An industrial Method for Reducing the Anisotropy Index of Aluminium 1200 Rolled sheets

B. D. Soh Fotsing[#1], M. Fogue[#2], A. Fomethe[*3], G. F. Anago[##4], E. Nguena[**5], Y. Njimkouo[#*6]

[#] “Laboratoire d'Ingénierie des Systèmes Industriels et de l'Environnement” University of Dschang
P.O. Box 134 Bandjoun – Cameroon Tel. +237 99 70 19 09, Fax. +237 33 01 46 01
[1] sohfotsing@aol.fr
[2] medard_fog@yahoo.com
[*] "Laboratoire de Mécanique et de Modélisation des Systèmes Physiques", University of Dschang
P.O. Box 96 Dschang – Cameroon Tel./Fax. +237 33 45 18 81
[3] safomethe@yahoo.fr
[##] “Ecole Polytechnique d'Abomey- Calavi”, Université d’Abomey- Calavi
BP 2009 Cotonou 01 – Benin, Tel. +229 93 60 01 17
[4] ganago@yahoo.fr
**SOCATRAL BP 291, *Edea – Cameroon*
[5] emile.nguena@alcan.com
#* “Ecole Polytechnique de Yaoundé BP 8390 Yaoundé – Cameroun.

***Abstract* –This work proposes a method for the optimisation of the parameters during the rolling of aluminium sheets in order to reduce its anisotropy index that is harmful during aluminium stamping works. The method suggested takes into account the evolution of the anisotropy index of a metal according to the hardening rate before annealing and dependent on the alloy type, the mode of reheating, the ranges of rolling and the conditions of annealing, as well as the variability of the various parameters.**

The results obtained show that the anisotropy index of products was reduced from 8% to less than 4% for aluminium sheets with thicknesses from 1.2 mm to 2.8 mm.

***Index terms* –Anisotropy, aluminium, rolling, stamping.**

I. INTRODUCTION

The anisotropy of aluminium sheets is induced by the rolling process; it involves defects during the operation of parts stamping. During the rolling of aluminium, all the parameters likely to affect the distribution of the insoluble elements in metal and on the deformation of the grains of metal have a considerable effect on the anisotropy. Under large strains, an anisotropic work-hardening occurs in the metallic materials. A number of models are developed to describe the evolution of this work-hardening and to reduce its effects on the microstructure.

In Cameroon, the aluminium ingots and plates produced by Alucam[1] are transformed by Socatral[2] by rolling into aluminium sheets of various thicknesses that is intended for industrial use in the manufacture of various products. The most common industrial manufacturing process is aluminium stamping.

The aptitude for stamping of aluminium sheets depends on several factors among which are factors related to the stamping process itself (play punch-matrix, stamping speed, lubrication, a number of passes etc.) and factors related to the metallurgical, mechanical and physical characteristics which strongly influence manufacturing methods [1], [2].

The rolling of aluminium sheets induces structural anisotropy in the material leading to the appearance of the horns on stamped parts. The anisotropy index of metal is represented by the rate of horns obtained after stamping. The anisotropy defects are most dreaded because they can cause significant rejection of stamped products. At Socatral, anisotropy defects account for an estimated loss of 15% in production and this limits considerably its local and export market possibilities [3].

The object of this paper is to define a methodology for the manufacture of aluminium 1200 sheets with anisotropy index that would be acceptable for aluminium stamping.

The method used is based on statistical analysis (statistical process control) of data banks on the manufacture of aluminium 1200 sheets by Alucam-Socatral Group, a branch of Rio Tinto Alcan, involved in the aluminium production and transformation in Cameroon.

The solution adopted increases the number of horns observed during the stamping process. The impact of each factor on anisotropy is analysed.

The work begins with a theory on aluminium anisotropy within which a state of the art is presented. The second part presents the experimental procedures carried out in order to reduce the anisotropy index of rolled sheets and the third part contains the results obtained after which a discussion is made.

II. THEORY ON ALUMINIUM ANISOTROPY

The starting stock for most rolled products is the DC (Direct Chill semi-continuous cast) ingot. The size of the ingot depends on the size of the DC unit available, the hot rolling mill capacity, the volume required for a particular end use and to some extent the alloys being cast. Ingots up to over 20 tons in weight, 500-600 mm thick, 2000 mm wide and 8000 mm long are produced.

