NUMERICAL AND EXPERIMENTAL INVESTIGATION ON SPRING BACK IN WARM BENDING OF AL-ALLOY SHEETS

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY
IN
PRODUCTION & INDUSTRIAL ENGINEERING

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I, Akash Chauhan (Roll No. 2K18/PIE/17), hereby certify that the project dissertation titled "Neumerical and experimental investigation on spring back in warm bending of al-alloy sheets" which is submitted by me to the Department of Mechanical, Production & Industrial and Automobile Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship, or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation Titled “Neumerical and experimental investigation on spring back in warm bending of al-alloy sheets” which is submitted by Akash Chauhan, 2K18/PIE/17 Department of Mechanical, Production & Industrial and Automobile Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Bachelor of Technology, is a record of the project carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ACKNOWLEDGEMENT

I wish to express my profound gratitude and indebtedness to Prof. Vijay Gautam, Department of Mechanical Engineering, Delhi Technological University, Delhi-110042 for introducing the present topic and for his inspiring guidance, constructive criticism and valuable suggestion throughout the project work.

I am also thankful to Prof Vipin, Head of Mechanical Engineering Department, Delhi Technological University, Delhi-110042 for his constant support and encouragement. I am also grateful to my seniors and classmates.

Lastly my sincere thanks to all my friends who have patiently extended all sorts of help for accomplishing this undertaking.

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Abstract

Springback is a very common and important phenomenon in sheet metal forming operations, which is caused by the elastic redistribution of the internal stresses after the removal of deforming forces. Spring-back compensation is completely essential for the accurate geometry of sheet metal components. Understanding about the springback in bending process gives an opportunity to modify the process beforehand which can produce accurate shape of the product. This saves a lot of money and time. In present work, a study of springback in V bending and U bending is performed. Also the effect of three different temperatures; 30°, 120° and 150° on the springback in the V bending and U bending is observed. An FEA of the V bending and U bending process is performed. Effect of temperature on the material property is considered while performing the analysis. The material considered is Aluminium alloy AA5083. Hill's isotropic yield and elastic plastic material model is used. ABAQUS/CAE is used to perform finite element analysis. The uniaxial tension test on the AA5083 was performed to calculate the input data for material modeling. The springback is predicted at three different temperatures and validated by experimantal results.

Keywords: Springback, Warn bending, V-bending, U-bending, FE simulations

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LIST OF SYMBOLS, ABBREVIATIONS

σ: Stress in material
P : Force applied on material
E : Young’s Modulus of Elasticity
ln : Natural Logarithm
A : Area of cross section
ε : Strain in material
L : Length of Specimen
K : Strength Coefficient
n : Strain Hardening Coefficient
U = Displacement
UR = Rotation

CHAPTER 1

INTRODUCTION

1.1 Bending

Bending is one among the foremost important sheet metal forming operations by which a straight length of metal strip is transformed into a curved one with the help of suitably designed die and punch. It is quite common process of forming steel sheets and plates into channels, drums, automotive and aircraft components. "Especially V-Bending process has been thoroughly studied and there;s many literature available, among which the most important contribution is Hill's basic theory on pure bending of sheet metals[1]. Bending is a manufacturing process that produces a V-shape,U-shape, or channel shape along a straight axis in ductile materials, most commonly sheet metal. In press brake forming, a work piece is positioned over the die block and therefore the die block presses the sheet to make a shape. Usually bending has to overcome both tensile stresses and compressive streeses. When bending is completed , the residual stresses cause the material to spring back towards its original position, therefore the sheet must be over-bent to achieve the proper bend angle.The amount of spring back depends on the material, and therefore the type of forming. When sheet metal is bent, it stretches length . The bend deduction is that the amount the sheet will stretch when bent as measured from the outside edges of the bend. The bend radius refers to the inside radius". The formed bend radius depends upon the dies used, the material properties, and therefore the material thickness.The V-punch forms a V-shape with a single punch.

1.2 Theory

Tensile tests are performed for several reasons. The results of tensile tests are utilized in selecting materials for engineering applications. "Tensile properties frequently are included in material specifications to make sure quality. Tensile properties often are measured during development of latest materials and processes, in order that different materials and processes are often compared. Finally, tensile properties often are wont to predict the behaviour of a material under forms of loading other than uniaxial tension. The strength of a material often is that primary concern. The strength of interest could even be measured in terms of either the stress necessary to cause appreciable plastic deformation or the maximum stress that the material can withstand. These measures of strength are used, with appropriate caution (in the form of safety factors), in engineering design. Also of interest is that the material's ductility, which may be a measure of what proportion it are often deformed before it fractures. Rarely is ductility incorporated directly in design; rather, it's included in material specifications to make sure quality and toughness". Low ductility during a tensile test often is accompanied by low resistance to fracture under other forms of loading. Elastic properties also could also be of interest, but special techniques must be wont to measure these properties during tensile testing, and more accurate measurements are often made by ultrasonic techniques.

Engineering Stress is the ratio of applied force P and cross section or force per area.

$\boldsymbol{\sigma} = \mathbf{P/Ao}$ is engineering stress

P is the external axial tensile load

$\boldsymbol{A}$**o** is the original cross-sectional area

There are three types of stresses as seen in Fig. 1.1

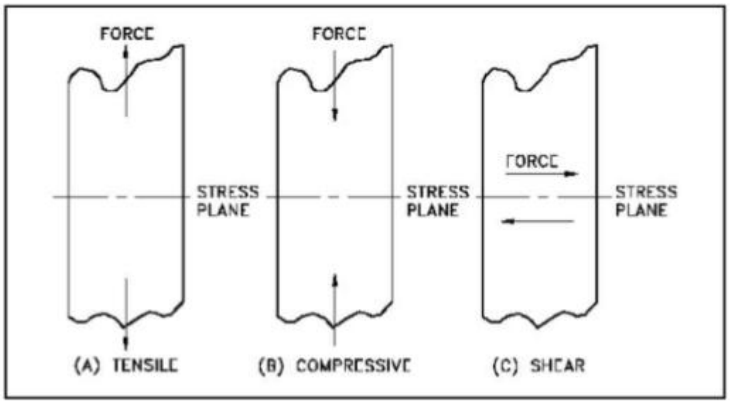


Figure 1.1. Types of the stresses

"**Engineering Strain** is defined as extension per unit length.

$\varepsilon = \Delta L / Lo = (Lf - Lo) / Lo$

ε is the engineering strain

Lo is the original length of the specimen

Lf is the final length of the specimen

An example of the engineering stress-strain curve for a typical engineering alloy is shown in Figure 1.2. From it some vital important properties are often determined. The elastic modulus, the yield strength, the ultimate tensile strength, and therefore the fracture strain are all clearly exhibited in an accurately constructed stress strain curve.

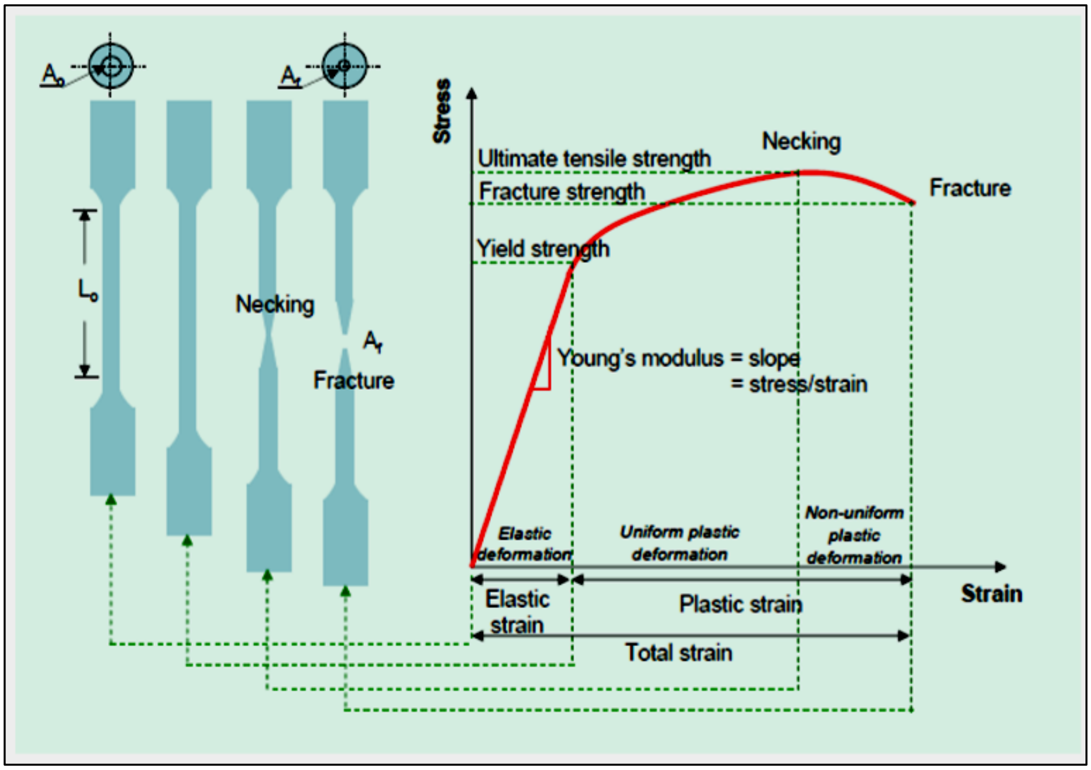


Figure 1.2. Stress-strain curve

True stress is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area (Fig.1.3).

$\sigma T = P/Ai$

True strain is the rate of instantaneous increase in the instantaneous gauge length (Fig.1.3).

$\varepsilon T = \ln (li / lo)$

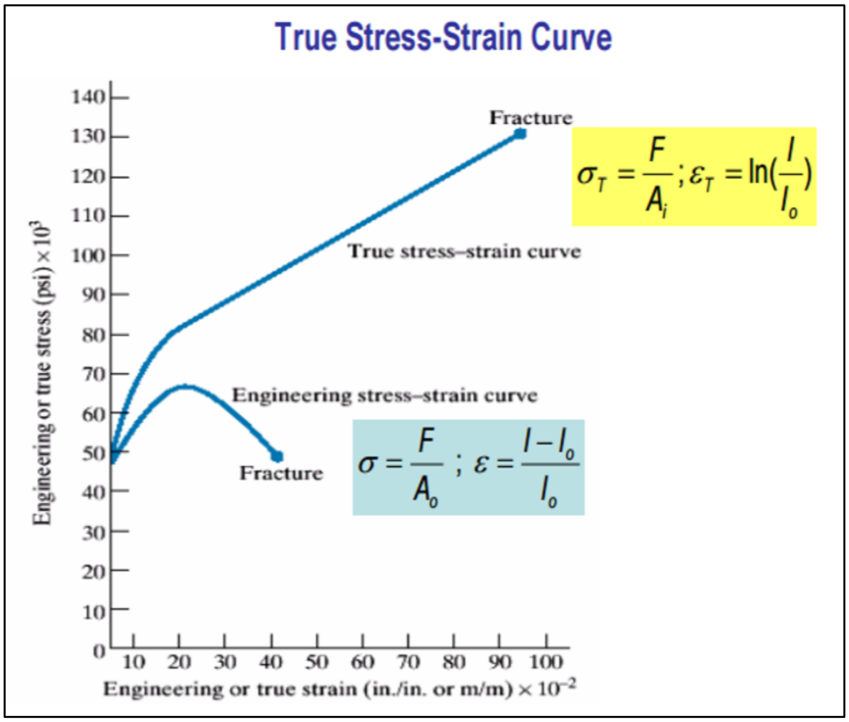


Figure 1.3. True Stress-strain curve

True stress-engineering stress relation:

$\sigma T = \sigma(\varepsilon + 1)$

True strain-engineering strain relation:

$\varepsilon T = \ln(\varepsilon + 1)$

Elastic region: The part of the stress-strain curve up to the yielding point. Elastic deformation is recoverable. In the elastic region stress and strain are associated one another linearly. E is Modulus of Elasticity or Young's Modulus which is specific for each type of material.

Hooke's Law:

$\sigma = E\varepsilon$

Power Law of Strain Hardening:

$\sigma = K\varepsilon^n$

Plastic region: The a part of the stress-strain diagram after the yielding point. At the yielding point, the plastic deformation starts. Plastic deformation is permanent. At the maximum point of the stress-strain diagram (σUTS), necking starts.

Ultimate Tensile Strength, $\boldsymbol{\sigma UTS}$ is that the maximum strength that the material can withstand.

$\sigma UTS = Pmax / A\mathbf{o}$

Yield Strength, $\boldsymbol{\sigma Y}$ is that the stress level at which plastic deformation initiates. The start of first plastic deformation is called yielding. 0.2% Offset method may be a commonly used method to determine the yield strength. σY (0.2%) is found by drawing a parallel line to the elastic region and therefore the point at which this line intersects with the stress-strain curve is about because the yielding point (Fig 1.4)".

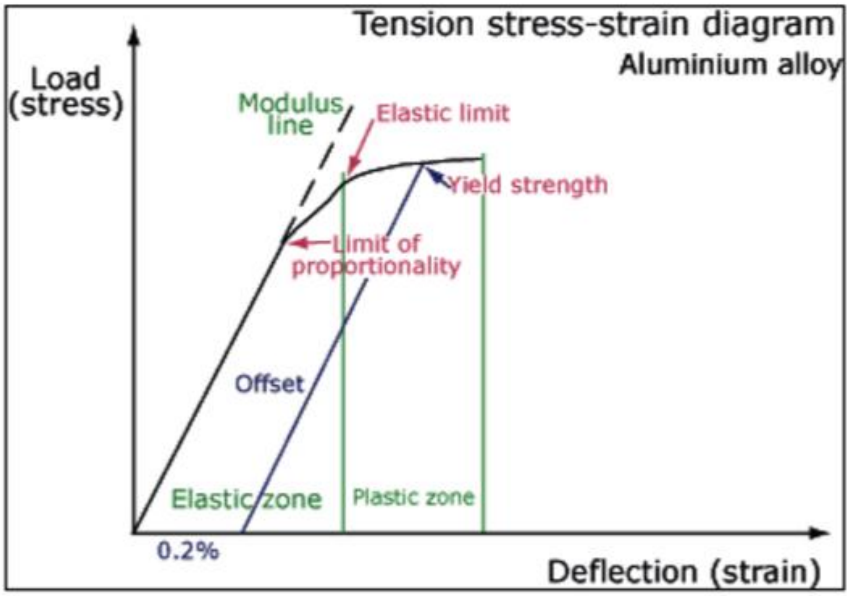


Figure 1.4. Stress-strain curve

Fracture Strength, $\boldsymbol{\sigma F}$: "After necking, plastic deformation isn't uniform and therefore the stress decreases accordingly until fracture.

$\sigma \mathbf{F} = P\mathbf{F} / A\mathbf{o}$

Toughness: The capability of a metal to deform plastically and to absorb energy within the process before fracture is termed toughness. The emphasis of this definition should be placed on the ability to absorb energy before fracture.

Ductility: may be a measure of what proportion something deforms plastically before fracture, but simply because a cloth is ductile doesn't make it tough. The key to toughness is a good combination of strength and ductility. A material with high strength and high ductility will have more toughness than a cloth with low strength and high ductility. Ductility are often described with the percent elongation or percent reduction in area

$\% Elongation = [(Lf - L0) \ / \ L0] \times 100$ (percent elongation)

$\%RA = [(A\text{o} - Af) \ / \ A\text{o}] \times 100$ (percent reduction in area)

Resilience: By considering the area under the stress-strain curve within the elastic region, this area represents the stored elastic energy or resilience.

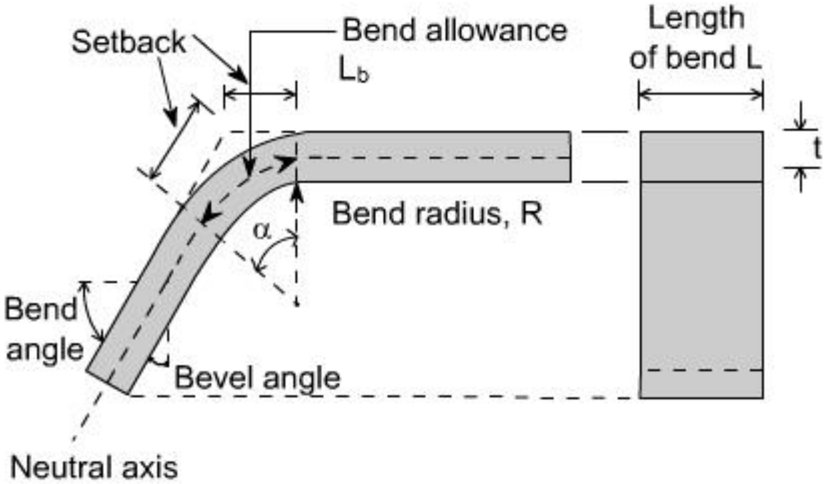


Figure 1.5 Bending Terminology

BEND ALLOWANCE: It’s the length of the neutral axis within the bend, Fig1.5 This determines the blank length needed for a bent part. It are often approximately estimated from the relation

$$L_b = a (R + kt)$$

where, L_b = bend allowance (mm)

a = bend angle (radian)

R = bend radius (mm)

t = thickness of sheet (mm), and

k = constant, whose value may be taken as 1/3 when $R < 2t$, and as 1/2 when $R \geq 2t$.

There are different types of metal bending operations such like air bending, V – and U – die bending, roll bending, roll forming, press brake forming. They considered variety of segments associated with the multi – sequences bending processes like bend modelling, bend sequences, tool selection and optimization also as ergonomic aspects of sheet metal forming. Special focus has been placed on collision detection between the punch and bent material. Unlike pure bending, V-die bending isn’t a steady process". A sheet metal is laid over a die and bent because the punch inserts into the die, the bending moment and curvature vary continuously along the sheet and through the deformation, the sheet is stressed in tension on one surface and compression on the opposite, it’s shift of the neutral surface during bending that complicates the analysis.

