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# Numerical and Experimental Analysis of Cold Stretching of Aluminium Sheets Using an Instrumented Bench

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**Abstract.** Cold stretching of a thin 5154 aluminium sheet is studied. An instrumented bench is developed to analyse the forming of double curvature panels. A numerical tool using ABAQUS software is developed to predict the behaviour of thin sheets during the stretching process and also to estimate the residual mechanical field in the formed shapes. The bench is calibrated by comparing experiments and numerical results in terms of deformed shape, in-plane strain levels and thickness evolution.

## INTRODUCTION

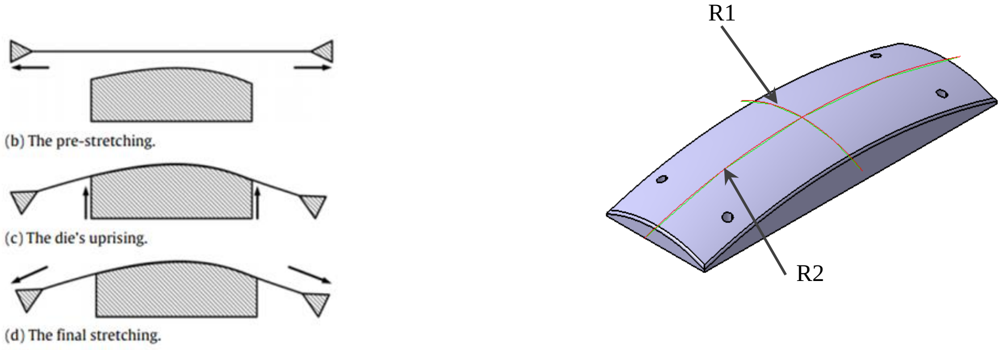
Sheet metal forming processes are widely used to manufacture industrial components. They are typically employed to produce parts for aeronautic and automotive industries. The final shapes have to respond to multiple criteria, such as weight, stiffness, dimensions, strength… In aerospace industry, structure elements use sets of large panels generally obtained by sheet forming processes of low density materials (like 5xxx, 7xxx and 2xxx series of aluminium alloys). Stretching processes are often chosen for the first stages of manufacturing. These operations are generally performed under cold forming conditions. Their main advantage is to prevent local buckling by applying an initial plastic strain in tension.

In this paper, an instrumented bench developed by the LAMPA laboratory is used to characterize the sheet behaviour and the forming process in the aim of adjusting a numerical tool. The main objective of this work is to validate the demonstrator performances by comparing experimental and numerical analysis of a well-known material forming. The designed bench is a reduced scale version of industrial machine. The stretching and wrapping motions are controlled separately and the axis displacements are measured by a set of specific transducers. The numerical model is implemented in the ABAQUS code and uses classical elastoplastic behaviour (with anisotropy described by Hill48 criterion). The validation operation consists in comparing deformed shape, strain level, and sheet thickness evolution of experimental and numerical models.

## INDUSTRIAL ISSUES OF FORMING BY STRETCHING

In stretching processes, parts are formed in several steps by applying to the material sequences of tensile states followed by wrapping operations as shown in Fig. 1. The process is mainly used in the aircraft industry to produce large double curved panels (Fig. 1b) [1].

