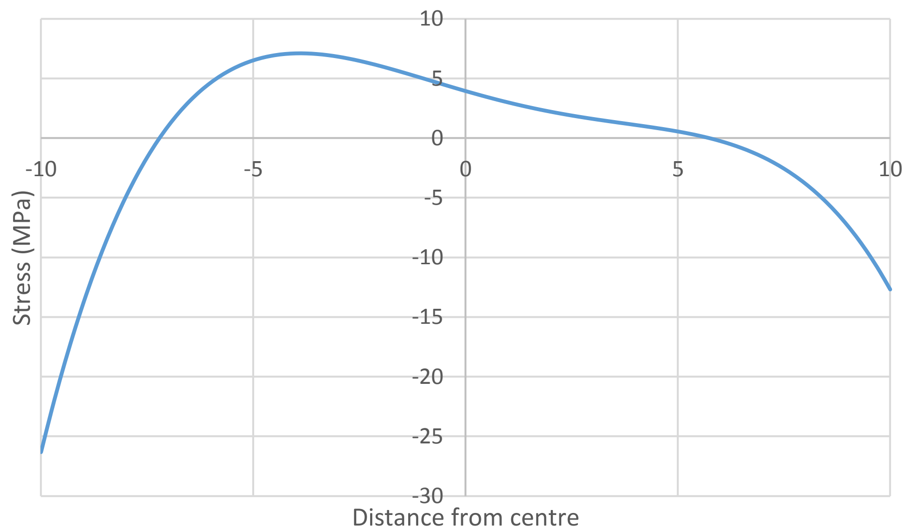


Figure 36: Stress Distribution Profile in Slitting Method [36]

Due to nature of cold rolled process, it is expected that there are uniform stress distribution on top and bottom surfaces of the material. However, there were some differences on measurements by slitting method. The reason for this can be that only one strain gage was used for measurement. The strain gage took measurements from bottom surface of the specimen. Thus, a signal taken from top surface during cutting process can be weak. These differences between top and bottom surfaces came up for Slitting Method **(Figure 36)**.

For the contour method, the mentioned differences were less than in slitting method. This is because data was optically collected through the thickness after cutting via EDM. This could cause that data were homogenous. Consequently, there were less differences between top and bottom surfaces of the specimen for the Contour Method **(Figure 35)**. As it was mentioned in previous, cutting process is very important for the contour method.

The difference between contour and slitting method was normal because only one strain gage was used to measure residual stresses for slitting method. Due to weakness of the signals, there can be variations between both two methods. More than one strain gages can be used to prevent this problem.

The stress distribution results obtained from specimen B5 were compared to the results from the sample made by same material via Ring Core Method **(Figure 37)**. The arc length was selected in between 0 and 5 milimeters for comparison. It was seen that the results were different. It has already been expected because two different approachments were used to map residual stresses through cross-section of the specimen. Despite the fact that the trends of the stress profiles of those two different methods were not similar to each other, minimum and maximum stress values were close with some percentage of errors. However, it can be mentioned that convergence exists.