1.3 Spring Back

Spring-back is a very common and important phenomenon in sheet metal forming operations, which is caused by the elastic redistribution of the internal stresses after the removal of deforming forces. "Spring-back compensation is completely essential for the accurate geometry of sheet metal components. After plastic bending, unloading takes place and punch removes from the workpiece to the initial position. Final shape of the workpiece after unloading differs from the punch /dies configuration in closed position. Occurrence of this difference is known as "spring back". In fig. 1.5 bent material is shown in two positions: a) bent and closed in the die (angle αi) and b) after unloading (angle αf) because it are often seen, after unloading bend angle is smaller than when being closed in the die (αi>αf). A sheet metal is laid over a die and bent because the punch inserts into the die, the bending moment and curvature vary continuously along the sheet and through the deformation, the sheet is stressed in tension on one surface and compression on the opposite, it's shift of the neutral surface during bending that complicates the analysis[2].

When the forming tool is faraway from the metal, the elastic components of stress cause spring back which changes both the angle and radius of the bent part as shown in Fig.1. The part tends to recover elastically after bending, and its bend radius becomes larger. This elastically-driven change in shape of a part upon unloading after forming is referred to as spring back".

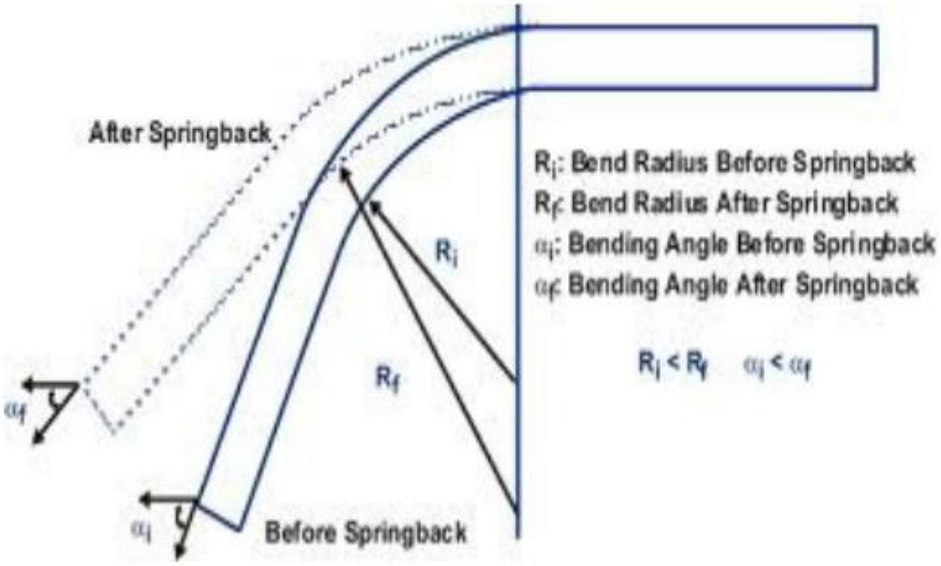


Figure 1.6: Terminology for springback in bending[3]

Springback characterization is expressed by springback ratio (factor) K:

$$K = \alpha f / \alpha i \qquad \text{------ (1)}$$

Where

αf – bend angle after unloading
αi – bend angle – workpiece is closed in the die

"From (1) is evident that in case K = 1 there is no spring back (αi = αf) and in case K = 0 complete elastic recovery of the bent material takes place (αf = 0).

Spring-back causes following problems in sheet-metal forming:

1) The assembly of the sheet metal components becomes problematic thereby increasing the

assembly time and reducing the productivity.

2) In automobile industry different punch corner radius are used for various bending operations which successively affects the spring-back in components.
3) A wide selection of thickness is used in sheet-metal components which again affects the spring-back.
4) High strength sheets are preferred for automotive body on reduce the thickness which results in reduction of the overall weight of the vehicle. Lighter vehicles are in demand for higher fuel efficiency.

1.4 Residual Stresses

Residual stresses or locked-in stresses are often defined as those stresses existing within a body within the absence of external loading or thermal gradients. In other words residual stresses during a structural material or component are those stresses which exsist within the object without the application of any service or other external loads.

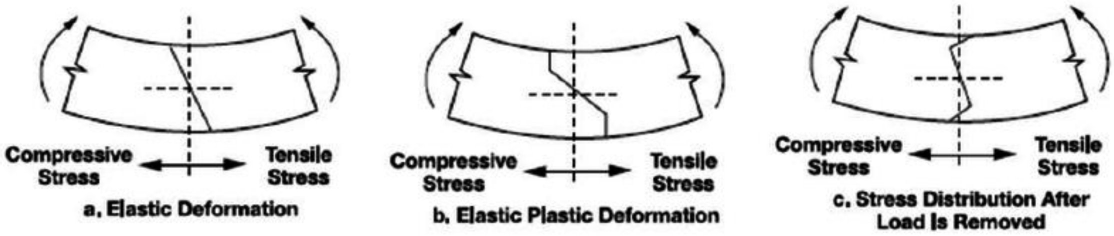


Figure 1.6. Residual streeses

Factors that cause residual stresses

Residual stresses are often present in any mechanical structure due to many causes. Residual stresses may be due to the technological process wont to make the component Residual stresses are often present in any mechanical structure due to many causes.

Residual stresses may be due to the technological process used to make the component. Manufacturing processes are the foremost common causes of residual stress. Virtually all manufacturing and fabricating processes like casting, welding, machining, molding, heat treatment, plastic deformation during bending, rolling or forging introduce residual stresses into the manufactured object. Residual stress might be caused by localized yielding of the material, because of a sharp notch or from certain surface treatments like shot peening or surface hardening. Among the factors that are known to cause residual stresses are the growth of deformation gradients in various sections of the piece by the development of thermal gradients, volumetric changes arising during solidification or from solid state transformations, and from differences within the coefficient of thermal expansion in pieces made up of different materials. Thermal residual stresses are primarily because of differential expansion when a metal is heated or cooled. The two factors that control this are thermal treatment (heating or cooling) and restraint. Both the thermal treatment and restraint of the component must be present to get residual stresses.

When any object is made through cold working, there is the possibility for the growth of residual stresses. A good common example of mechanically applied residual stresses may be a bicycle wheel. A bicycle wheel is a very light and strong due to the way during which the components are stressed. The wire spokes are radial aligned and tightening the spokes creates tensile radial stresses. The spokes pull the rim inward, creating circumferential compression stresses within the rim. Conversely, the spokes pull the tubular hub outward. If the thin spokes were not under a proper tensile preload load the thin wire spokes couldn’t adequately support the load of the rider.

Residual stresses are often sufficient to cause a metal part to suddenly split into two or more pieces after it’s been resting on a table or floor without external load being applied.

Residual stresses may result in visible distortion of a component.

Residual stresses relaxation can deform a peace when it’s in machining.

Role of residual stresses

Residual stresses have the same role during a structure’s strength as common mechanical stresses. However, while stress due to external loads are often calculated with a degree of accuracy, residual stresses are difficult to foresee. It is, therefore, very important to have a reliable method able to measure them directly with minimum damage to the surface. Residual stresses can play a significant role in explaining or preventing failure of a component at times. One example of residual stresses preventing failure is that the shot peening of component to induce surface compressive stresses that improve the fatigue life of the component. Unfortunately, there also are processes or processing errors which will induce excessive tensile residual stresses in locations which may promote failure of a component. It must be kept in mind that the internal stresses are balanced during a component. Tensile residual stresses are counter balanced by compressive residual stresses. Residual stresses are three dimensional".

CHAPTER 2

LITERATURE REVIEW

In the research we determine the spring back of aluminium alloy sheet metal in v bending at elevated temperatures. "V-Bending process has been thoroughly studied and there is plenty of literature available, among which the most important contribution is Hill’s basic theory on pure bending of sheet metal[4]. Pure bending is hardly achieved in actual bending process, except that, it’s the specified profile of a bend than the temporal stress and strain distribution that is important. The assumptions made within the study of pure bending are generally different from real conditions in v-die bending. Unlike pure bending, V-die bending isn’t a steady process. A sheet metal is laid over a die and bent because the punch inserts into the die, the bending moment and curvature vary continuously along the sheet and through the deformation, the sheet is stressed in tension on one surface and compression on the opposite it’s shift of the neutral surface during bending that complicates the analysis.

Lloyd (1980) [5]have investigated the deformation of commercial Al-Mg alloys AA5083 (4.46 wt. % Mg) over a wide range of strain rates and temperatures and the major factors influencing their deformation. The strain hardening strengthening increases the alloy strength to twice than that of the strength of the annealed state of this alloy.Thiyaneshwaran and Sureshkumar (2013)[6] have conducted microstructural and mechanical property studies in Aluminium 5083 Alloy processed by equal Channel Angular Extrusion. It can be concluded that processing by ECAE increased the mechanical and wear properties of aluminium 5083 alloys.

The elastic stresses remaining within the bend area after bending pressure is released will cause a small decrease within the bend angle. Metal movement during this type is understood as spring back, as shown in figure 1.6. The magnitude of the movement will vary according with the material type, thickness and hardness. A larger bend radius also will cause grater spring back[7]. Commercially available finite element analysis (FEA) software is used to analyze bending and spring back of various aluminum materials of various thickness. For forming process the material is stressed beyond elastic limit so that the permanent deformation takes place. The material state becomes the plastic deformation zone; hence the sheet metal can be formed Figure 2.1 shows the principle of spring back. The spring back is affected by the factors like sheet thickness, material properties, tooling geometry etc.

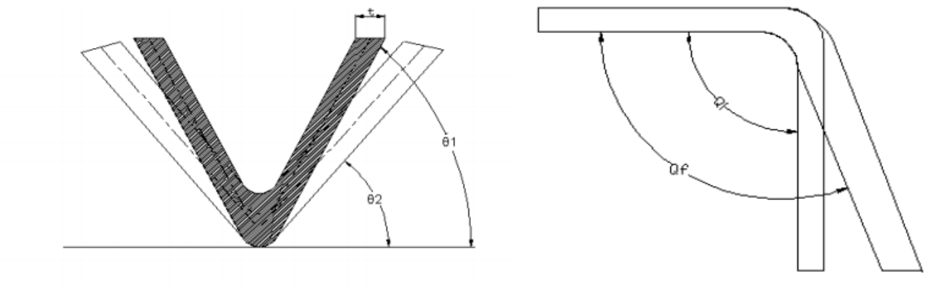


Figure 2.1. Principle of Spring back θ1> θ2 or (Qf>Qi)

The finite element program used in the research is ABAQUS/Standard, which is a commercial program available from Hibbitt, Karlsson and Sorensen, Inc. of the United States [8]. The application field for ABAQUS is large, particularly for plastic deformation and manufacturing processes.

Spring back based on residual differential :

H K Yi,[9] studied a model based on differential strains after relief from the maximum bending stress, derived for six different deformation patterns in order to predict spring back analytically. The spring back for each deformation pattern is estimated by the residual differential strains between outer and inner surfaces after elastic recovery. Each of the six deformation patterns has a valid region of applicability, based on elastic modulus, yield strength, applied tension, and bending geometry.

Nguyen et. al [10] conducted experimental and numerical studies on springback reduction in warm bending of magnesium alloy (AZ31) at various temperatures ranging between room temperature to 200°C. The finite element analysis used a Johnson Cook material model and modified kinematic hardening model. It was concluded that the proposed hardening model in FE simulations produced good results which are in agreement with the experimental results.

Residual stresses or locked-in stresses are often defined as those stresses existing within a body within the absence of external loading or thermal gradients. In other words residual stresses during a structural material or component are those stresses which exsist within the object without the application of any service or other external load[11]".

Residual stresses are often sufficient to cause a metal part to suddenly split into two or more pieces after it’s been resting on a table or floor without external load being applied. Residual stresses may result in visible distortion of a component. Residual stresses relaxation can deform a peace when it’s in machining.

CHAPTER 3

MATERIAL SELECTION

3.1 TYPES OF ALUMINIUM

Aluminium (symbol Al) is a light alloy which makes up around 8% of earth’s crust, by mass. "The material occur in many forms, with properties varying with grade depending upon principal alloying material. The wrought aluminium alloy designation system is as follows:

- 1xxx: Controlled unalloyed composition, used primarily within the electrical and chemical industries
- 2xxx: Alloys during which copper is that the principal alloying element, although other elements, notably magnesium, could even be specified
- 3xxx: Alloys during which manganese is that the principal alloying element, used as general-purpose alloys for architectural applications
- 4xxx: Alloys during which silicon is that the principal alloying element, utilized in welding rods and brazing sheet
- 5xxx: Alloys during which magnesium is that the principal alloying element, used in boat hulls, gangplanks, and other products exposed to marine environments of high moisture content
- 6xxx: Alloys during which magnesium and silicon are the principal alloying elements, commonly used for architectural extrusions and automotive components
- 7xxx: Alloys during which zinc is that the principal alloying element, utilized in aircraft structural components and other high-strength applications.
- 8xxx: Alloys characterizing miscellaneous compositions. The 8xxx series alloys may contain appreciable amounts of tin, lithium, and/or iron.
- 9xxx: Reserved for future use.

TABLE 3.1. Tempered Designations

LETTER	MEANING
F	Applies to products of a forming process in which no special control over thermal or strain hardening conditions is employed
O	Annealed-Applies to product which has been heated to produce the lowest strength condition to better ductility and dimensional stability
H	Strain Hardened-Applies to products which are strengthened through cold-working .The strain hardening could also be followed by supplementary thermal treatment, which produces some reduction in strength.
W	Solution Heat treated-An unstable temper applicable only to alloys which age spontaneously at room temperature after solution heat treatment.
T	Thermal Treated- To produce stable tempers aside from F, O or H . Applies to product which has been heat treated, sometimes with supplementary strain –hardening to produce a stable temper.

3.2 PROPERTIES OF ALUMINIUM

3.2.1 Physical Properties of Aluminium

Weight- Al is a light material as compared to other materials having density of around 2.700 kg/m^3

Strength- Commercially pure aluminium has a tensile strength of about 90 Mpa. Thus its usefulness as a structural material during this type is somewhat limited By working the metal, as by cold rolling, its strength are often approximately doubled. Much larger increases in strength are often obtained by alloying Aluminium with small percentages of one or more other elements like manganese, silicon, copper, magnesium, or zinc.

Elasticity- the Young’s modulus of Aluminium is around 69 Gpa, though it depends upon the alloying material, temperature etc.

Formability- Aluminium has the good formability characteristics, which may be used to the full in extrusion. Aluminium can also be cast drawn and milled.

Machinability- Aluminium alloys are often machined rapidly and economically due to their complex metallurgical structure, their machining characteristics are superior to those of pure aluminium. The micro-constituents present in Aluminium alloys have important effects on machining characteristics.

Thermal and Electrical Conductivity- Aluminium is a brilliant conductor of both heat and electricity. As aluminium has conductivity almost twice the conductivity of copper, therefore it’s commonly used for power transmission.

Linear Expansion- Aluminium is comparatively high coefficient linear expansion compared to other metals. This will be taken into account for the design stage to compensate the difference within the expansion.

Corrosion Resistance- When the surface of aluminium metal is exposed to air, the protective oxide coating form almost instantaneously. This oxide coating protects aluminium metal from corrosion. Hence, aluminium has a good corrosion resistance".

3.2.2 5083 Aluminium Alloy

Aluminium 5083 may be a strong magnesium-manganese-chromium-aluminium alloy.

It are often hardened by cold work but it cann't be heat treated for higher strength.

The AA5083 are often used as plate alloy in marine application or structural component in transportation

It is highly immune to attack by seawater and industrial chemicals.

Alloy 5083 retains exceptional strength after welding. It has the high strength of the non-heat treatable alloys.

TABLE 3.2. Chemical Composition of AA5083

Elements	**%Present**
Magnesium (Mg)	4.50
Manganese (Mn)	0.60

Iron (Fe)	0.20
Silicon (Si)	0.25
Chromium (Cr)	0.15
Titanium (Ti)	0.15
Others (Total)	0.075
Copper (Cu)	0.10
Zinc (Zn)	0.125
Aluminium (Al)	93.5

CHAPTER 4

FEA SIMULATION

ABAQUS (version 2019) is a Computer-Aided Engineering (CAE software), which was used for the simulations of the engineering real-life problems. In this work, the minimization of earing defects in two problems cases was considered. The first case was a deep drawing of circular cups and the second case was a deep drawing of square cups. The software used three different stages that are pre-processing, solution, and post-processing to solve problems. These three stages were linked together by files as shown in Fig. 4.1:

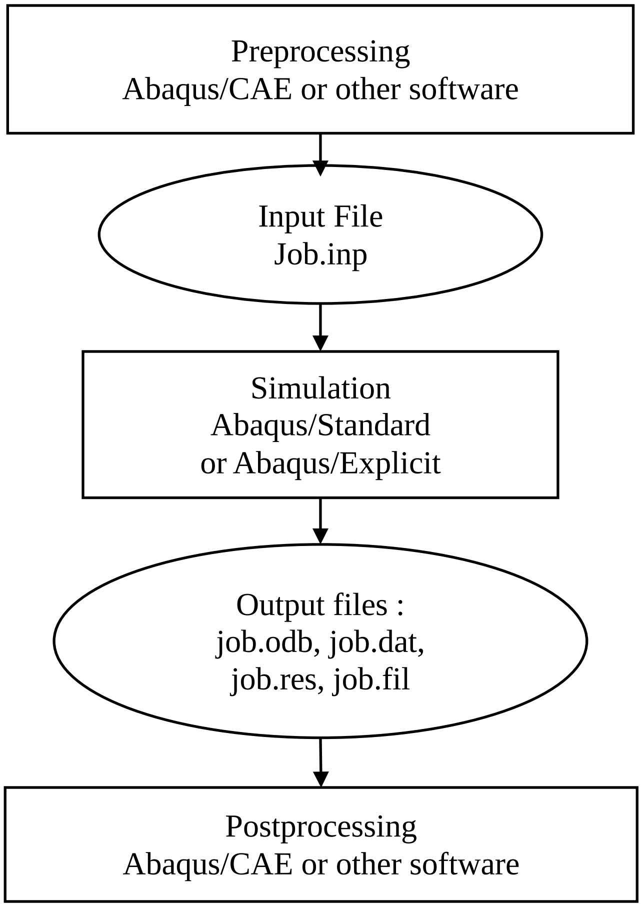


Figure 4.1. Three stages in Abaqus

In Preprocessing (Abaqus/CAE) stage the model of the physical problem was defined and an Abaqus input file was created. The model was created graphically using Abaqus/CAE. Abaqus/Explicit solved the numerical problem defined in the model in the simulation stage. The simulation generally runs behind the scenes. Examples of output from the deep drawing analysis include stresses and displacements that were kept in binary files and prepared for post processing. The results were evaluated when the simulation was completed the stresses, displacements, or other basic variables were computed. The analysis was done interactively with the help of the Visualization module of Abaqus/CAE. The Visualization module read the neutral binary output database file. It had diverse options for displaying the results, like X–Y plots, color contour plots, animations deformed shape plots and color contour plots.