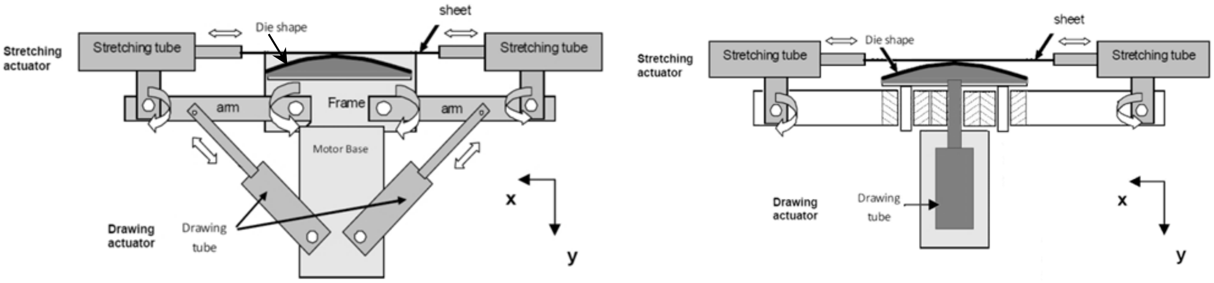
Figure 2a shows a typical stretching industrial case. Stretching and shaping phases are produced by combining two arms motions actuated by hydraulic jacks (closed loop mechanism). This machine architecture induces complex kinematics control to manage the stretching and forming operations. Thus, the process parameters adjustment is quietly difficult.


(b) The pre-stretching.
(c) The die's uprising.
(d) The final stretching.
R1
R2

(a) (b)

**FIGURE 1.** Stretching process [2] (a) and die shape (b)

Other machines are present in the industry with an open loop mechanism inducing a separated control of the stretching and wrapping motions (Fig. 2b). The proposed design of the bench is directly inspired by these architectures.


Stretching actuator
Stretching tube
Die shape
sheet
Stretching tube
arm
Frame
arm
Motor Base
Drawing actuator
Drawing tube
x
y
Stretching actuator
Stretching tube
Die shape
sheet
Stretching tube
Drawing actuator
Drawing tube
x
y

(a) (b)

**FIGURE 2.** Parallel architecture [3] (a) and serial architecture (b)

# PROCESS DESCRIPTION

## Description of the Instrumented Bench

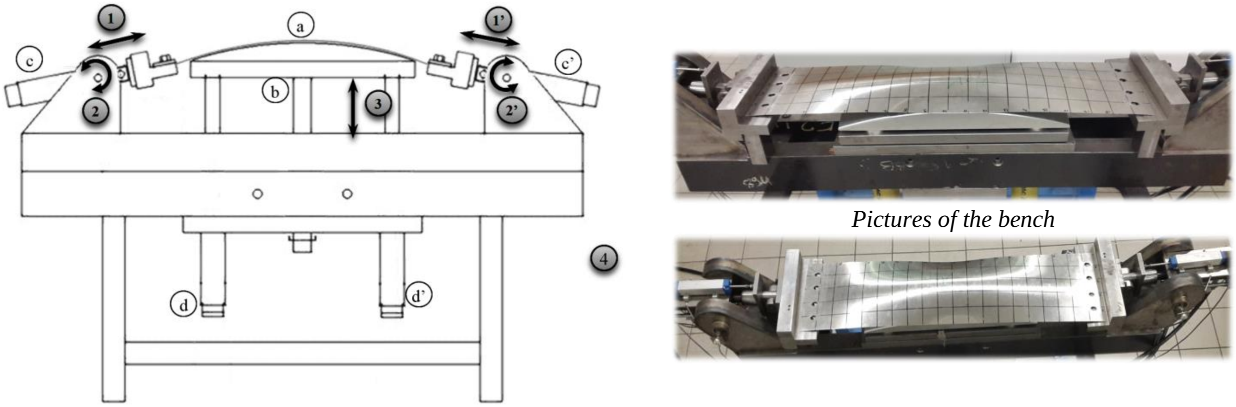

1
a
1'
c
c'
2
b
3
2'
4
d
d'
Pictures of the bench

**FIGURE 3.** Sketch of the forming machine with: deformed sheet (a), die (b), stretching hydraulic jacks (c and c'), forming hydraulic jacks (d and d') and sensors (from no.1 to no.4)