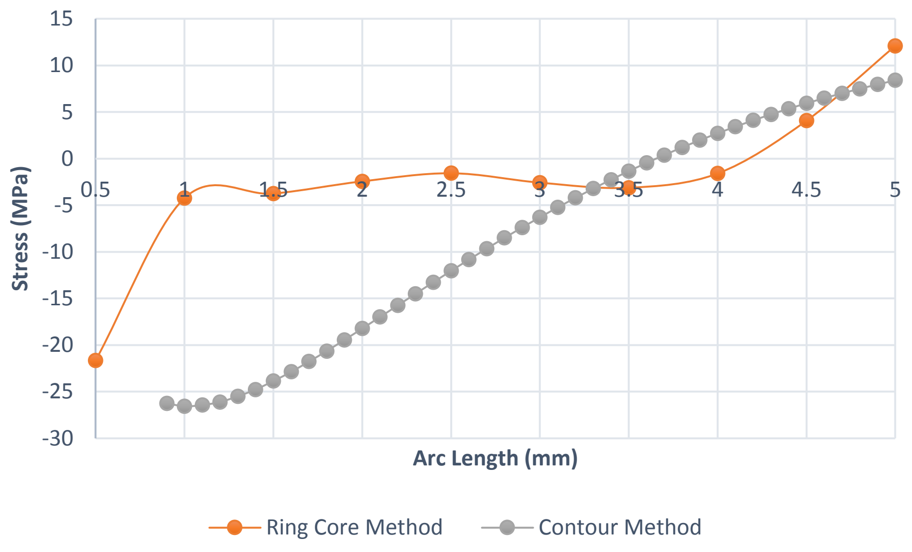


Figure 37: Ring Core Method [36] and Contour Method Stress Measurement Comparison

In **Figure 38**, stress profiles attained from two different approaches which are Slitting and Ring Core methods were compared [36]. It was observed that differences existed. Therefore, the trends of the stress distributions were dissimilar. Minimum and maximum values of stresses were close.

According to the results, the closest similarity was seen in comparison between Contour and Slitting methods **(Figure 39)**. The stress profile trends exist very close. Also, stress values obtained from contour and slitting methods are nigh close too. This study has already the characteristics of continuing of slitting method as it was mentioned before. As a result, the contour method has similar agreement with comparing other residual stress measurement techniques. Thus, this research was a good experiment on cold rolled parts.

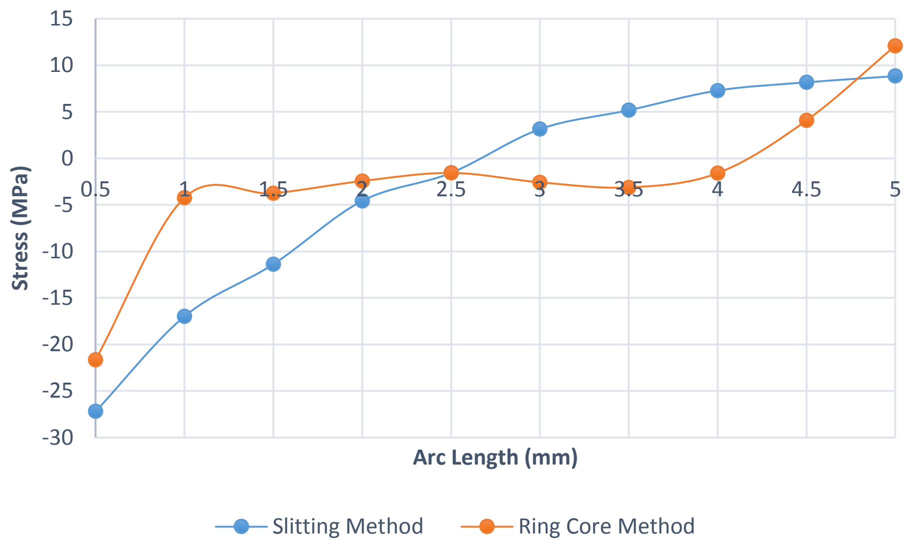


Figure 38: Slitting Method and Ring Core Method Stress Measurement Comparison [36]

