INVESTIGATION OF BENDING CHARACTERISTIC OF 5XXX – SERIES ALUMINUM ALLOYS

5XXX SERİSİ ALÜMİNYUM ALAŞIMLARININ BÜKÜM KARAKTERİSTİĞİNİN İNCELENMESİ

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ABSTRACT

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In this study, strains and fraction formation which occur in the parts was examined by creating a bending simulation in the MSC.Marc finite element analysis program for En AW-5083-H321 series of aluminium which are more frequently used in industry. According to the literature, such studies have been conducted with the MSC.Marc finite element analysis program. Similarly, there are many fracture models in the literature. In this thesis analysis was made by selecting the appropriate fracture model which is Cockroft-Latham in order to detect the cracks on the material. After the bending analysis, pieces were bended and crack dimension was measured by microscope with the help that parameters of fracture model were determined. Fracture model parameter that has been determined was applied on different thickness with different bending radius with the help of that fracture model parameters was verified.

With this study, it is aimed both minimize failures which may occur while bending and help for the reducing the standards dependence.

Keywords: Bending, Sheet Metal, Damage, Finite Element Analysis, Bending Radius, Cockroft-Latham

ÖZET

5XXX SERİSİ ALÜMİNYUM ALAŞIMLARIN BÜKÜM KARAKTERİSTİĞİNİN İNCELENMESİ

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Tez Danışmanı: Dr. Öğr. Üyesi Mehmet Okan GÖRTAN

Ocak 2023, 37 Sayfa

Bu çalışmada endüstride fazlaca kullanılan EN AW-5083-H321 serisi alüminyum alaşımlarında büküm sırasında oluşan gerinim ve çatlak oluşumu MSC.Marc sonlu elemanlar analizi programı ile oluşturulan büküm simülasyonlarında incelenmiştir. Literatüre göre MSC Marc sonlu elemanlar analiz programı ile çeşitli çalışmalar yapılmıştır. Aynı zamanda literatürde pek çok kırılma modeli bulunmaktadır. Tezin kapsamı içerisinde yapılan analizlerde malzemedeki çatlağı bulabilmek için, Cockroft-Latham kırılma modeli kullanılmıştır. Büküm analizi sonrasında, parçaların büküm işlemleri yapılıp çatlak miktarları mikroskop altında ölçülmüş ve bu sayede kullanılan kırılma modelinin parametreleri belirlenmiştir. Belirlenen bu parametreler farklı kalınlıklardaki ve farklı büküm açıklarındaki parçalara da uygulanıp kırılma modeli doğrulanmıştır. Standartlar ile gerekli karşılaştırmaları yapabilmek adına numuneler farkı büküm yarıçaplarında 90° bükülerek analizler ile karşılaştırılmıştır. Doğrulanmış veriler ile büküm yarıçaplarının standart veriler ile karşılaştırması yapılmıştır.

Bu çalışma ile büküm sırasında yaşanan hataların en aza indirilmesi ve standartlara olan bağlılığın azaltılması hedeflenmiştir.

Anahtar Kelimeler: Büküm Yarıçapı, Sonlu Elemanlar Analizi, Sac Metal Şekillendirme, Kırılma Modeli, Cockroft-Latham

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LIST OF SYMBOL AND ABBREVIATIONS

Symbols

σ	Engineering Stress
σ_{true}	True Stress
e	Engineering Strain
ϵ	True Strain
$\epsilon_{true\ plastic}$	True Plastic Strain
D	Lemaitre Damage Value
D_c	Critical Damage Value

Abbreviations

FE	Finite Element
FEA	Finite Element Analysis
UTS	Ultimate Tensile Strength
YS	Yield Stress

1. INTRODUCTION

Aluminium alloys are frequently used in the defence industry thanks to their lightweight and comparatively high strength. These materials usually take their final form with various shaping processes. A representative sketch of safety critic component which produced by shaping method is shown in Figure 1.1. Bending is one of the major processes to form these metals to the desired shape. During bending process, surface cracking may occur. Surface cracks cause decreased strength. Considering the mission scenarios of defence vehicle, consequences of such defects can be fatal. In order to prevent crack formation, bending operations must comply with various restrictions. These restrictions constitute bending limits. Therefore, subject of this thesis is "Investigation of Bending Characteristic of EN AW-5083-H321 Aluminium Alloy"

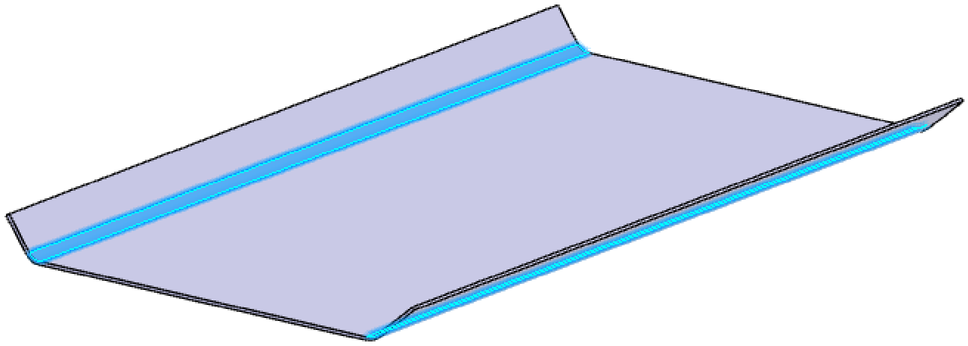


Figure 1.1 A representative sketch of bottom plate of vehicles

The purpose of this thesis is to investigate the bending characteristics of 5xxx series aluminium. In this study EN AW-5083-H321 aluminium alloy was examined and thickness of examined parts were 3, 4 and 6 mm.

In the first part of the thesis, strains in certain bending angles and bending radius of materials was numerically calculated using the MSC.Marc FEA software. After obtaining results, the bending process was conducted by simulating the analysis in the real environment. Subsequently, the bent parts were verified with various tests in order to support the analysis. Finally, the values between given to the standards and obtained as a result of the tests were compared.

With this study, it is aimed to minimize failures which may occur while bending. In current systems, bending process are done according to old standards. Designer selects the bending angle and radius value according to the given thickness interval in standards. Eigenvalue of this study is that finding the bending radius for every thickness unlike standards. This will help for the reducing the standards dependence. As a result of this study, it is aimed that the designers make the design of the bending piece with verified data.

2. STATE OF THE ARTS

2.1 Theory of Bending

Bending of plates is a common process in manufacturing industry. From a general point-of-view, bending characterizes the behaviour of a structural element subjected to an external load applied perpendicularly to a longitudinal axis of the element, aiming to create desired curved final geometry. In the bending processes sheet metal parts have always both tension and compression stresses. In the middle of the tension and compression zones, there is a section without any strains which is called as neutral axis. [1]. After the bending processes neutral axis may shift in the thickness of the material which is called as neutral axis shift. Neutral axis divides materials into two regions; tension and compression. The magnitude of those stresses increases while moving away from the neutral axis. A representative sketch is shown in Figure.2.1, where R is the bending radius, r is the radius of the neutral axis, Mt is the thickness of the plate and t is the neutral axis shift.

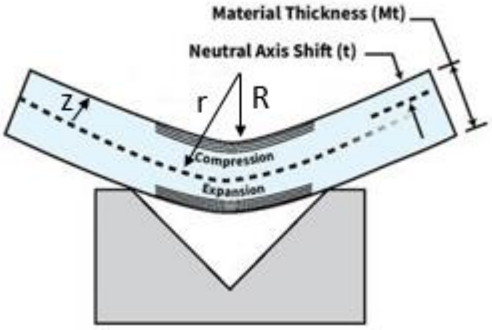


Figure 2.1 A representative of pure bending operation [2]

If the deformation mode is taken into the consideration, it can be easily seen that the bending process is different from other metal forming methods. The size and the thickness of the part, material properties and die design are major factors affecting permissible bending angle and bending radius. All of these factors have a direct effect on the strain values [3]. All materials have a specific maximum strain value to resist. That value determines materials formability limits. If that limit is exceeded, surface crack occurs on the material.

The strain values on the plate could be calculated by the following formulas:

$$\varepsilon_x = \ln\left(\frac{L}{L0}\right) = \frac{z\theta}{r\theta} = \frac{z}{r} \tag{2.1}$$

$$\varepsilon_x = \ln\left(\frac{L}{L0}\right) = \ln\left(1+\frac{z}{r}\right) = \ln(1+ \varepsilon_x) \tag{2.2}$$

For many bends the strain is low enough so we can approximate

$$e_x = \varepsilon_x = \frac{z}{r} \tag{2.3}$$

For pure bending case, where the bending moment is constant bending may produce a very small change in sheet thickness.

To simplify the calculations, the neutral axis is accepted as the mid-plane of the plate. Actually, this assumption is not entirely correct since the neutral axis slightly moves toward the compression zone. The basic factors, which cause this shift are, (i) material is thickening at the inside of the part, (ii) the true compressive strains at the inside are greater in magnitude than the strains at the outside. Inside and outside region are illustrated in Figure 2.1 [1]

Neutral axis shit affects the K factor value. K factor formula is given below.

$$K = \frac{t}{M_t} \tag{2.4}$$

K has always a value between zero and one. A K-factor of 0.25 means that the neutral axis is 25% of the way into the part, 0.5 means that the neutral axis is 50% of the way into the part and so-on [4]. K factor depends on; material, material thickness, material temperature, size of bend radius and size of bend angle.