[1] Aluminium du Cameroun, branch of Rio Tinto Alcan
[2] Société Camerounaise de Transformation de l’Aluminium, a company of Alucam-Alcan group

The DC ingot is usually cooled after casting to room temperature and then re-heated to around 500 °C prior to successive passes through a hot rolling mill where it is reduced in thickness to about 4-6 mm.

The strip from the hot rolling mill is coiled for transport to the cold mill which might be on the same site or elsewhere. Cold mills, in a wide range of types and sizes are available; some are single stand, others 3 stands and some 5 stands. Cold rolling speeds vary but modern mills operate at exit speeds as high as 3000 m per minute and alloys may be cold rolled to thickness of around 0.05 mm [1].

These processes introduce anisotropy in the material.

Anisotropic properties can have a major effect on subsequent process stages, especially sheet metal forming processes such as deep drawing and stretch forming, and on in-service performance [4].

Plastic anisotropy results from fundamental mechanisms of deformation of grains in a textured polycrystal. It can present critical problems for certain applications, in particular aluminium stamping [4], [5]. The measurement of anisotropy index can be done by a coefficient defined by the relationship between the rheological response of a sheet to stress according to a given direction and that according to the rolling direction. If the stress is applied at various angles α compared to the rolling direction, the anisotropy of aluminium is characterized by a curve $r(\alpha)$ [2], [14].

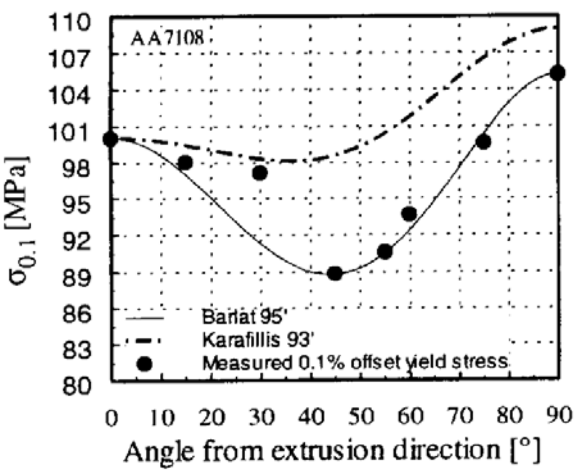


Fig. 1. Yields stress at 0.1% plastic strain for AA7108 alloy from [14]

Many works have been carried out for modelling the plastic anisotropy of aluminium and its evolution during rolling or forming. Some theoretical methods are proposed in order to yield the anisotropy.

Takahashi [5], studies the Plastic anisotropy evolution in aluminium sheets which was investigated experimentally and theoretically. The anisotropy was evaluated by flow stress and r-value of tensile tests in various directions in the sheets. A new rule for lattice rotation was proposed, which is a generalization of the Schmid rule for simple tension of a single crystal. The anisotropy developed by the numerical simulation of rolling showed good agreement with the experiment.

The anisotropy of textured aluminium is approximated by a yield criterion with an exponent of eight is proposed [6]. The effect of anisotropy on the limiting drawing ratio in cupping is less than that expected from the quadratic Hill yield criterion and the effect of texture on forming limit diagrams is negligible.

The development of intergranular stresses between groups of grains possessing certain crystallographic orientations was studied by Alexander M. Korsunsky [7], using diffraction of penetrating radiation. Due to aluminium's highly isotropic elastic modulus, the variation of measured strains in the alloy matrix with orientation can be attributed to the anisotropy of the crystal yield surface and plastic flow parameters.

Mezziane Rabahallah [8] used numerical simulation of sheet metal forming, and more advanced phenomenological functions to model the anisotropic yielding which can be described by an adjustment of the coefficients of the yield function or the strain-rate potential to the polycrystalline yield surface determined using crystal plasticity and X-ray measurements.

The influence of heat-treatment on plastic anisotropy in strength, plastic flow and strain hardening has been investigated by performing tests with three loading directions with respect to the extrusion axis. It is found that the plastic anisotropy is affected by the temper condition, but identical shape of the yield surface can be used for all tempers with reasonable accuracy. The variation in strength and strain hardening with heat-treatment is accounted for calibration of the non-linear isotropic hardening rule [9], [10].