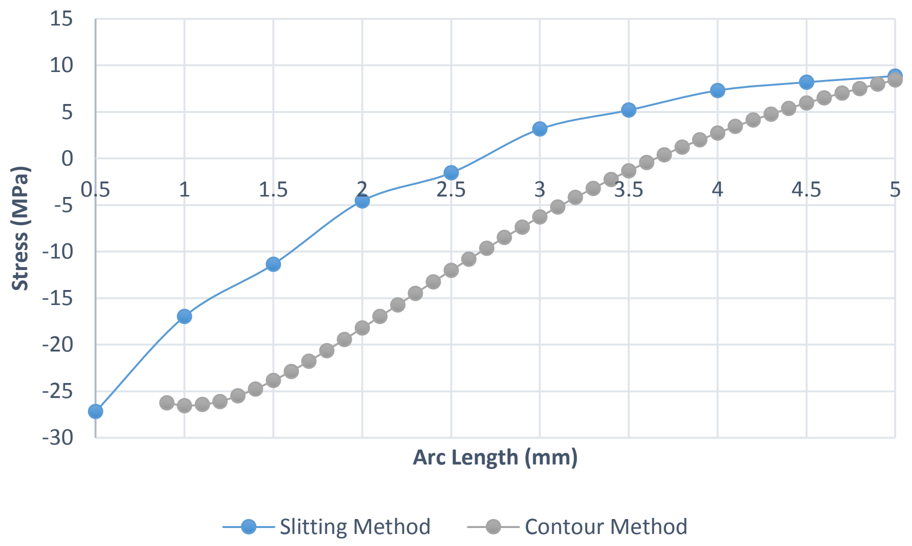


Figure 39: Contour Method and Slitting Method [36] Stress Measurement Comparison

In addition to all these, FE analysis was done in 3D. The two 3D models with different numbers of elements were built. The aim of this modelling step is to reach the stress distribution along the cut surfaces of the specimen B5 similar to experiment in real life. FE modelling is an important step of the Contour Method as it was mentioned in previous chapters. The results of 3D FEM can be shown in **Figure 40** and **Figure 41**. The stress profile trends occurred as similar as in 2D FEM. Moreover, these results contributed to this study about calculating residual stress measurement. Due to the contour method is effective and simple, the appropriate and expected responses were acquired fast.

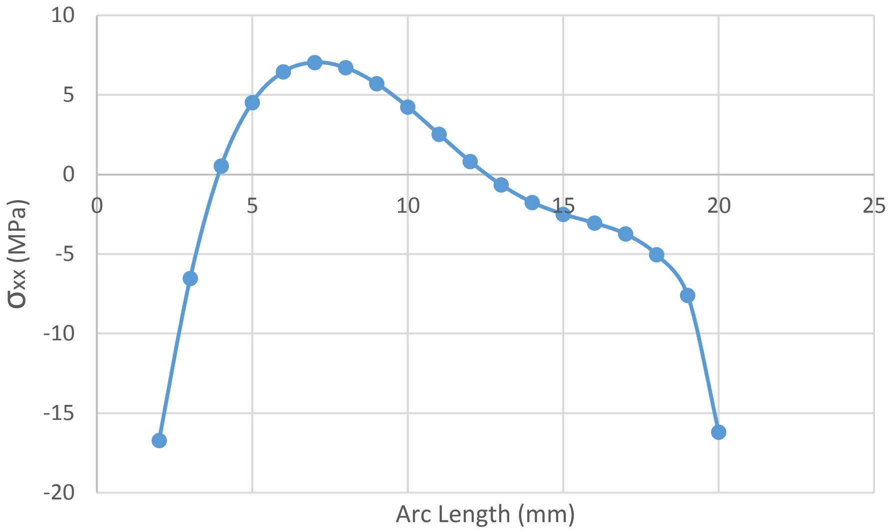


Figure 40: Stress Profile on Cut Surface o Left Side of B5 Sample by Contour Method (60000 Elements in 3D)