2.2. Types of Bending

2.2.1. Air Bending Process

In air bending operation, while the sheet metal part is supported by the die at the left and right end, necessary angle occurs when the punch descends to the bottom of the die. The die gap is set according to requirements of design. Punch touches at the midpoint of the sheet metal part and pushes it down to gain the necessary angle. If the punch stroke changes, the output angle will change. As a result, there is no need to change any costly equipment to change output angle. This is the most important advantage of the air bending. In air bending process the necessary punch force is relatively small with respect to other bending types [4]. Thanks to this property, relatively low wear occurs at the punch and die surfaces, therefore lifecycle of the equipment higher than other types. Punch and dies are illustrated in Figure 2.2

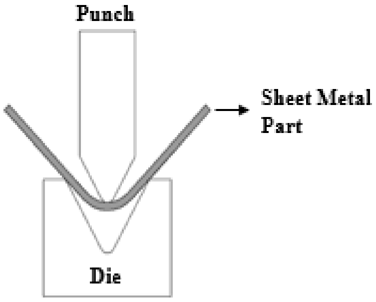


Figure 2.2 Air bending [5]

2.2.2. V-Die Bending Process

The V-die bending is a bending type which is generally used in industries. V-die bending has similarities with the air bending. In the initial condition, sheet metal part is supported by the die. The sheet metal part is bent with the punch force and takes desired angle with the help of the V-shaped die. At the beginning of the process, punch touches the midpoint of the sheet metal then both ends of the part slightly leave the die. At the end of the process, sheet metal part entirely contacts with the both punch and die sides. For this reason, it is varied from the air bending. The major advantage of the V-die bending is reasonable set up time even part shape is complex [6]. In the V-die bending process, the most common thickness of the sheet metal is between 0.5 mm and 25 mm [7]. An example of punches and die is shown in Figure 2.3

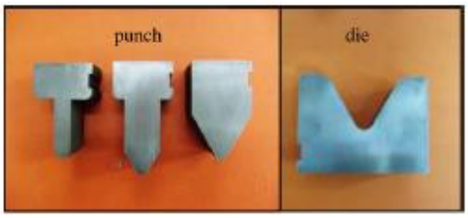


Figure 2.3 V-die bending [6]

2.2.3. Flanging

Flanging method has commonly usage in industry to produce flanges. Flanging is also known as wipe-bending. In the flanging method, the sheet is held in a fixed position by clamped between the blank holder and die. The punch descends down and shapes the part. If the length of bending part is relatively short with respect to remaining parts, this method is preferred [7]. Both in air bending and V-die bending, the sheet metal part is free to upward, but in the flanging method the sheet metal part is clamped. Therefore, compare with other methods flanging methods have an extra part which is blank holder. A representative sketch is shown in Figure.2.4.

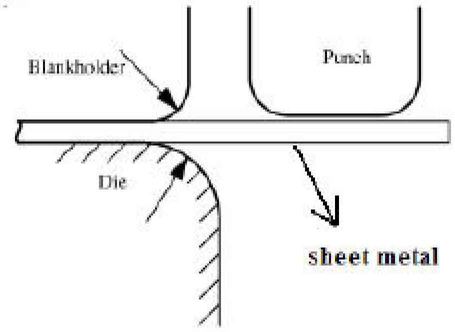


Figure 2.4 Flanging [7]

2.3. Forming Limits in Bending

Bendability is basically related to material properties. During bending operations, two major failures might occur; one of them is tensile failure on the outside and the other is buckling on the inside. Tensile failure or cracking on the outside of the part depends on the strain values. If the strain values on the outside of the part reaches a critical value, failure will occur [1]. The critical strain values depend on the material, thus different materials have different elongation values when the cracking occurs.

The most frequent problem is tensile failure in the bending operations. Tensile failure occurs when the effective tensile stress at a plane in the part exceeds a critical limit. As a result, stresses materials stretch. Percentage of this stretch is called elongation, for this reason, elongation becomes the important value for bending operations to prevent cracking. Stretching occurs between the outside and the neutral axis of the bending part. Cracking starts on the outside of the part because elongation value is maximum there.

This value calculation, as mentioned in the formula (2.1), needs the initial and final dimensions of the part. The initial length of the bending piece of part calls as bend allowance.

Bend allowance is also equal to arc length of the neutral axis of the bending part. A representative sketch is shown in Figure 2.5.

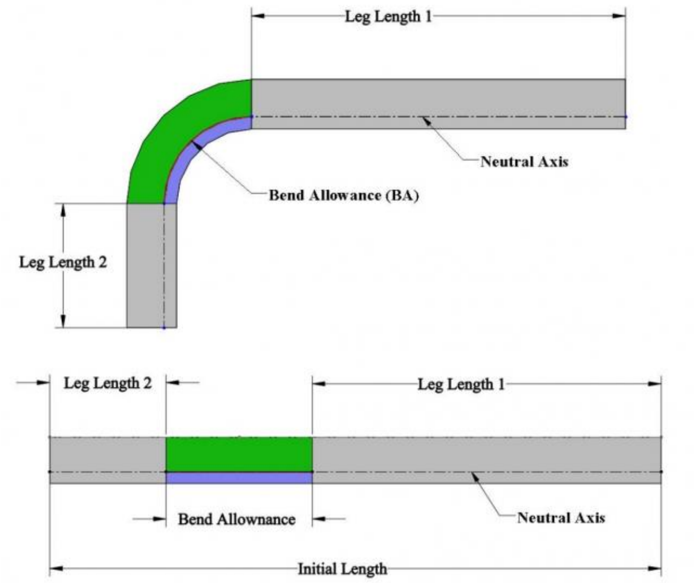


Figure 2.5 A representative figure of bend allowance [8]

The final length is equal to arc length of the outside of the bending part. Strain value at the bending part can be calculated using the bend allowance and the final length of the bending part. If the calculated strain value is higher than the maximum strain value of the material, eventually cracking will occur. For this reason, critical strain value directly effects on the bendability. Bend allowance is the most important value for the bending limits finding, however this value cannot be calculated with the straight forward mathematical works. For finding bend allowance value, firstly neutral axis shift has to be found. Neutral axis shift also cannot calculated with mathematical works; it is only detected with the bending analysis.

Material thickness, bending radius and bending angle are changeable inputs of the bending operations. All these factors have a direct influence on the plastic strain value exerted on the materials. In other words, they affect the formability or the possible fractures which may occur.

2.4.Tests

As mentioned above, if the strain reaches the maximum value, cracks can easily occur during the bending. In some cases, cracks, which occur due to the bending, are very small to be seen with the eye. For this reason, after bending operations every piece has to be tested, otherwise catastrophic failures might be occurred. In the industry there are two major tests are used. First one is liquid penetrant and the other is grid marking.

2.4.1. Liquid Penetrant Testing

Liquid penetrant testing is the major and the simplest non-destructive testing method to find surface cracks or surface discontinuities. This technique is mainly used on after welding operations to find weld defect.

Liquid penetrant testing is based on a liquid penetration. In this technique, coloured liquid should be used. In the first step, this liquid is poured to the material and it easily fills the discontinuity. After that the dye developer is applied by operator. Eventually, if the liquid is observed on the surface of the material, that means material has surface crack. A representative sketch of the liquid penetrant testing is shown in Figure 2.6 [9]

One of the advantages of liquid penetrant test is the operator can easily detect the surface cracks with only visual inspection. Other advantage is the test is highly sensitive and even small discontinuity can be detected.

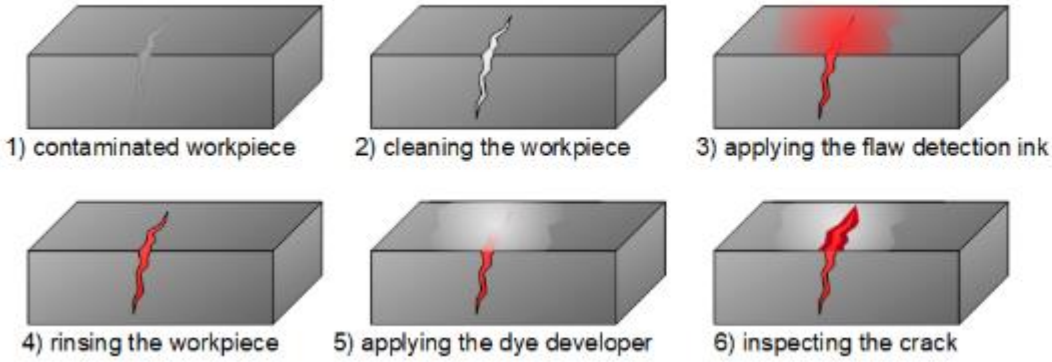


Figure 2.6 Liquid Penetrant Testing [9]

In bending operation surface cracking might occur at the outside of the material which is the most common failure. With liquid penetrant testing this failure can be easily detected.

2.4.2. Grid Marking

Marking is a frequently used process in industry. Some of marking process is used to specify identity of the materials, while some of marking process to specify the date of production.

Grid marking in bending process is different from general use. The marking is made to examine the deformations that occur during forming process and this is called grid marking. Grid marking process is mainly relevant for making line patterns on the surface of the forming part of the material. There are lots of type of grind marking some of them are serigraph or silk-screen printing, electro chemical etching, photochemical etching and laser etching. The most important thing during the grid marking, marking must not affect the forming process otherwise strain measurements will wrong [10]. A representative sketch is shown in Figure 2.7.

Laser etching method has the best grid marking accuracy. Applications of this method takes lots of time due to that the size of the part becomes important. Compared to other methods, laser etching is expensive.

This method is mainly related with the strain measurement. For taking of strain measurement accurately grids on the part surface should be measured before and after the forming process. Finite element analysis can be verified by using this method.