4.2 ABAQUS/CAE

The modules in sections from 4.2.1 to 4.2.7 belongs to the pre-processing stage. The module of section 4.2.8 creates a job.inp file for the simulation stage. The module of section 4.2.9 is the post-processing stage.

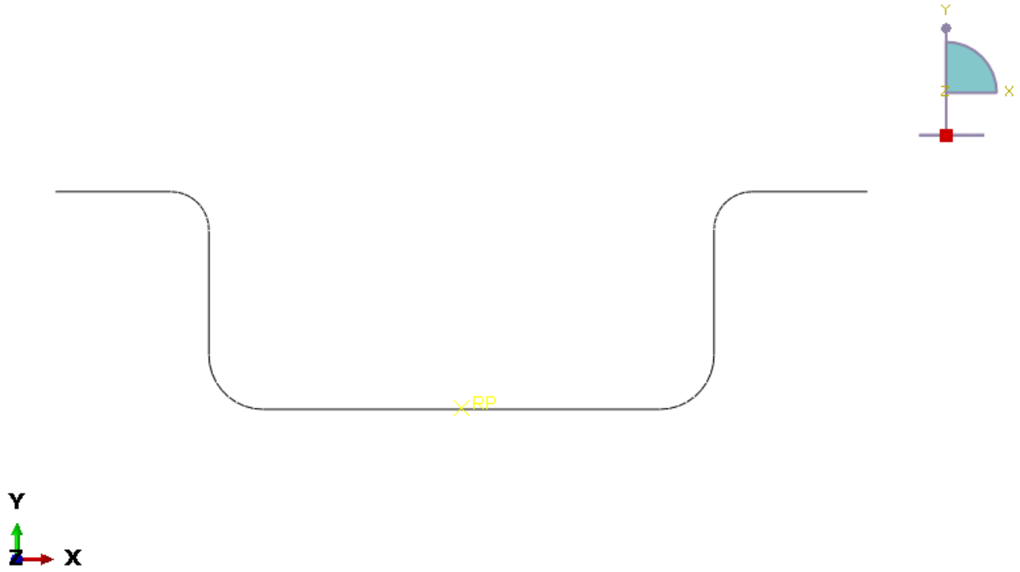
4.2.1 Part Module

To simulate the bending process three parts were required: 1) Blank, 2) Punch and 3) Die. A two dimensional plain strain model will be used. The assumption that there is no strain in the out-of-plane direction of the model is valid if the structure is long in this direction.

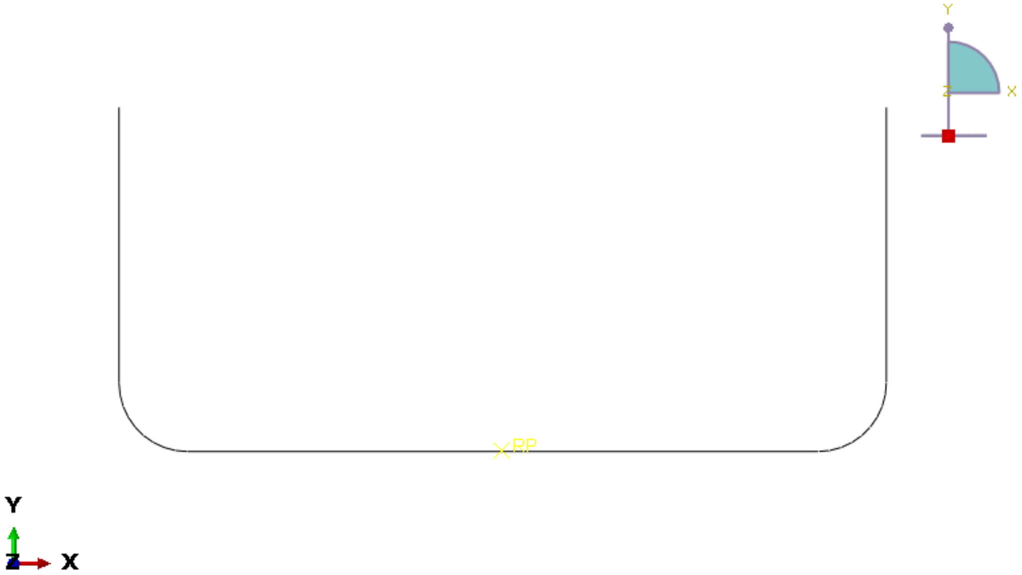
4.2.1.1 U-bending

All the parts required to simulate the U-bending process are shown in Fig. 4.2

(a) Blank



(b) Die/Blank holder



(c) Punch

(d) Figure 4.2. Parts of U-bending simulation model

Blank was a 2D deformable shell part with a planar base type. Sketch of the blank is shown in Fig. 4.3. The shape of the cross-section of the sheet is rectanglular in shape. The width of the sheet is 150 mm and thickness is 1.2mm. Hence to sketch the cross-section a rectangle of 1.2mm height and 150 mm width was drawn.

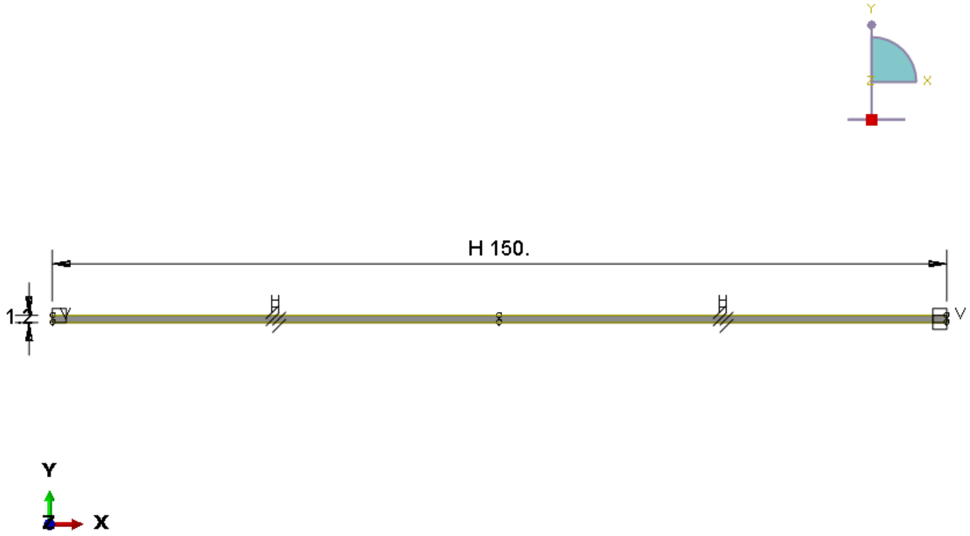


Figure 4.3 Sketch of the cross-section of the sheet

Punch and die holder were 2D analytical rigid shell with wire base feature.The bend angle was 90° with the corner and sketch of punch and die is shown in Fig. 4.4 and Fig. 4.5 respectively. Each of these bodies was assigned a rigid body reference point.

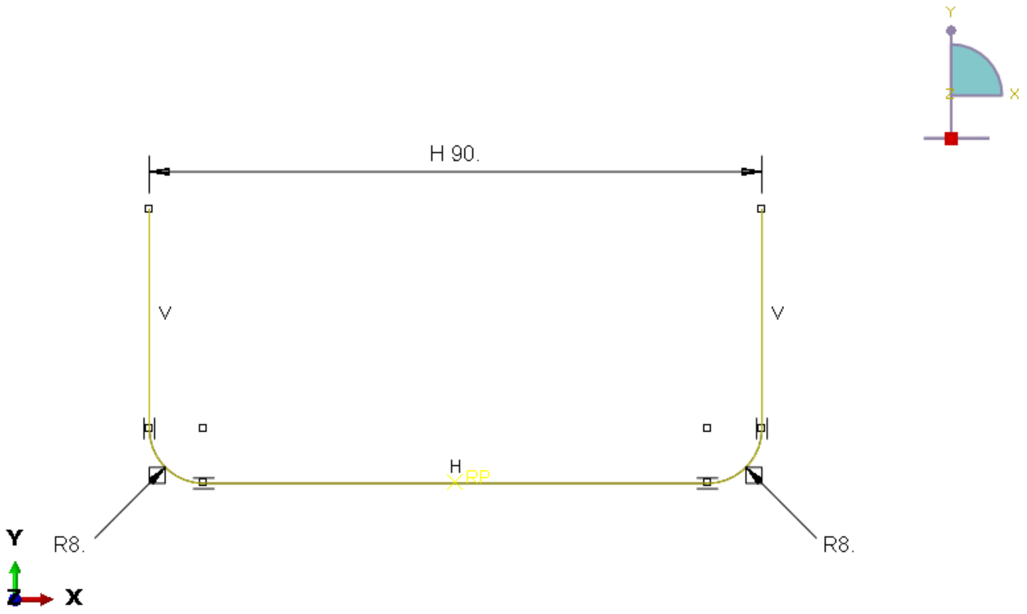


Figure 4.4 Sketch of the punch

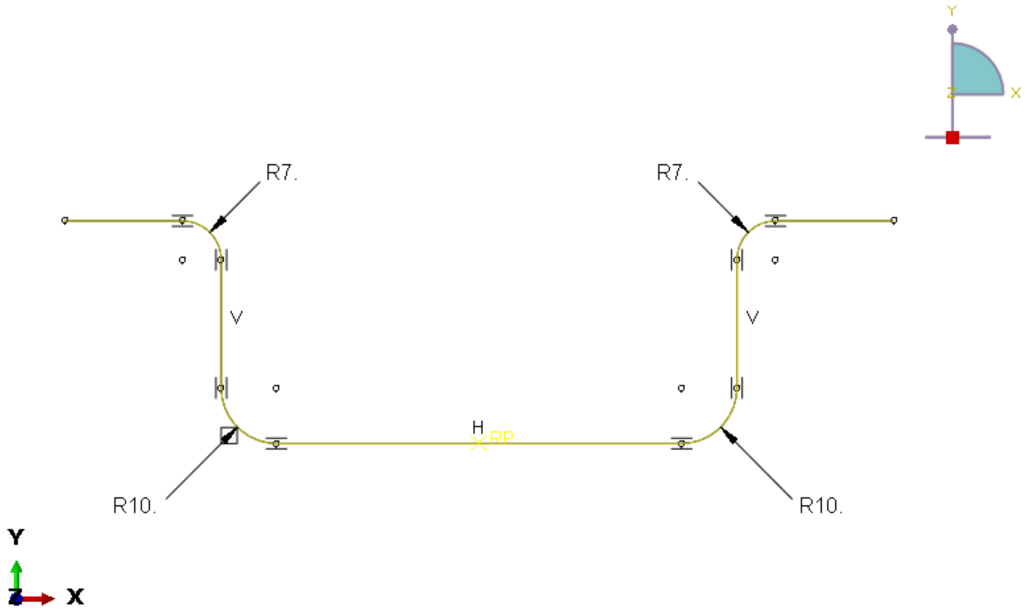


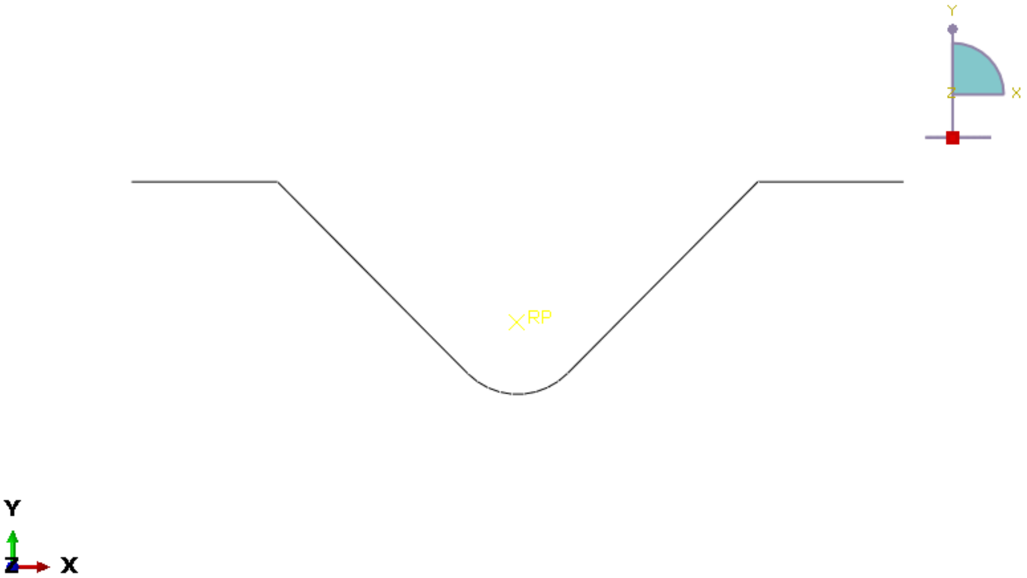
Figure 4.5 Sketch of the die

The reason to make punch, die, and holder as analytic rigid bodies was that contact with discrete rigid bodies tends to be more noisy than contact with analytical rigid surfaces. It was because discrete rigid bodies were inherently faceted whereas analytical rigid surfaces can be smooth. Therefore, by defining rigid bodies as analytical rigid, saved a lot of computation time.

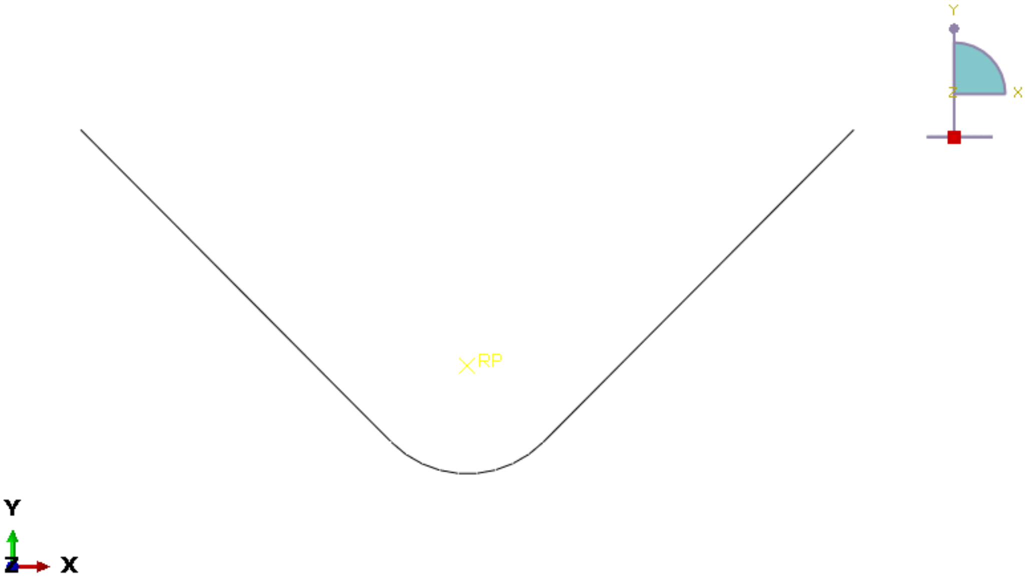
4.2.1.2 V-bending

All the parts required to simulate the V-bending process are shown in Fig. 4.6

(a) Blank



(b) Die



(c) Punch

Figure 4.6. Parts of V-bending simulation model

Blank was a 2D deformable shell part with a planar base type. Sketch of the blank is shown in Fig. 4.7. The shape of the cross-section of the sheet is rectanglular in shape. The width of the sheet is 150 mm and thickness is 1.2mm. Hence to sketch the cross-section a rectangle of 1.2mm height and 150 mm width was drawn.

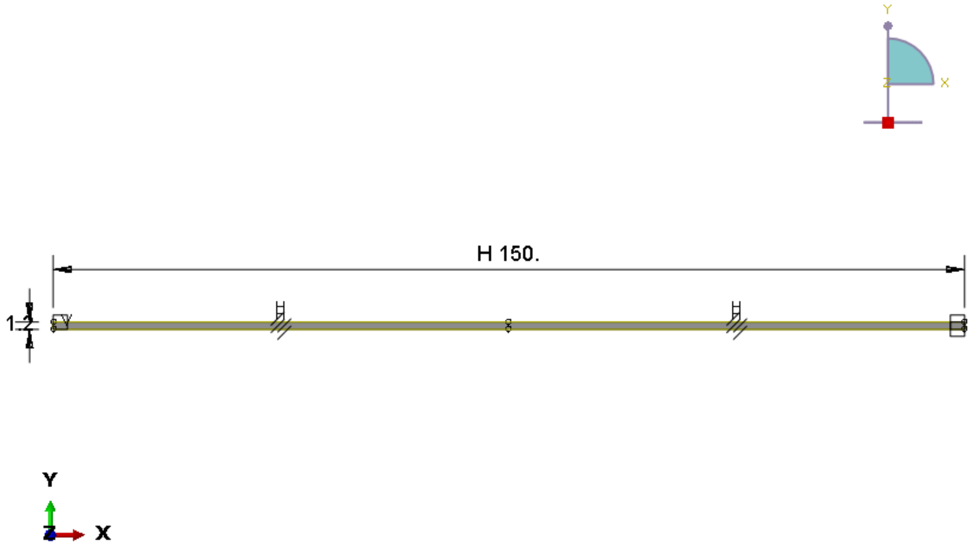


Figure 4.7 Sketch of the cross-section of the sheet

Punch and die holder were 2D analytical rigid shell with wire base feature.The bend angle of punch and die was 90°and sketch of punch and die is shown in Fig. 4.8 and Fig. 4.9 respectively. Each of these bodies was assigned a rigid body reference point.