The main concept for this drawing bench is to separate the tensile stretching and the wrapping operation. A simplified architecture of the proposed machine is sketched in Fig. 3. The die is a double curvature dome located in the central zone of the supporting table. Its primary and secondary radii are about 1000mm and 250mm, respectively. The process cycle is defined by several stages. The flange is fixed by two grips respecting a reference horizontal frame centred on the middle vertical planes of the machine. Flange dimensions are 1000mm x 250mm x Xmm, with the thickness X inferior to 2mm. The grip zone is equal to 70mm. During the first step, two hydraulics jacks draw the sheet metal horizontally in opposite directions. The motion of the stretching jacks is measured by two resistive displacement sensors (1) and (1’). The pressure of actuators is given by an electronic pressure sensor (4). In the second step, two vertical hydraulic jacks pull up the die to wrap the sheet. This motion induces rotations of the stretching jacks which are measured by resistive rotation sensors (2) and (2’). The vertical position of the die is obtained by a long distance draw-wire sensor (3). The main machine capabilities are detailed in Table 1.

**TABLE 1.** Technical characteristics of the bench

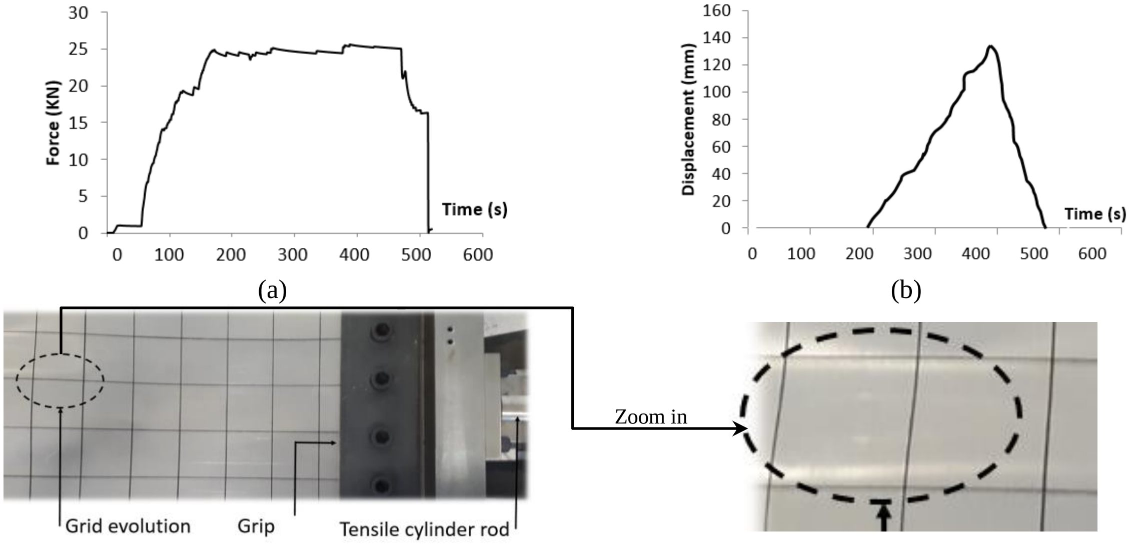
| | |
|---|---|
| Maximum stretching force | 120 kN |
| Maximum punching force | 80 kN |
| Hydraulic jacks stroke for stretching | 80 mm |
| Hydraulic jacks stroke for forming | 180 mm |
| Grip zone dimension | 70 mm |

## Preliminary Forming Test on 5154 Aluminum Alloy

Preliminary tests on a 5154 aluminum sheet (i.e. Al-Mg alloy) have been conducted to calibrate the bench. This alloy that combines a moderate strength with very good formability is very interesting for high strained forming processes. It is used in a broad range of applications, especially in automotive and airplane industries. The flange thickness is 1mm. The forming cycle uses three major steps:

(1) The initial stretching operation. During this step, the stretching cylinder force evolves from 0 to 25 kN (hydraulic pressure: 285 bar), inducing in the material a tension stress of 102 MPa (82% of yield stress).
(2) The punching operation, corresponding to a vertical displacement of 140mm of the die.
(3) The spring back, corresponding to the reverse displacement of the punch following by the pressure shut down.

