Presentation overview

- From tensile test to stamping tests…
- Influent parameters on stampability and specific stainless characteristics
- How to predict the feasibility of stamped parts?
- Analysis of practical cases, stamping of bipolar plate

Presentation overview

- **From tensile test to stamping tests…**

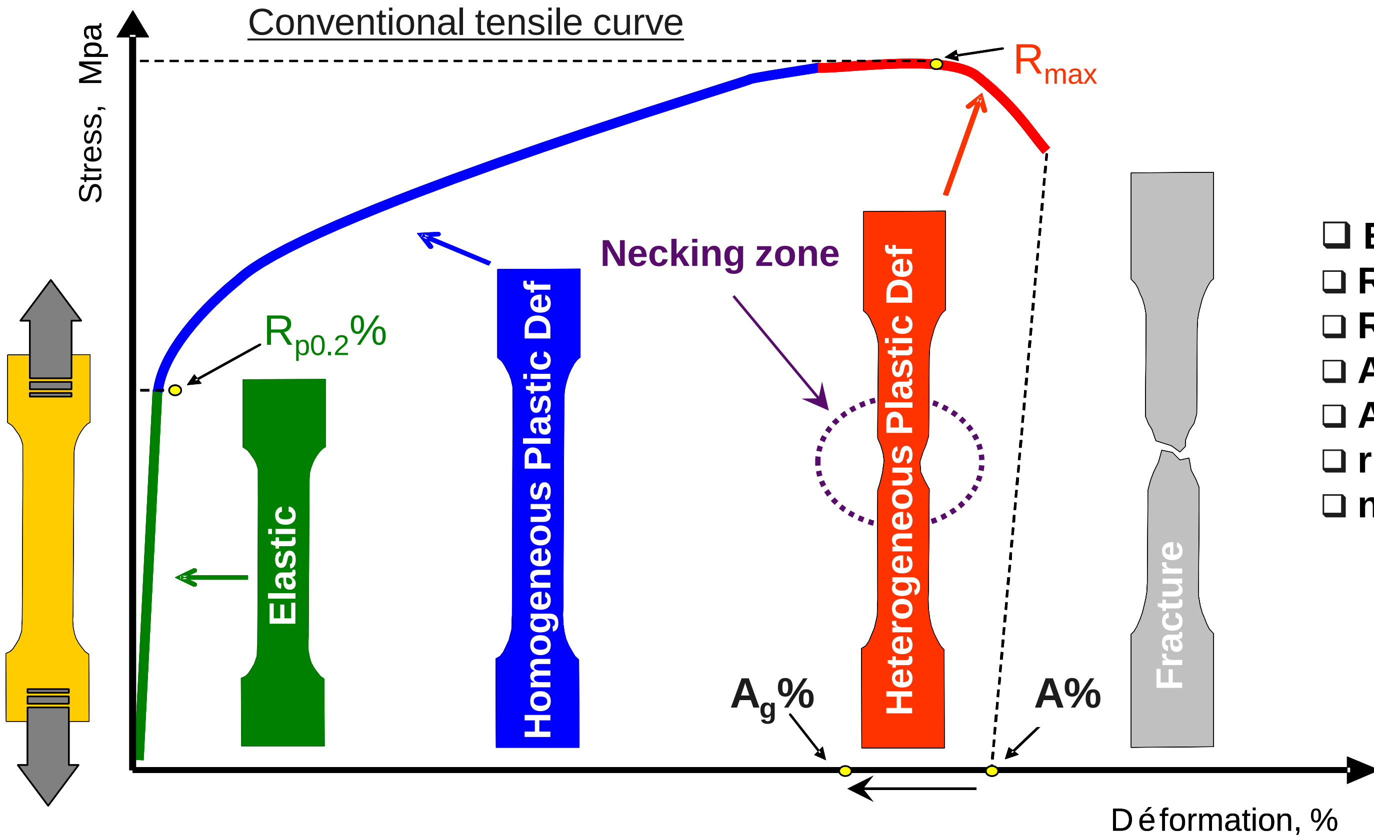
From tensile test to stamping tests…

1.1. Tensile curve and main mechanical characteristics

❖ **Uniaxial tensile test**: principle

$$\sigma = \frac{F}{S_0}$$

where *F*: the applied force
S₀: initial cross-section



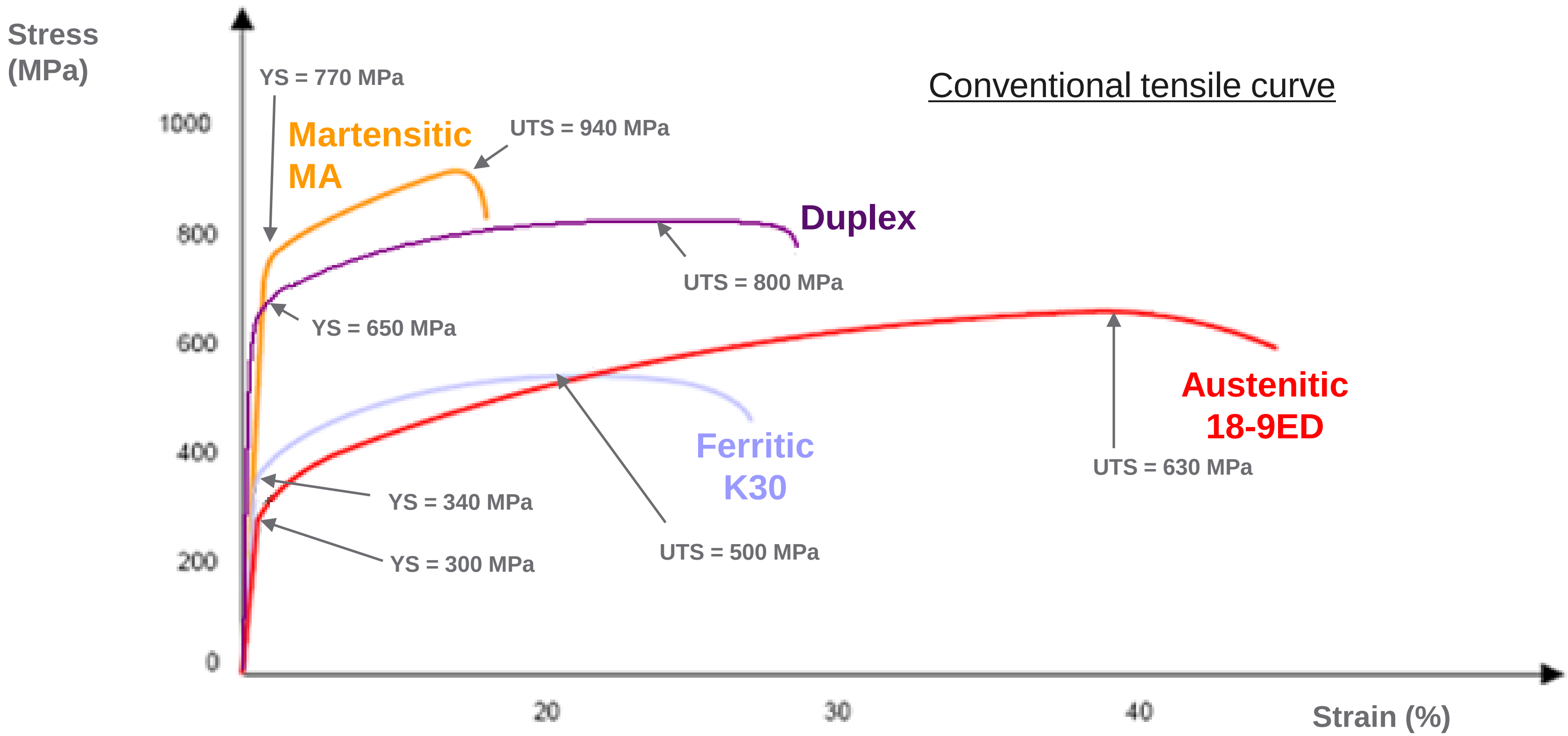
- **E:** Young modulus
- $R_{p0.2}$: Yield Strength (YS)
- R_m: Ultimate tensile stress (UTS)
- **A%:** Maximal deformation
- $A_g\%$: Homogeneous deformation
- **r**: Lankford coefficient
- **n**: Hardening coefficient

Variation of the initial cross-section → Variation of the stress values
→ **From the conventional (engineer) curve to the true curve**

From tensile test to stamping tests…

1.1. Tensile curve and main mechanical characteristics

- 4 families of stainless steels…



- The YS/UTS ratio gives an “idea” of the grade stampability

<u>Lower is the ratio, better is the stampability</u>

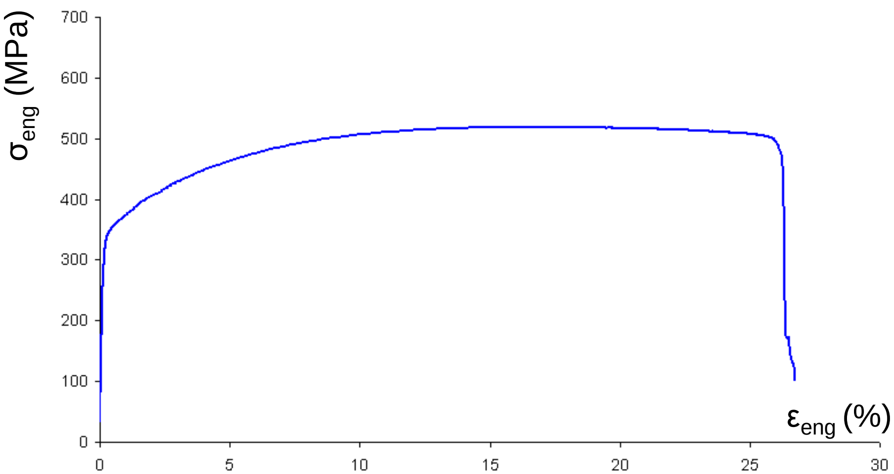
Martensitic	Duplex	Ferritic	Austenitic
0,82	0,81	0,68	0,48

From tensile test to stamping tests…

1.1. Tensile curve and main mechanical characteristics

- Curve calculation…
  - Engineering or conventional tensile curve: initial sample section
  - True or rational tensile curve: instantaneous sample section