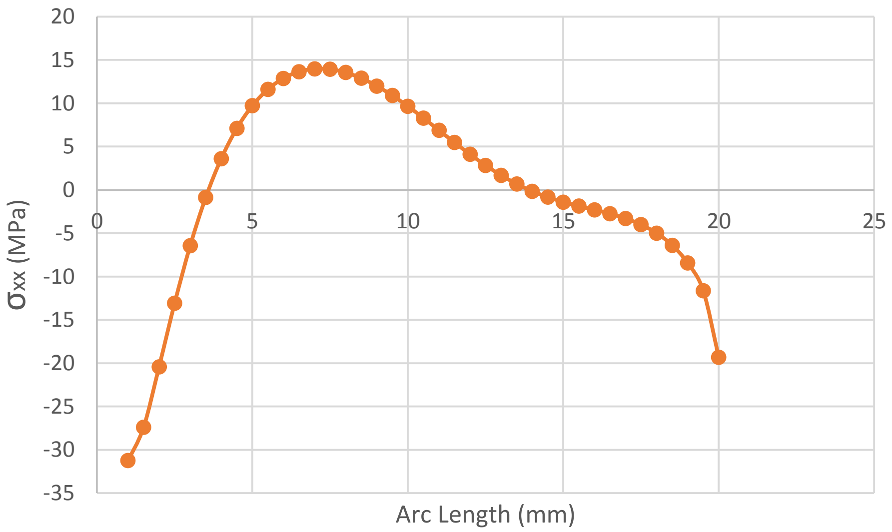


Figure 41: Stress Profile on Cut Surface o Left Side of B5 Sample by Contour Method (240000 Elements in 3D)

CHAPTER 6

SUMMARY

The main aim of this study was to calculate residual stresses through cross-section of the cold rolled aluminum plate by using the contour method. For this purpose, specimens are machined from a cold rolled AA 5083 plate. There were two specimens C1 and B5 in this thesis. These parts were cut in two by using wire-EDM. The contours were measured from the cut surfaces. An optical surface profiler using focus variation method was used for this process. As it was mentioned in previous chapters, using focus variation for measuring the surface profile in contour method was a contribution to the literature. The measured contours were processed to avoid noise or an asymmetric effects caused by the cutting. By using finite element analysis, the stress profile along the cutting plane was obtained for both specimens. Both 2D (plane strain) and 3D analyzes were conducted.

As explained in Chapter 5, some differences occurred for two specimens. It was seen that specimen C1 had stress values higher than expected. The unexpected appearance on the specimen C1 was shown in the **Figure 34** in the results. It was said that this is because plastic deformation during cutting of the specimen. Therefore, the displacement values during measurement step was bigger. This caused in a great increase in the stress values obtained from the analysis.

As a result, the stress profile was observed in the specimen B5 as expected after cold rolling process. By the nature of cold rolling, compression exists on location close to surface of the specimen and a transition from tension to light compression exists in the middle of the specimen B5 **(Figure 35)**.

Then, the results of the contour method were compared to the results of Slitting and Ring Core methods. Although there were differences about 29%, a close trend was found between the contour method and the slitting method.

Aside from slitting method, the results were compared with Ring Core Method measurement **(Figure 37)**. Although there were some similarities in minimum and maximum stress values, the trends of the stress profiles of those two methods are quite different.

Similar to the 2D analyzes, expected stress distribution profile in the sample was observed after the cold rolling process in 3D analyzes **(Figure 40 and 41)**. The purpose of three-dimensional modeling is to capture similarity with the real world and to verify that with simulation.

Finally, it can be concluded that the residual stress distribution has been successfully determined along cross section of cold rolled aluminum plate by the contour method. Considering that destructive residual stress measurements such as hole drilling have a repeatability up to 30%, the differences between different methods can be considered reasonable.

REFERENCES

[1] M. Engineering, R. Process, S. Ray, U. G. Programmes, and T. Teachers, *Principles and applications of metal rolling*. Cambridge University Press., 2016.

[2] G. Johnson, "Residual stress measurements using the contour method," University of Manchester, 2008.

[3] P. Withers and P. Webster, "Neutron and Synchrotron X-ray Strain Scanning," *Strain*, vol. 37, 2001.

[4] M. B. Prime and A. R. Gonzales, "The Contour Method: Simple 2-D Mapping of Residual Stresses," *Sixth Int. Conf. Residual Stress. Int. Conf. Residual Stress. July 10-12*, vol. 836, pp. 617–624, 2000.

[5] M. B. Prime, "The Contour Method: A New Approach in Experimental Mechanics," *Proc. SEM Annu. Conf.*, vol. 836, 2009.

[6] G. S. Schajer, *Practical residual stress measurement methods*. John Wiley & Sons, 2013.

[7] M. B. Prime, "Cross-sectional mapping of residual stresses by measuring the surface contour after a cut," *J. Eng. Mater. Technol.*, vol. 123(2), pp. 162–168, 2001.