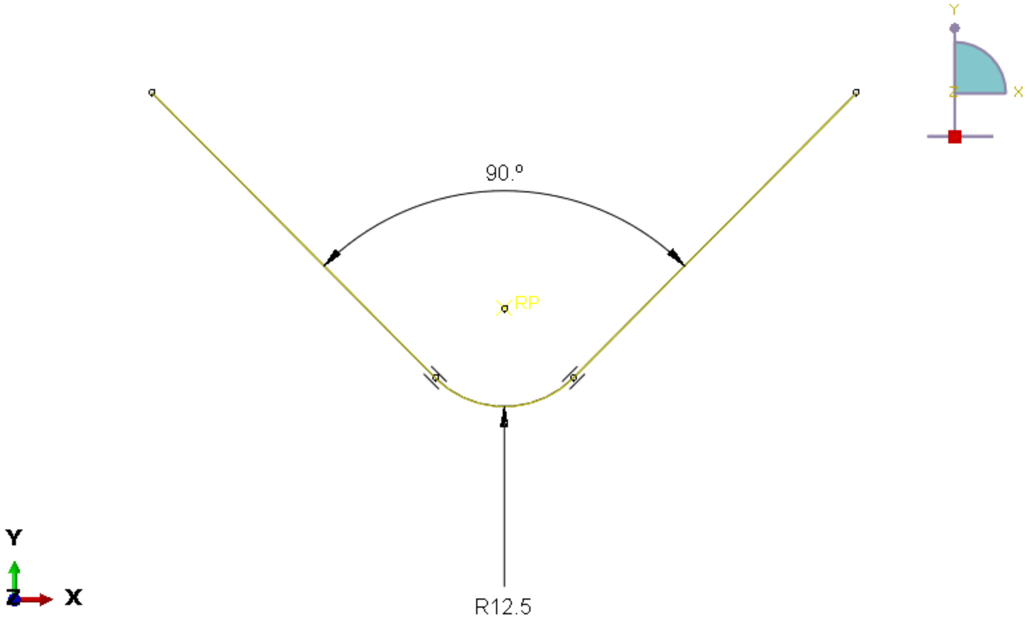


Figure 4.8 Sketch of the punch

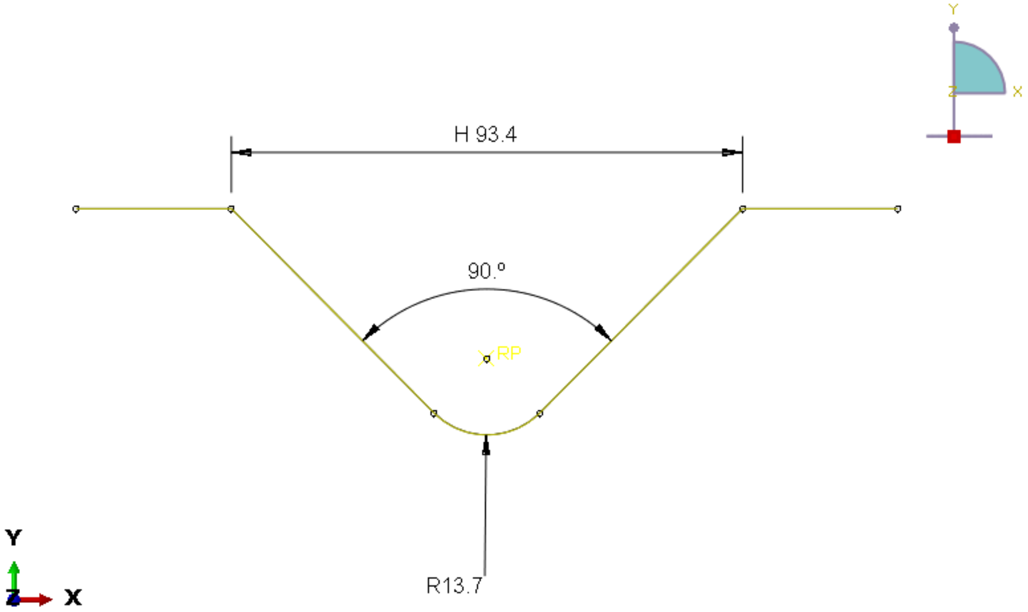


Figure 4.9 Sketch of the die

The reason to make punch, die, and holder as analytic rigid bodies was that contact with discrete rigid bodies tends to be more noisy than contact with analytical rigid surfaces. It was because discrete rigid bodies were inherently faceted whereas analytical rigid surfaces can be smooth. Therefore, by defining rigid bodies as analytical rigid, saved a lot of computation time.

4.2.2 Property module

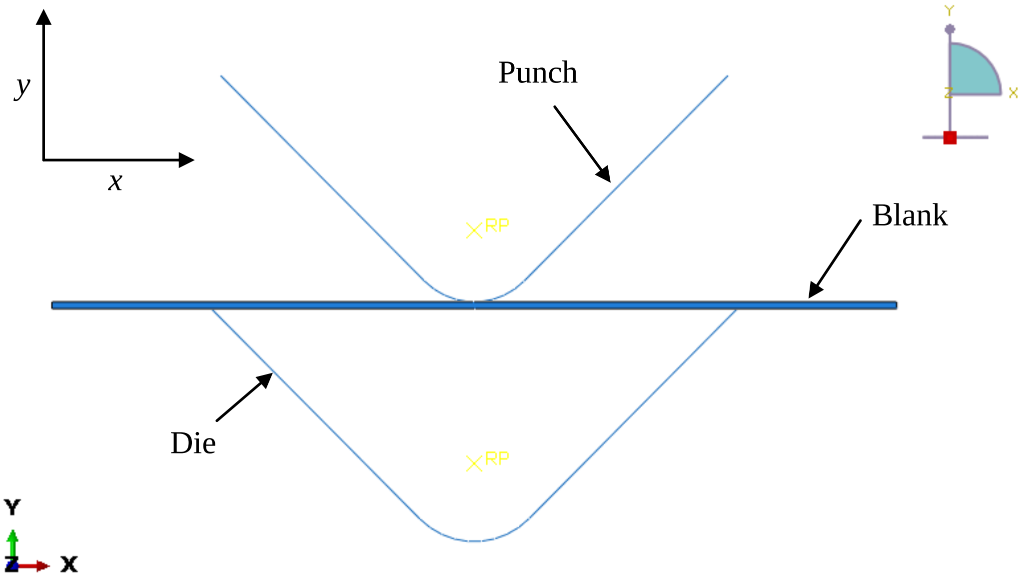
As punch and die were rigid bodies they did not require any material to be assigned. Only blank was assigned material properties. The material of blank was aluminium alloy AA5083. The material properties used for the material model were determined from uniaxial tension test. Material properties of AA5083 at different temperature is shown in Table 2.1. To model the plastic behaviour of the material, the tabular output data of UTM for load and corressoponding displacement was used to calculate tabular data for plastic stress and coreesponding plastic strain. After defining the material, a section was defined with the same material. Then this section property was assigned to the blank.

Table 4.1. Material Properties of AA5083

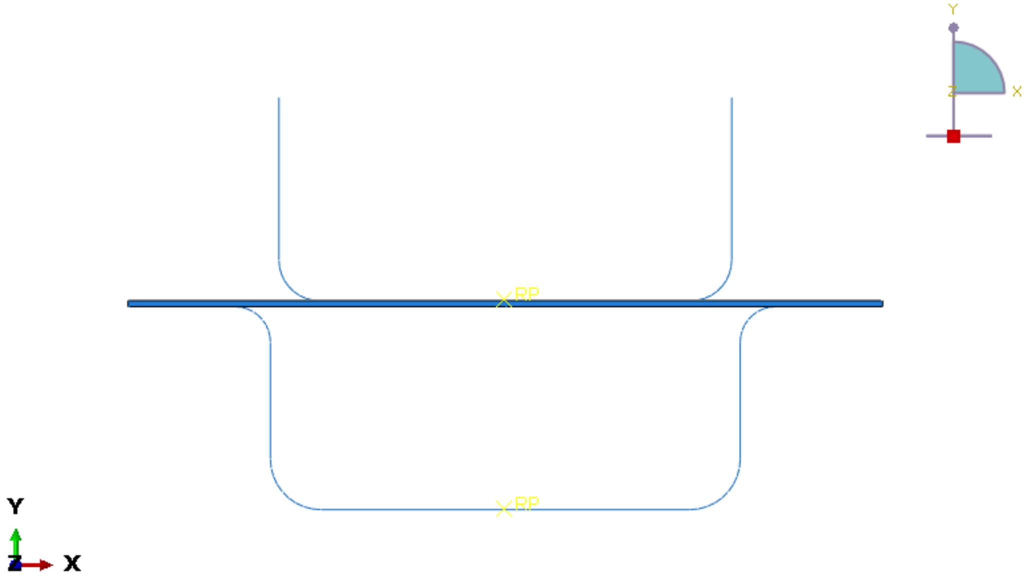
Temperature (°C)	Yield stress (MPa)	Ultimate stress (MPa)	n (Strain hardening exponent)	K (Strength coefficient) (MPa)
30	146	337	0.33	809
120	140	304	0.40	766
150	134	296	0.45	646

4.2.3 Assembly module

All the parts were created as dependent instances with auto offset from other instances toggled on. Blank was placed such that the global z-axis was perpendicular to the blank cross-sectional plane. Then die and punch was assembled around blank with assembly constraints. The Assembly of all three parts is shown in Fig. 4.10.



(a)



(b)

Figure 4.10. Assembly of (a) V-bending simulation parts (b) U-bending simulation parts

4.2.4 Step Module

The first step was the initial step which was auto-generated to solve the boundary conditions without any loading. Then the second step was created to apply force on the blank and named as Apply force. It was an explicit dynamic step. Step time for Apply force was 1 s. This time period was suitable for the application of the force because it was long enough to avoid dynamic effects but short enough to prevent a significant impact on the run time for the job. The default field output request and history output request were defined.

4.2.5 Interaction module

Here two interaction properties were required. One for friction contact between blank and die. And second for contact between blank and punch. All inter-action properties are shown in Table 4.2.

Table 4.2. Interaction properties

Interaction property	Contact Property	Friction coefficient	Mechanical Constraint formulation
Between blank and die	Tangential behavior	0.125	Penalty contact method
Between blank and punch	Tangential behavior	0.05	Penalty contact method

4.2.6 Load Module

In this module loads and boundary conditions were to be defined for the analysis. The boundary conditions can be specified using a “direct” or “type” format. In the “direct” format, the constraints on degrees of freedom are specified directly. The “type” format is a way of conveniently specifying common types of boundary conditions in stress/displacement analyses. For example, pinned boundary condition, built-in boundary condition, symmetry about a specific plane, etc.

The model is in 2D space. Therefore, the convention used for 3 degrees of freedom is shown in Fig. 4.11. For the reference point of die, the Mechanical Encastre boundary condition was defined in the initial step and propagated to subsequent steps. Encastre is a built-in type of boundary condition which restricts motion in all six degrees of freedom. For the reference point of the punch, all the degrees of freedom in the initial step. But this boundary condition was modified in Apply force step and U2 was set to be -39 with a smooth amplitude. All the boundary conditions are listed in Table 4.3**.**

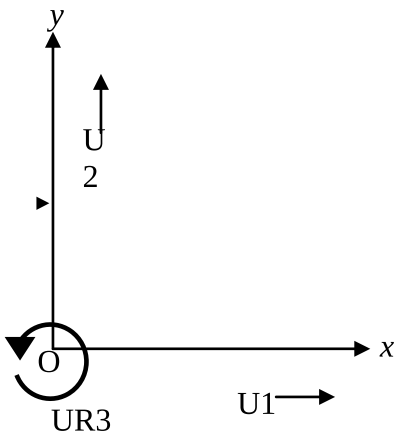


Figure 4.11. Three degrees of freedom

Table 4.3 Boundary conditions

Region	Boundary condition	
	Initial step	Apply force step
The reference point of the die	Encastre	Encastre
Reference point of the punch	U1=0, U2=0, UR3=0	U1=0, U2=-39, UR3=0

4.2.7 Meshing

As mentioned earlier punch, die and holder were not required to mesh. The blank was modeled using a 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control (CPE4R). which is shown in Fig. 4.12. The approximate global size of elements was 0.5 and total number of nodes were 1505 and total number of element was 1200. Meshed Blank is shown in Figure 4.13.

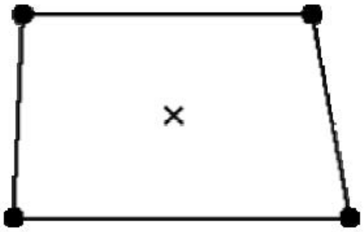


Figure 4.12. A 4-node bilinear plane strain quadrilateral, reduced integration, hourglass control (CPE4R)

Figure 4.13. Meshed Blank

4.2.8 Job Module

A job for deep drawing simulation was created. The source for this job was the model created above in the pre-processing stage. Defaults setting were used to submit the job. When a job is submitted for a simulation stage, a job.inp file is created automatically by the software and saved in the work directory. The name and location of the job.odb output file of the job and the model.cae pre-processing files were noted.

4.2.9 Visualization Module

In this module, the deformed shape of blank and various output variables was plotted.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

The experimental and numerical studies of V-bending of AA5083 sheet metal at three diffrent temperatures: 30°, 120° and 150° provided very valuable information for warm forming of Al alloy AA5083 sheets. Only numerical studies have been performed for U-bending at different temperatures due to lockdown in COVID-19.

The tensile properties of aluminium alloys are characterized at three different temperatures i.e. room temperature(30°C), 120°C and 150°C by uniaxial tension tests performed in an environmental chamber attached to the UTM and are shown in Figures 5.1 to 5.9. It is observed that yield strength, tensile strength and and strength coefficients decreased due to increase in temperature. The strain hardening exponent and percentage elongation increased due to increase in temperature. The true stress true strain data recieved from uniaxial tension tests were used to define the material model in the FE simulations for V and U-bending procedures.

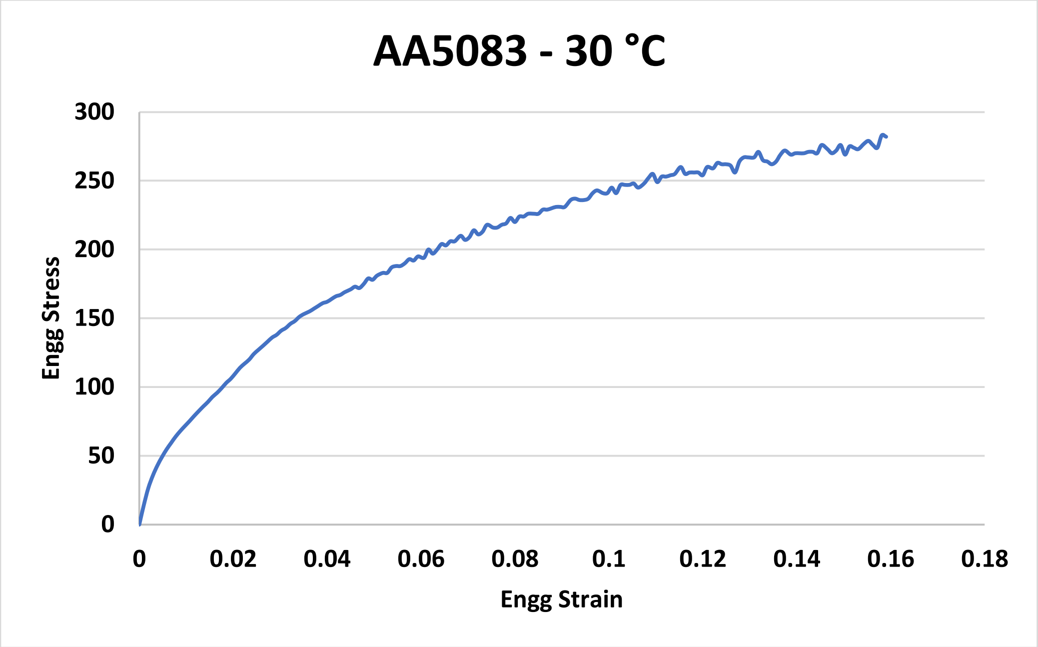


Figure 5.1 Engineering Stress vs engineering strain at room temperature

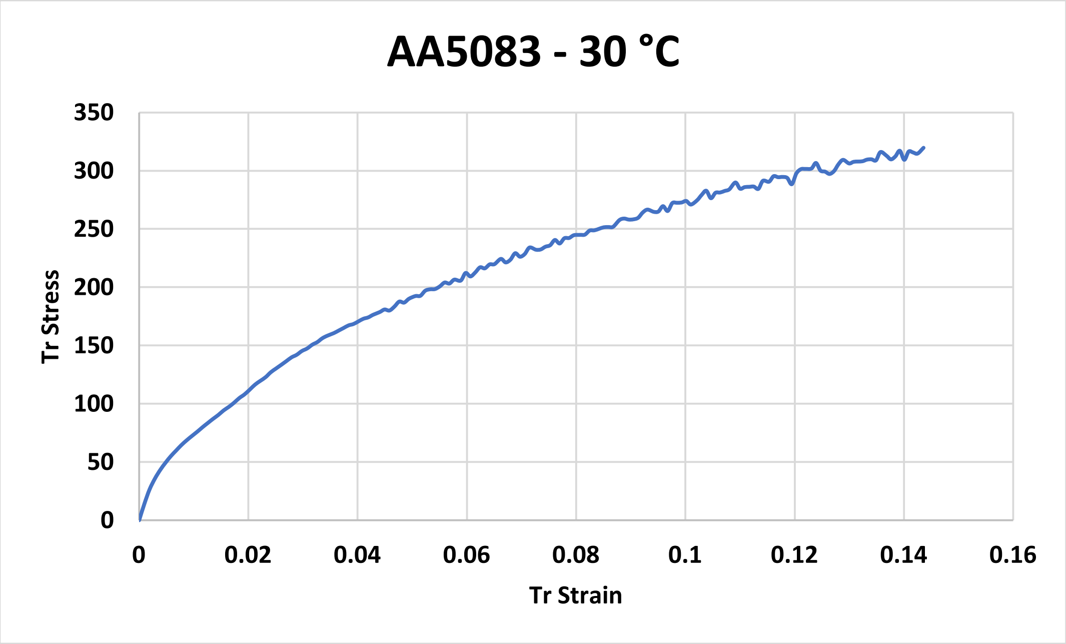


Figure 5.2 True Stress vs True Strain

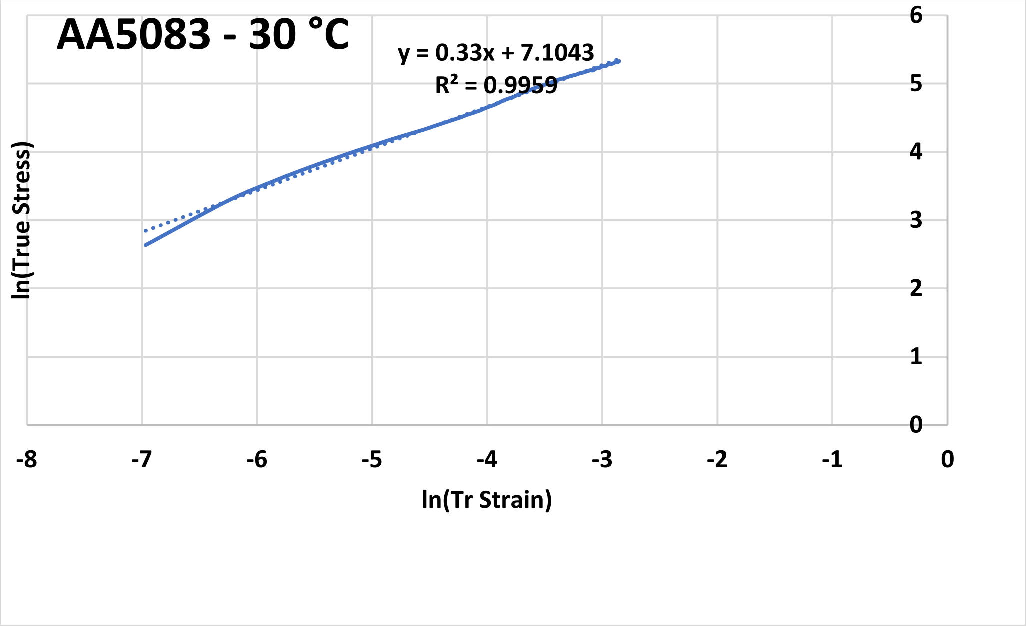


Figure 5.3 ln(True Stress) vs ln(True Strain) plots obtained from true stress and strain