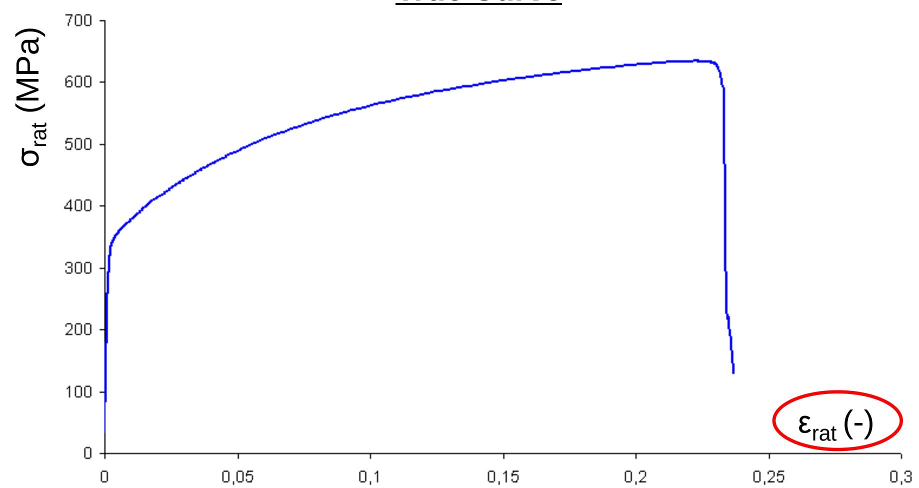
Conventional curve



$$\sigma_{eng} = \frac{F}{S_0}$$

$$\varepsilon_{eng} = \frac{L - L_0}{L_0} \times 100$$

True Curve

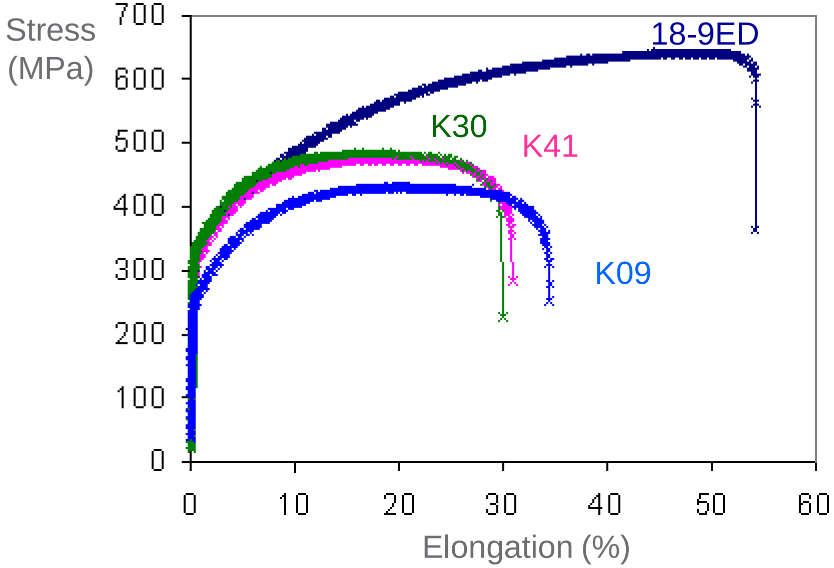


$$\sigma_{rat} = \frac{F}{S} = \sigma_{eng} \times \left(1 + \frac{\varepsilon_{eng}}{100}\right)$$

$$\varepsilon_{rat} = \int_{L_0}^{L} \frac{dl}{l} = \ln\left(\frac{L}{L_0}\right) = \ln\left(1 + \frac{\varepsilon_{eng}}{100}\right)$$

From tensile test to stamping tests…

1.2. Tensile based evaluation criteria for stampability



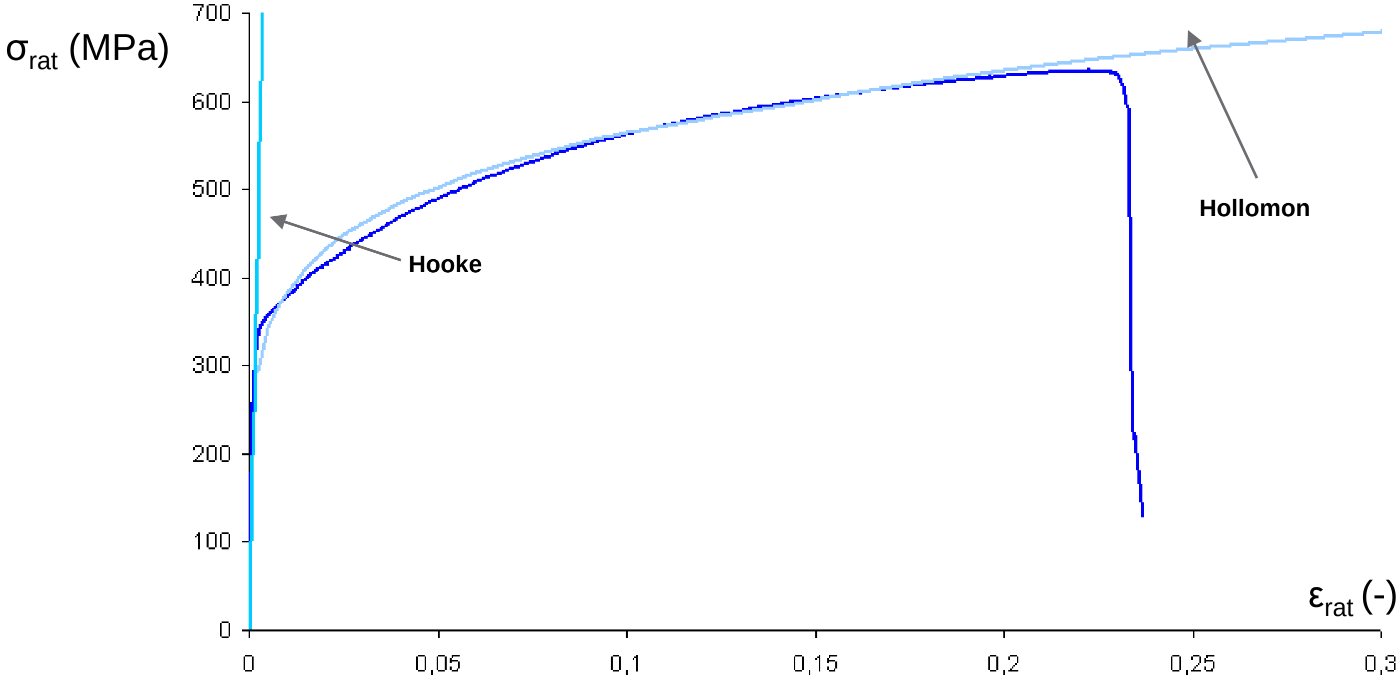
- **$R_{p0.2}/R_m$ ratio** → stampers' method
- Hardening coefficient « n » (for stretching solicitations)
- Normal anisotropy « r_N » (for deep-drawing solicitations)

AMSE	AISI	EN	A_g (%)	A (%)	$R_{p0.2}$ (MPa)	R_m (MPa)	$R_{p0.2}/R_m$	n	r_N
18-9ED	304	1.4301	48	54	310	640	0.48	0.42	0,98
K09	409	1.4512	20	34	250	420	0.59	0.26	1,49
K30	430	1.4016	17	29	330	480	0.68	0.19	0,98
K41	441	1.4509	19	31	310	470	0.66	0.21	1,36

From tensile test to stamping tests…

1.3. Hardening coefficient, n

- Definition
  - n is defined by the Hollomon's Law: $\sigma_{rat} = K \cdot \varepsilon_{rat}^{n}$
  - Represents plastic part of the true tensile curve as the Hooke's law for the elastic one
  - "physical" meaning: steel ability to homogenize strains via hardening
  - High n value ↔ good behavior regarding to stretching deformation mode



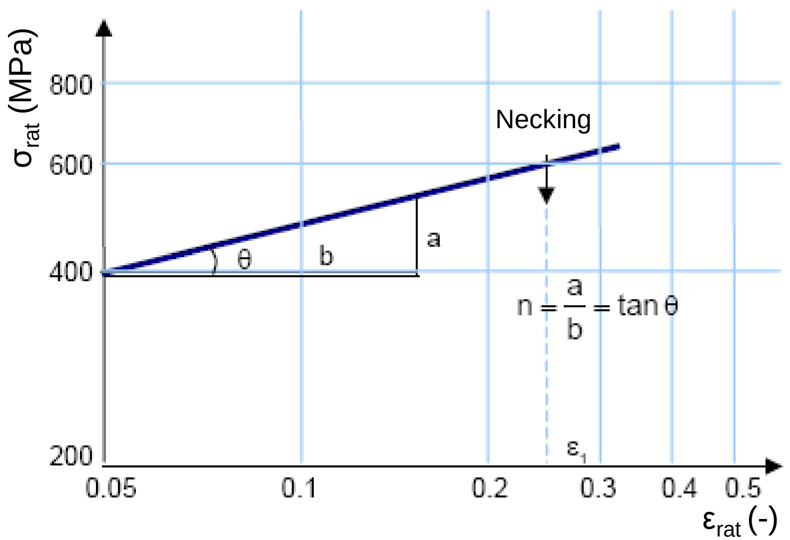
From tensile test to stamping tests…

1.3. Hardening coefficient, n

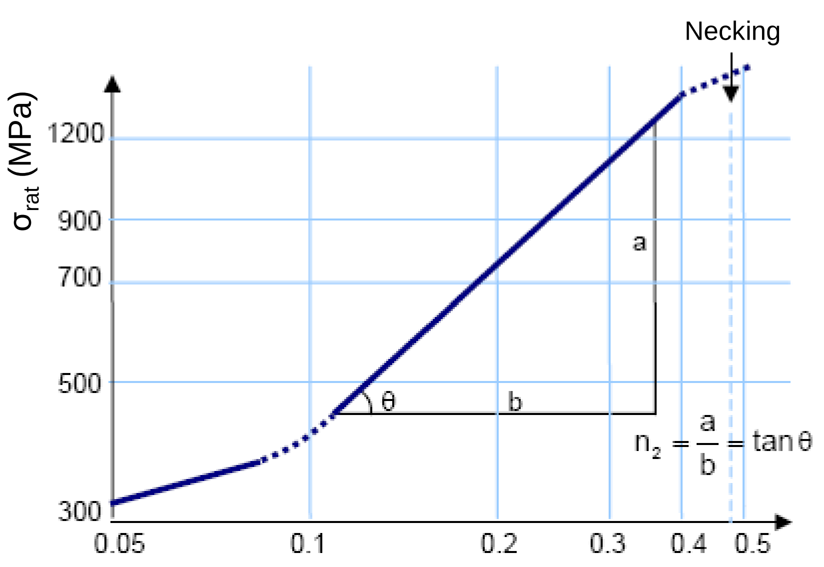
- Determination

$$\sigma_{rat} = K \cdot \varepsilon_{rat}^{\ n} \xrightarrow{\ln} \ln(\sigma_{rat}) = \ln(K) + n \times \ln(\varepsilon_{rat})$$

- Between 5 and 13% for ferritic grades → n ~ 0.15 - 0.25
- Between 18 and 40% for austenitic grades → n ~ 0.4 -0.5



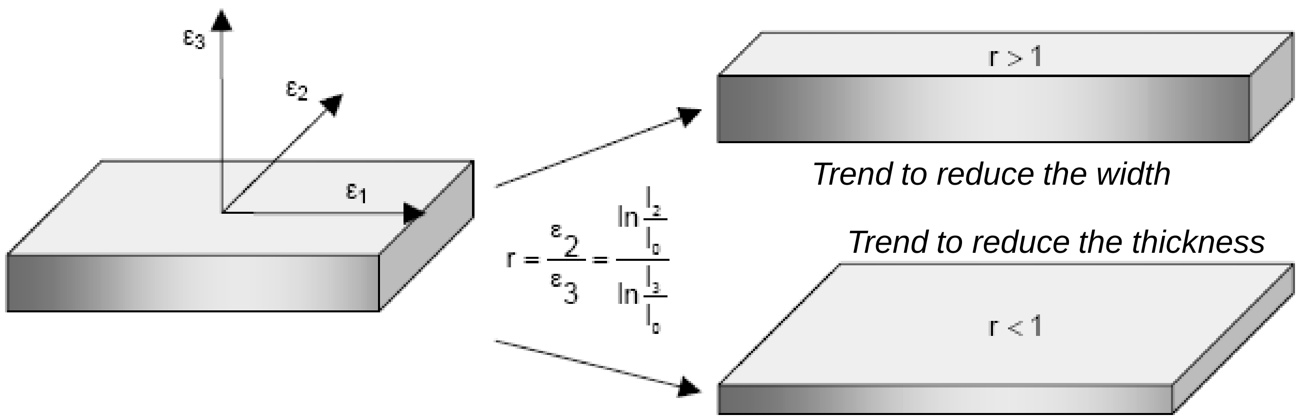
K30



17-7C

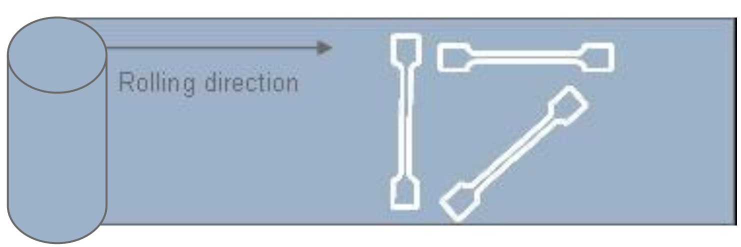
1.4. Anisotropy coefficients r, r_N, Δr

- Isotropic material = same behavior everywhere
- Steel = rolled material → preferential orientation for each grain
- Definition
  - r = ε (width) / ε (thickness) $\Rightarrow$ **r** = $\varepsilon_2/\varepsilon_3$ [Lankford coefficient]



$$r = \frac{\varepsilon_2}{\varepsilon_3} = \frac{\ln \frac{l_2}{l_0}}{\ln \frac{l_3}{l_0}}$$