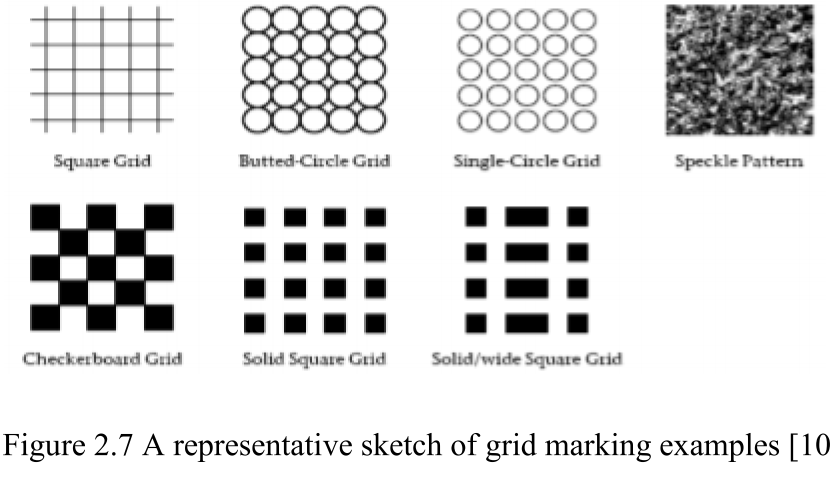


Figure 2.7 A representative sketch of grid marking examples [10]

2.5. Analysis

There are two types of deformation. First one is elastic and the other one is plastic deformation.

Elastic deformations are reversible. In this type of deformation, there are no permanent deformations on the material. Due to that reason, elastic deformations also called as bond stretching. Up to yield point deformation type is elastic and also linear.

Plastic deformation is non-reversible and it starts after the yield point and deformation becomes permanent and the type is non-linear. A representative sketch of elastic and plastic region is shown in Figure 2.8 [11]

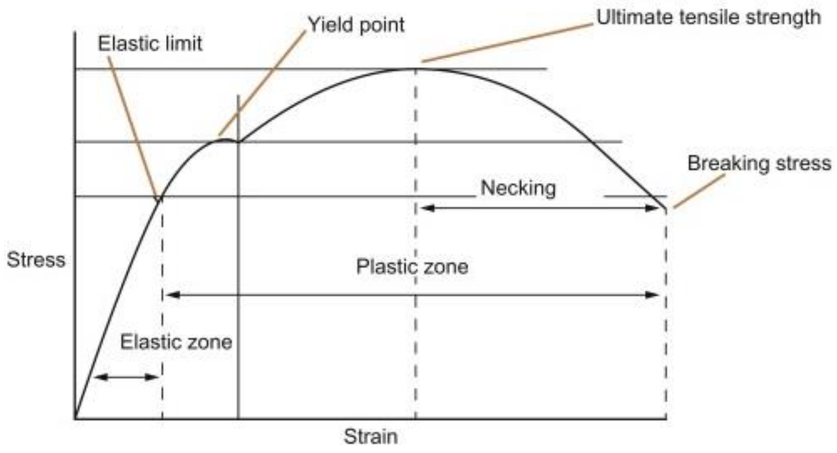


Figure 2.8 A representative sketch of elastic and plastic region [10]

In forming processes deformation must be permanent, so that the analysis must be done at non-linear type. Both Ansys and MSC.Marc analysis programs can solve non-linear types.

Generally, in the past projects, both analysis programs are used. In this thesis, MSC.Marc will be used.

MSC.Marc is the ideal option for the non-linear simulations. In the bending operations investigation of the damage, failure and crack propagations are the most important things. MSC.Marc is able to make all of these.

As mentioned at the 3rd chapter it is not possible to find K-factor with mathematical works. Analysis give a chance to find value of K-factor and all other important data. All of these data can be verified with the real bending operations and tests which are mentioned above.

2.6. Fracture Models

Damage development and crack formation are the most important things of the bending process that need to be investigated. Up to now more investigations were made about the springback effect than the damaging. Because springback effect is directly related with the production. In bending process, large deformations occur. In order to find the exact location of the large deformations and damages, there have to be used suitable fracture models [12].

Fracture models are basically related with the void growth, nucleation and coalescence. There are lots of fracture models in the literature. Earlier models McClintock (1968), Rice and Tracey (1969), Gurson (1975), Tvergaard and Needleman (1984) and recent models Leblond (1995), Pardoen and Hutchinson (2000), Benzerga (2004), Nahshon and Hutchinson (2008). However, sometimes these models may not fully meet the requirements. Updating the fracture models with the data obtained from the results of the bending processes will facilitate the design. Unfortunately, the most of the fracture models mentioned above are not eligible for this calibration [13].

There are also more commonly used fracture models in the literature such as Lemaitre and Cockcroft-Latham. Lemaitre is a ductile damage model and it is based on a thermodynamic framework. In this model damage (D) is represented by the ratio of damaged are of unit surface (S_D) to the total surface (S) [14]. Damage formula is given below.

$$D=\frac{S_D}{S} \tag{2.5}$$

According the formula above Lemaitre damage value must be between 0 and 1. In Lemaitre damage models a critical damage value D_c is used to account for macroscopic fracture. When the damage variable D reaches D_c, D is immediately set to 1 in order to model fracture.

Cockcroft-Latham is also ductile damage model and it depend on maximum principle stress and equivalent strain. It needs only one material constant to express the amount of ductile damage. Material constant can be determined only by experimental methods [15]. Material constant formula is given below.

$$\int_0^{\overline{\varepsilon_f}} \sigma_{\max} \, d\bar{\varepsilon} = c_1 \qquad (2.6)$$

where, σmax is the maximum principle stress, $\bar{\varepsilon}$ is the equivalent strain, $\bar{\varepsilon} f$ is the equivalent strain at which the fracture occurs, C_1 is the material constant to express the limit of ductile damage. In this thesis Cockcroft-Latham damage model was used to find crack zone and size accurately.

3. MOTIVATION AND METHODOLOGY

3.1 Motivation

Aluminium alloys are frequently used in the defence industry. These materials usually take their final form with bending processes. 5xxx series of aluminium are suitable for welding operations and EN AW-5083-H321 alloy have comparatively high good strength. EN AW-5083-H321 alloy was examined in this study.

Motivation of this study can be given below remarks.

- Finding appropriate material modelling method.
- To create appropriate damage model and parameter in order to get accurate results with investigated thickness values.
- Minimizing the bending failures to decrease both production cost and time.
- Reducing the standards dependence

3.2 Methodology

In this study, bendability characteristics of 5xxx series of aluminium are investigated by experiments and finite element analyses. Sheets with three different thicknesses, namely 3 mm, 4 mm and 6 mm are investigated.

Table 3.1 EN AW-5083 Chemical Composition [16]

Alloy Designation		Si	Fe	Cu	Mn	Mg
Numerical	Chemical Symbols					
EN AW-5083	EN AW-Al Mg4,5Mn0,7	0,40	0,40	0,10	0,40-1,0	4,0-4,9
		Cr	Ni	Zn	Ti	Al (min)
		0,05-0,25	-	0,25	0,15	Reminder

First of all, mechanical properties of the material with different thicknesses are characterized using tensile tests according to ASTM E8/E8M standard. Used specimen geometry is shown in Figure 3.1. Tensile tests are conducted on a Zwick / Roell servo-hydraulic test machine. A picture of the test machine is shown in Figure 3.1.

Figure 3.1 A representative picture of tensile test process

Bending characteristics of the aluminium alloys are investigated according to the ISO 7438:2020 standard. Used specimen dimensions are shown in Figure 3.2.

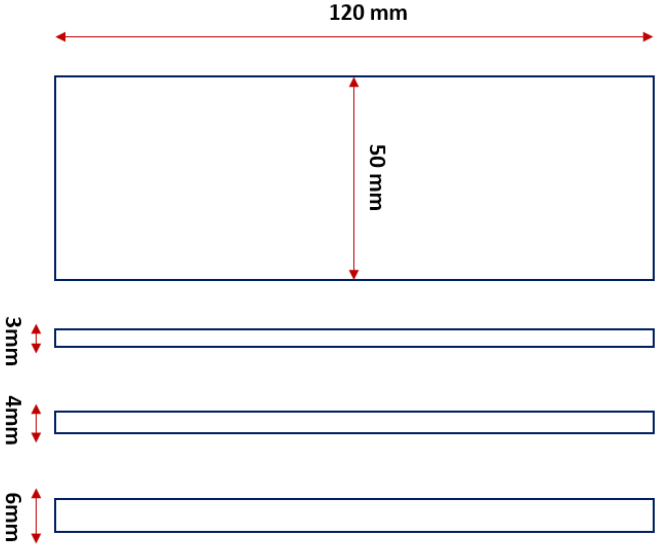


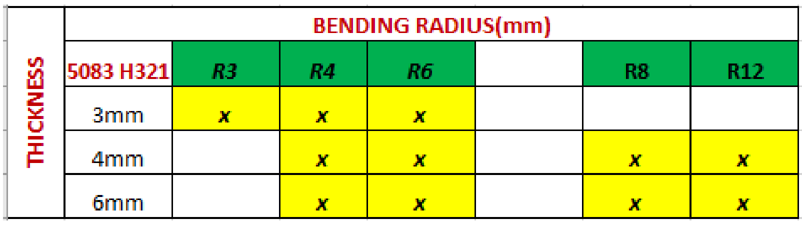
Figure 3.2 Examined Parts Dimensions

Bending process is applied using TruBend 5230 hydraulic press with a capacity of 2300 kN and equipped with a CNC unit. Punch speed kept constant at 15 mm/sec for all tests. In order to prevent any bending or deformation on the tools, die materials with a hardness of 60 HRC is used. A picture of bending device is shown in Figure 3.3.