The anisotropy can also observed with the strain-stress curves and the texture of material grains according to the rolling direction.

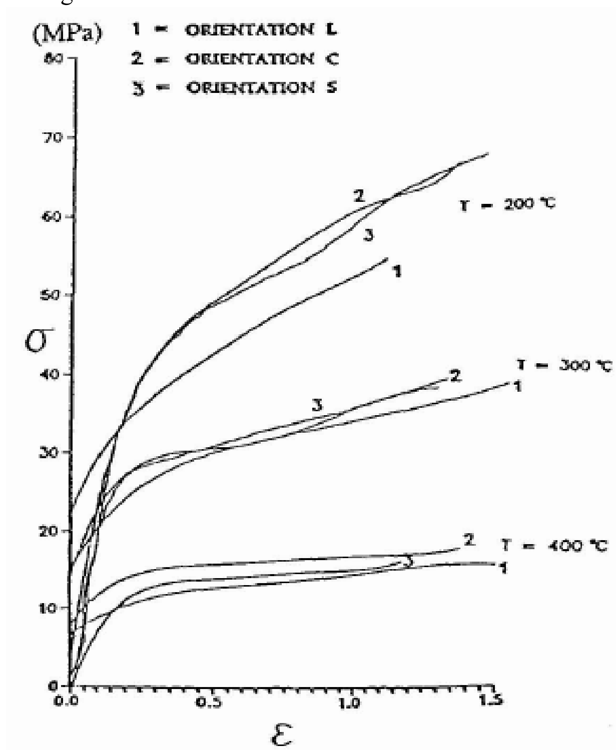
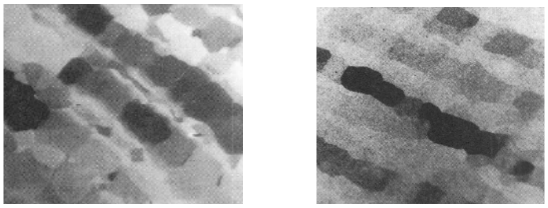


Fig. 2. Curves strain-stress for 3 directions L{112}, C{111} and S{100} at 200, 300 and 400°C [12]



(a) (b)

Fig. 3. Microstructure in the direction S for a strain (a) ε=0.15 and (b) ε=0.97 (400°C, 10^{-1} s^{-1})

The anisotropy of the plastic flow in the plan of the sheet leads to the formation of very awkward stamping horns for the manufacturer.

The anisotropy can be seen from the earing profile of a stamped cup and the anisotropy index I_S or the rate of horn formation is given by the following expression:

$$I_s = \frac{\sum_{i=1}^{i=n} H_i - \sum_{i=1}^{i=n} h_i}{nH_m} \quad (1)$$

with

$$H_m = \frac{\sum_{i=1}^{i=n} H_i + \sum_{i=1}^{i=n} h_i}{2n} \quad (2)$$

where n is the number of horns, H_i is the height of i-th horn and h_i is the height of the hollow between horns (Fig. 4).

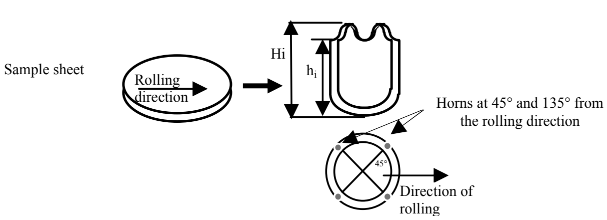


Fig. 4. Cup of anisotropy measurement

The height of horns can be predicted by the use of finite element models and compared against experimental results [15]. This profile is due to the plastic strain rate which is gives by:

$$\dot{\Gamma} = \sqrt{1 + (-q_{UT})^2 + (q_{UT} - 1)^2}\,\dot{\varepsilon}_{11}^P Q_{UT} = y\dot{\varepsilon}_{11}^P \quad (3)$$

Where, Q_{UT} and q_{UT} are respectively the value of the series expansion and the contraction ratio between the width and length plastic strains, corresponding to uniaxial tension.