The average duration of the cycle is 2500 s. Figure 4 shows the time evolution of the stretching force and the punch displacement. In the purpose of evaluating displacements and in plane strains on the top of the sheet a 50mm X 50mm grid is drawn on the flange, as shown in Fig. 4c.



(a)

(b)

(c)

**FIGURE 4.** Actuators evolution during the forming cycle: stretching force (a) and punching displacement (b)

# NUMERICAL SIMULATION

## Material Parameters

Mechanical behavior of the 5154 aluminum alloy has been investigated by performing tensile tests at room temperature on a Zwick machine equipped with a 100 kN load cell and with longitudinal and transverse extensometers to evaluate plastic anisotropy. The main mechanical characteristics of the alloy are summarized in Table 2 as a function of the tested orientation compared to the sheet rolling direction (i.e. 0°, 45° and 90°). It can be noted that: the highest stress level is obtained for an orientation of 0° whereas the highest strain at failure is obtained for an orientation of 45°. This can generally be explained by crystallographic texture and grain morphologies. The alloy exhibits a strong anisotropy with a Lankford coefficient about 0.75.

**TABLE 2.** Mechanical characteristics of the 5154 aluminum alloy obtained by using tensile experiments

| Orientation α | 0° | 45° | 90° |
|---|---|---|---|
| Yield stress (MPa) | 123 | 116 | 119 |
| Tensile strength (MPa) | 230 | 221 | 223 |
| Elongation at rupture (%) | 19 | 26 | 23 |
| Anisotropy coefficient $R_\alpha$ | 0.60 | 0.82 | 0.76 |
| Young Modulus (GPa) | | 76 | |
| Poisson ration | | 0.33 | |

## Numerical Model

The numerical model of the forming process is implemented in the ABAQUS finite element code. Figure 5 shows the assembly of the deformable flange, the rigid surfaces describing the machine elements and the connectors associated to the stretching cylinders. To be able to take machine defaults measured by sensors into account, no symmetries boundary conditions are applied to the model.

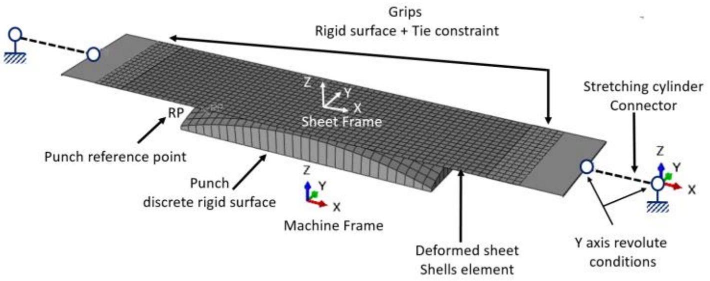


**FIGURE 5.** Numerical model of the stretching process

The punch and the grips are modeled by discrete rigid surfaces. The Aluminum 5154 sheet is meshed using linear shell elements with full integration (S4 element in ABAQUS). In this primary approach, after a sensitivity analysis balancing CPU time to precision, the global mesh size is fixed to 20mm for the discrete surface and 15mm for the shell elements associated to the deformed sheet. Surface to surface contact with hard contact and coulomb friction are used for the punch (master) to sheet (slave), the flange to lost sheet and the lost Sheet to die interfaces. A global friction coefficient of 0.2 is chosen for this contact property. The grips surfaces are joined to the sheet in the grip zone (length of 70 mm at the sheet ends) by rigid tie conditions. Connectors are used for the stretching cylinders to permit a force or a displacement control. Soft axial stiffness and damping are defined in the connector properties to prevent instabilities during the force control. The connector is fixed to each end (ground and grip surface) with Y axis revolute conditions. The forming step is controlled by a Z axis translation applied to the punch reference point. The other degrees of freedom of the punch are fixed to ground. The simulation process is organized in three steps using implicit time integration (ABAQUS standard): stretching step; punching step; spring back. The punch return and the stretching force decrease are controlled by amplitude curves during the third steps.