Figure 3.3 Picture of bending device

It is intended to investigate different thickness and bending radii. So, it is planned to analyse the bendability of the aluminium alloy for different r/t ratios. Used parameter matrix is shown in Table 3.2. After the bending process liquid penetrant test was applied due to determine the possible crack formation.

Table 3.2 Bending Matrix



	BENDING RADIUS(mm)						
THICKNESS	5083 H321	R3	R4	R6		R8	R12
	3mm	x	x	x			
	4mm		x	x		x	x
	6mm		x	x		x	x

In order to be able to model crack formation during bending of 5xxx series aluminium alloys, finite element model of the process has been built using MSC.Marc software. As a basic geometry, 4 mm thick sheets are used. Due to the symmetry characteristics, only half of the proses is modelled. A representative sketch is shown in Figure 3.4.

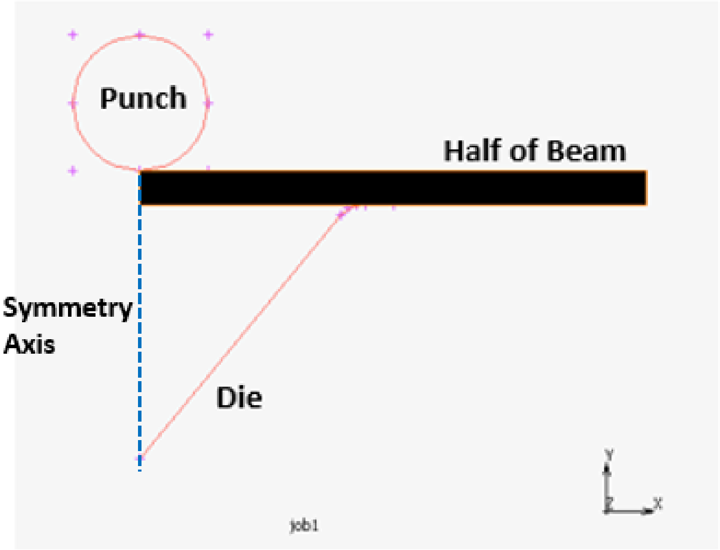


Figure 3.4 Analysis model for 4mm Aluminium

Beam is modelled as deformable with quad (4) element type, while punch and die are modelled as geometric. Die is fixed and punch movement is provided by displacement table.

Mechanical properties of aluminium alloys are modelled using Voce Strain Hardening Rule. Elastic modulus and Poisson's Ratio are assumed as 70 GPa and 0.33, respectively. Damage formation in the FE is modelled using Cockroft-Latham fracture model. After the right damage model parameters are defined using the base model and comparison with experimental results, their validity is checked also with different thicknesses.

4. EXPERIMENTAL STUDIES

4.1 Tensile Tests

As stated above chapter tensile tests of these parts were made to create an accurate material model.

First of all, with the help of tensile tests, displacement with respect to force data was collected for each thickness of parts. With using these data Engineering Stress and Strain and True Stress and Strain values was calculated for each part.

With using True Stress and Strain values, flow curve was created for each part. Flow curve is a choice for material modelling but flow curve formula does not have any limitation at the Ultimate Tensile Strength point. UTS point is a very critical parament for making crack detection due to that reason Voce Equation was used for material modelling. Voce equation formula is given below.

$$\sigma_{\text{true}} = \text{UTS}\ (\ 1 - e^{(\ -K\ (\ \varepsilon\ +\ c))}) \qquad (4.1)$$

In this equation K and c parameters are depend on the material thickness. These parameters were determined with the help of the flow curve. Both 3, 4 and 6mm parts material modelling curves as shown below in Figure 4.1, 4.2 and 4.3. K and c parameters were calculated as stated below.

- K=24.32, c=0.038 for 3mm thickness
- K=22.8, c=0.043 for 4mm thickness
- K=19.05, c=0.051 for 6mm thickness

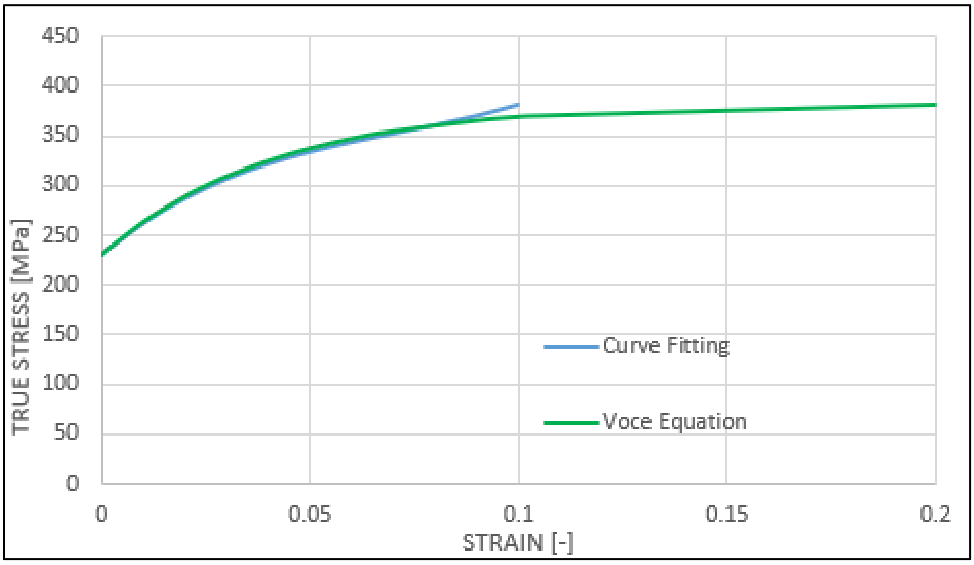


Figure 4.1 3mm Material Modelling

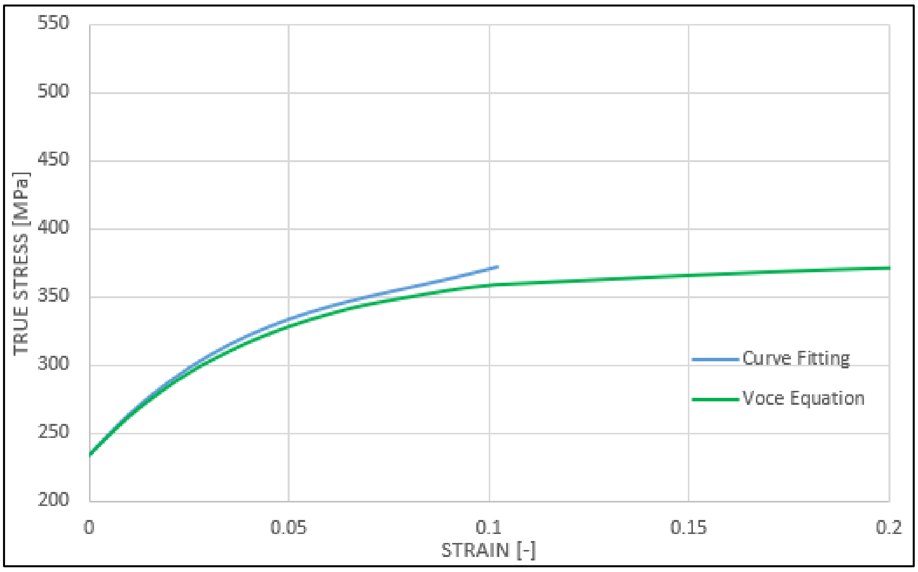


Figure 4.2 4mm Material Modelling

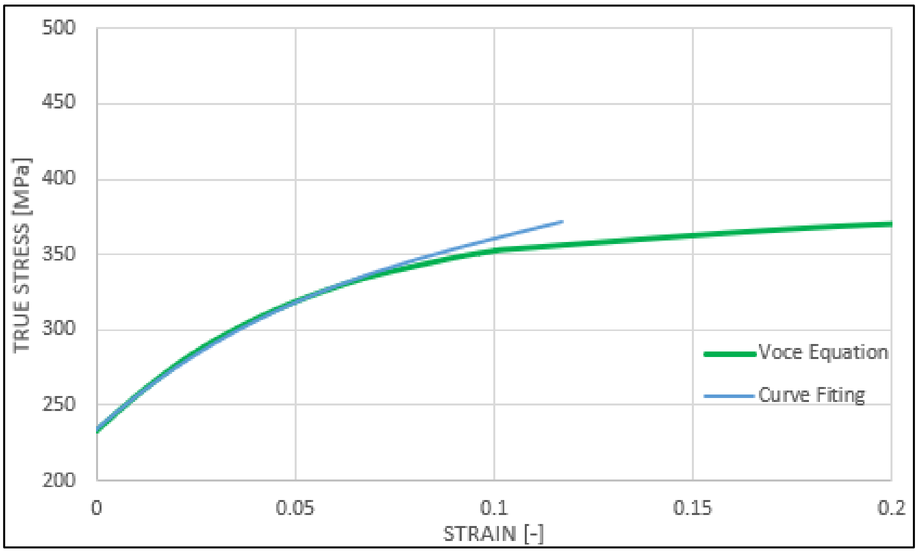
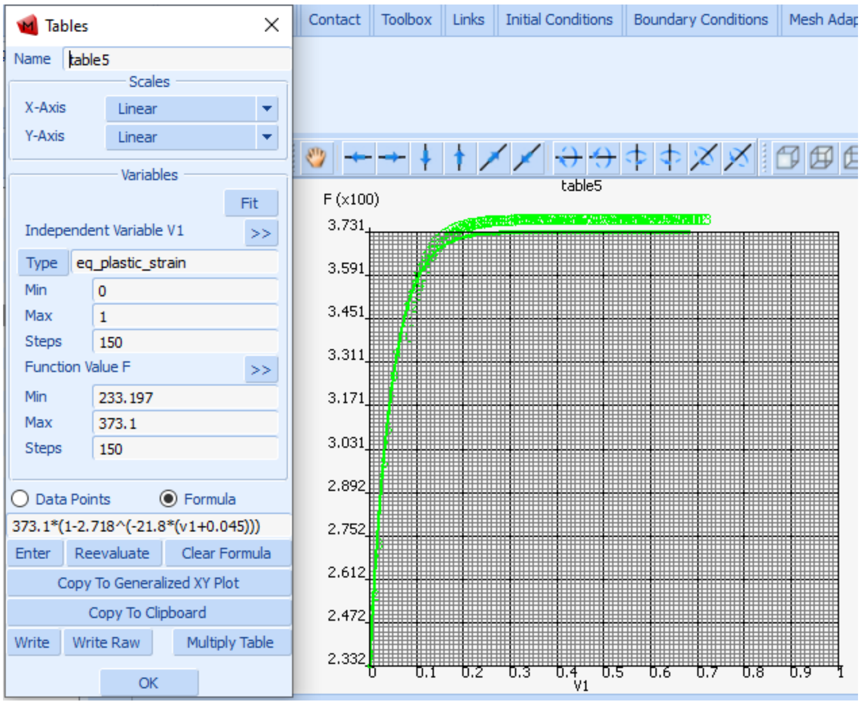


Figure 4.3 6mm Material Modelling

When the material modelling study was done, finite element analysis model was created.