For an uniaxial stress state, the general isotropic hardening law is given by

$$\sigma_{11} = k(\varepsilon_0^P + \varepsilon_{11}^P)^n \quad (4)$$

Where σ_{11} and ε_{11}^p are respectively the uniaxial stress and plastic strain during uniaxial tensile test. The parameters k, ε_0^p and n are reference stress, offset plastic strain and hardening exponent. The Von-Iso model [15] of this law is given by

$$\tau = k'(\Gamma_0 + \Gamma)^n \quad (5)$$

Where Γ is the plastic strain.

Assuming that the internally dissipated frictional work rate over the polycrystalline material is as

$$\dot{W}_i = \tau\dot{\varepsilon}^p Q(A) = \tau\dot{\Gamma} \quad (6)$$

With (4) and (5), it gives

$$k(\varepsilon_0^P + \varepsilon_{11}^P)^n \dot{\varepsilon}_{11}^p = k'(\Gamma_0 + \Gamma)^n \dot{\Gamma} \quad (7)$$

Then, the plastic hardening modulus associated with the isotropic hardening at time ti, Hi can be derived,

$$H_i = \frac{\partial \tau_i}{\partial \Gamma_i} \quad (8)$$

The figure below shows the profile of the test cup at different directions to the rolling direction.

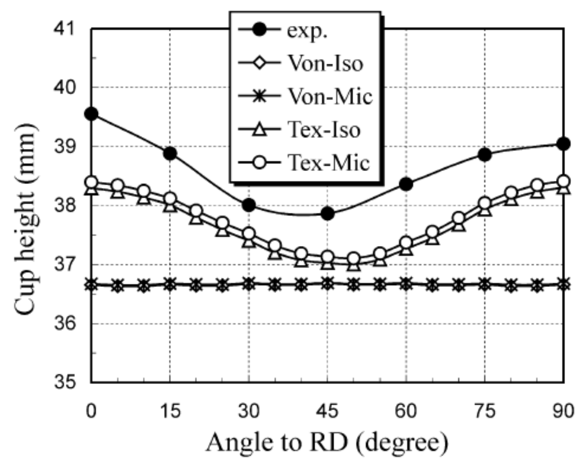


Fig. 5. Cup profile according to the angle to rolling direction [15]

From these models, the computed values of Is are shown in the table below.

Table I

ANISOTROPY INDEX FOR THE MODELS IN LITERATURE

	Experimental	Von-Iso	Von-Mic	Tex-Iso	Tex-Mic
Is (%)	3.76	0	0	3.19	3.17

The principal parameters that influence the anisotropy of aluminium are [3]:

- The mode of stream of plates
- The speed of cooling during the stream of plates at the foundry
- The format of plates
- The chemical composition of plates
  - Iron and silicon rate
  - Iron/Silicon ratio
- The heat treatment
  - Temperature of reheating of plates

  - Duration of reheating of plates
  - Intermediate annealing process
- The conditions of plastic deformations
  - Initial temperature of hot rolling
  - Final temperature of hot rolling
  - Final thickness of hot rolling
  - Rate of cold working (final thickness)

An analysis of the influence of these various parameters on the anisotropy of the metal produced metal at Socatral, made it possible to identify the most significant parameters (Table II) [3].

Table II
ANISOTROPY PARAMETERS OF ALUMINIUM 1200

Parameters	**Horns at 0° and 90**	**Horns at 45° and 135°**
Mode of plate casting	■	
Reheating temp.>550°		■
Reheating duration > 20h		■
Reheating temp.<550°	■	
Reheating duration < 20h	■	
Final temperature >400°	■	
Final temperature <300°		■
Final thickness > 12 mm	■	
Final thickness < 12 mm		■
Intermediate annealing	■	
Final Thickness < 1.2 mm		■
Final Thickness > 1.2 mm	■	
Iron/Silicon ratio	No influence observed	

After rolling, some treatment can modify the anisotropy index, such as annealing. But annealing may change the anisotropy of tensile properties. The softening rate can go up to 82% cold work. The chart below (Fig. 6) shows the effect of annealing at different temperatures. In the as-rolled condition, the transverse direction is the strongest and 45 degrees to the rolling direction is the weakest. On annealing at 280 and 300 °C the anisotropy is unchanged but annealing at 340 °C affects anisotropy [2].

