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STATISTICAL ANALYSIS OF SHEET STEEL FLATNESS AFTER THE INSERTION OF CENTRE BUCKLES

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Abstract. *Buckles-free flatness is an essential requirement for sheet steels applied to long panels of white goods, which also demands for low thickness and relatively high strength. Batch annealed cold rolled steels represent an option within this market, although due to some natural limitations of the production processes, meeting the flatness requirements are much of a challenge, mainly due to the occurrence of quarter buckles. This article addresses the correction of quarter buckles and the overall flatness improvement of an ABNT NBR 5915 batch annealed steel ranging from 0.50 to 0.60 mm in thickness and 1,100 to 1,550 mm in width, for application in refrigerator cabinets. The selected technique involved the introduction of steady and controlled center buckles of around 30 i-units into the coils during cold rolling, and its correction during skin pass within a single stand temper mill. A set of ten coils produced according to this method were evaluated and their flatness results were statistically compared to the production records. Test results demonstrated that the insertion of center buckles into the cold rolled strip was effective to eliminate the quarter buckles but the overall sheet flatness did not experience statistically significant improvement.*

Keywords: *Flatness, Plastic instability, Quarter buckles, Sheet steel, Cold rolling.*

1. INTRODUCTION

The cold mill deforms metal strips in the rolling direction, thus can add shape defects. Mill stands fix the lack of flatness by correcting center buckles, wavy edges and, with limited actuators, quarter-buckles. Buckles can be understood as length increments throughout the fibers of the material, with a corresponding reduction in the local thickness. Figure 1 shows a strip with occurrence of quarter buckles and its representation, where (L_0) is the straight length of a flat sheet fiber, ($L_0 + \Delta L$) is the deformed fiber wavelength and (F) represents the wave´s amplitude.
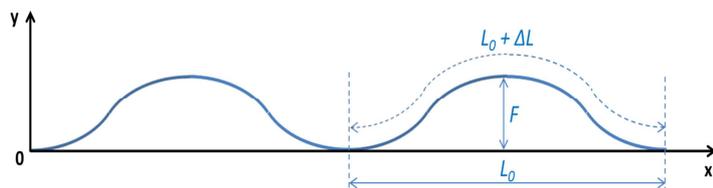

Figure 1. Quarter buckles in steel strip and its representation. Adapted SMS-DEMAG (2003)

Buckles can be represented by a non-linear sinusoidal modified model (SMS-DEMAG, 2003) where the relative elongation ($\Delta L/L$) can be calculated by the Eq. (1).

$$\frac{\Delta L}{L} = \left(\frac{\pi}{2}\frac{F}{L}\right)^2 \tag{1}$$

Flatness can be achieved by multiplying the relative elongation by 10^5 as in Eq. (2) (Theis and Hazen, 2009).

$$\text{i-units} = \left(\frac{\Delta L}{L}\right) \cdot 10^5 \tag{2}$$

A shapemeter roll is a device that estimates the flatness of a strip, transforming tensioned and loosened areas of the strip width into i-units measures. A flat strip profile is achieved when the measure approaches to zero i-units. The bigger this measure, more wavy gets the strip. Cold rolled products of about 15 i-units are quite acceptable. Finished products require smaller figures.

2. EXPERIMENTAL PROCEDURE

The experiment aims to eliminate quarter-buckles by inserting controlled central buckles to exceed the quarter-buckle peaks during the cold rolling process and fix this lack of flatness at the Temper Mill by applying ordinary techniques and actuators. Figure 2 shows the difference between these strip profiles at the exit of the cold rolling mill.
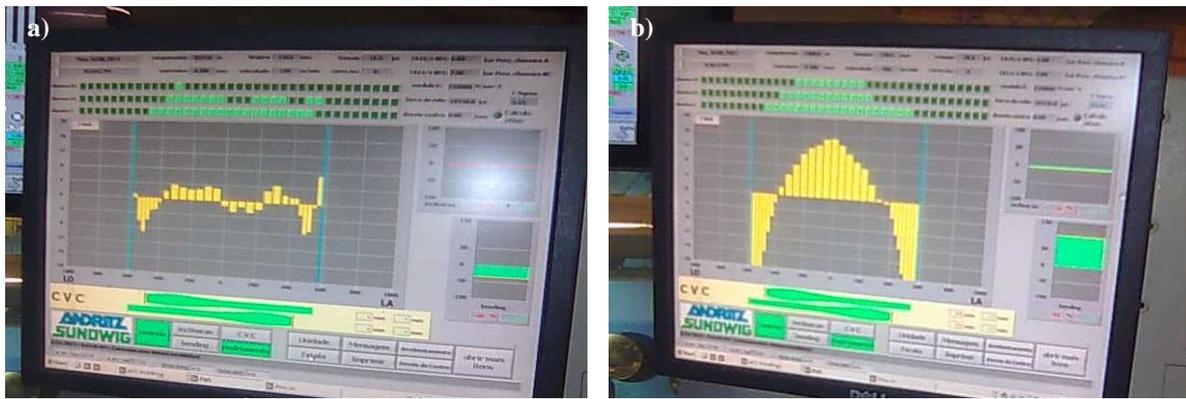

Figure 2. Strip profiles. (a) Almost flat with quarter-buckles peaks, (b) Heavy center buckles free of quarter buckles´ peaks.