4.2 Finite Element Converge Analysis

Analysis model was created with these material models. A representative sketch of 3mm aluminium part material model on the analysis as shown below in Figure 4.4.



Name table5

X-Axis Linear

Y-Axis Linear

Type eq_plastic_strain

Min 0

Max 1

Steps 150

Min 233.197

Max 373.1

Steps 150

○ Data Points ● Formula

373.1*(1-2.718^(-21.8*(v1+0.045)))

Figure 4.4 3mm Material Modelling on the MARC

After the material modelling, other critical work was done which is mesh size determination. To find appropriate mesh size, analysis was done repeatedly for same thickness of aluminium with different mesh size. Damage localization and analysis time versus mesh size charts are shown below in Figure 4.5 and 4.6.

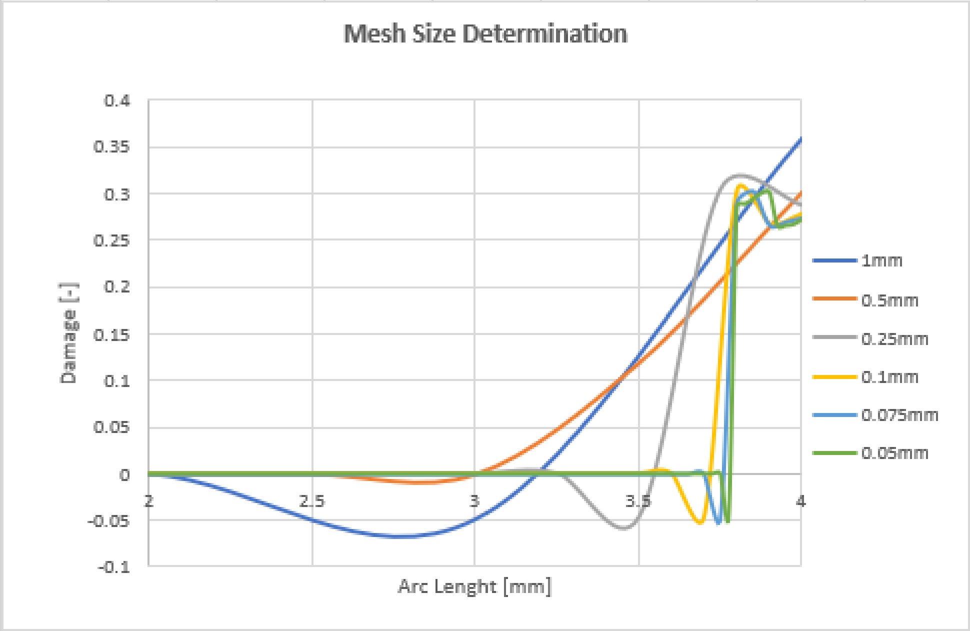


Figure 4.5 Mesh size determination chart

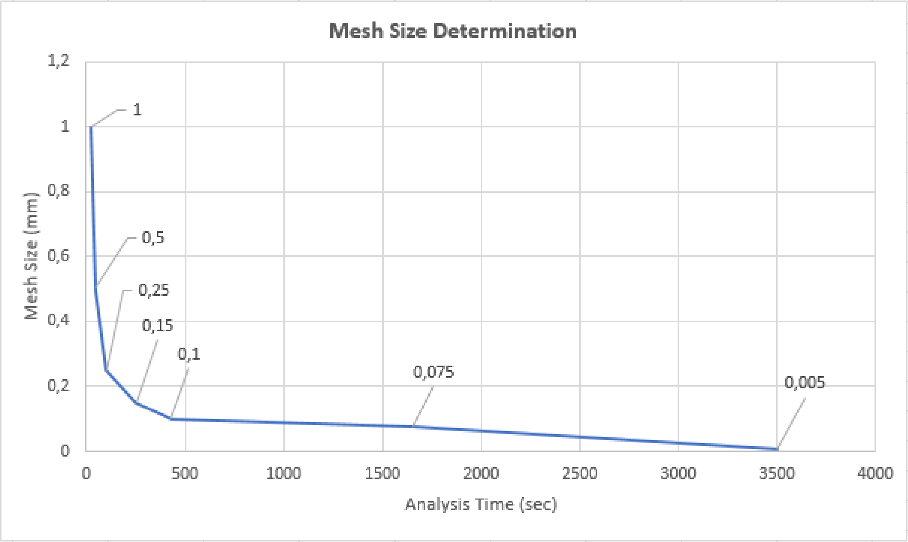


Figure 4.6 Mesh size & Analysis Time

Figure 4.5 shows that damage zone gets closer to correct region while mesh size gets smaller. When mesh size is dropped below 0.1 mm damage localization is not very different from the analysis that have mesh size 0.1 mm but the analysis time is much longer (Figure 4.6). Therefore, appropriate mesh size was selected as 0.1 mm.

After the mesh size selection correct damage parameter is found. In this study Cockcroft-Latham damage model was used. In this damage model there are two major parameter one of them is damage threshold and the other is element removal threshold values. To find these parameters real bending works were done. First 4 mm thick aluminium part was bend until crack initiation point with 4 mm radius. According to that bending process, crack initiate at 115° and crack size was measured as 0.4mm with 100X microscope. That measuring work can be seen in Figure 4.7.

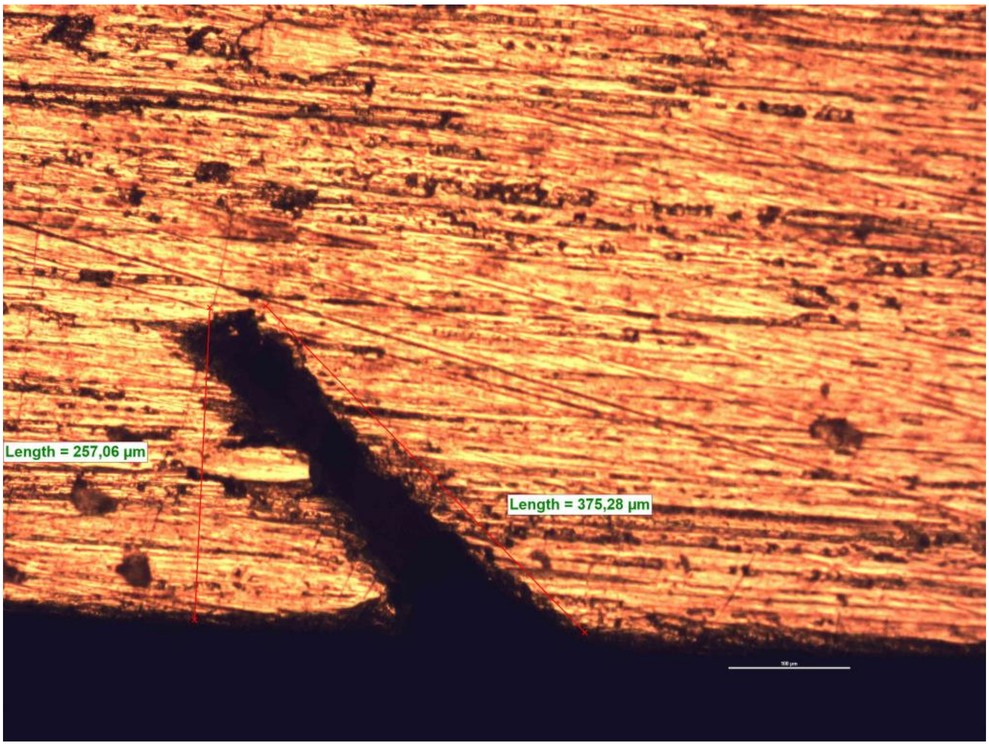
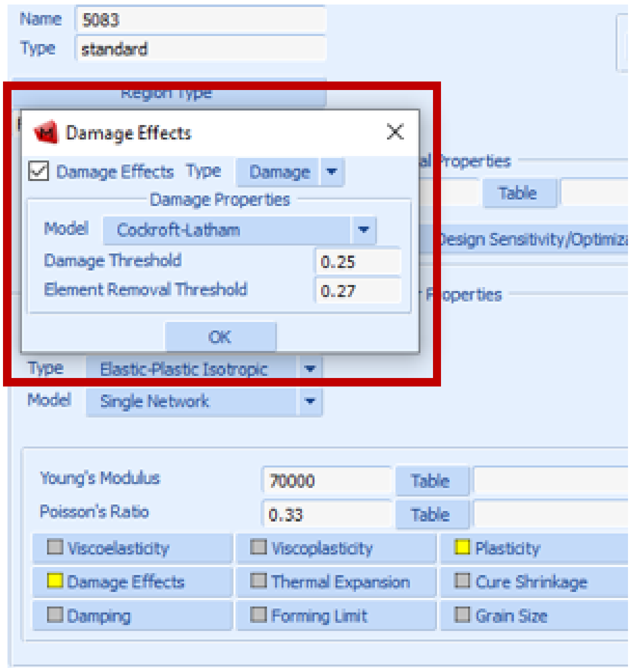


Figure 4.7 4mm Aluminium Crack Size Measuring

After that, analysis was done with same bending radius and bending angle, in this stage different damage parameters were tried. Suitable damage parameters for 4 mm thickness are shown in Figure 4.8.