# Numerical Results

Simulations using a stretching control with the force time law given in Fig. 4a or with the corresponding average measured displacement give similar results. The average displacement is computed taking into account an adjustment induced by the initial position between the machine and sheet frames respectively. The vertical punch displacement is controlled using the experimental law shown in Fig. 4b. If the machine and the sheet frames are precisely aligned at the initial state, the symmetric behaviour is respected as shown in Fig. 6 in which are plotted the principal strains at two different stages of the process.

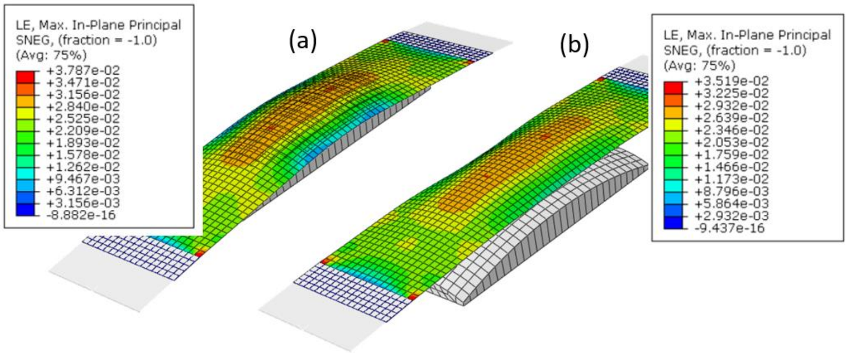
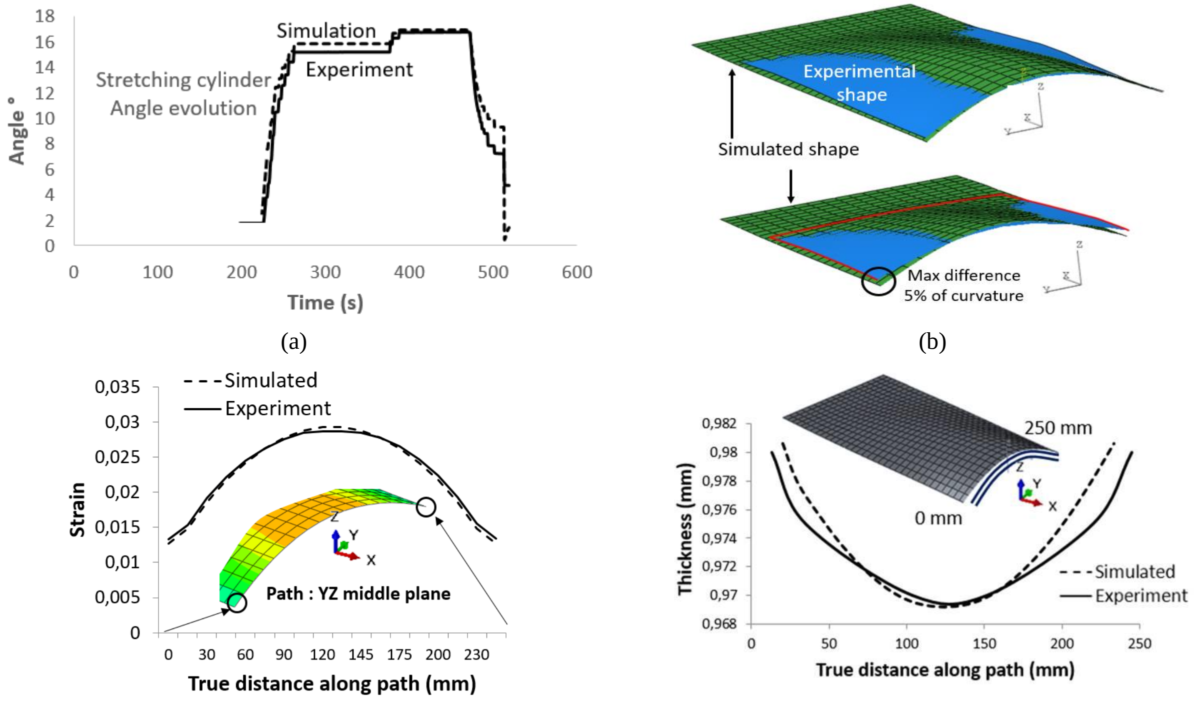