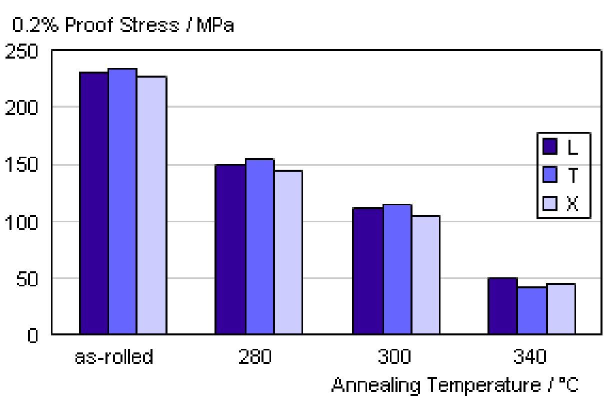


Fig. 6. Effect of annealing on anisotropy

III. EXPERIMENTAL PROCEDURES

A. Objective

The purpose of the tests is to define a disc manufacturing method that guarantees anisotropy that is acceptable to customers of Socatral (rate of horns lower than 6% for sheets of all thickness). This manufacturing method must simultaneously cause the appearance of 4 horns at 90° and 4 horns at 45°.

The presence of this mixed texture increases the number of horns and decreases the differences between the average height of the hollows and that of the tops, resulting in a reduction in the rate of horns I_S .

B. Methodology

The rolling process uses a rolling machine as shown in figure below. The thickness of the sheets is obtained by controlling the distance between the rollers. J. L. Estival and A. Huguel [11] propose a program to regulate the thickness of sheets which take in account the inlet and outlet thicknesses, the rolling speed and the rolling pressure.

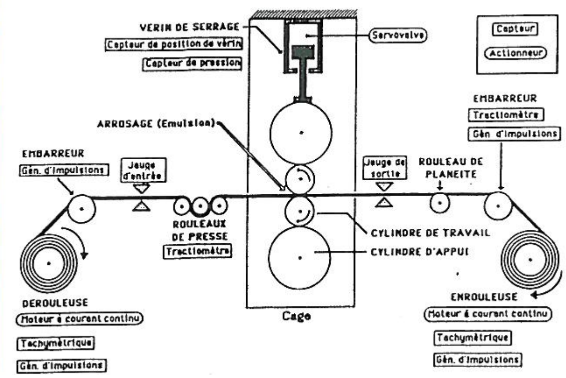


Fig. 7. Rolling mill machine

Sheets with thickness greater than 1.2 mm show a rate of anisotropy higher than 6% whereas those with thickness lower than 1.2 mm show a rate of anisotropy lower than 6%.

At Socatral, parameters that encourage the appearance of the horns at 90° dominate those that cause the appearance of the horns at 45°.

To attain the objective of this paper, the possibility of increasing the effects of the parameters that encourage the appearance of horns at 45° and of decreasing the effects of the parameters that encourage the appearance of the horns at 90° will be considered.

This corresponds respectively to an increase in the rate of cold hardening, the time of reheating and the iron content by reducing the silicon content simultaneously reducing the final temperature of the rolling and intermediate annealing processes.

Three actions are thus recommended:

1. Determining a mode for reheating of the plates which will allow good homogenisation and good conditions for hot rolling.
2. Determining a range of hot rolling that would encourage the beginning of cold hardening during hot rolling.
3. Stopping the intermediate annealing process

C. Tests schedule

The reduction in the final temperature of hot rolling (temperatures in the range 330-380°C) can consist of a reduction in the rate of welding and the initial temperature hot rolling or an increase in the time of rolling.

Priority is placed on plates intended for the manufacture of the discs with large thicknesses greater than 1.4 mm with initial thickness of 380 mm.

Table III
ROLLING PARAMETERS

Temperature of the zones	Maintained temperature	Duration of reheating	Initial temperature	Rolling passes
570°C	560°C	18 and 20hrs	530-545°C	Pass=20 Pass=25

Three ranges of hot rolling are envisaged through the rolling mill: 15 mm, 20 mm and 25 mm passes (Table IV).

Table IV
RANGES APPLIED FOR HOT ROLLING

	Pass of 15 mm	Pass of 20 mm	Pass of 25 mm
Initial Thickness	380	380	380
Final Thickness	10	10	10
Number of passes	25	19	16
Final temperature	320-340°C	370-400°C	400- 420°C

D. Measurements

From metal sheets of draft thickness 10 mm, rolling with hot roll gives marketable sheets with thicknesses in the range 0.5-2.8 mm.