Name 5083
Type standard
Region Type

Damage Effects
☑ Damage Effects Type Damage
Damage Properties
Model Cockroft-Latham
Damage Threshold 0.25
Element Removal Threshold 0.27
OK

Type Elastic-Plastic Isotropic
Model Single Network

Young's Modulus 70000 Table
Poisson's Ratio 0.33 Table

☐ Viscoelasticity ☐ Viscoplasticity 🟨 Plasticity
🟨 Damage Effects ☐ Thermal Expansion ☐ Cure Shrinkage
☐ Damping ☐ Forming Limit ☐ Grain Size

Figure 4.8 Damage Parameters

Cockroft-Latham damage parameter was determined as;

- Damage Threshold: 0.25
- Elemental Removal Threshold: 0.27

With using this parameter analysis was gave very close result with respect to real process. 4 mm thick aluminium bending analysis and test result is shown in Figure.4.9.

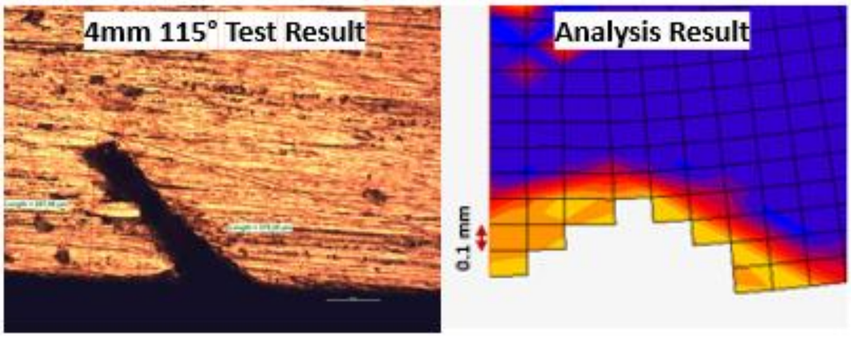


Figure 4.9 4mm Aluminium Test & Analysis Result

While 0.4mm crack occurred in real bending, 0.55mm crack occurred in the analysis. To verify these damage parameters same process was applied both 3- and 6-mm aluminium parts. These works results can be seen in Figure 4.10. and 4.11.

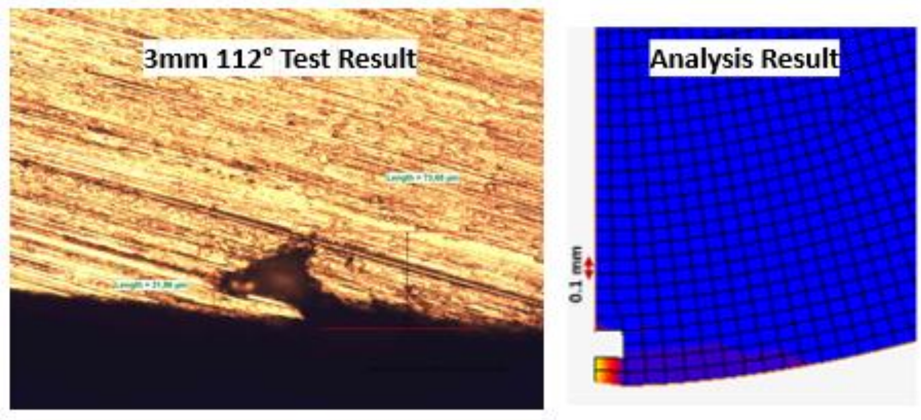


Figure 4.10 3mm Aluminium Crack Size Measuring

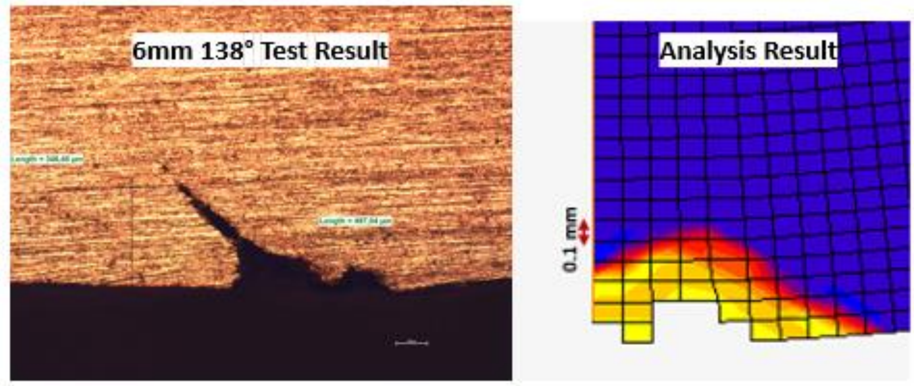
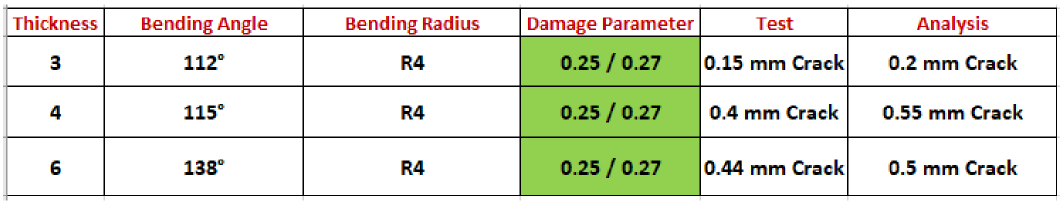


Figure 4.11 6mm Aluminium Crack Size Measuring

Comparison between real bending and analysis table is shown below.

Table 4.1 General View



Thickness	Bending Angle	Bending Radius	Damage Parameter	Test	Analysis
3	112°	R4	0.25 / 0.27	0.15 mm Crack	0.2 mm Crack
4	115°	R4	0.25 / 0.27	0.4 mm Crack	0.55 mm Crack
6	138°	R4	0.25 / 0.27	0.44 mm Crack	0.5 mm Crack

According to above table determined damage parameters are suitable for this study.

5. RESULTS AND DISCUSSION

5.1 Bending Tests and Analysis

After the analysis examinations, the bending process was realized in the real environment. According to DIN EN 00485-2 standard every aluminium part has different minimum bending radius depend on the series, tempering and thickness [17]. Due to the aim of this study which are making comparisons with standard values and to find actual minimum bending radius, determined aluminium parts was bent up to 90° with different bending radius. Bending matrix is shown in Table 3.2 before. First every piece part was bent with specific bending radius after that analysis was done with same process. Bending test and analysis results can be seen in Figure 5.1 to5.8.

- **3mm Thick Aluminium**

Analysis and test result can be seen below for 3mm thick aluminium

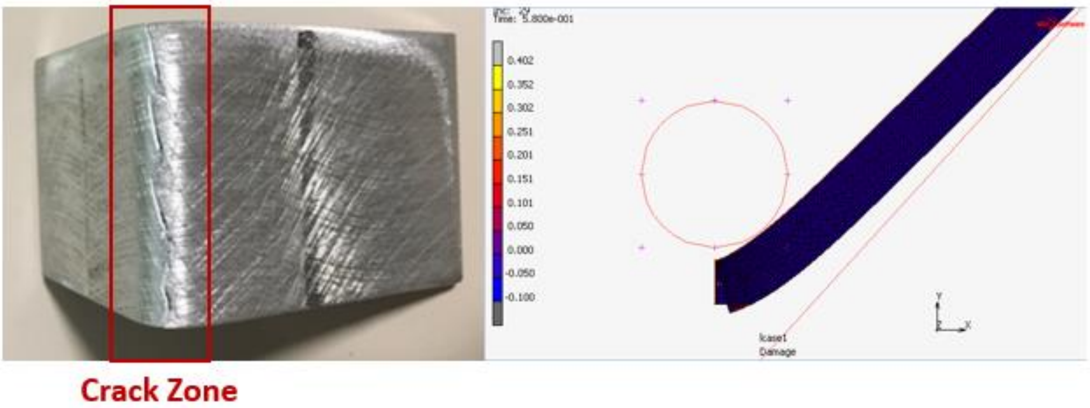


Figure 5.1 3mm Aluminium with R4mm – Test & Analysis

As can be seen in right of Figure 5.1, 3 mm thick aluminium bending analysis was made with R4 and surface crack occurred. To verify the analysis bending test was made and similar crack occurred on the material. Test result is shown in left of the Figure 5.1.