LE, Max. In-Plane Principal
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.787e-02
+3.471e-02
+3.156e-02
+2.840e-02
+2.525e-02
+2.209e-02
+1.893e-02
+1.578e-02
+1.262e-02
+9.467e-03
+6.312e-03
+3.156e-03
-8.882e-16
(a)
(b)
LE, Max. In-Plane Principal
SNEG, (fraction = -1.0)
(Avg: 75%)
+3.519e-02
+3.225e-02
+2.932e-02
+2.639e-02
+2.346e-02
+2.053e-02
+1.759e-02
+1.466e-02
+1.173e-02
+8.796e-03
+5.864e-03
+2.932e-03
-9.437e-16

**FIGURE 6.** Principal strains in-plane on the top of the deformed sheet at the end of the punching step (a) and after the spring back (b)

# VALIDATION



(a) (b)

(c) (d)

**FIGURE 7.** Comparison between experimental and numerical results for: stretching cylinder rotations (a), deformed shapes (b), absolute principal in-plane strains (c) and thickness evolution (d)

General performances of the stretching demonstrator are validated by comparing numerical and experimental results. Firstly, measured actuators displacements and rotations have been compared and results show a good agreement between experiment and simulation, as shown in Fig. 7a. Secondly, deformed shape and in-plane strains have been compared. The displacements of the initial grid nodes are obtained by means of a 3D coordinate measuring machine. The measured points are imported in the CAD software CATIA V5 and the deformed shape is obtained by a surface reconstruction technique. The points of the deformed mesh obtained by the numerical simulation are then imported to CATIA and the simulated shape is built by the same technique. Figure7b gives the comparison of the experimental and simulated surfaces. A globally good agreement is found between the two geometries within the forming zone (with an error of 3%). The main differences appear on the edges near the grip zone which seems to be due to the manual control of the stretching pressure release. The in-plane strains are determined by analysis of the grid deformation. It leads to the same precision difference in the same zones as shown in Fig. 7c in which strain evolution along a Y axis in the middle of the sheet is given. Finally, the sheet thickness evolution in the central zone has been studied by using ultrasonic technique and compared to numerical results. A good agreement is also obtained as shown in Fig. 7d along a Y axis in the middle of the sheet.

## CONCLUSION

Cold stretching of a thin 5154 aluminium sheet has been investigated. An instrumented bench has been developed to check the numerical simulation models of the forming process implemented in ABAQUS software. Mechanical behaviour of the 5154 aluminium alloy as well as data measured by the different sensors during the forming experiments are used to simulate the forming of a double curvature part. The numerical tool has thus been validated by comparing experimental and numerical results in terms of: deformed shapes, in-plane strains or thickness evolution. In this first approach, the experimental measurements and numerical results show a globally good agreement. Some defaults are despite observed, due to manual actuators control. Future works will consist in: (i) adding other sensors to take into account the stiffness of the machine during the deformation of thickest sheet; (ii) improving the forming process actuators control and (iii) adding a heating system to perform hot stretching.

## ACKNOWLEDGEMENTS

The authors wish to associate academic partners: Vianney Piron and Serge Boude from ENSAM LAMPA.

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