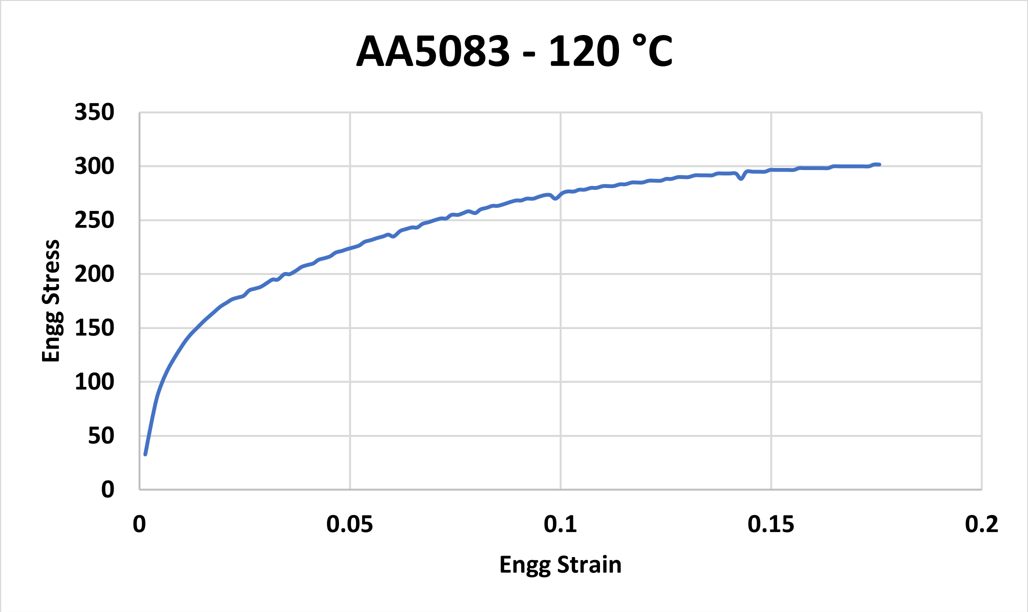


Figure 5.4 Engineering Stress vs Engineering Strain at 120°C

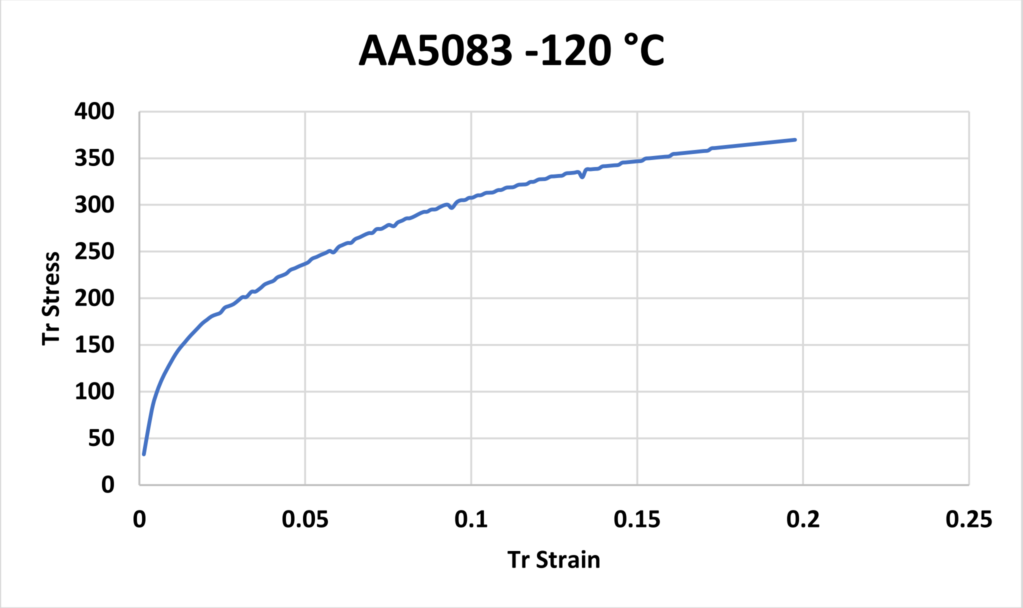


Figure 5.5. True Stress vs True Strain

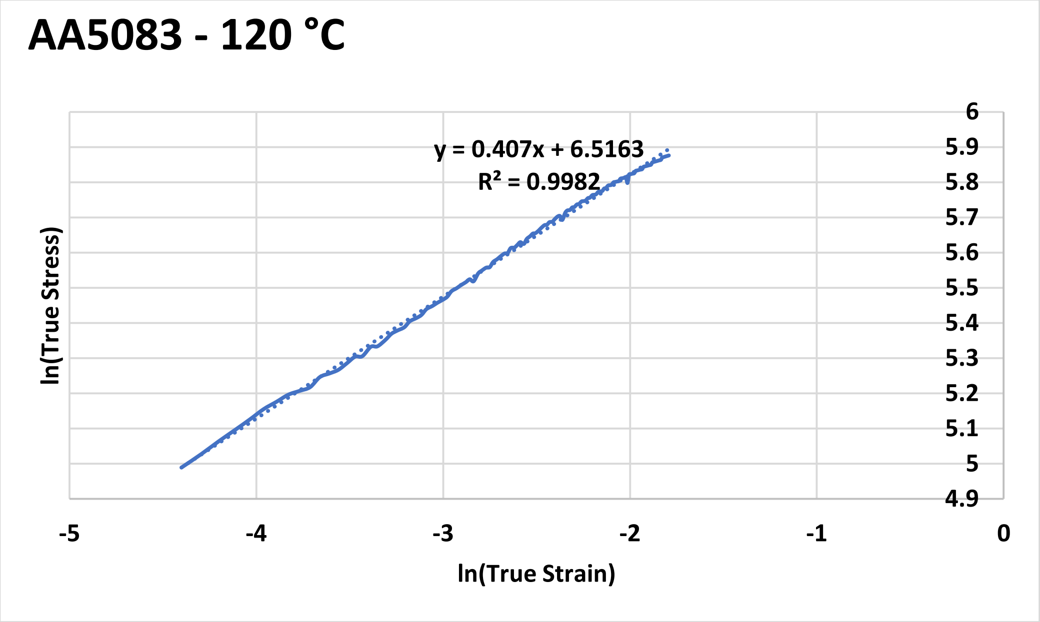


Figure 5.6 ln(True Stress) vs ln(True Strain)

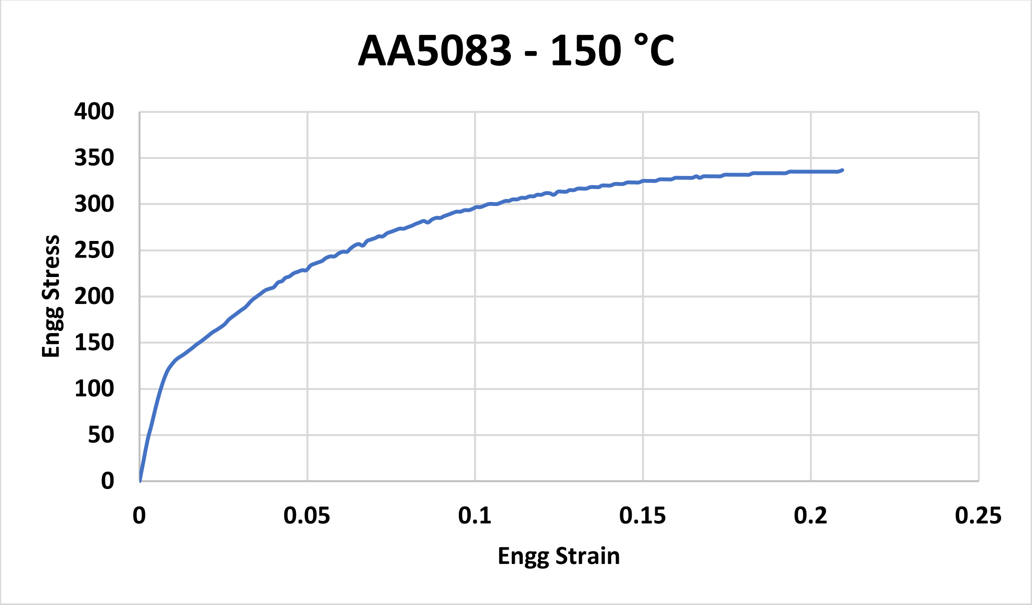


Figure 5.7 Engineering Stress vs Engineering Strain

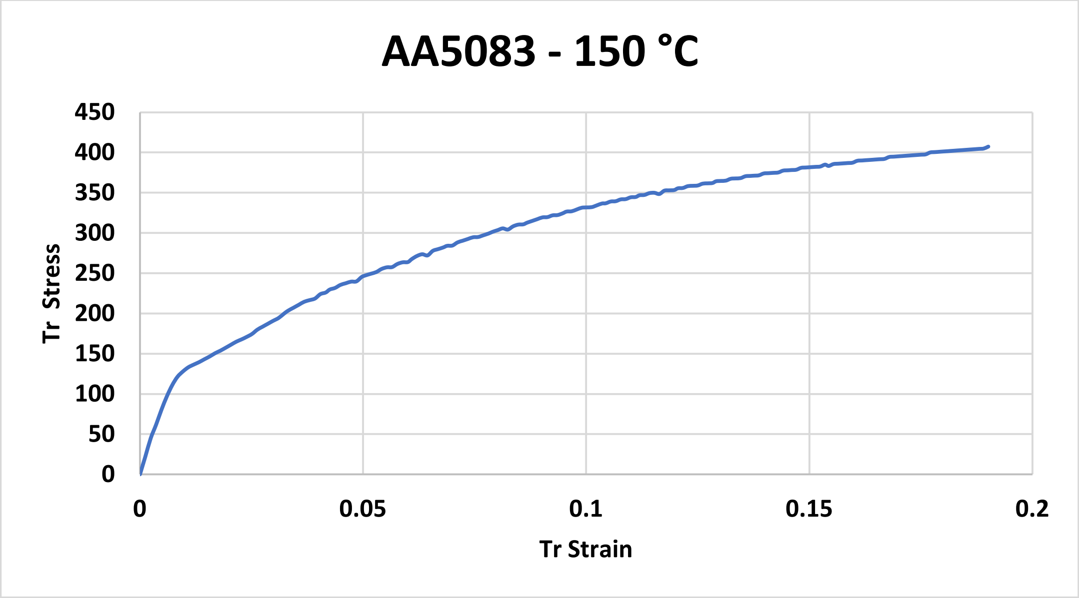


Figure 5.8. True Stress vs True Strain

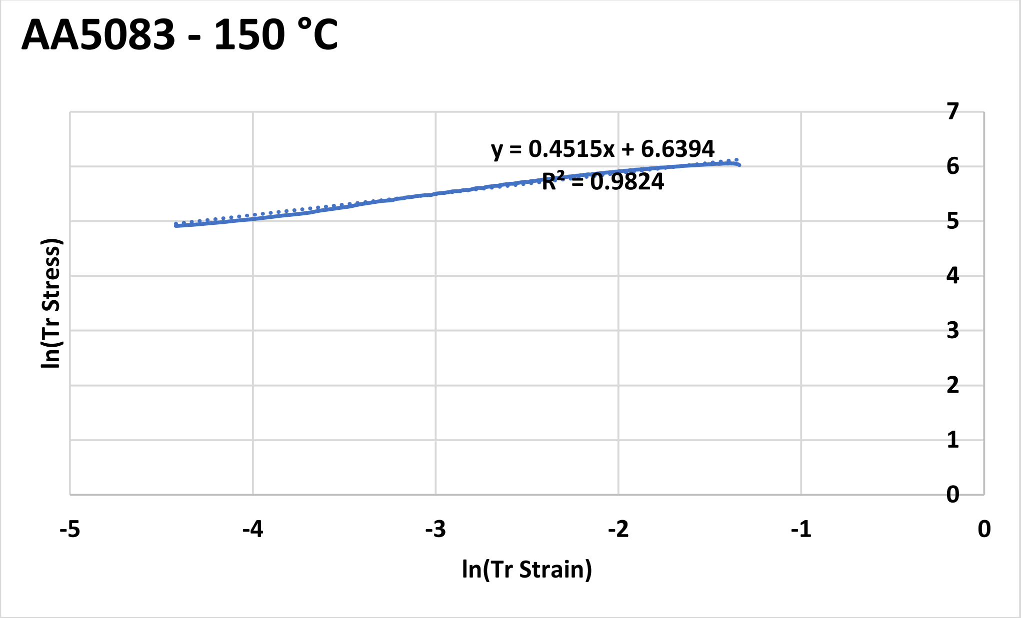
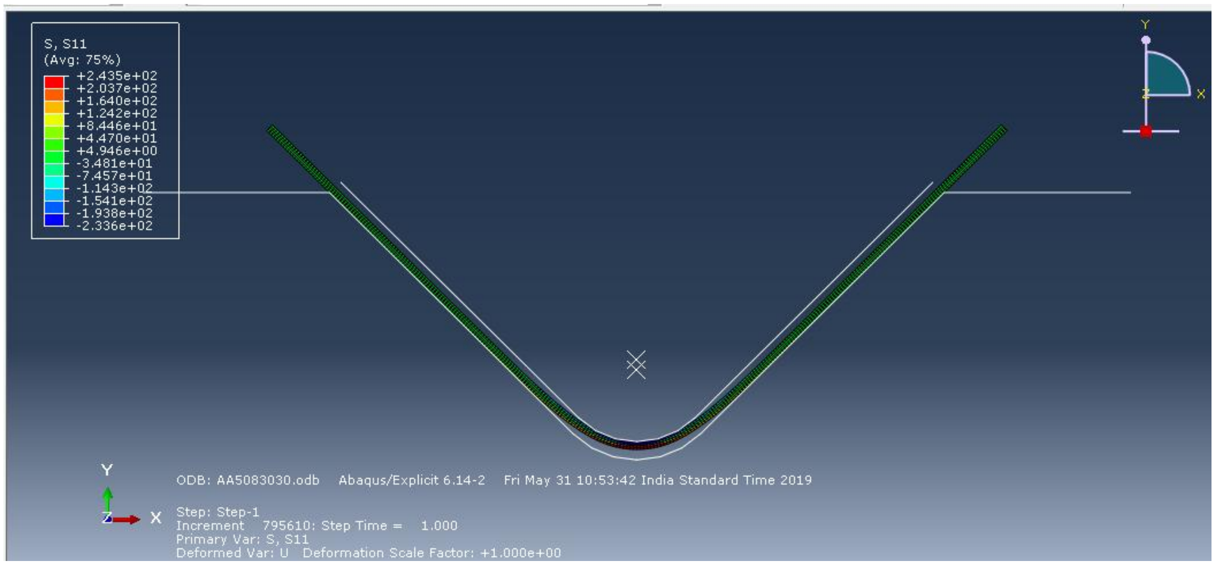


Figure 5.9 ln(True Stress) vs ln(True Strain)

5.2 SIMULATIONS

The simulation results for V-bending are shown in Figures 5.10-5.15. The experiments performed for V-bending in environmental chamber at different temperatures showed decrease in springback values as the temperature increased. A highest value of springback is observed at room temperature whereas the lowest value of springback is obtained at 150°C. The FEA results are in agreement with the experimental results. The decrease in springback results in bending if performed at higher temperatures could be attributed to the lower tensile and higher strain hardening exponents. At higher temperatures, recovery, recrystallization and grain growth phenomenons are operative so that the strength values are affected accordingly. If the bending tests are conducted at higher temperature than 150°C then the springback will reduce further. A temperature will be reached when the springback phenomenon may completely vanish in the experiments and simulations.