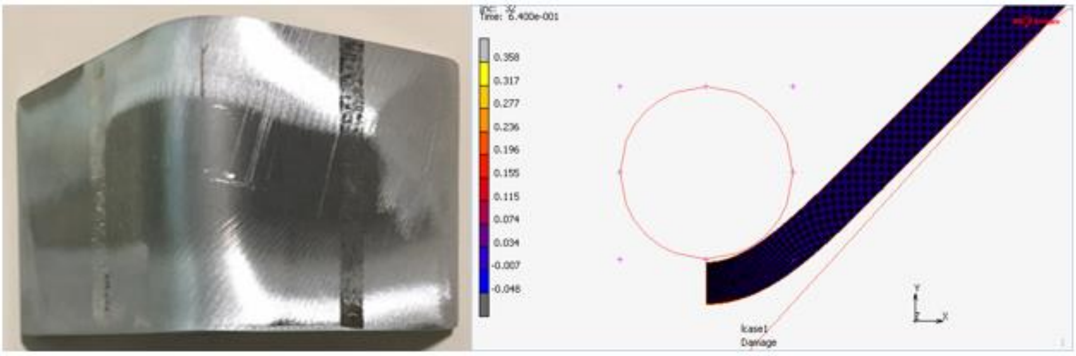


Figure 5.2 3mm Aluminium with R6mm –Test & Analysis

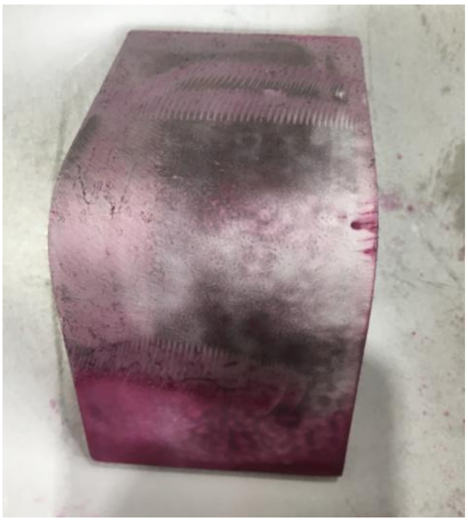


Figure 5.3 3mm Aluminium with R6mm – Liquid Penetrant Test

After the R4 test, bending test was made with R6. As can be seen in the right of Figure 5.2 there was no surface crack occurred at bending analysis. Likewise, real test passed without failure. The above tests show that the minimum bending radius of 3mm aluminium is 6 mm.

- **4mm Thick Aluminium**

Analysis and test results can be seen below for 4mm thick aluminium

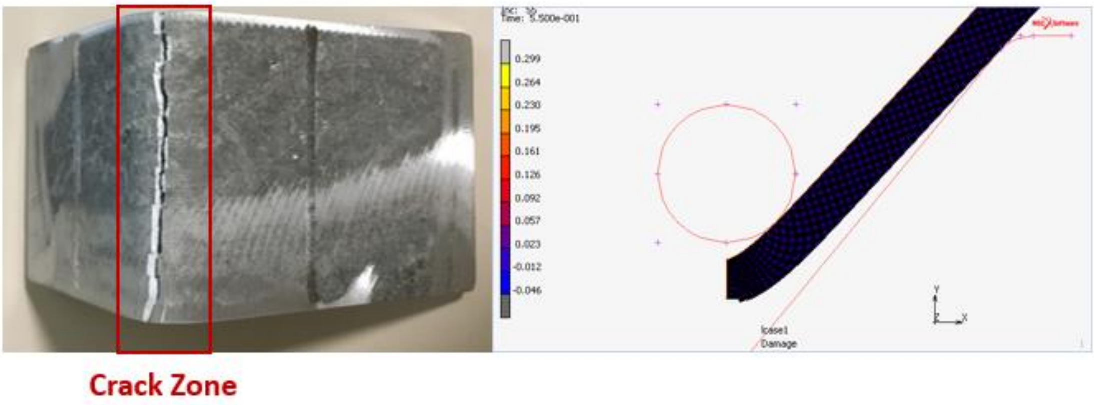


Figure 5.4 4mm Aluminium with R6mm – Test & Analysis

As can be seen in right of Figure 5.4, 4 mm thick aluminium bending analysis was made with R6 and surface crack occurred. To verify the analysis bending test was made and similar crack occurred on the material. Test result is shown in left of the Figure 5.4.

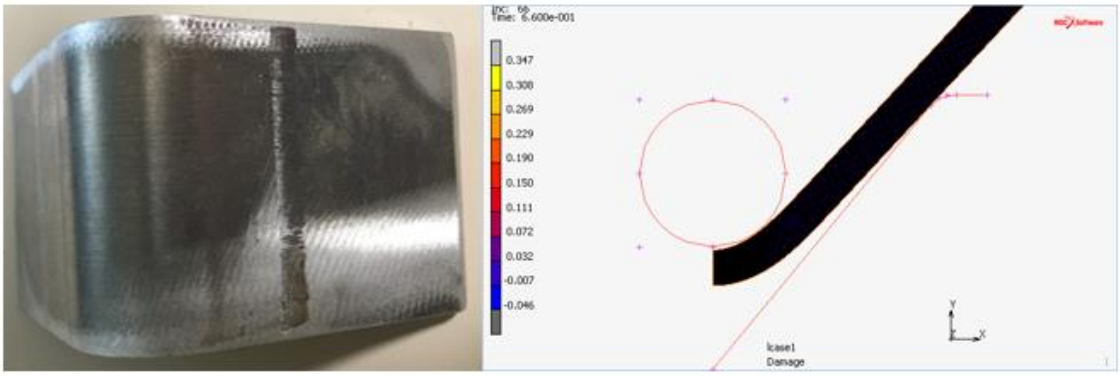


Figure 5.5 4mm Aluminium with R8mm –Test & Analysis

Figure 5.6 4mm Aluminium with R8mm – Liquid Penetrant Test

After the R6 test, bending test was made with R8. As can be seen in right of Figure 5.5 there is no surface crack occurred at bending analysis. Likewise, real test passed without failure. The above tests show that the minimum bending radius of 4mm aluminium is 8 mm.

- **6mm Thick Aluminium**

Analysis and test results can be seen below for 6mm thick aluminium

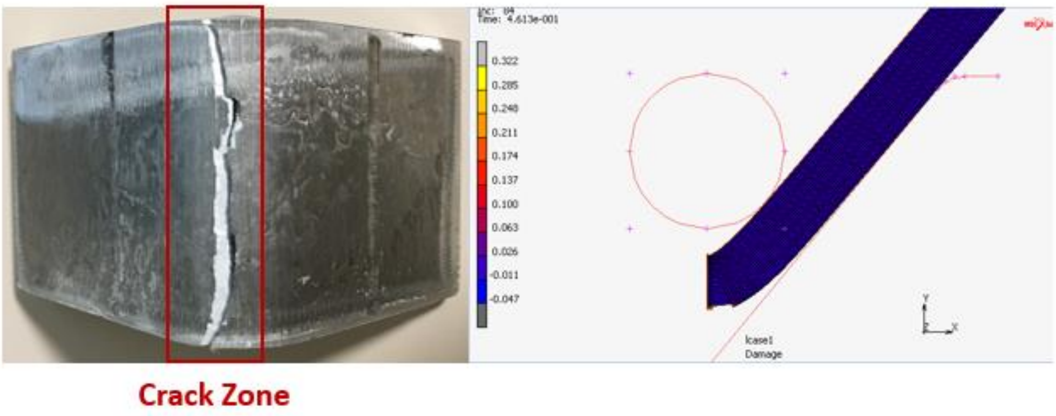


Figure 5.7 6mm Aluminium with R8mm – Test & Analysis

As can be seen in right of Figure 5.7, 6 mm thick aluminium bending analysis was made with R8 and surface crack occurred. To verify the analysis bending test was made and similar crack occurred on the material. Test result is shown in left of the Figure 5.7.

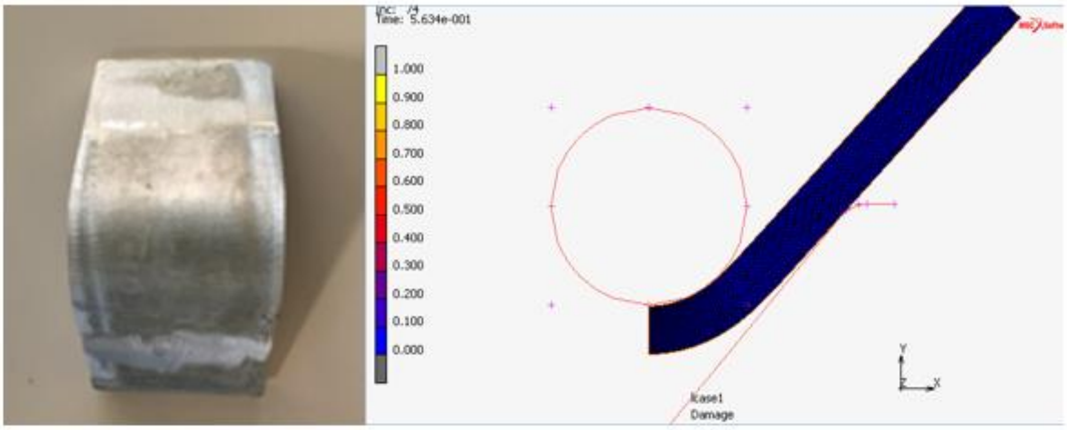


Figure 5.8 6mm Aluminium with R12mm – Test & Analysis

Figure 5.9 6mm Aluminium with R12mm – Liquid Penetrant Test

After the R8 tests, bending test was made with R12. As can be seen in right of Figure 5.8 there is no surface crack occurred at bending analysis. Likewise, real test passed without failure. The above tests show that the minimum bending radius of 6mm aluminium is 12 mm.

Above Figures implies that Cockroft-Latham damage parameters can show real situation of the material after the bending operations.

According to DIN EN 00485-2 standard minimum bending radius of EN AW-5083-H321 aluminium is given below.