[8] N. Murugan and R. Narayanan, "Finite element simulation of residual stresses and their measurement by contour method," *Mater. Des.*, vol. 30, no. 6, pp. 2067–2071, 2009.

[9] P. J. Bouchard, P. Ledgard, S. Hiller, and F. Hosseinzadeh, "Making the cut for the contour method," *15th Int. Conf. Exp. Mech.*, vol. 1, pp. 1–7, 2012.

[10] M. B. Prime and A. T. Dewald, "The contour method," in *Practical Residual Stress Measurement Methods*, 2013, pp. 109–138.

[11] M. B. Prime, M. A. Newborn, and J. A. Balog, "Quenching and cold-work residual stresses in aluminum hand forgings: contour method measurement and

FEM prediction," *Process. Manuf. Adv. Mater.*, vol. 426–432, pp. 435–440, 2003.

[12] P. Pagliaro, M. B. Prime, H. Swenson, and B. Zuccarello, "Measuring Multiple Residual-Stress Components using the Contour Method and Multiple Cuts," pp. 187–194, 2010.

[13] M. B. Prime, T. J. Lienert, W. L. J. Stellwag, and R. S. Casey, "Residual Stress Measurement in Friction Stir Welded Ti-6Al-4V," *Fabtech Int. AWS Weld. Show 2005*, 2005.

[14] M. Turski and L. Edwards, "Residual stress measurement of a 316l stainless steel bead-on-plate specimen utilising the contour method," *Int. J. Press. Vessel. Pip.*, vol. 86, no. 1, pp. 126–131, 2009.

[15] M. B. Prime, M. R. Hill, A. Dewald, R. J. Sebring, V. R. Dave, and M. J. Cola, "Residual stress mapping in welds using the contour method," in *Proceedings of the 6th International Conference*, 2003, pp. 891–896.

[16] P. Pagliaro, "Mapping Multiple Residual Stress Components Using the Contour Method and Superposition," Universita Degli Studi Di Palermo, 2008.

[17] P. J. Withers, H. K. D. H. Bhadeshia, P. J. Withers, and H. K. D. H. Bhadeshia, "Residual stress . Part 1 – Measurement techniques Residual stress Part 1 – Measurement techniques," vol. 836, no. 2001, 2013.

[18] A. T. DeWald and M. R. Hill, "Improved data reduction for the deep-hole method of residual stress measurement," *J. Strain Anal. Eng. Deseign*, vol. 38(1), pp. 65–78, 2003.

[19] A. T. Dewald and M. R. Hill, "Multi-Axial Contour Method for Mapping Residual Stresses in Continuously Processed Bodies," *Exp. Mech.*, vol. 46(4), pp. 473–490, 2006.

[20] P. Pagliaro *et al.*, "Measuring Inaccessible Residual Stresses Using Multiple Methods and Superposition," *Exp. Mech.*, 2010.

[21] G. Alpsten and L. Tall, "Residual-stress Measurement by the Sectioning Method Preparation of Test Specimen," no. February, pp. 88–96, 1973.

[22] P. S. Prevey, "X-Ray Diffraction Residual Stress Techniques," vol. 10, pp. 380–392, 1986.

[23] O. Anderoglu, "Residual stress measurement using X-ray diffraction," Taxes A&M University, 2004.

[24] *Residual Stress Measurement by X-ray Diffraction: HS-784*. SAE International, 2003.

[25] A. Stacey, H. J. Macgillivary, G. A. Webster, P. J. Webster, and K. R. A. Ziebeck, "Measurement of Residual Stresses by neutron diffraction," *J. Strain Anal. Eng. Des.*, vol. 20(2), pp. 93–100, 1985.

[26] P. Taylor *et al.*, "Advances in Physics Neutron diffraction methods for the study of residual stress fields," no. December 2012, pp. 37–41.

[27] Y. Traoré, F. Hosseinzadeh, and P. J. Bouchard, "Plasticity in the Contour Method of Residual Stress Measurement," *Adv. Mater. Res.*, vol. 996, pp. 337–342, 2014.