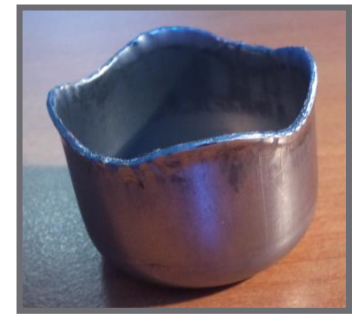
- r is measured on the 3 main directions: rolling, transverse and 45°

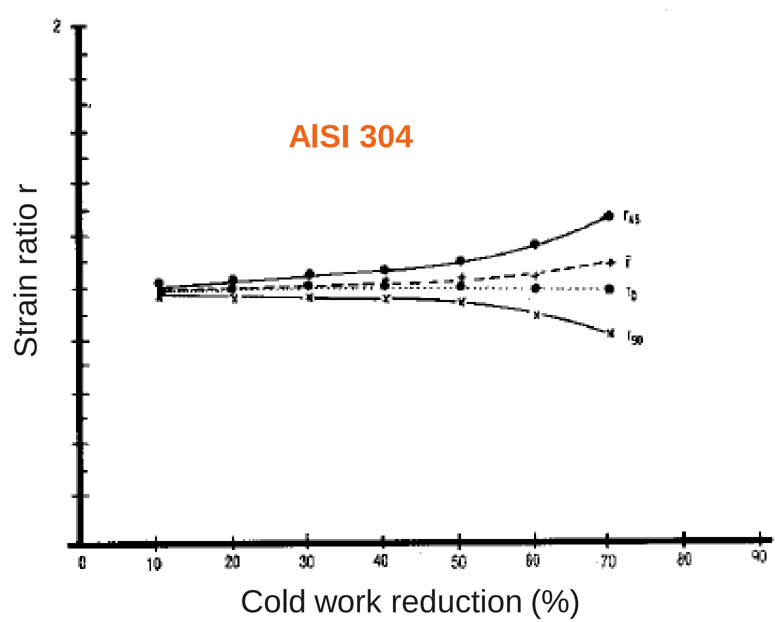


From tensile test to stamping tests…

1.4. Anisotropy coefficients r, r_N, Δr

- Normal anisotropy r_N → Ability for deep-drawing deformation
  - $r_N = (r_L + 2\, r_{45°} + r_T)/4$
  - High value of r_N → Good behavior for deep-drawing deformation
- Planar anisotropy Δr → Ability to form ears
  - $\Delta r = (r_L - 2\, r_{45°} + r_T)/2$
  - High values of Δr → Formation of significant ears
- r depends on the grade and the process





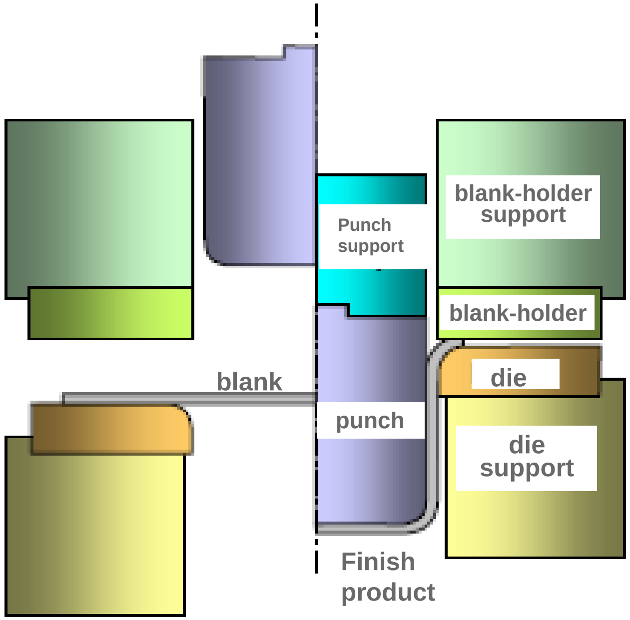
Presentation overview

- **From tensile test to stamping tests…**

  1. Mechanical characteristics of stainless steels
  2. Characterization of stainless steels stampability
     - 2.1. Generalities about stamping
     - 2.2. Stretching deformation mode
     - 2.3. Deep drawing deformation mode
     - 2.4. To sum up…
     - 2.5. Notion of Forming Limit Curves (FLC)

- Influent parameters on stampability and specific stainless characteristics
- How to predict the feasibility of stamped parts?
- Analysis of practical cases, stamping of bipolar plate

2.1. Generalities about stamping

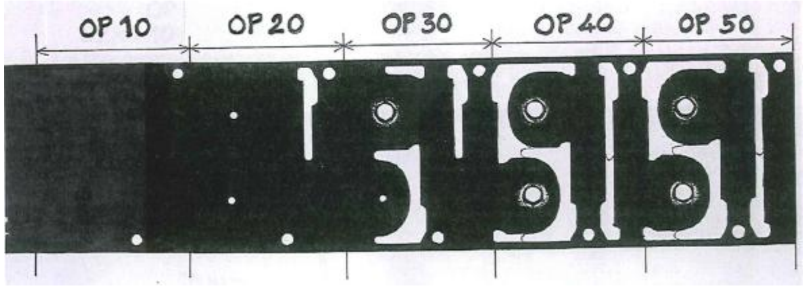


- The initial sheet (=**blank**) is introduced by force in a concave shape (= **die**) by the use of a convex shape (=**punch**).
- This operation can provoke some wrinkles on the edges of the blank. These wrinkles can be erased thanks to a **blank-holder**.
- All these tools are installed in a press

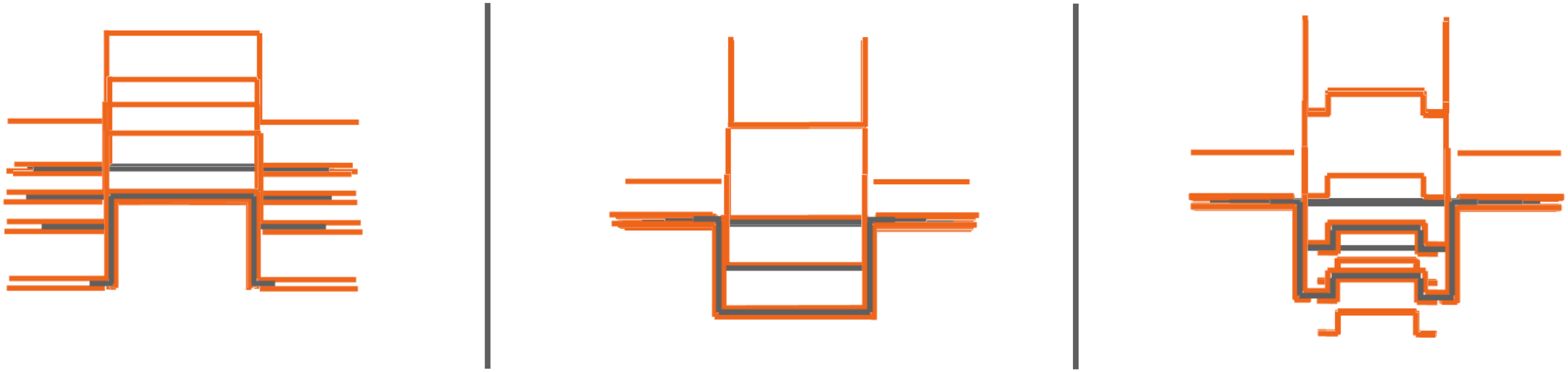
Characterization of stainless steels stampability

2.1. Generalities about stamping

- Press types
  - ❑ Mechanical or hydraulic
  - ❑ Single, transfer or with progressive tools



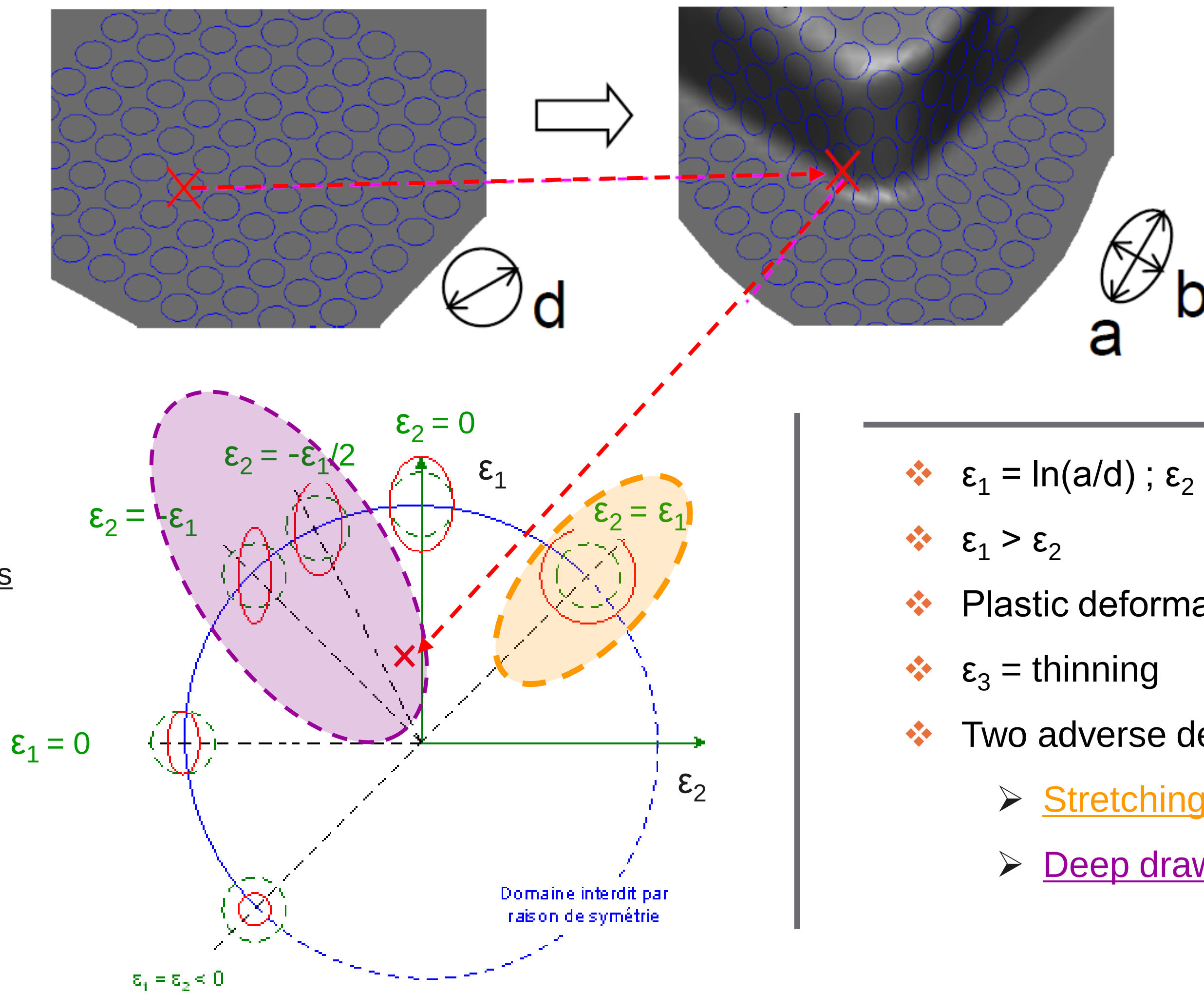
  - ❑ Single-acting, double-acting, triple acting…