The original production flow and main process parameters were kept unchanged, except the cold mill flatness profile that received an increment of at least 15 i-units as shown in Tab. 1. All coils were batch annealed and skin passed at the same batch annealing and temper mill shops, according to the same process recipes and parameters. The final flatness measurements were performed at an inspection line over a standstill strip. A set of 10 coils generated 90 data that were statistically compared to the production records of 441 data.

Table 1. Flatness outcoming the cold mill.

Historic Average (i-units)	Experimental Average (i-units)
≤ 15	≥ 30

For the evaluation of the experimental results and comparison with the historical batch, Minitab version 16 was adopted. A confidence interval of 95% was set, and the hypothesis tests were formulated according to the Tab. 2.

Table 2. Statistics for the Flatness Evaluation (Montgomery and Runger, 2012).

Parameter	Hypothesis	Statistic Test	Δ
1) Average flatness at the Cold Mill exit	$H_0: \mu_{hist} - \mu_{exp} = \Delta$ $H_1: \mu_{hist} - \mu_{exp} \neq \Delta$	$z_0 = \dfrac{\bar{x}_1 - \bar{x}_2 - \Delta}{\sqrt{\left(\dfrac{\sigma_1^2}{n_1} + \dfrac{\sigma_2^2}{n_2}\right)}}$	−15
2) Average wave amplitude at the inspection line	$H_0: \mu_{hist} - \mu_{exp} = 0$ $H_1: \mu_{hist} - \mu_{exp} > 0$	$z_0 = \dfrac{\bar{x}_1 - \bar{x}_2 - \Delta}{\sqrt{\left(\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}\right)}}$	0
3) Average wavelength at the inspection line	$H_0: \mu_{hist} - \mu_{exp} = 0$ $H_1: \mu_{hist} - \mu_{exp} < 0$		0

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H_0 represents the null hypothesis and H_1 the alternative hypothesis, (μ_{hist}) and (μ_{exp}) are the historic and experimental averages, (z_0) is the test statistic for the standard normal distribution, ($\bar{x}_n$) represents the random sample average, (σ) is the flatness variance, (s_n) is the sample´s flatness variance, (n_n) is the sample size and Δ is the difference between the averages.

3. RESULTS AND DISCUSSION

Flatness measurements of the coils outcoming the Cold Mill are shown in Tab. 3. Results matched the requirement of the experiment, as shown in Figure 3. Normality tests were applied to the experimental lot (Tab. 2) and an historic records random sample via Minitab 16 (Fig. 4).

Table 3. Flatness Outcoming the Cold Mill.

Coil	Flatness [i-units]
1	25.1
2	29.3
3	33.7
4	38.5
5	30.4
6	28.7
7	30.4
8	26.4
9	30.2
10	31.6

Statistics	Before	After	Change
Mean	14,47	30,43	15.96
Standard deviation	4,1673	3,7440	-0,42330

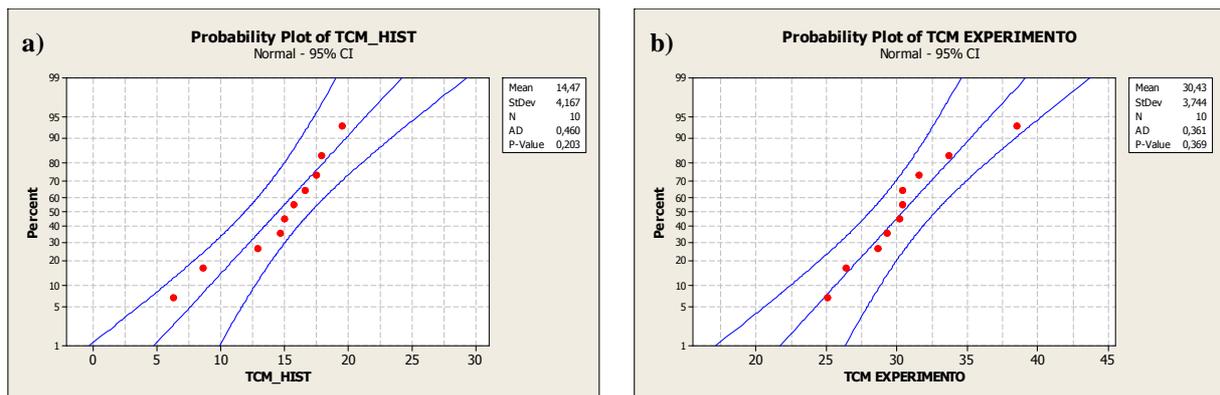Figure 3. Flatness Before (historic sample) and After (experimental lot).

Figure 4. Normality test. (a) Historic sample, (b) Experimental lot.