[28] M. B. Prime, D. J. Hughes, and P. J. Webster, "Weld Application of a New Method for Cross-Sectional Residual Stress MApping," in *Society for Engineering Mechanics Annual Conference and Exposition*, 2001.

[29] M. B. Prime and R. L. Martineau, "Mapping residual stresses after foreign object using the contour method," *Mater. Sci. Forum*, vol. 404–407, pp. 521–526, 2002.

[30] M. B. Prime, "Residual Stresses Measured in Quenched HSLA-100 Steel Plate," in *Proceedings of the 2005 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, 2005.

[31] C. Liu and X. Yi, "Residual stress measurement on AA6061-T6 aluminum alloy friction stir butt welds using contour method," *Mater. Des.*, vol. 46, pp. 366–371, 2013.

[32] H. Cetinel and M. Ayvaz, "Microstructure and Mechanical Properties of AA 5083 and AA 6061 Welds Joined with AlSi5 and AlSi12 Wires *," *Mater. Test. Weld. Appl.*, vol. 56(10), pp. 884–890.

[33] F. Hosseinzadeh, P. Ledgard, and P. J. Bouchard, "Controlling the Cut in Contour Residual Stress Measurements of Electron Beam Welded Ti-6Al-4V Alloy Plates," *Exp. Mech.*, vol. 53, pp. 829–839, 2013.

[34] R. Leach, *Optical Measurement of Surface Topography*. Berlin: Springer, 2011.

[35] F. Hosseinzadeh, Y. Traore, P. J. Bouchard, and O. Muránsky, “Mitigating cutting-induced plasticity in the contour method, part 1: Experimental,” *Int. J. Solids Struct.*, vol. 94–95, pp. 247–253, 2016.

[36] D. K. Aksungur, “Applications of Slitting Method for Measurements of Cold Rolling Residual Stresses,” Atilim University, 2018.

APPENDIX A

MATLAB CODE

MATLAB codes used to plot the displacement profile at **Figure 21** and **Figure 23** are shown below.

For specimen C1,

```
clc
clear all
mfilename('YZ_2D_Plot_LR');
%YZ Data 2-D Plot Left and Right Sides

data1=xlsread('C1_5XLeft.xlsx');
data2=xlsread('C1_5XRight.xlsx');
data3=xlsread('C1_10XLeft.xlsx');
data4=xlsread('C1_10XRight.xlsx');

figure(1) %5X Left and Right Lens Data
hold on;
plot(data1(:,2),data1(:,9),'o')    %5X Left Data
plot(data2(:,2),data2(:,3),'or')   %5X Right Data
xlabel('Distance (milimeter)','FontSize',18);
ylabel('Displacement (micrometer)','FontSize',18);
set(gca,'FontSize',18);

%10X Left and Right Lens Data%hold on;
plot(data3(:,2),data3(:,9),'og')   %10X Left Data
plot(data4(:,2),data4(:,3),'om')   %10X Right Data
hold off;
```

For Specimen B5,

```
clc
clear all
mfilename('B5_YZ_2D_Plot_LR');
%YZ Data 2-D Plot Left and Right Sides

data_1=xlsread('B5_5XLeft.xlsx');
data_2=xlsread('B5_5XRight.xlsx');
```

```
data_3=xlsread('B5_10XLeft.xlsx');
data_4=xlsread('B5_10XRight.xlsx');

figure(1) %5X Left and Right Lens Data
hold on;
plot(data_1(:,2),data_1(:,3),'o')   %5X Left Data
plot(data_2(:,2),data_2(:,3),'or')  %5X Right Data
xlabel('Distance (milimeter)','FontSize',18);
ylabel('Displacement (micrometer)','FontSize',18);
set(gca,'FontSize',18);

%%10X Left and Right Lens Data
plot(data_3(:,2),data_3(:,9),'og')  %10X Left Data
plot(data_4(:,2),data_4(:,3),'om')  %10X Right Data
hold off;
```