Characterization of stainless steels stampability

2.1. Generalities about stamping

- Deformation modes



<u>Hypothesis</u>
r=1

- $\varepsilon_1 = \ln(a/d)$; $\varepsilon_2 = \ln(b/d)$
- $\varepsilon_1 > \varepsilon_2$
- Plastic deformations: $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$
- ε_3 = thinning
- Two adverse deformation modes
  - <u>Stretching</u> ($\varepsilon_1 > 0$; $\varepsilon_2 > 0$)
  - <u>Deep drawing</u> ($\varepsilon_1 > 0$; $\varepsilon_2 < 0$)

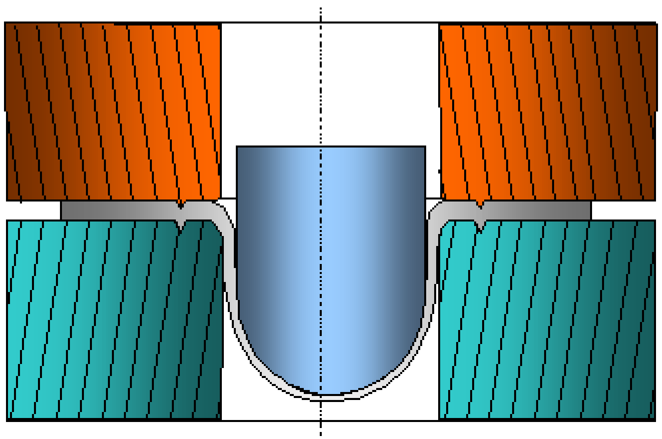
Characterization of stainless steels stampability

2.1. Generalities about stamping

- Two main deformation modes

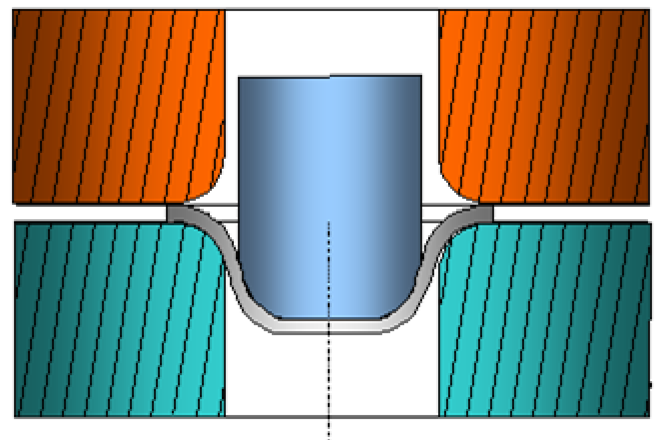
Stretching

- No metal flow
- Significant thinning of the metal



Deep drawing

- Free metal flow
- Low thinning of the metal



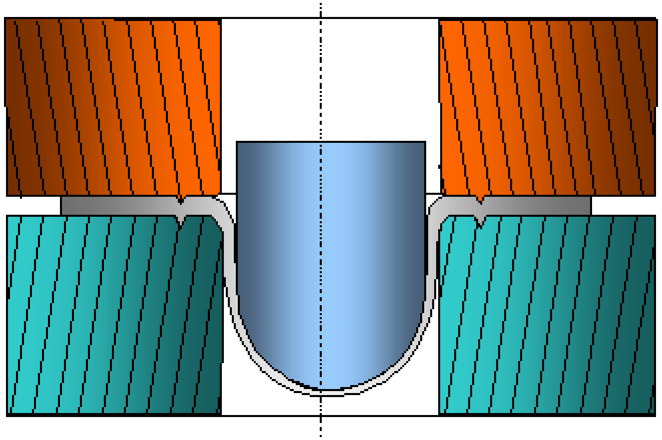
→ In most of cases, the stamping solicitations are a mix of these two ones

Characterization of stainless steels stampability

2.1. Generalities about stamping

- Two main deformation modes

Stretching

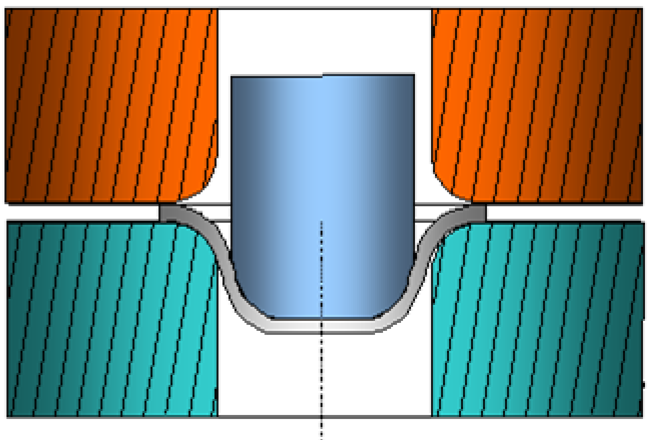


Well adapted to a metal with…

- High elongation A%
- High hardening coefficient n (~a low $R_{p0.2\%}/R_m$ ratio)

→ Well adapted to austenitic grades

Deep drawing



Well adapted to a metal with…

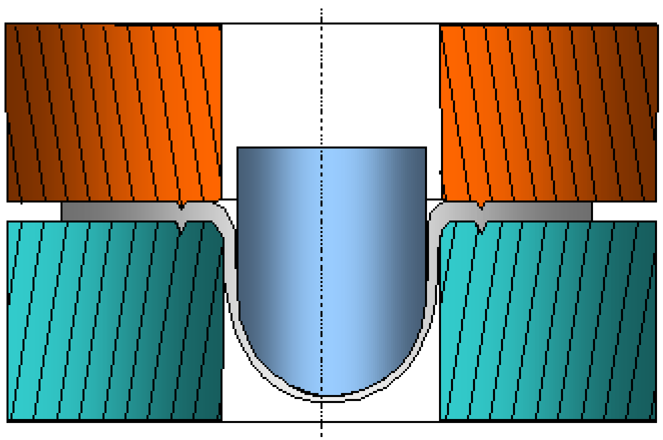
- A high anisotropy coefficient r_N

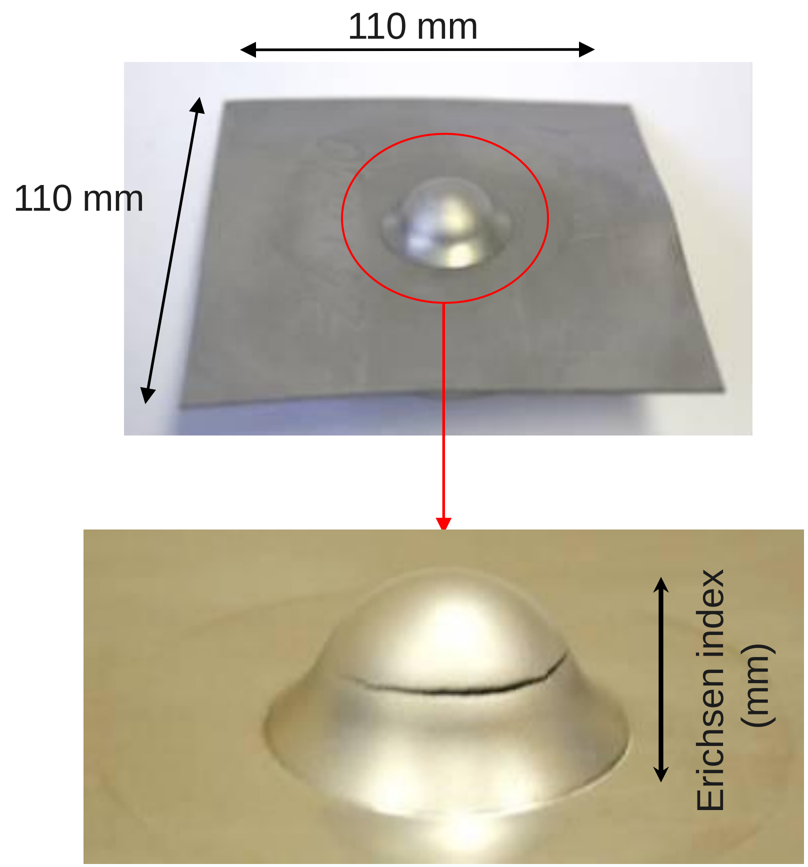
→ Well adapted to ferritic grades

Characterization of stainless steels stampability

2.2. Stretching deformation mode

- Erichsen test



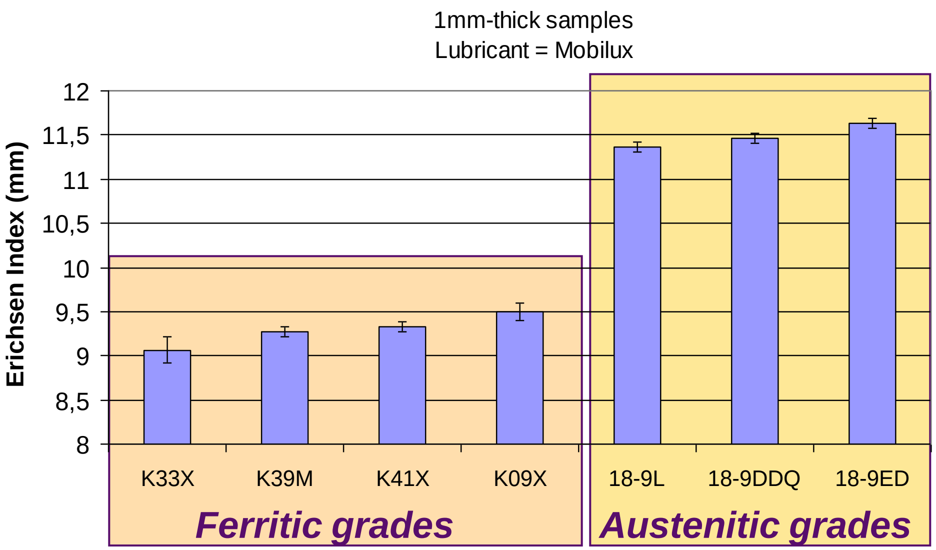


→ Erichsen Index = height of the stamped part at failure (mm)