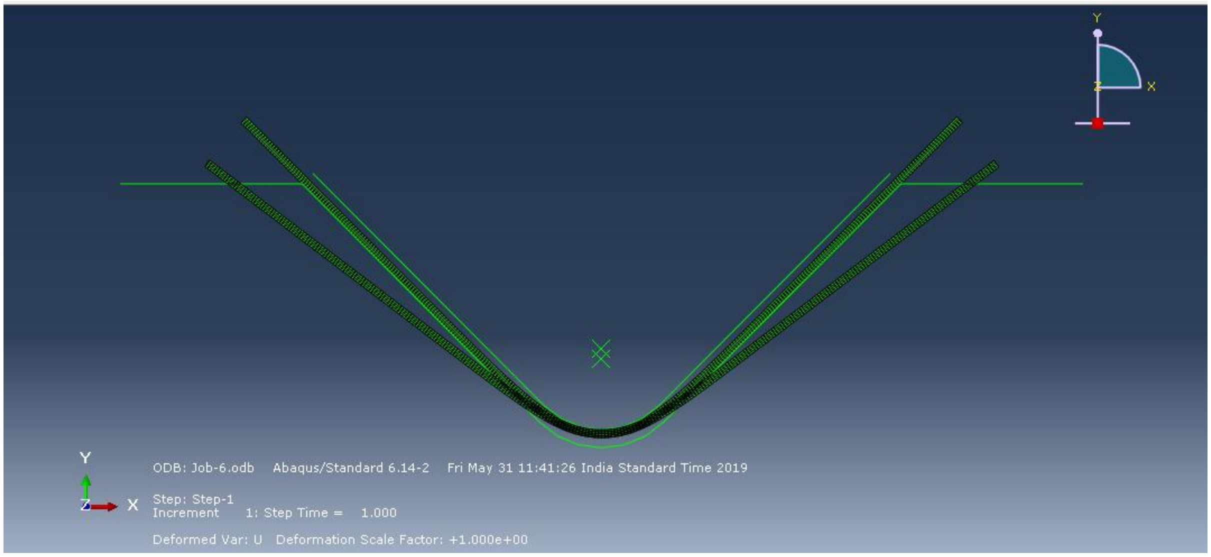
For v bending



```
ODB: AA5083030.odb    Abaqus/Explicit 6.14-2    Fri May 31 10:53:42 India Standard Time 2019

Step: Step-1
Increment    795610: Step Time =    1.000
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

Figure 5.10 FEA of AA5083 at 30ºC



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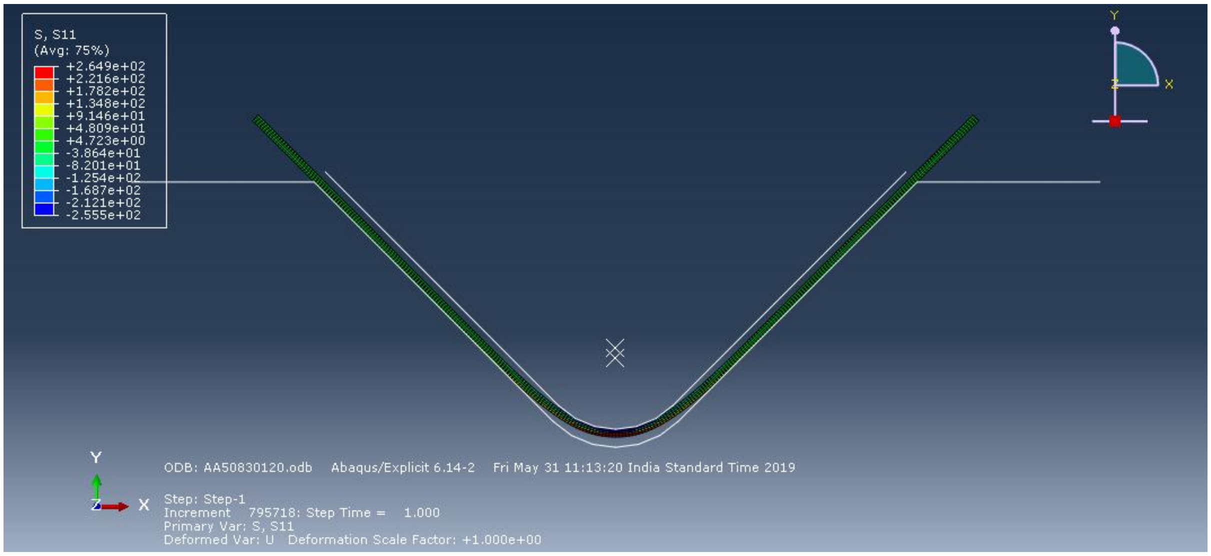
Step: Step-1
Increment      1: Step Time =    1.000

Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

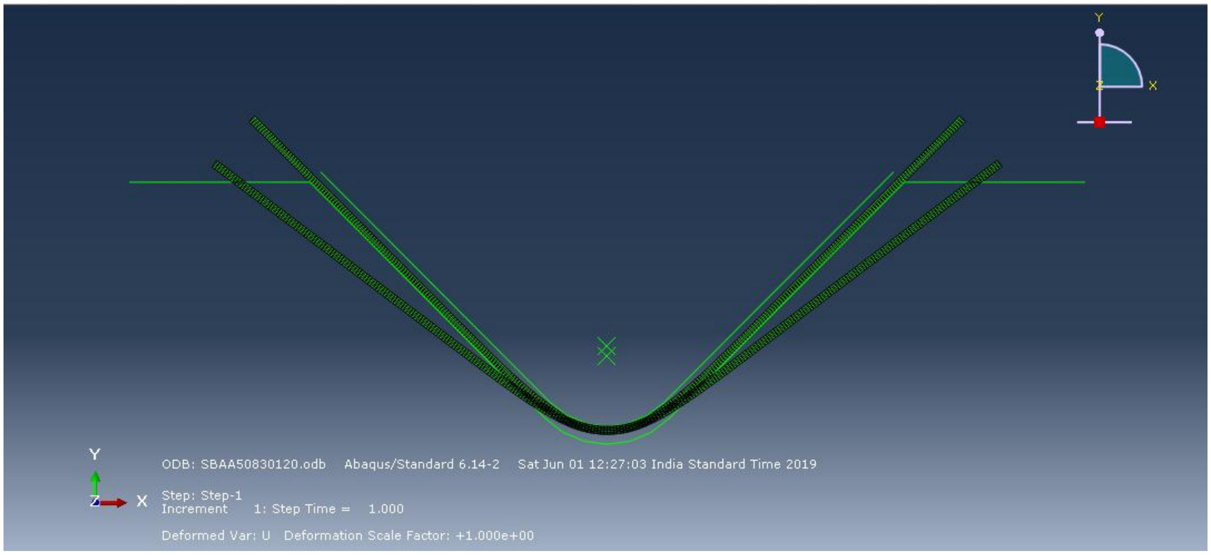
Fig 5.11 overlay plot showing springback of AA5083 at 30ºC



```
ODB: AA50830120.odb    Abaqus/Explicit 6.14-2    Fri May 31 11:13:20 India Standard Time 2019

Step: Step-1
Increment    795718: Step Time =    1.000
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

Figure 5.12. FEA of AA5083 at 120ºC



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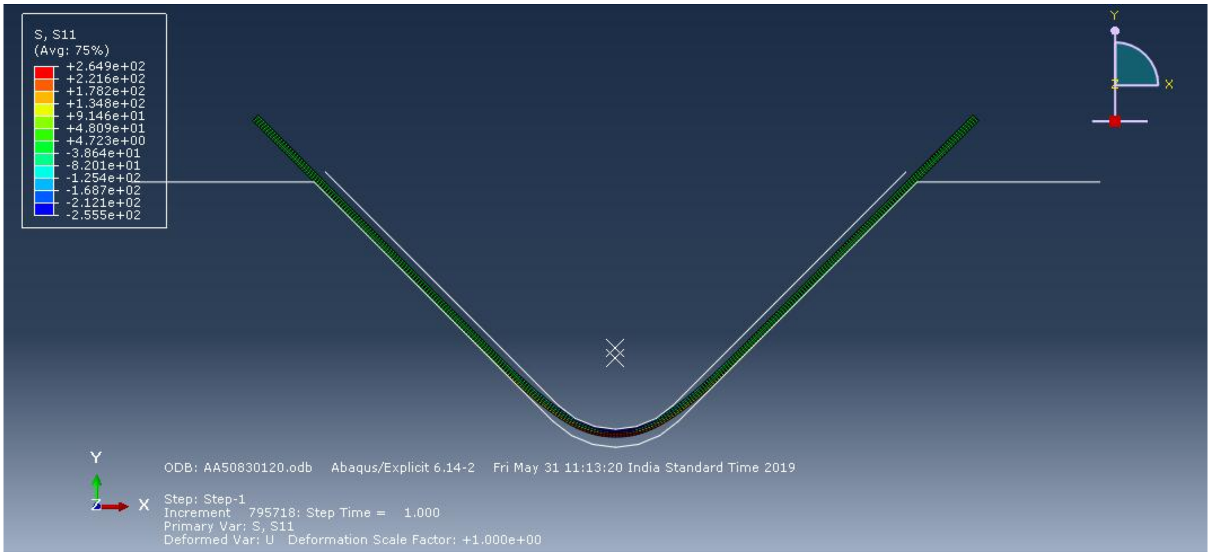
Step: Step-1
Increment      1: Step Time =    1.000

Deformed Var: U   Deformation Scale Factor: +1.000e+00
```

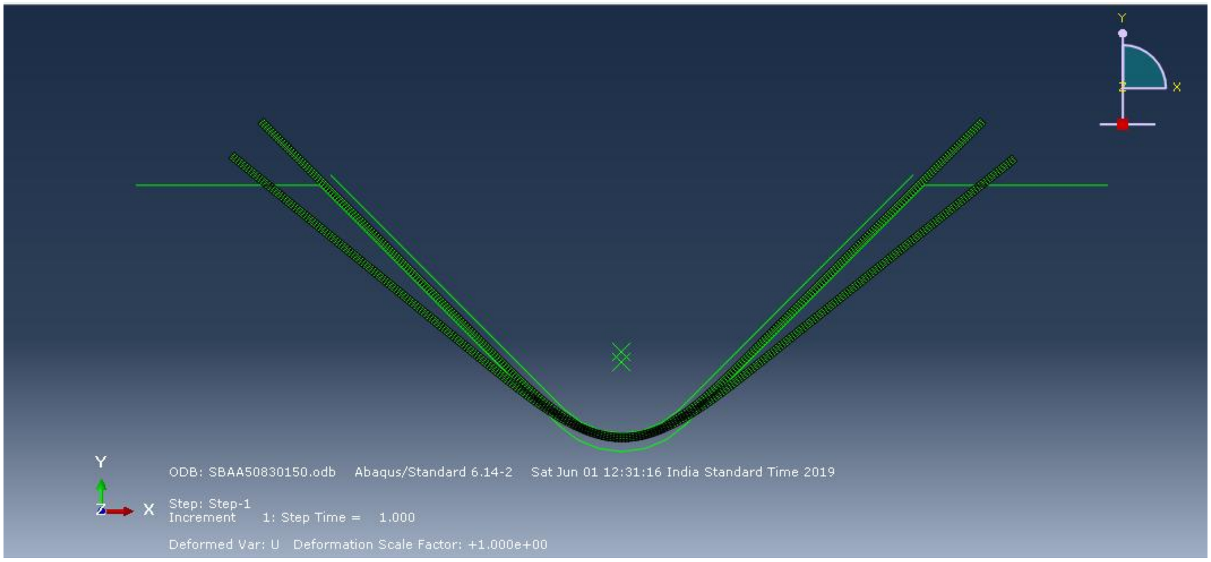
Figure 5.13 overlay plot showing springback of AA5083 at 120ºC



ODB: AA50830120.odb   Abaqus/Explicit 6.14-2   Fri May 31 11:13:20 India Standard Time 2019

Step: Step-1
Increment   795718: Step Time =   1.000
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +1.000e+00

Figure 5.14 FEA of AA5083 at 150ºC



ODB: SBAA50830150.odb   Abaqus/Standard 6.14-2   Sat Jun 01 12:31:16 India Standard Time 2019

Step: Step-1
Increment   1: Step Time =   1.000

Deformed Var: U   Deformation Scale Factor: +1.000e+00

Figure 5.15 overlay plot showing springback of AA5083 at 150ºC

U-bending results

The bending simulations are also performed for U-bending at different temperatures and are shown in Figures 5.16 to 5.21. The similar results are observed in U-bending i.e. as the temperature increased during bending operation, springback reduced accordingly. The springback values obtained in U-bending are much lower than the V-bending. The lower values of springback in U-bending can be attributed to the stretch force acting at the web section under the punch at differnt temperatures.

```
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Step: Step-1
Increment    798342: Step Time =    1.000
Primary Var: S, Mises
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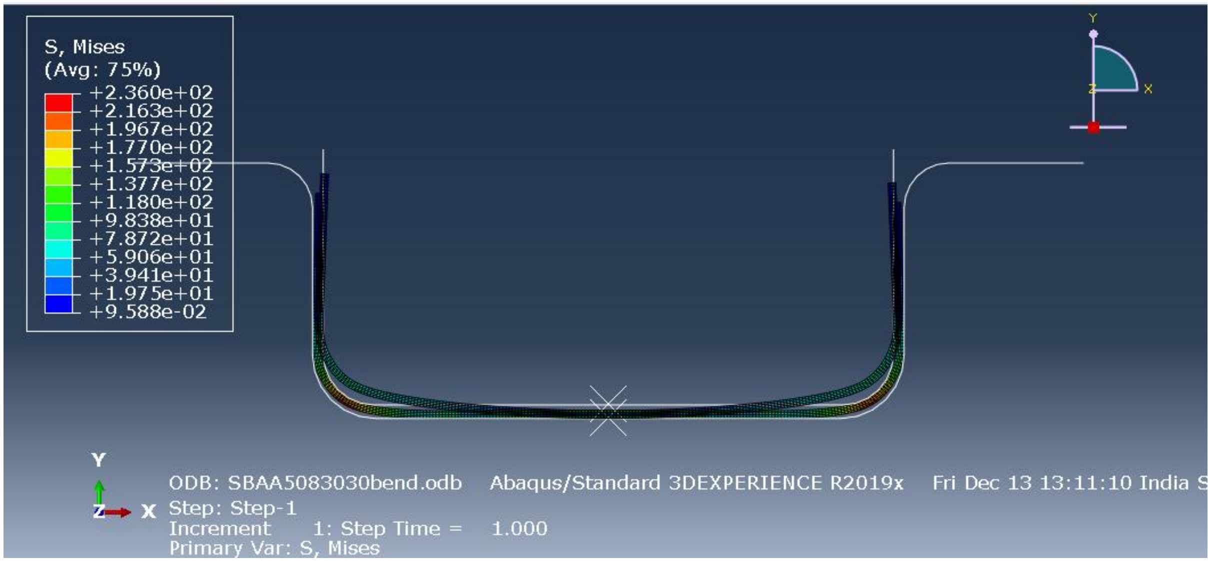
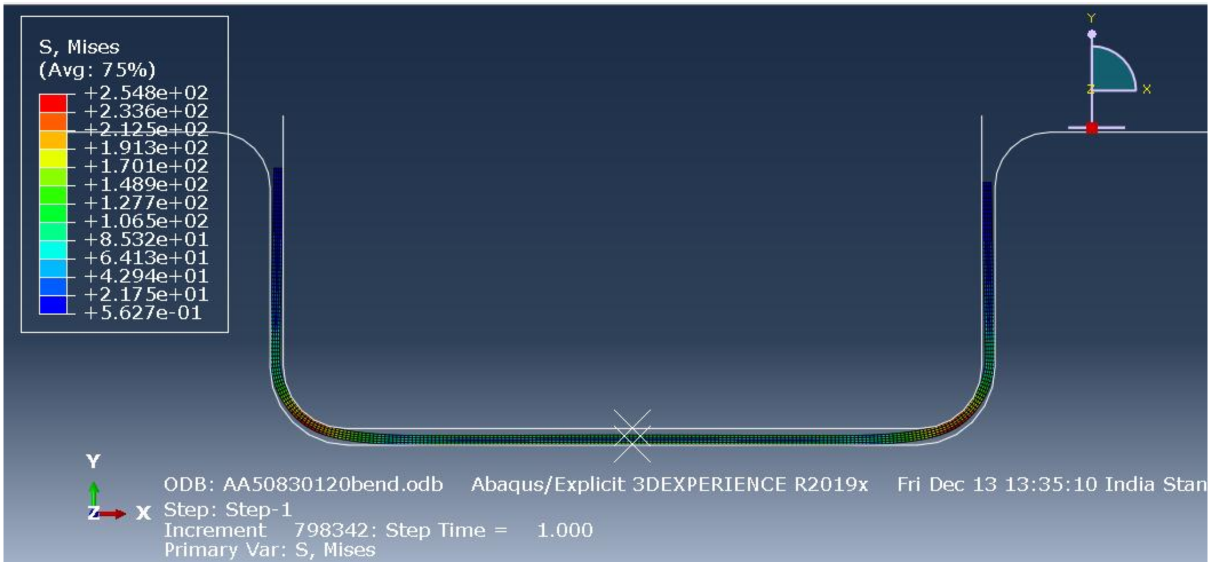
Figure 5.16 FEA of AA5083 at 30ºC



ODB: SBAA5083030bend.odb   Abaqus/Standard 3DEXPERIENCE R2019x   Fri Dec 13 13:11:10 India S
Step: Step-1
Increment   1: Step Time =   1.000
Primary Var: S, Mises

Figure 5.17.overlay plot showing springback of AA5083 at 30ºC



ODB: AA50830120bend.odb   Abaqus/Explicit 3DEXPERIENCE R2019x   Fri Dec 13 13:35:10 India Stan
Step: Step-1
Increment   798342: Step Time =   1.000
Primary Var: S, Mises