Measurements were carried out on sheets with thicknesses 1.4 mm, 1.6 mm, 1.8 mm, and 2 mm on 48 plates with 4 plates per rolling range for each final thickness of sheet obtained. For each plate, 5 measurements were carried out and the value of the rate of horns retained is the average of the measured rates of horns (Fig. 8).

From these tests, it is observed that the rate of horns decreases with the final temperature of hot rolling and that two types of horns appear at low final temperatures of rolling.

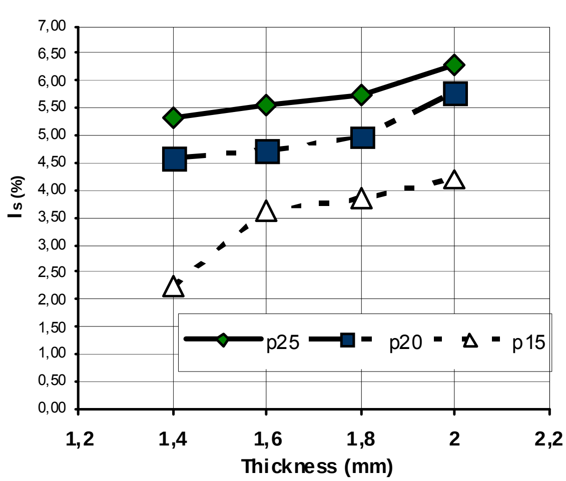


Fig. 8: Influence of hot rolling range

IV. RESULTS

The manufacturing range suggested integrates two factors: the mode of reheating and the final temperature of rolling. An initial temperature of rolling will be sought which allows for:

- a reduction in the number of rolling passes as well as duration of hot rolling;
- a reduction in the final temperature of rolling at about 330°c (last temperature of re-crystallization).

A. Mode of reheating

The principle requires the homogenization of the plates and the reduction of the temperature of reheating of plates in order to have an initial temperature at the beginning of each hot rolling that oscillates between 540-550°C

Order of reheating of the plates:

First stage

- Temperature for indexing of zones: 560°C
- Duration period 14 hours

Second stage after 14 Hours

- New indexing of the furnace: 520°C
- Duration period 2 hours

B. Hot rolling

In order to maintain maximum rolling pressure of 200 bars for all rolling passes of rolling, a variable range of passes was adopted with a high number of passes at the beginning and a low number of passes at the end of hot rolling. By taking into account the initial temperature of hot rolling (540-550°C) the hot rolling range was improved by decreasing the number of passes. They comprise 23 rolling passes distributed as follows: 360 - 340 - 320 - 300 - 280 - 260 - 240 - 220 - 200 - 185 - 170 - 155 - 140 - 125 - 110 - 95 - 95 - 80 - 65 - 55 - 45 - 35 - 25 - 15 - 10.

The objective of this range is to make it possible to obtain band temperatures between 300°C and 340°C at the end of hot rolling.

C. Measurements

Measurements were taken on a series of sheets with thickness varying between 0.5 mm and 2.8 mm. For each plate, 5 measurements were carried out and the maximum and minimal values of the rate of horns were recorded (Fig. 9).

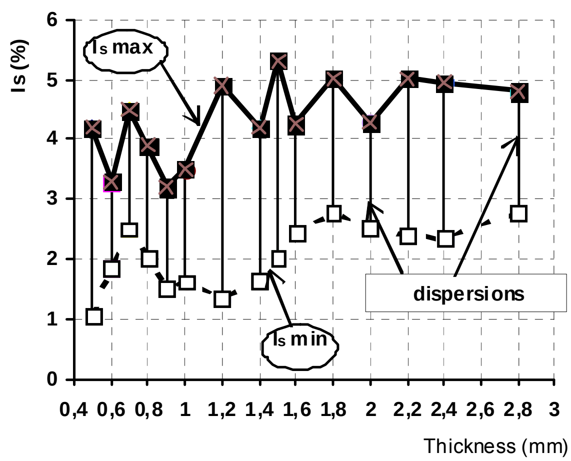


Fig. 9. Rate of horns according to the final thickness.