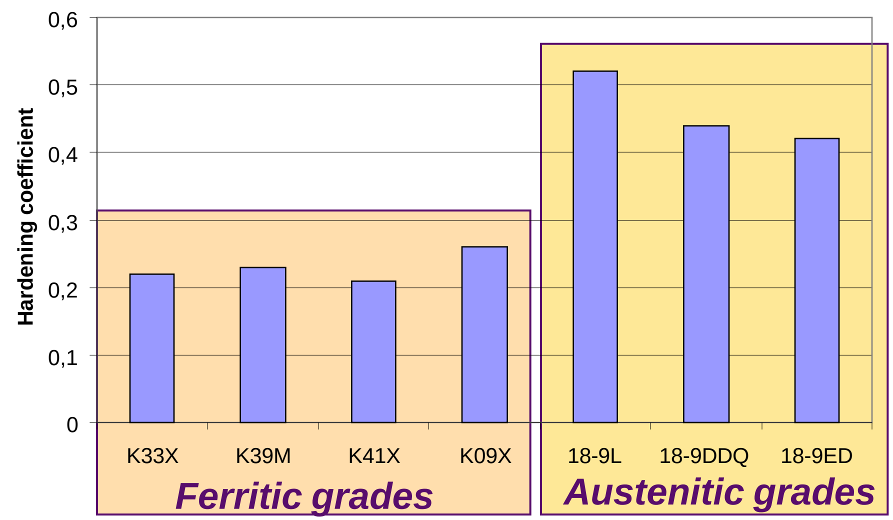
Characterization of stainless steels stampability

2.2. Stretching deformation mode

Erichsen index (mm)



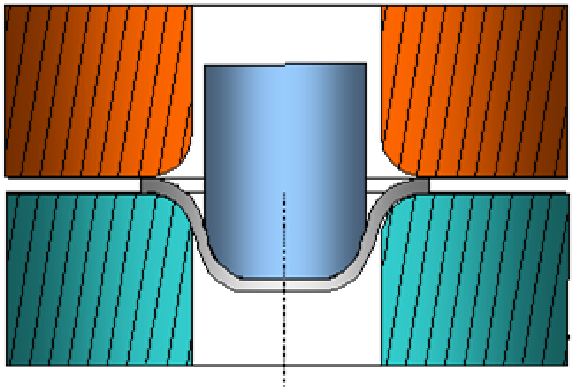
Hardening coefficient

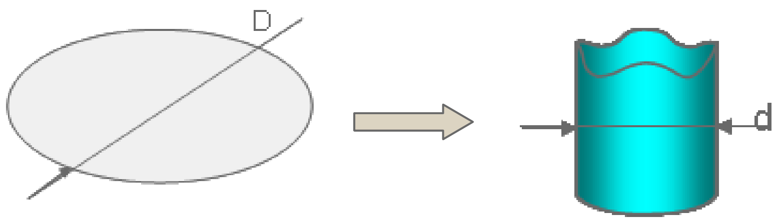


→ Under stretching deformation mode, thanks to higher hardening coefficients, austenitic grades are better than ferritic ones for this deformation mode

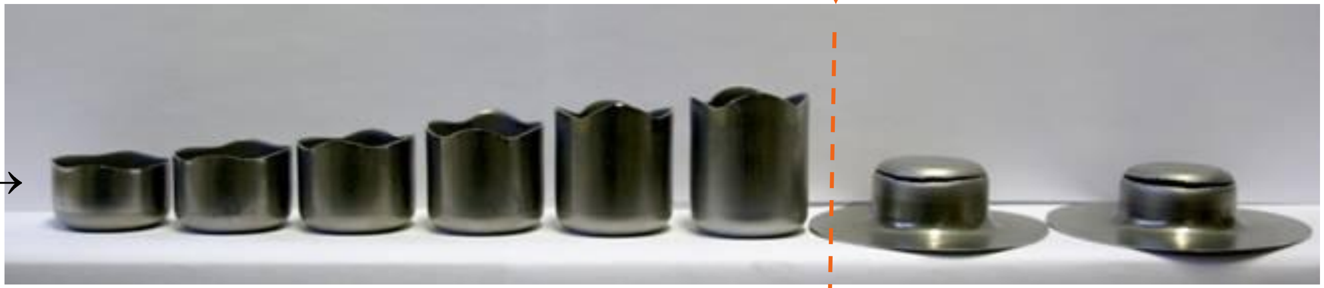
2.3. Deep drawing deformation mode

- For a given tool (d), bigger and bigger blanks are stamped (consequently, taller and taller cups are obtained).
- We are looking for the critical blank diameter (D_{max}) for which the cup is no more stamped successfully. (too many force required → failure)





$$LDR = D_{max} / d$$



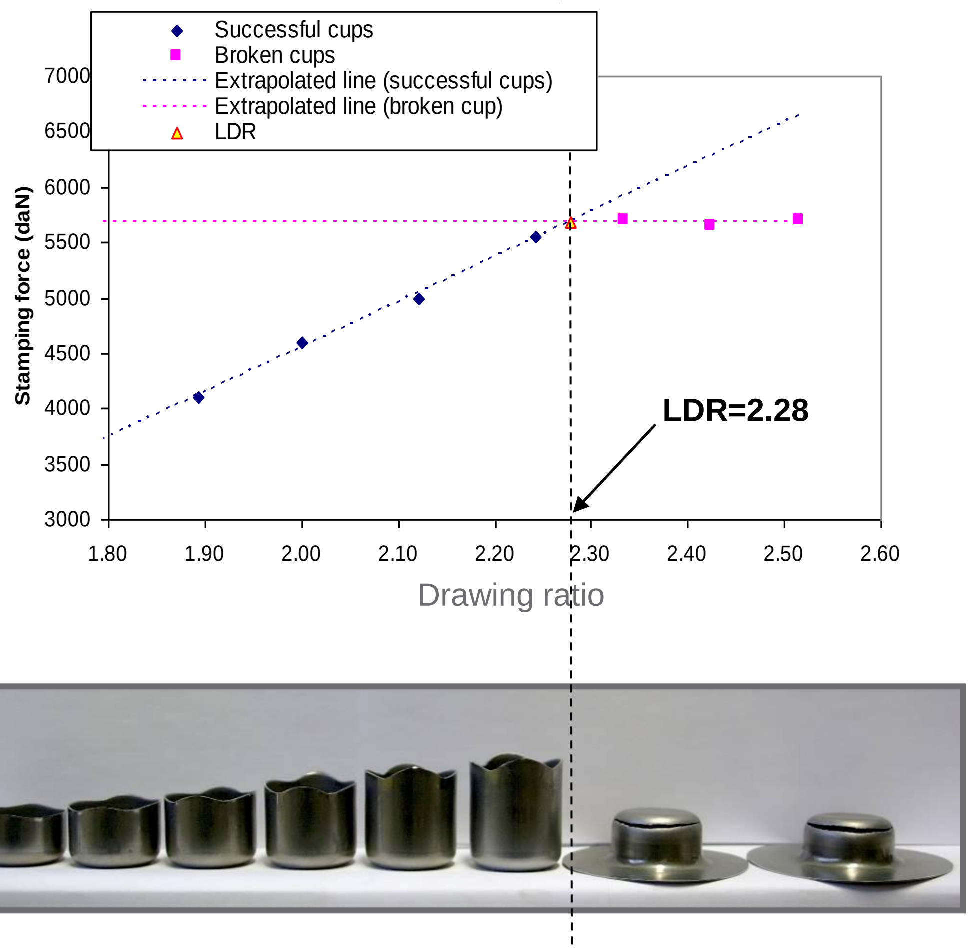
Cup diameter **d** = 33mm →

Blank diameter **D** (mm) →	55	58.5	62.5	66	70	74	77	80
Drawing **R**atio →	1.66	1.77	1.89	2	2.12	2.24	2.33	2.42