Figure 5.18 FEA of AA5083 at 120ºC

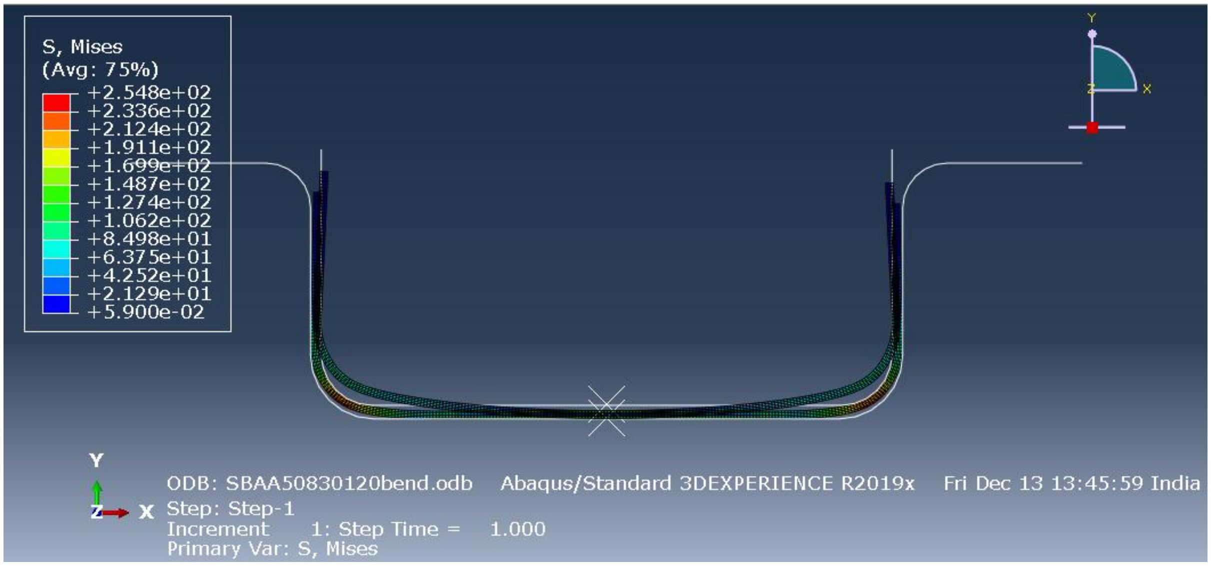


Figure 5.19. overlay plot showing springback of AA5083 at 120ºC

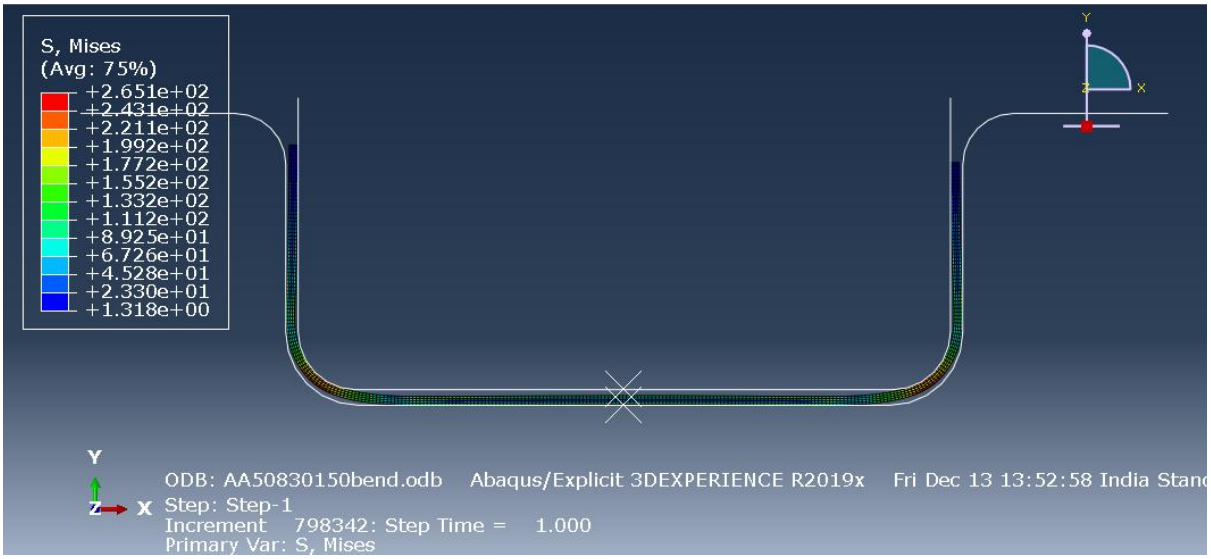


Figure 5.20 FEA of AA5083 at 150ºC

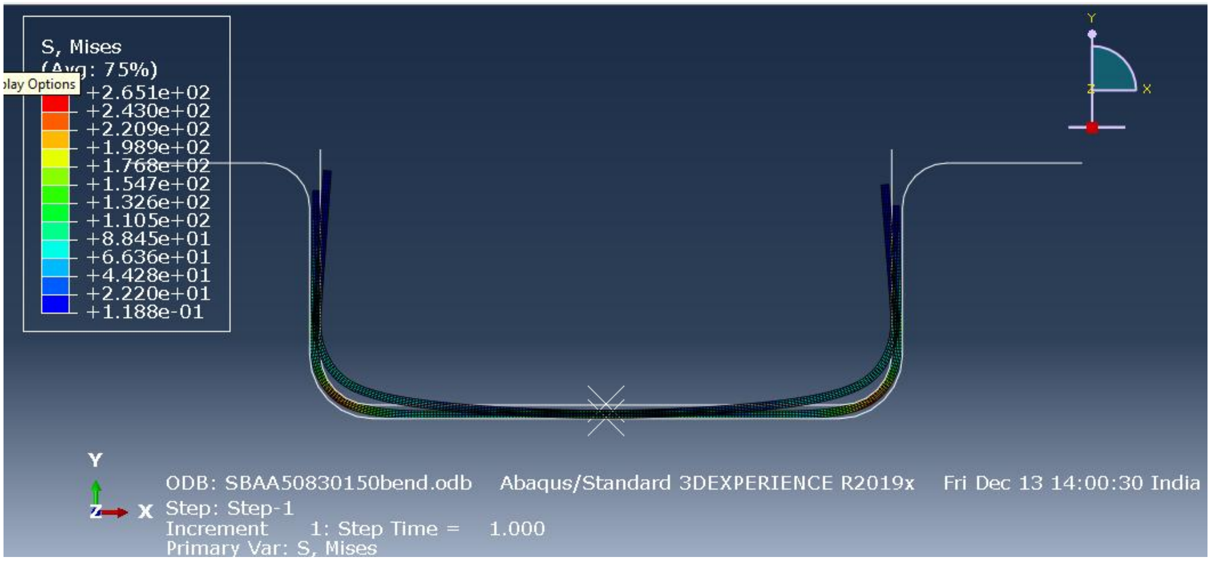


Figure 5.21. overlay plot showing springback of AA5083 at 150ºC

5.3 SIMULATION RESULTS

For v bending

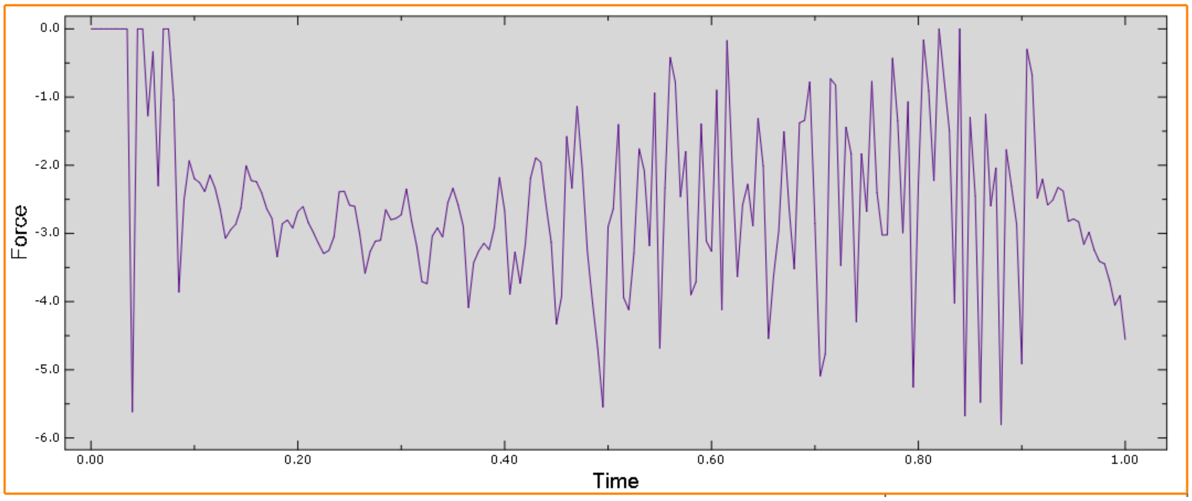


Figure 5.22. bending force v/s displacement of AA5083 at 30˚C

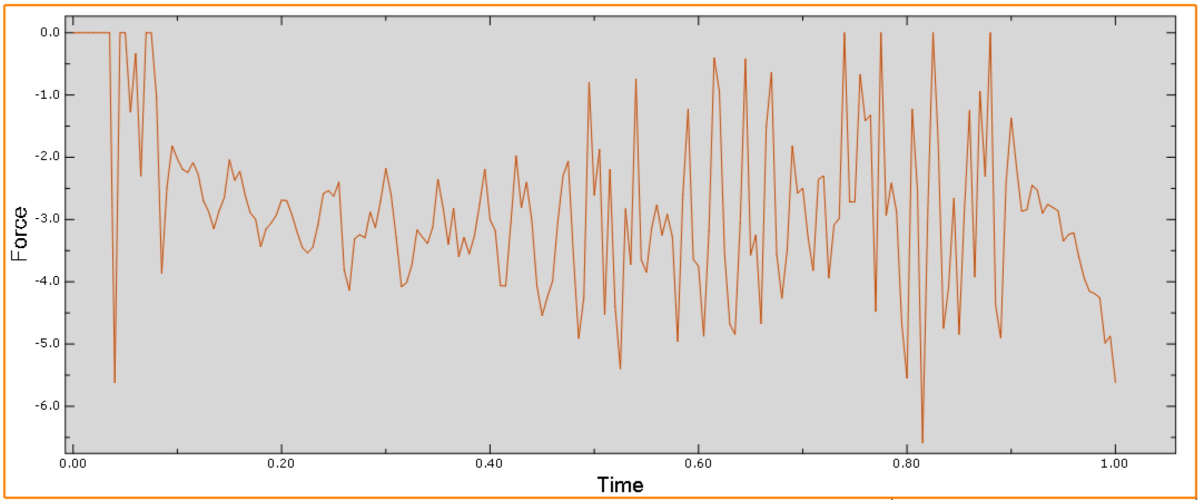


Figure 5.23. bending force v/s displacement of AA5083 at 120˚C

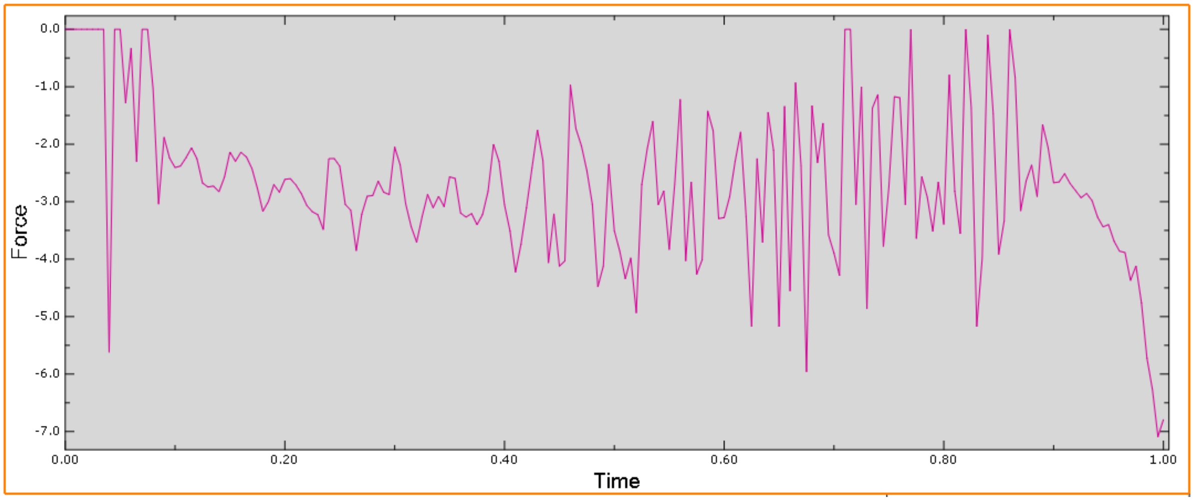


Figure 5.24. bending force v/s displacement of AA5083 at 150˚C

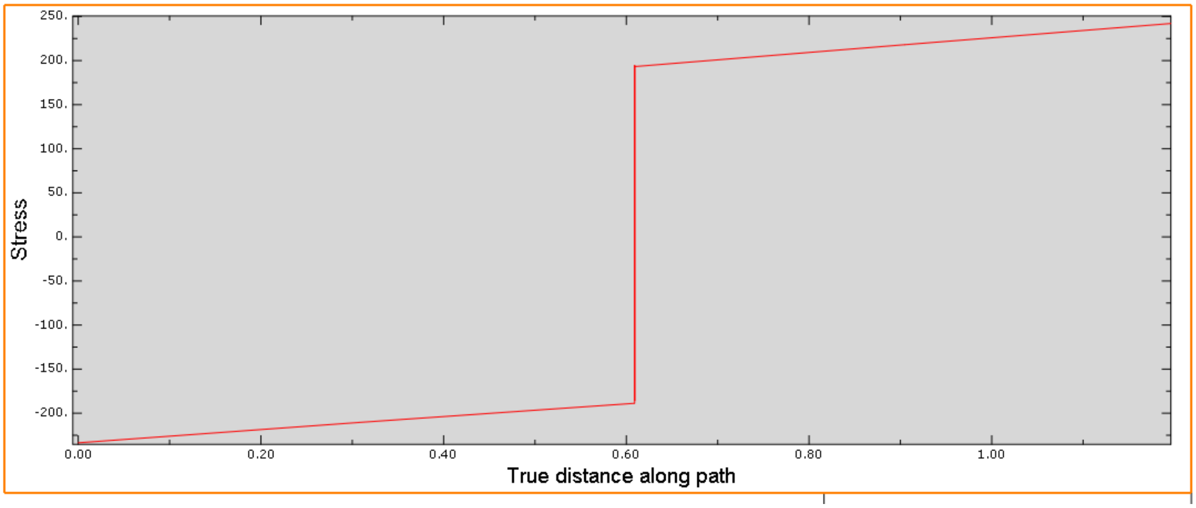


Figure 5.25. True distance along cross section vs in bending stress of AA5083 at 30˚C

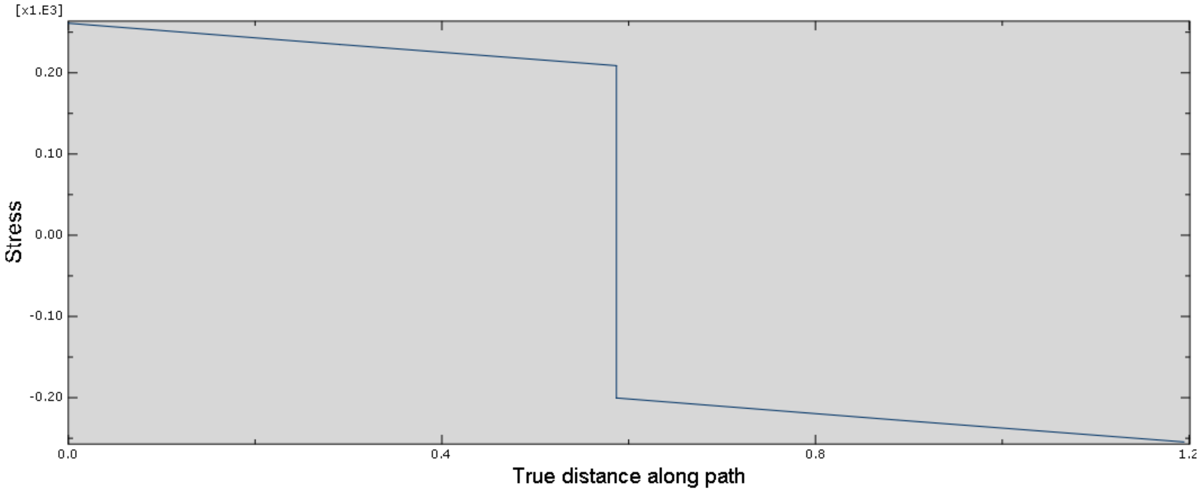


Figure 5.26. True distance along cross section vs in bending stress of AA5083 at 120˚C

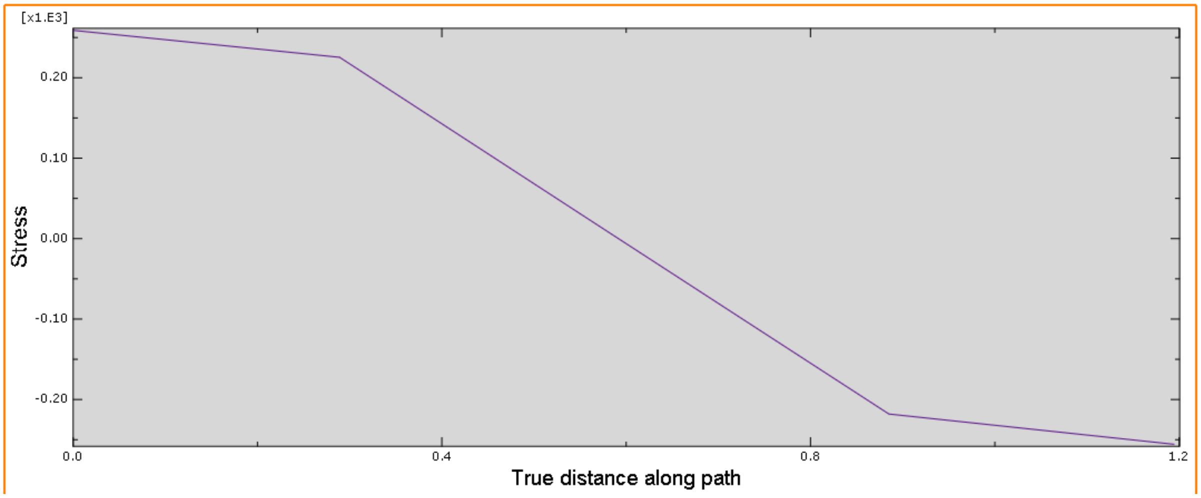


Figure 5.27. True distance along cross section vs in bending stress of AA5083 at 150˚C