A clear improvement in the rates of horns is observed in Fig. 9, since the maximum values for the rate of horns are lower than 6.00%.

These modes of reheating and hot rolling encourage the high prevalence of a mixed texture strong prevalence of a mixed texture (horns at 45° and 90°). At low thicknesses (0.5 – 0.60 mm) the exclusive presence of horns at 45° is distinguished in some cases. This phenomenon is explained by the prevalence of effects that encourage the appearance of the horns at 45° for example reheating, cold rolling (high rate of cold working), hot rolling which brings a supplement of cold working.

D. Mechanical properties

With each thickness, we carry out tension tests in direction 0°, 45°, and 90° for various thicknesses at 0.1% of plastic strain.

Table V
YIELDS STRESS IN TENSION FOR DIRECTIONS 0°, 45°, AND 90°

Thickness (mm)	0° σ_m (MPa)	45° σ_m (MPa)	90° σ_m (MPa)
0.5	60,00	59,70	59,82
1.4	60,18	59,67	59,73
2.8	60,07	59,66	59,73

From this table, the figures below show that the procedure suggested assume a significant reduction of the anisotropy on the aluminium 1200 rolled sheets. The yields stress varies between 59.6 MPa to 60.1 MPa from 0° to 90° to the rolling direction.

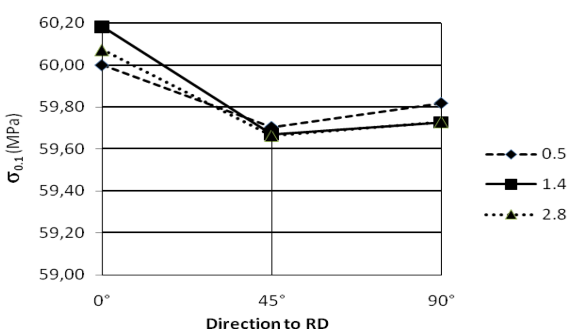


Fig. 10. Yield stress at 0.1% of plastic strain for the proposed procedure

V. DISCUSSIONS

A. Dispersions on a disc

On a disc of thickness and diameter respectively of 1.4 mm and 720 mm from Band Number: E8 – 10712, 30 tests of stamping were carried out with 30 measurements. The results obtained are shown in Table VI.

Table VI
MEASUREMENTS OF THE RATES OF HORNS ON A DISC

	1	2	3	4	5	6	7	8
Is	3.2	2.87	2.74	3.06	2.87	2.43	2.80	2.78
	9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Is	2.98	2.72	2.91	2.64	2.63	2.55	2.53	2.70
	17	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Is	2.90	2.27	2.65	2.99	3.02	2.50	2.77	2.62
	25	**26**	**27**	**28**	**29**	**30**		
Is	2.46	2.52	3.02	2.55	2.64	2.44		

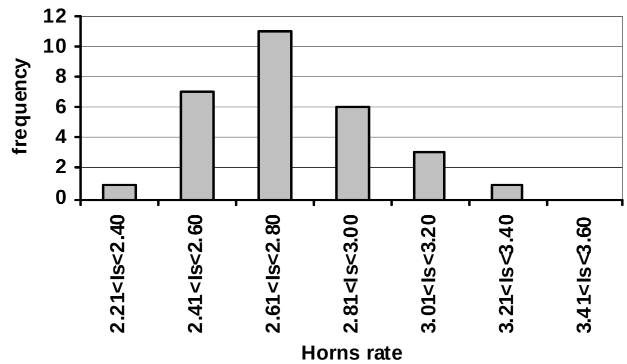


Fig. 11. Distribution of results obtained on aluminium 1200 disc

The statistical evaluation of these measurements (Fig. 11) provides the following characteristic values:

Mean Is = 2.73%
Minimum Is = 2.27%
Maximum Is = 3.29%
Standard deviation = 0.23

The variations of the rate of horns on the same disc are about 1%.

The values obtained with the former procedure varied between 4% and 8% [3]. This shows that the new procedure yields the anisotropy of sheets.

B. Capability of the method

The reproducibility of the proposed method within a period (Fig. 6 and Fig. 7), on the production of aluminium 1200 was observed (Table VII).