Characterization of stainless steels stampability

2.3. Deep drawing deformation mode

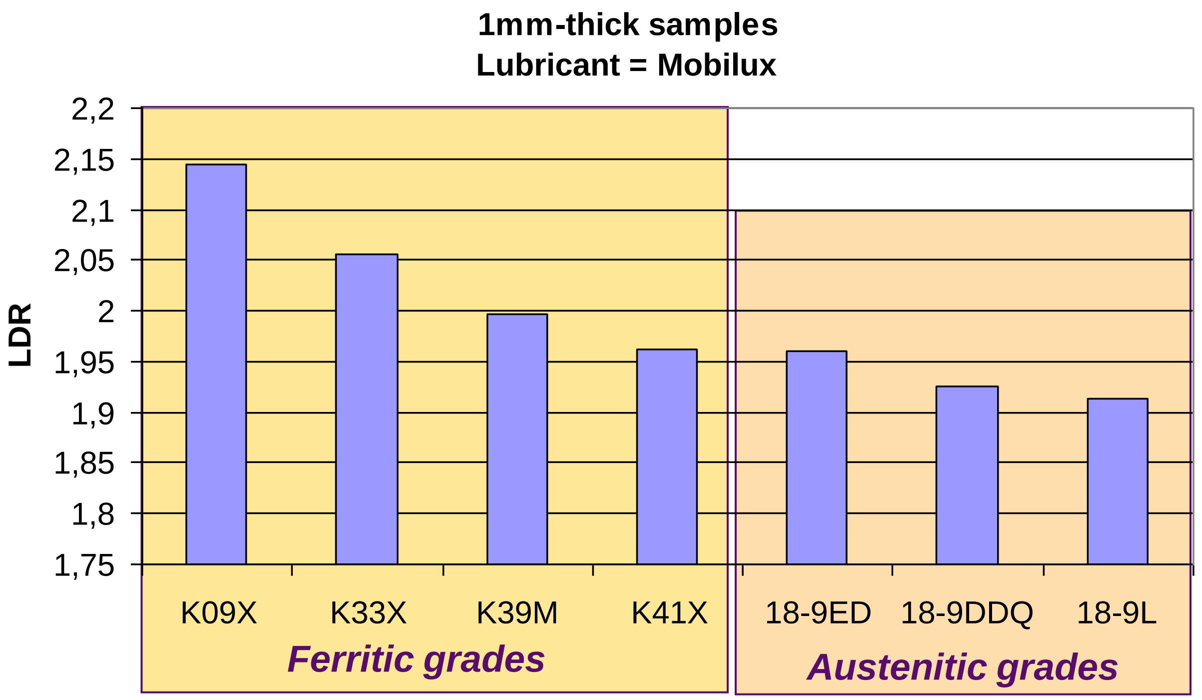
- LDR graphical determination



Characterization of stainless steels stampability

2.3. Deep drawing deformation mode

- Limit Drawing Ratio

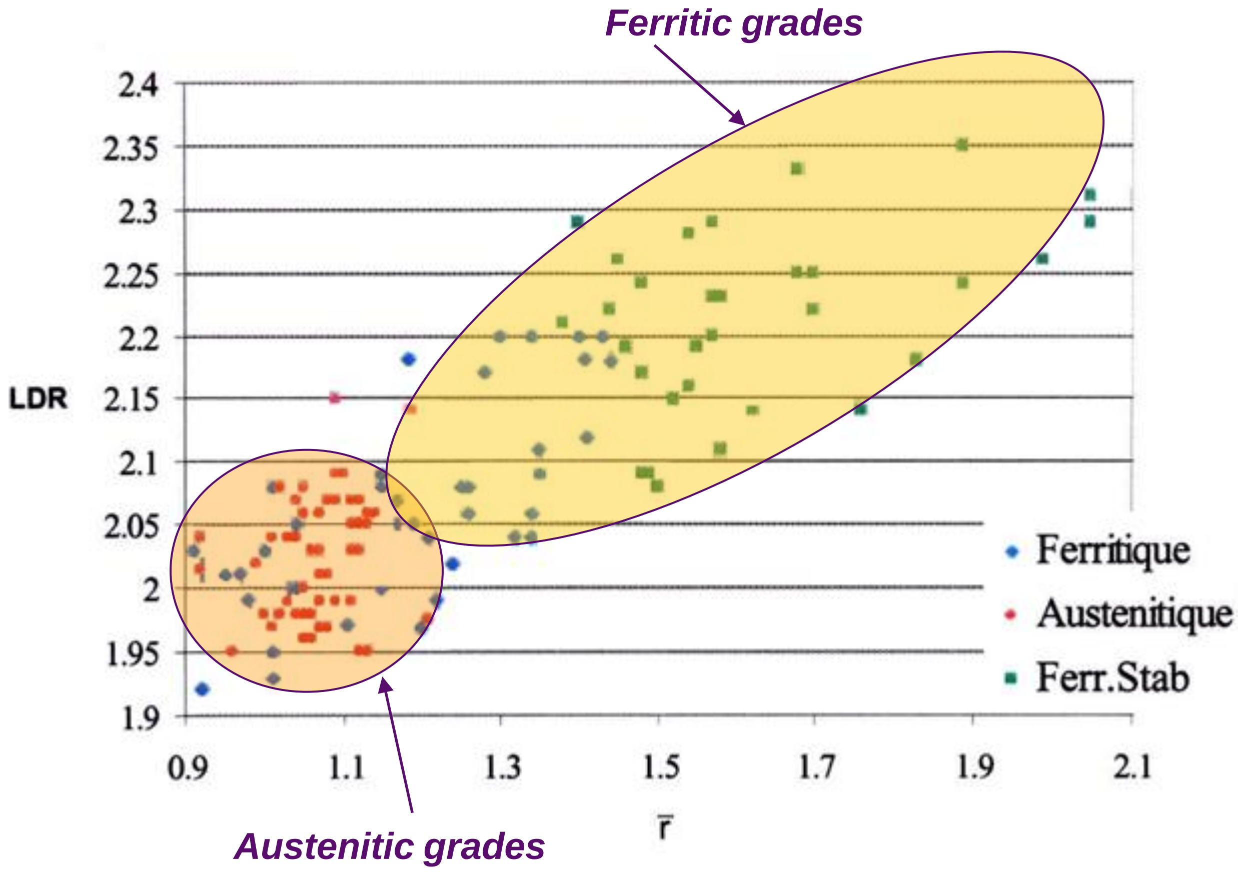


→ Under deep-drawing deformation mode,
ferritic grades are better than the austenitic ones

Characterization of stainless steels stampability

2.3. Deep drawing deformation mode

❖ L.D.R. vs. normal anisotropy



→Thanks to their high anisotropy, ferritic grades are better than austenitic ones under deep-drawing deformation mode

Characterization of stainless steels stampability

2.4. To sum up…

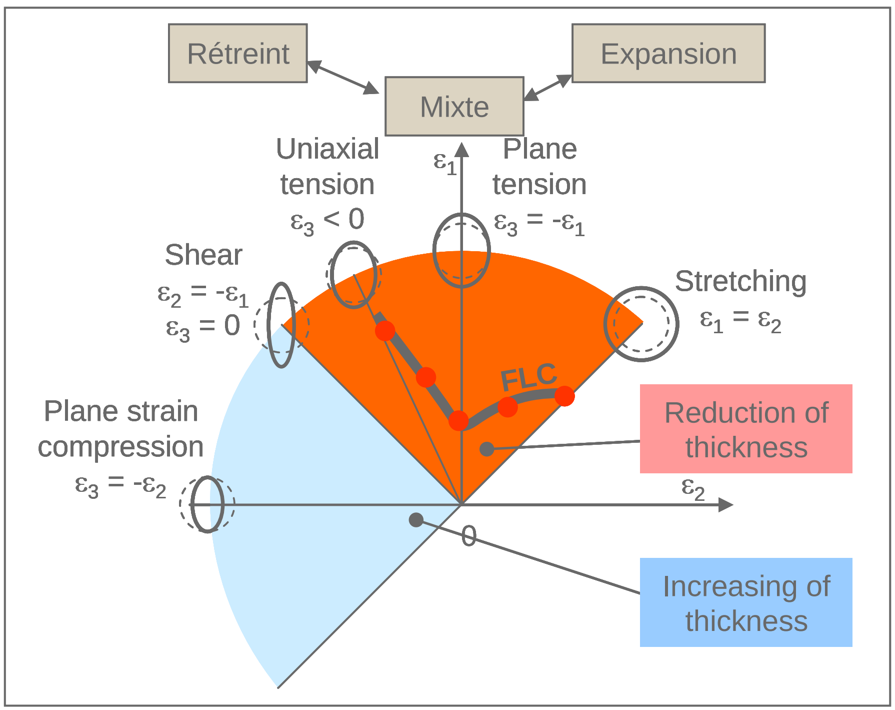
Grade	Stretching deformation mode		Deep drawing deformation mode	
	Hardening Coefficient n	Erichsen (t= 0.8mm)	Anisotropy Coefficient r_N	LDR D_{max}/d
430	0.18	8.7 mm	1.0	2.05 –2.10
430Ti	0.20	9.6 mm	1.8	2.15 – 2.20
444		8.6 mm		
304	0.50	11.5 mm	1.05	1.95 – 2.00
316L		11 mm		

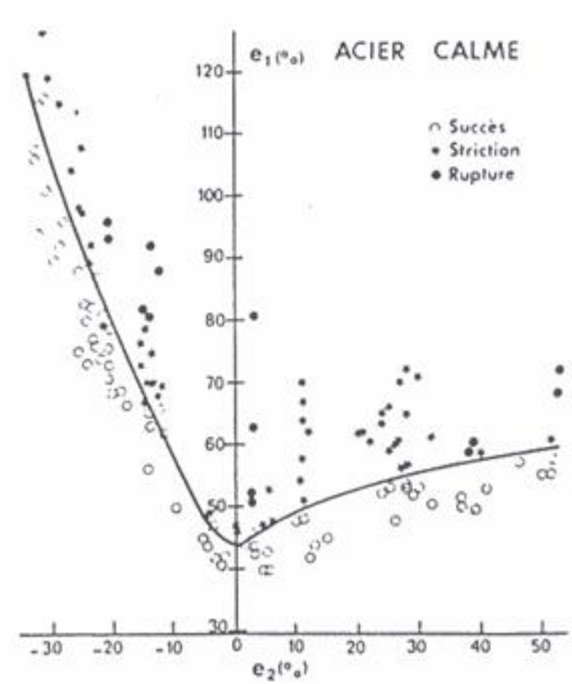
Well adapted to austenitic grades

Well adapted to ferritic grades

2.5. Notion of Forming Limit Curve

- Whatever the kind of solicitations, there is a domain not to go further if necking wants to be avoided
- The FLC is the border of this domain in the deformation plane e1, e2

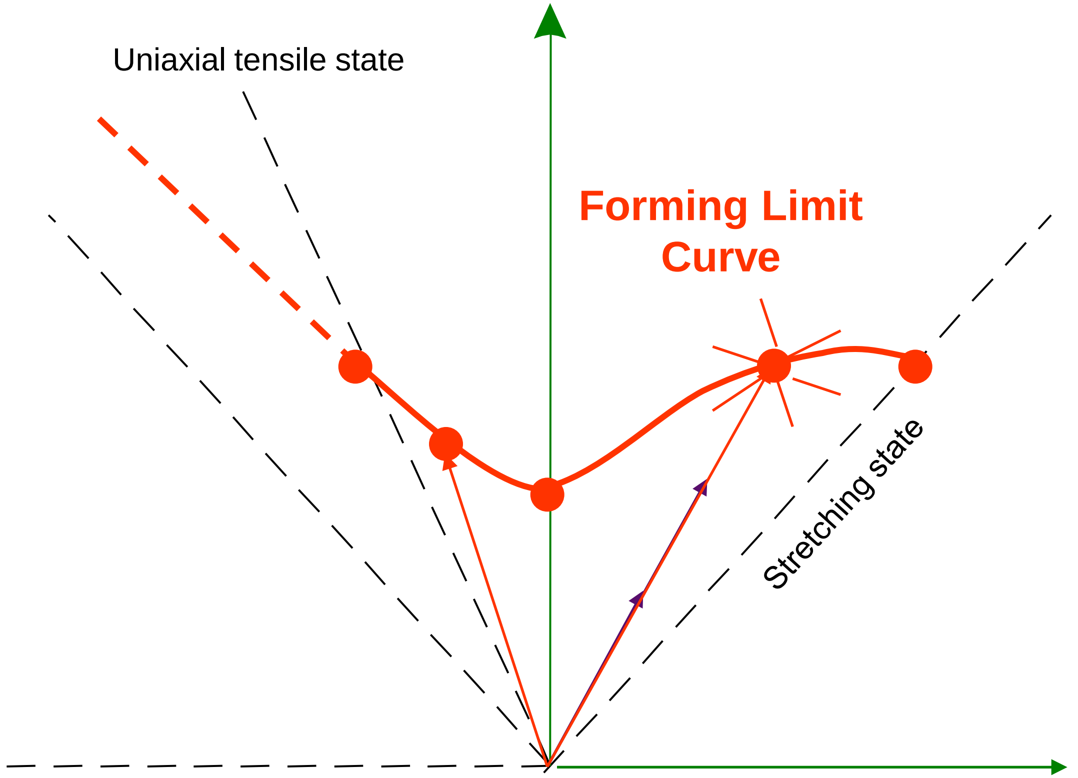




Characterization of stainless steels stampability

2.5. Notion of Forming Limit Curve

- Experimental determination: **Principle**

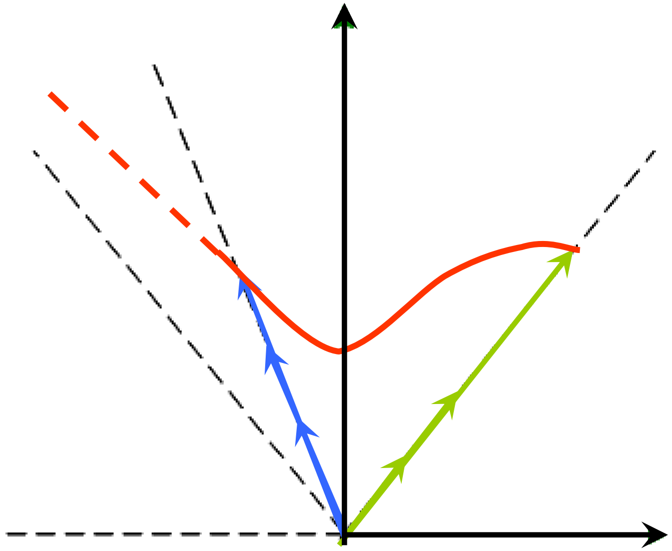


- Use of samples enabling to warranty constant $\varepsilon_1/\varepsilon_2$
- The failure of the sample enables to determine 1 critical value
- The FLC goes through all critical points determined and constitute the boarder of the "safe" domain

Characterization of stainless steels stampability

2.5. Notion of Forming Limit Curve

- Experimental determination: **Nakazima method**
  - Hemispherical punch (100mm), clamped blank (drawbead + blank-holder force=400kN)
  - Blanks with the same length (200mm) but different widths → different $\varepsilon_2/\varepsilon_1$ ratios
  - **Samples with small width : close to uniaxial tension**
  - **Symmetrical blank : equibiaxial tension (=stretching strain state)**



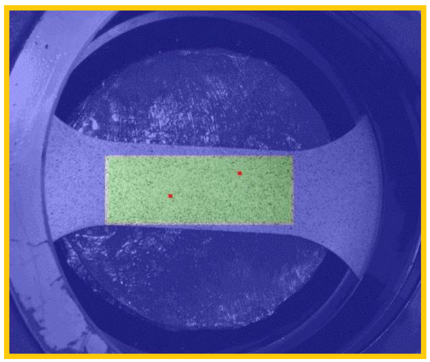
Characterization of stainless steels stampability

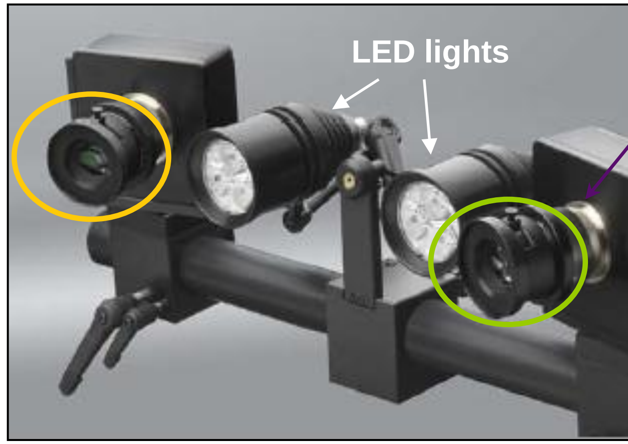
2.5. Notion of Forming Limit Curve - The use of 3D **D**igital **I**mage **C**orrelation (**DIC**)...