- Minimum 7.5R for 3mm thickness
- Minimum 10R for 4mm thickness
- Minimum 24R for 6mm thickness [17]

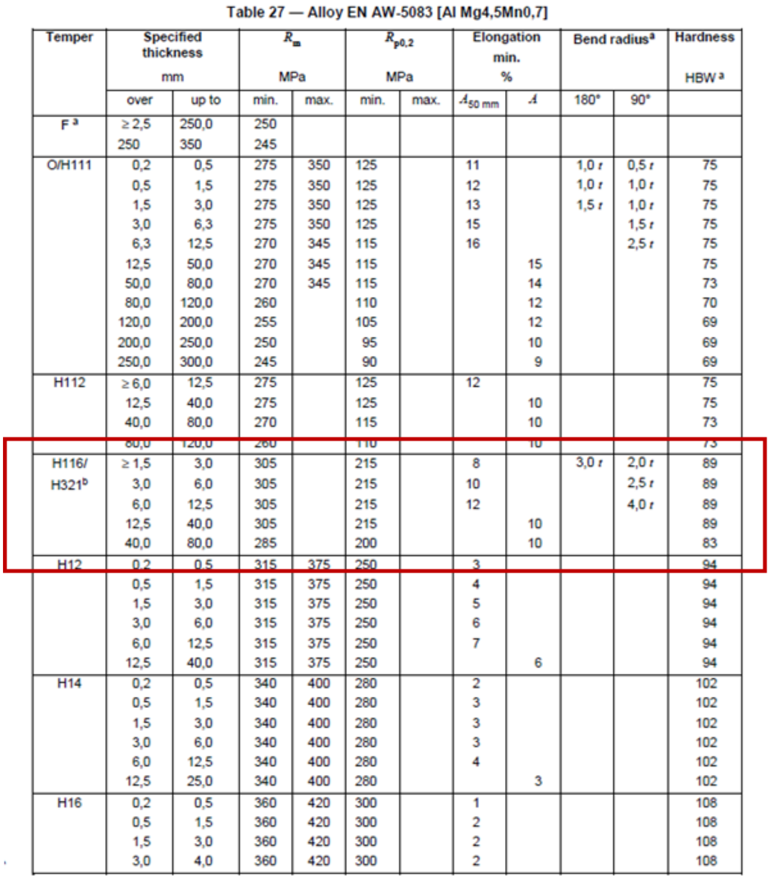


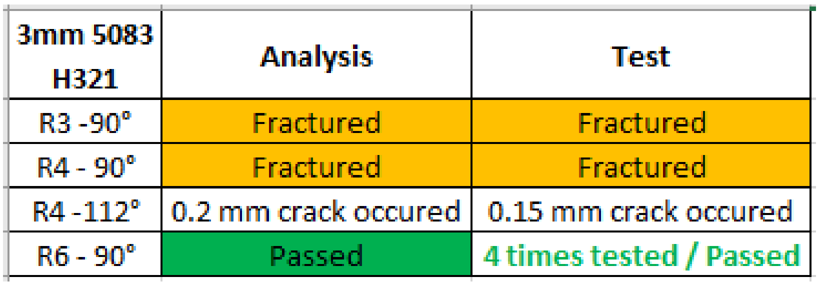
Table 27 — Alloy EN AW-5083 [Al Mg4,5Mn0,7]

Temper	Specified thickness mm		R_m MPa		$R_{p0,2}$ MPa		Elongation min. %		Bend radius[a]		Hardness HBW[a]
	over	up to	min.	max.	min.	max.	$A_{50\,mm}$	A	180°	90°	
F[a]	≥ 2,5	250,0	250								
	250	350	245								
O/H111	0,2	0,5	275	350	125		11		1,0 *r*	0,5 *r*	75
	0,5	1,5	275	350	125		12		1,0 *r*	1,0 *r*	75
	1,5	3,0	275	350	125		13		1,5 *r*	1,0 *r*	75
	3,0	6,3	275	350	125		15			1,5 *r*	75
	6,3	12,5	270	345	115		16			2,5 *r*	75
	12,5	50,0	270	345	115			15			75
	50,0	80,0	270	345	115			14			73
	80,0	120,0	260		110			12			70
	120,0	200,0	255		105			12			69
	200,0	250,0	250		95			10			69
	250,0	300,0	245		90			9			69
H112	≥ 6,0	12,5	275		125		12				75
	12,5	40,0	275		125			10			75
	40,0	80,0	270		115			10			73
	80,0	120,0	260		110			10			73
H116/ H321[b]	≥ 1,5	3,0	305		215		8		3,0 *r*	2,0 *r*	89
	3,0	6,0	305		215		10			2,5 *r*	89
	6,0	12,5	305		215		12			4,0 *r*	89
	12,5	40,0	305		215			10			89
	40,0	80,0	285		200			10			83
H12	0,2	0,5	315	375	250		3				94
	0,5	1,5	315	375	250		4				94
	1,5	3,0	315	375	250		5				94
	3,0	6,0	315	375	250		6				94
	6,0	12,5	315	375	250		7				94
	12,5	40,0	315	375	250			6			94
H14	0,2	0,5	340	400	280		2				102
	0,5	1,5	340	400	280		3				102
	1,5	3,0	340	400	280		3				102
	3,0	6,0	340	400	280		3				102
	6,0	12,5	340	400	280		4				102
	12,5	25,0	340	400	280			3			102
H16	0,2	0,5	360	420	300		1				108
	0,5	1,5	360	420	300		2				108
	1,5	3,0	360	420	300		2				108
	3,0	4,0	360	420	300		2				108

Figure 5.10 DIN EN 00485-2 Standard [17]

Test and analysis results can be seen in Table 5.1,2,3

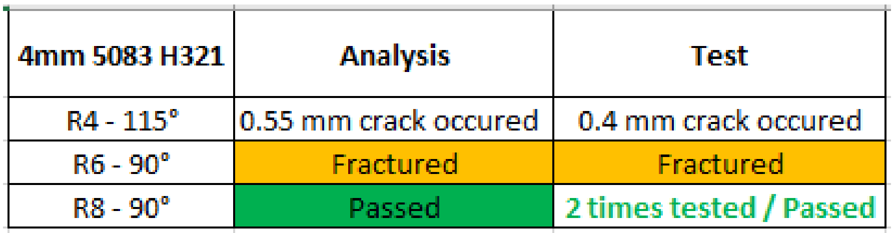
Table 5.1 3mm Thickness Aluminium Test and Analysis Result



3mm 5083 H321	Analysis	Test
R3 -90°	Fractured	Fractured
R4 - 90°	Fractured	Fractured
R4 -112°	0.2 mm crack occured	0.15 mm crack occured
R6 - 90°	Passed	4 times tested / Passed

While standard referring that 3mm thickness of aluminium should be bent minimum 7.5mm radius, this study showed that 3mm thickness aluminium can be bent with minimum 6mm.

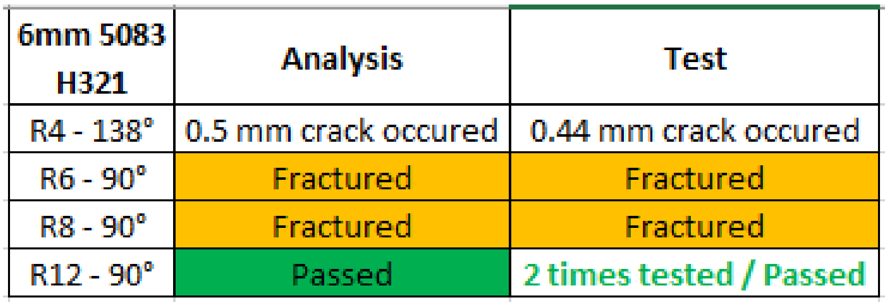
Table 5.2 4mm Thickness Aluminium Test and Analysis Result



4mm 5083 H321	**Analysis**	**Test**
R4 - 115°	0.55 mm crack occured	0.4 mm crack occured
R6 - 90°	Fractured	Fractured
R8 - 90°	Passed	2 times tested / Passed

While standard referring that 4mm thickness of aluminium should be bent minimum 10mm radius, this study showed that 4mm thickness aluminium can be bent with minimum 8mm.

Table 5.3 6mm Thickness Aluminium Test and Analysis Result



6mm 5083 H321	**Analysis**	**Test**
R4 - 138°	0.5 mm crack occured	0.44 mm crack occured
R6 - 90°	Fractured	Fractured
R8 - 90°	Fractured	Fractured
R12 - 90°	Passed	2 times tested / Passed

While standard referring that 6mm thickness of aluminium should be bent minimum 24mm radius, this study showed that 6mm thickness aluminium can be bent with minimum 12mm.

6. SUMMARY AND OUTLOOK

Within the scope of this study, 3,4 and 6mm thickness of aluminium was processed with analysis and conventional bending methods. The results were compared between each other and standards. The following statements could be made as concluding remarks.

- For creating material model in the analysis, Voce Equation, Swift Equation and Curve Fitting method was examined and only Voce equation gave the best results.
- For creating appropriate analyse model Cockroft-Latham damage model was examined. This study showed that with using Cockroft-Latham damage model, damage condition on the material can be determined. Other damage models can be examined in further studies.
- Mesh size is very important factor for analysis. To get better result mesh size should be as small as possible. In this study due to the wall time of analysis, mesh size limited at 0.1mm. With more complex computer, mesh size can be made more smaller in the further studies to reduce the error.
- With this study it has been determine that to be under standard values for bending radius for different thickness.
- With this study EN AW-5083-H321 aluminium alloys were examined which are frequently used types in military industry, the other type is EN AW-5083-H131 ballistic aluminium can be examined in the further studies.

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