Table VII
RECORD OF MEASUREMENTS IN TESTS ON ALUMINIUM 1200

Thickness (mm)	Is mini (%)	Is mean (%)	Is maxi (%)	Number of tests
0.5	0.50	2.02	4.20	122
0.6	1.85	3.45	4.30	150
0.7	2.51	3.40	4.50	110
0.8	2.5	2.88	4.20	80
0.9	1.50	3.20	3.67	50
1.0	1.52	2.73	4.50	150
1.2	1.24	3.82	4.90	126
1.3	1.54	3.6	4.2	110

1.4	2.67	4.2	5.02	90
1.6	2.50	3.97	4.80	124
1.8	2.26	4.22	5.22	100
2	2.52	3.86	4.70	58
2.2	2.58	4.21	5.21	40
2.4	2.34	3.29	4.98	32
2.8	2.61	2.88	4.87	8

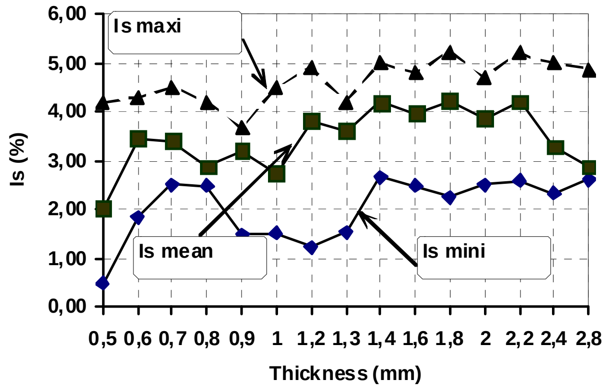


Fig. 12. Variation of the rate of horns in a production period

C. Remarks

Hot rolling is the principal method used in the regulation of the isotropy of metal at Socatral. In order to attain very low rates of horns less than or equal to 4.00% in discs of all thicknesses, the roller will have to follow the same range of passes for rolling as described previously but with a modification on the rolling speed level of the two last rolling passes. The roller must:

1. Find at the end of rolling a temperature ranging between 320°C and 350°C for plates intended for the manufacture of discs with thickness lower than 1.2mm at a speed of 80 m/mn.
2. Find at the end of rolling a temperature ranging between 300°C and 330°C for plates intended for the manufacture of discs with thickness in the range 1.2-1.8mm at a speed of 50 m/mn.
3. Find at the end of rolling a temperature that oscillates around 300°C and 350°C for plates intended for the manufacture of discs with thickness greater than 1.2 mm at a speed of 31 m/mn.

The relative curves obtained are shown in Fig.13.

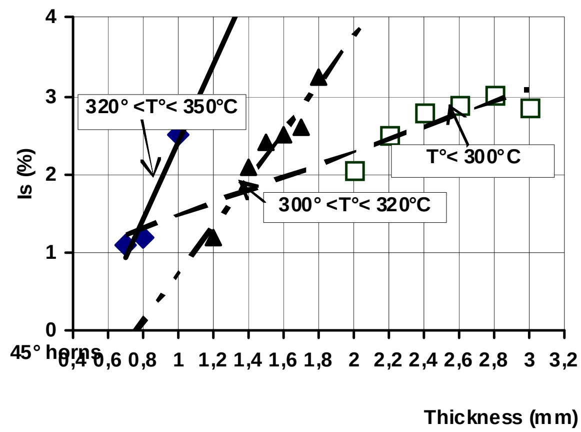


Fig. 13. Rate of horns (mean value) as a function of the final hot rolling temperature of homogenized plates at 560°C during 14 hours and rolled between 552°C and 535°C

VI. Conclusions

An industrial method is proposed in this work in order to reduce the anisotropy index of rolling sheets of aluminium 1200 produced in Cameroon by Alucam-Socatral Group.

This method is based on statistical analysis (statistical process control) of data banks on the manufacture of aluminium 1200 sheets. The solution adopted decreases the rate of horns observed during the stamping process. The impact of each factor on anisotropy is analysed.

The results obtained show that the anisotropy index of Socatral products was reduced from 8% to less than 4% for aluminium sheets with thicknesses greater than 1.2 mm. Products with thickness in this range which account for about 80% of the production are more attractive to the customers.

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