ARAMIS System composed of:

- 2 lenses
- 2 LED lights

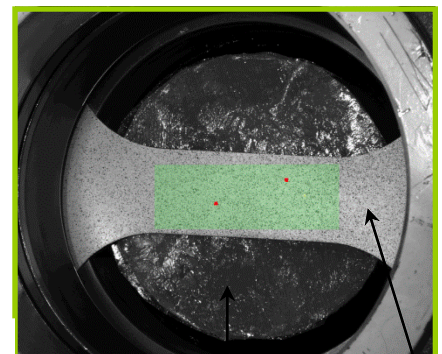
Left lens





Lens

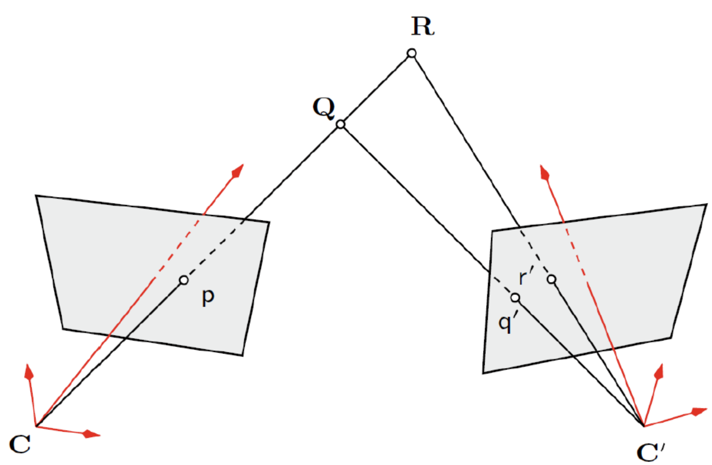
Right lens



Lubricant system

Sample

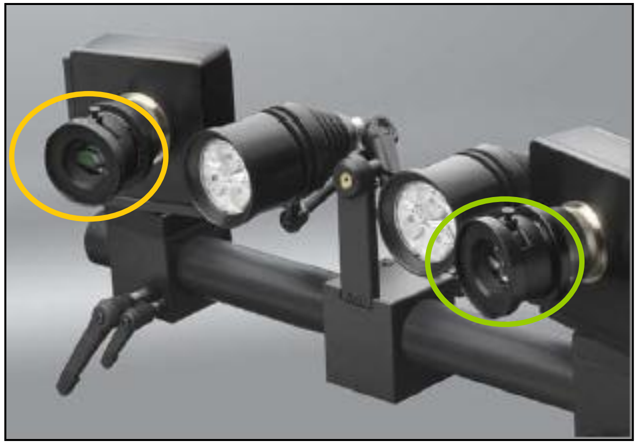
Principle of the 3D DIC



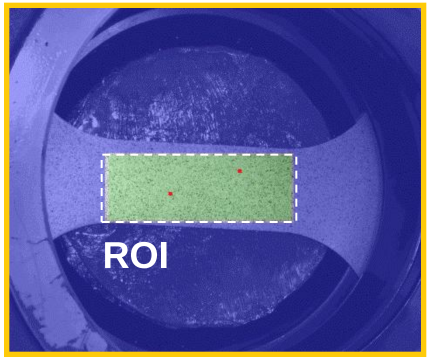
2.5. Notion of Forming Limit Curve - The use of 3D **D**igital **I**mage **C**orrelation (**DIC**)...

ARAMIS System composed of:

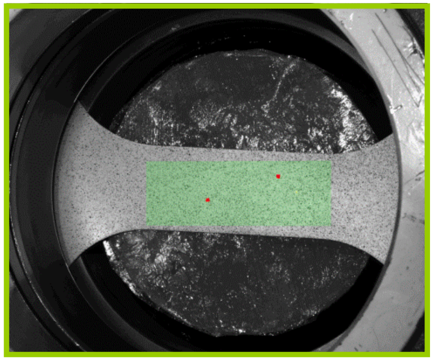
- 2 lenses
- 2 LED lights

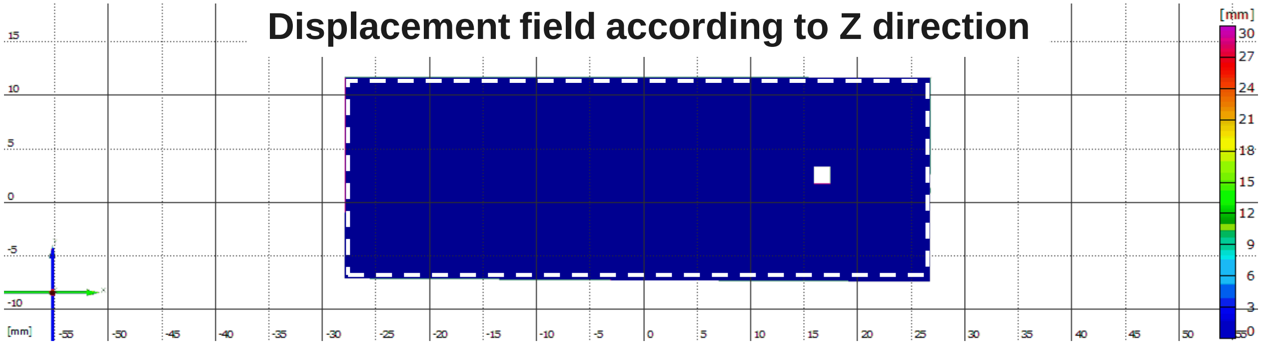


Left lens



Right lens





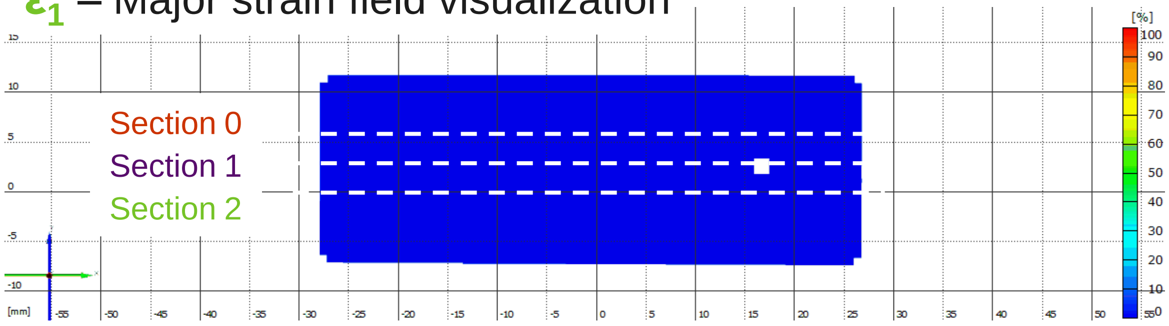
→ Determination of the displacement fields according to the 3 main directions (X, Y & Z)

Characterization of stainless steels stampability

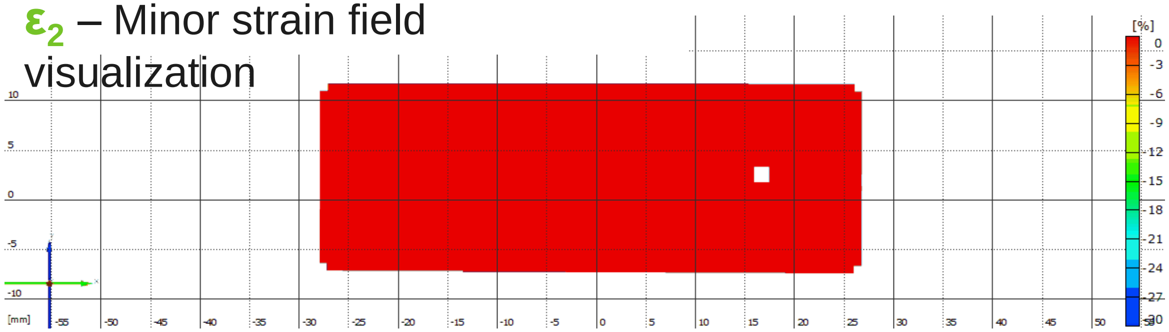
2.5. Notion of Forming Limit Curve - The use of 3D **D**igital **I**mage **C**orrelation (**DIC**)...

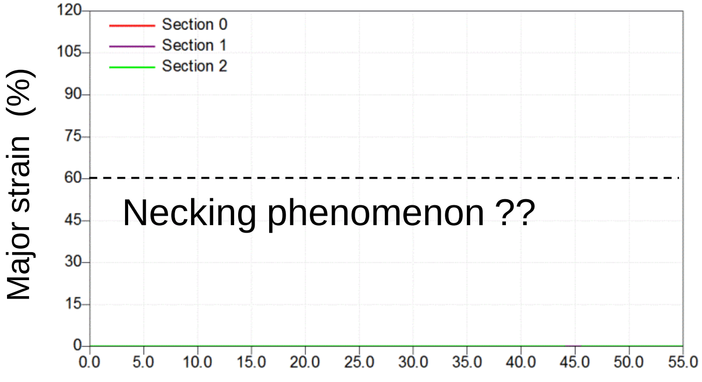
From the determination of the displacement fields → Calculation of the equivalent strain fields

ε_1 – Major strain field visualization



ε_2 – Minor strain field visualization





Determination of the major and minor strains before necking appeared...