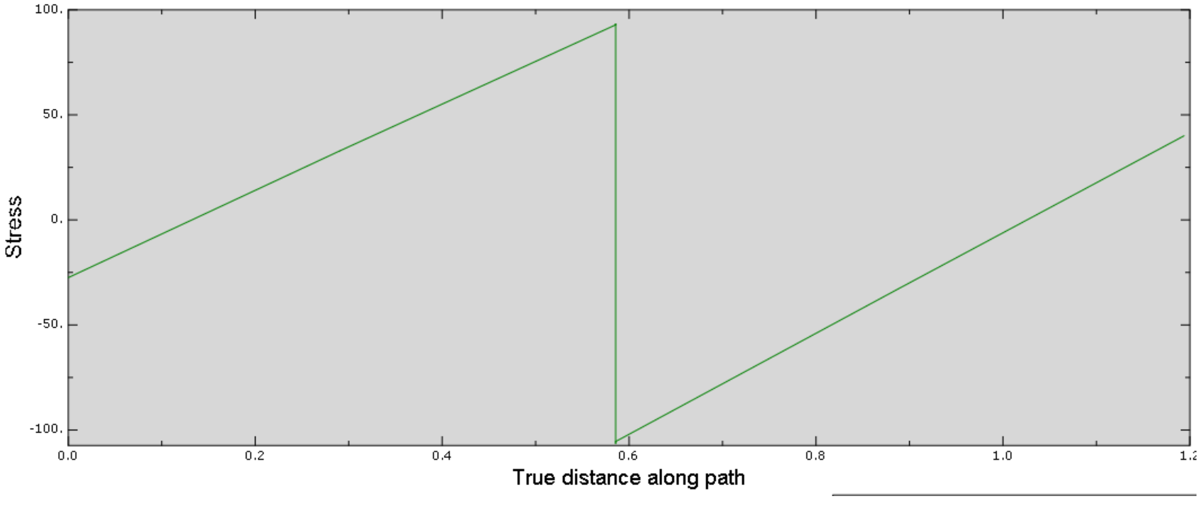


Figure 5.28. True distance along cross section vs in residual stress of AA5083 at 30˚C

Figure 5.29. True distance along cross section vs in residual stress of AA5083 at 120˚C

Figure 5.30. True distance along cross section vs in residual stress of AA5083 at 150˚C

Force vs time plots for U-bending

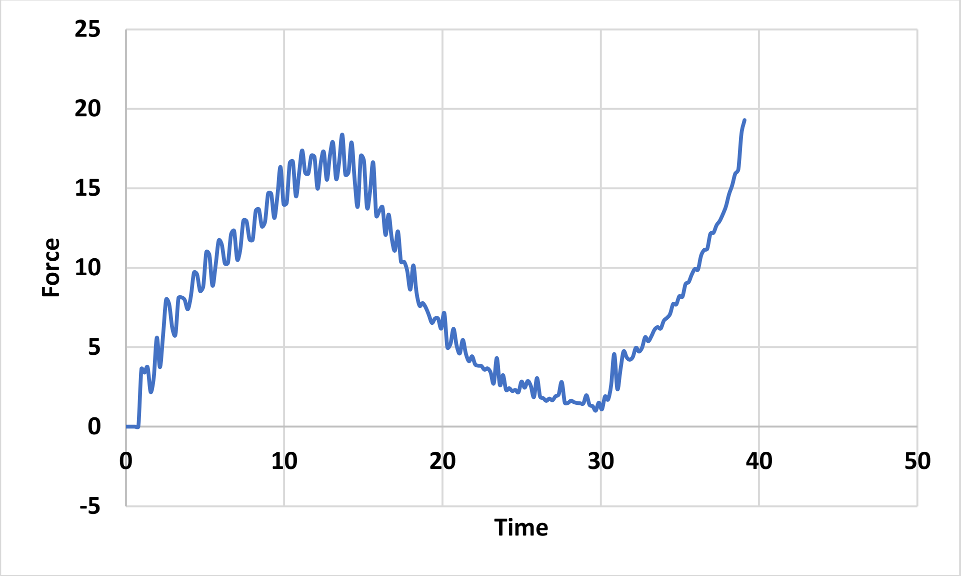


Figure 5.31. bending force v/s displacement of AA5083 at 30˚C

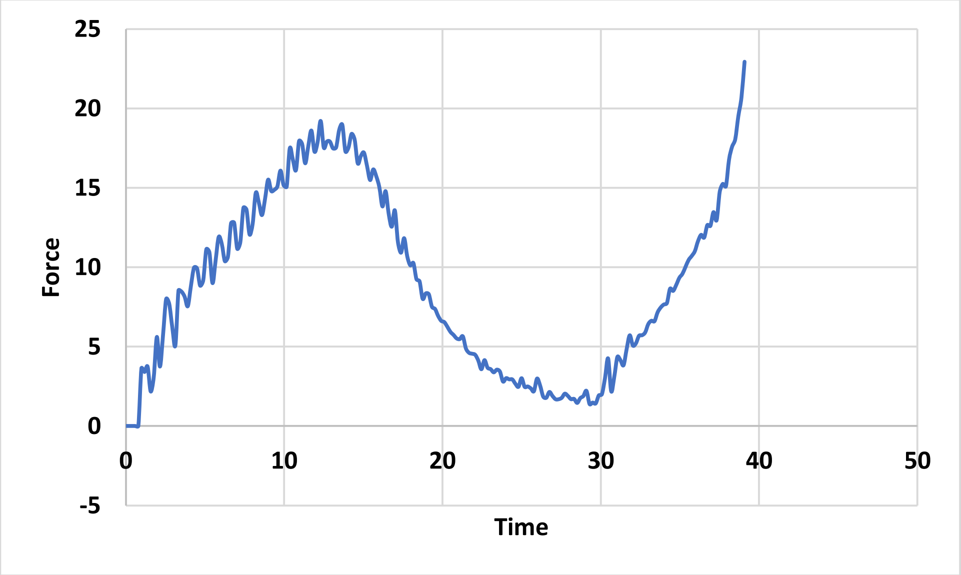


Figure 5.32. bending force v/s displacement of AA5083 at 120˚C

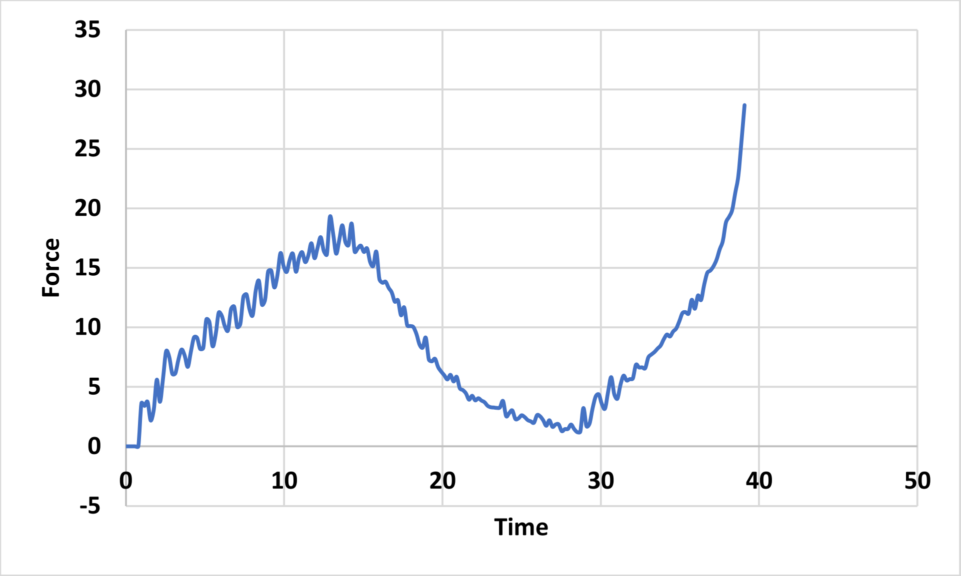


Figure 5.33. bending force v/s displacement of AA5083 at 150˚C

Figure 5.34. True distance along cross section vs in bending stress of AA5083 at 30˚C

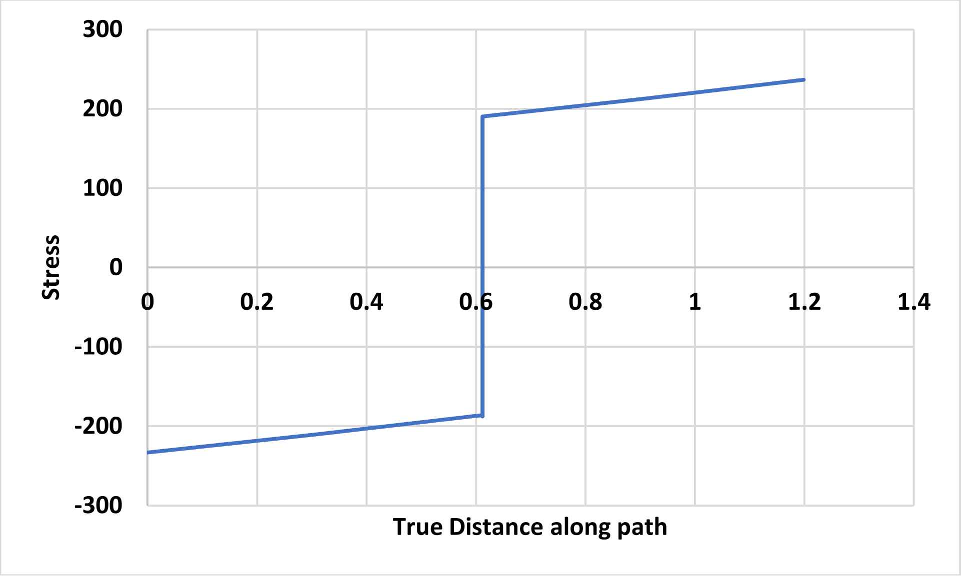


Figure 5.35. True distance along cross section vs in bending stress of AA5083 at 120˚C

Figure 5.36. True distance along cross section vs in bending stress of AA5083 at 150˚C

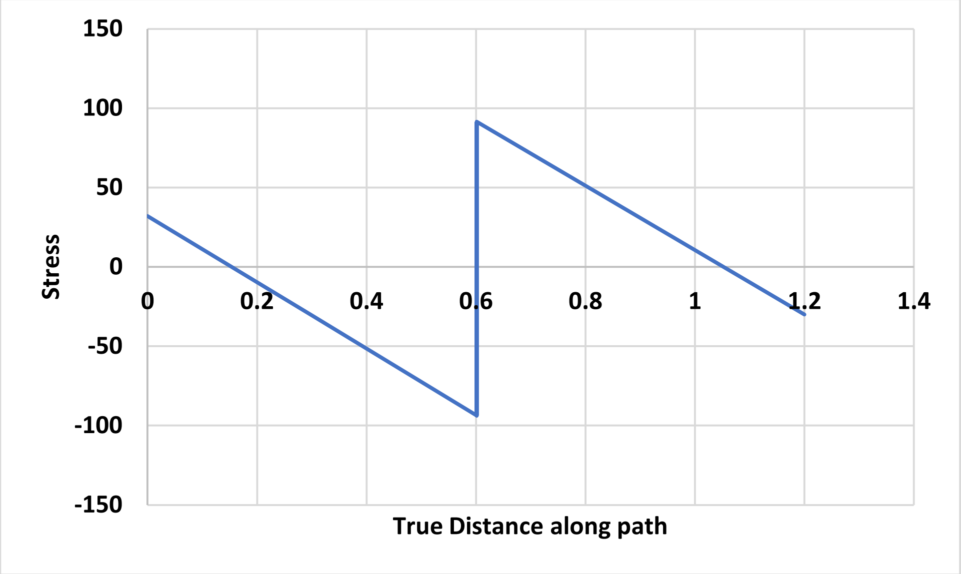


Figure 5.37. True distance along cross section vs in residual stress of AA5083 at 30˚C

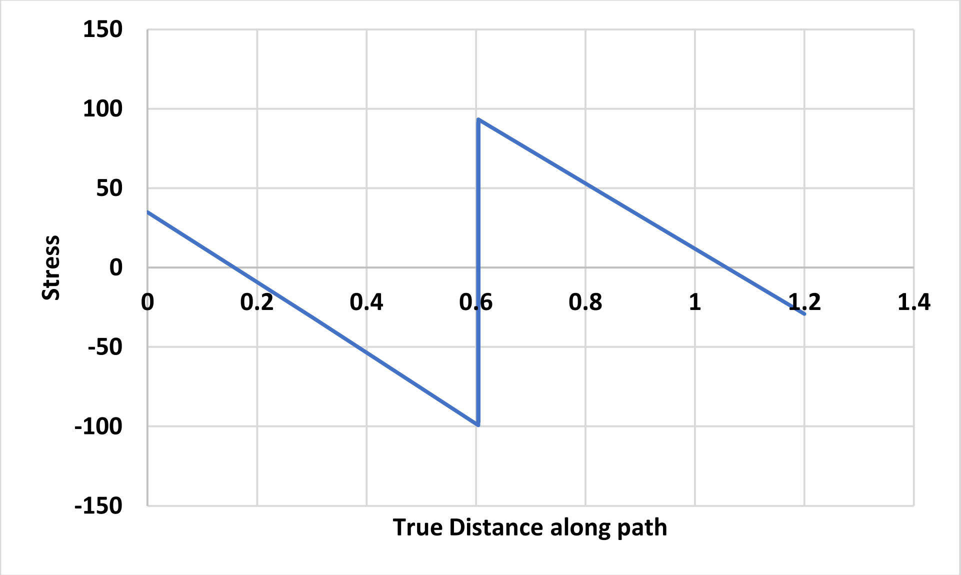


Figure 5.38. True distance along cross section vs in residual stress of AA5083 at 120˚C

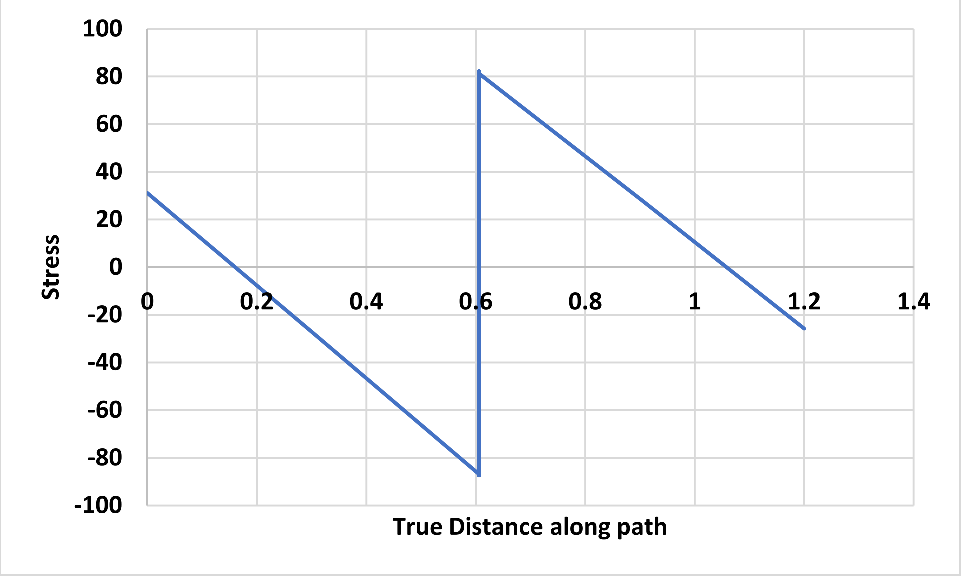


Figure 5.39. True distance along cross section vs in residual stress of AA5083 at 150˚C

The experimental and simulation results for V and U-bending are given in Table 5.1 and 5.2, respectively. Highest value of springback is observed in the case of bending at room temperature. The springback value decreases at a temperature of 120°C and reduced further at 150°C.

Table 5.1. Comparison of springback values in experimental and simulation results in V bending

Sheet thickness (mm)	Temperatures (°C)	By simulation (in degree)	Experimental (in degree)
1.25	30	5.68	4.38
1.25	120	4.02	3.82
1.25	150	3.83	2.09

Table 5.2. Springback values for simulation results by U bending

Sheet thickness (mm)	Temperatures(°C)	By simulation(in degree)
1.25	30	4.78
1.25	120	3.98
1.25	150	2.68

Hence, the warm bending of sheets of Al alloy AA5083 is more advantages than the bending at room temperature. The force required for bending operation is also less and more accurate dimensions can be obtained. The lower press capability can be employed to bend the sheets in V and U bending operations.

CHAPTER 6

CONCLUSIONS

The experimental and numerical studies of V-bending of AA5083 sheet metal at three diffrent temperatures: 30°, 120° and 150° provided very valuable information for warm forming of Al alloy AA5083 sheets. Only numerical studies have been performed for U-bending at different temperatures due to lockdown in COVID-19.

The tensile properties of aluminium alloys are characterized at three different temperatures i.e. room temperature(30°C), 120°C and 150°C by uniaxial tension tests performed in an environmental chamber attached to the UTM. It is observed that yield strength, tensile strength and and strength coefficients decreased due to increase in temperature. The strain hardening exponent and percentage elongation increased due to increase in temperature. The true stress true strain data recieved from uniaxial tension tests were used to define the material model in the FE simulations for V and U bending procedures.

The experiments performed for V-bending in environmental chamber at different temperatures showed decrease in springback values as the temperature increased. A highest value of springback is observed at room temperature whereas the lowest value of springback is obtained at 150°C. The FEA results are in agreement with the experimental results. The decrease in springback results in bending if performed at higher temperatures could be attributed to the lower tensile and higher strain hardening exponents. At higher temperatures, recovery, recrystallization and grain growth phenomenons are operative so that the strength values are affected accordingly.

If the bending tests are conducted at higher temperature than 150°C then the springback will reduce further. A temperature will be reached when the springback phenomenon may completely vanish in the experiments and simulations.

The bending simulations are also performed for U-bending at different temperatures. The similar results are observed in U-bending i.e. as the temperature increased during bending operation, springback reduced accordingly. The springback values obtained in U-bending are much lower than the V-bending. The lower values of springback in U-bending can be attributed to the stretch force acting at the web section under the punch at differnt temperatures. Higher bending force is required to bend the sheets in U-bending than V-bending. This could be attributed to the bending at two places in U-bending process.

Hence, the warm bending of sheets of Al alloy AA5083 is more advantages than the bending at room temperature. The force required for bending operation is less and more accurate dimensions can be obtained.

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