→ ARAMIS software was developed to respect the **ISO 12004-2 standard** for the determination of the FLC

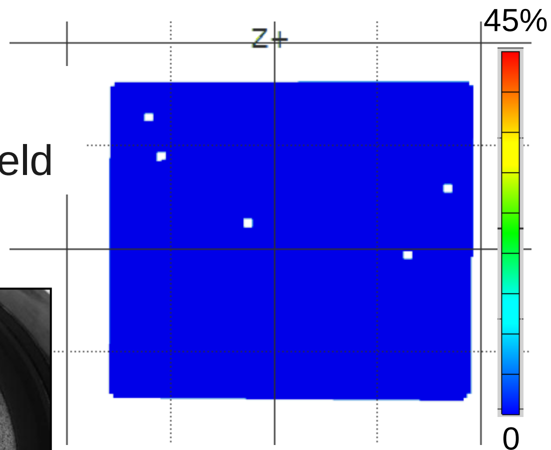
Characterization of stainless steels stampability

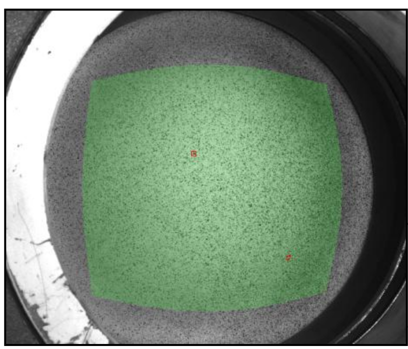
2.5. Notion of Forming Limit Curve - The use of 3D **D**igital **I**mage **C**orrelation (**DIC**)...

This approach is used for each sample and each deformation path...

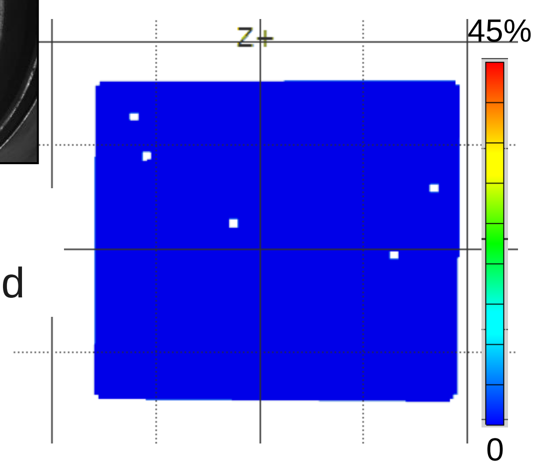
Other example: Sample corresponding to a stretching strain state (200 x 200 mm^2)

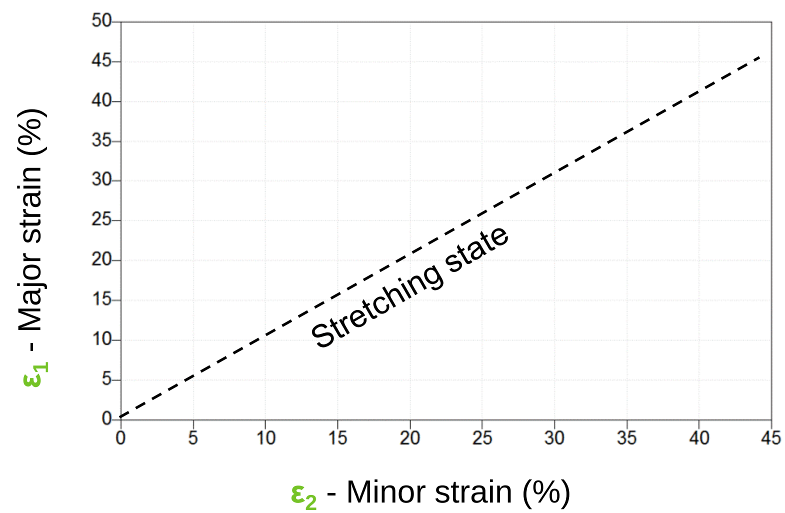
ε_1
Major strain field





ε_2
Minor strain field



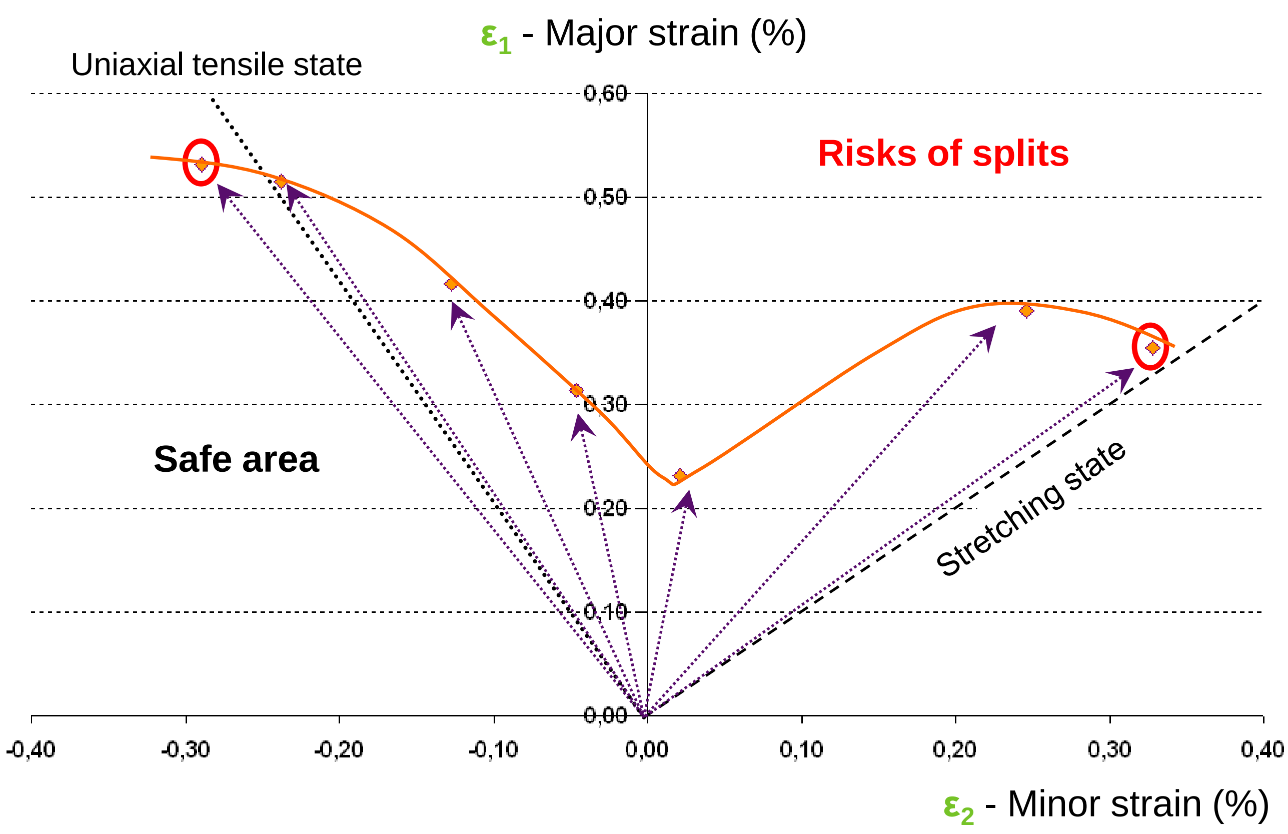


→ Linearity of the deformation path
→ Accurate determination of the strain levels
→ Possibility to follow each step of the deformation path

2.5. Notion of Forming Limit Curve - The use of 3D **D**igital **I**mage **C**orrelation (**DIC**)...

From minimum 7 different samples, it possible to obtain an accurate FLC...

Global FLC curve



2.5. Notion of Forming Limit Curve

❖ Influent material characteristics

- **Hardening coefficient (*n*)**
  - The most significant coefficient
  - An increase of n leads to an increase of the FLC-level
- **Strain rate sensitivity coefficient (*m*)**
  - Similar effect as n, but less significant
  - In the necking area, strain rate increases if m-value is high, which slows down the localization
  - m is inversely dependent with $R_{p0.2}$ (for ferritics) and R_m (for austenitics).
- **Normal anisotropy coefficient (r_N)**
  - Second order effect
  - When r increases, stretching abilities are reduced
- **Thickness (t)**
  - Thicker materials lead to an increase of the FLC-level

2.5. Notion of Forming Limit Curve

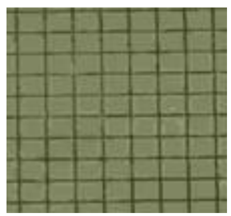
❖ Older experimental method:

Blanking → ***Gridding*** → ***Stamping*** → ***Strain evaluation***

Rectangular blanks

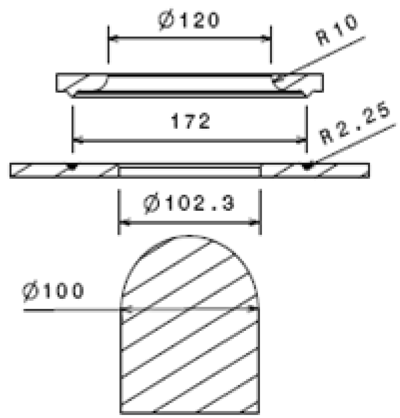
L=210mm,

l = 50 ↔ 210mm



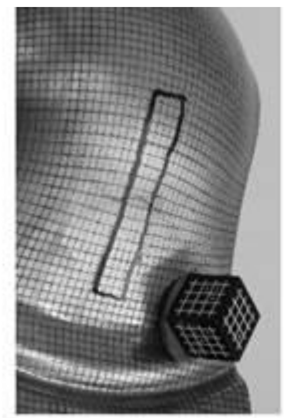
Electrolytic gridding

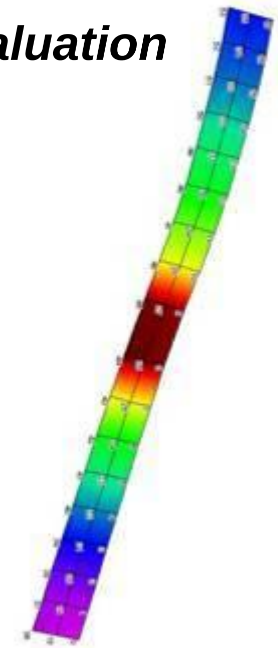
Squares of 2mm



Nakazima stamping

Hemispherical punch





ASAME analysis

3D reconstitution of the sample

→ This technique is still used on complex geometry to appreciate strain level induced by a forming process

Presentation overview

- From tensile test to stamping tests…
- **Influent parameters on stampability and specific stainless characteristics**

    1. Influent parameters

- How to predict the feasibility of stamped parts?
- Analysis of practical cases, stamping of bipolar plate

Influent parameters on stampability and specific stainless characteristics

1. Influent parameters on stampability

Surface finish (roughness, ...) → **Sheet** ← Mechanical characteristics
- ✓ Rheology
- ✓ Metallurgy

Sheet ↓

Blanking ↓

Orientation of the blank under the press → **Blank** ← Cutting burrs and orientations of burrs

Blank ↓

- ✓ Quality and nature of tools (hardness, roughness)
- ✓ **Lubrication conditions**

→ **Forming : bending, stamping (stretching, drawing), ...** ← Blank holder pressure, Stamping rate, ...

Forming ↓

Final part

A good lubricant decreases the friction between the sheet and the blank-holder

- ➢ Less punch force required
- ➢ Higher LDR

How to predict the feasibility of stamped parts ?

Study of Complex designs: Stamping Simulations with AutoForm

- **AutoForm** = software for stamping simulations
- Aims of the software :
  - Evaluate the feasibility of a part
  - Localize the risky areas
- **Input data**:
  - Geometry of the part to stamp (CAD-file type IGS), — DESIGN data
  - True stress/strain curve extrapolated to high deformations
  - Anisotropy coefficients in the 3 directions
  - Forming Limit Curve — MATERIAL data
  - Blank-holder pressure
  - Stamping rate
  - Lubrication coefficient — PROCESS data
- **Output (for all points on the part):**
  - Strain paths, thinning, plastic strain, wrinkles sensitivity, …