1) Average Flatness Statistic

$$z_0 = \frac{14.47 - 30.43 - (-15)}{\sqrt{\left(\frac{4.167^2}{10} + \frac{3.744^2}{10}\right)}} = -0.54 \tag{3}$$

Because $z_0 = -0.54$, P-value is $P = 1 - \Phi(z) = 1 - 0.29 = 0.71$, so we cannot reject H_0 at the $\alpha = 0.05$ level. We conclude that the experiment´s average is >15 i-units higher than the historic records and this is a strong conclusion.

The flatness final measurements are presented on the Tab. 4.

Table 4. Experimental lot final flatness measurements.

Coil	Measures: Wavelength [mm] x Wave amplitude [mm]								
	1	2	3	4	5	6	7	8	9
1	1000x0	280x2	290x3	230x3	1000x0	1000x0	230x3	1000x0	1000x0
2	1000x0	250x3	1000x0	1000x0	250x3	1000x0	1000x0	1000x0	1000x0
3	1000x0	1000x0	1000x0	1000x0	500x1.5	1000x0	1000X0	370X3	1000x0
4	1000x0	300x2	1000x0	1000x0	270x2	1000x0	1000x0	1000x0	1000x0
5	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0
6	700x3	1000x0	1000x0	700x3	1000x0	420x2	650x3	1000x0	460x2.5
7	600x3	1000x0	1000x0	530x4	1000x0	500x3	1000x0	1000x0	700x3
8	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0
9	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0
10	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0	1000x0

The reports for the (a) historic and (b) experimental lots are presented on Fig. 5 for wave amplitude and on Fig. 6 for wavelength.
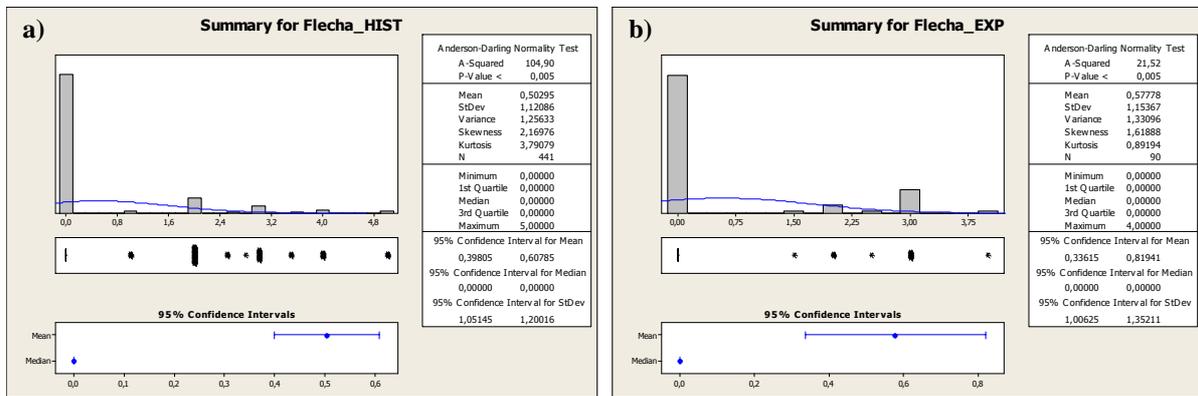

Figure 5. Wave amplitude summary showing (a) Historic, (b) Experimental lots.
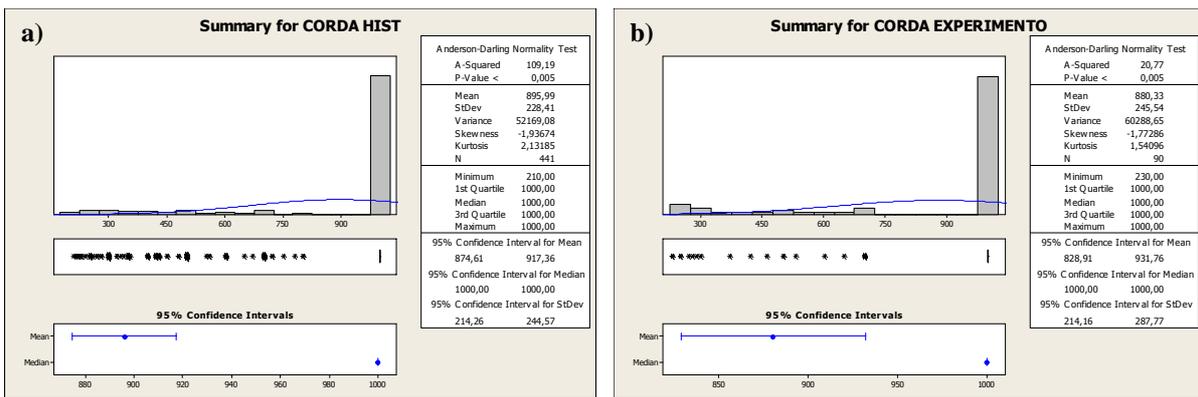

Figure 6. Wavelength summary showing (a) Historic, (b) Experimental lots.

2) Average Wave Amplitude Statistic

$$z_0 = \frac{0.50295 - 0.57778 - 0}{\sqrt{\left(\frac{1.25633}{441} + \frac{1.33096}{90}\right)}} = -0.56 \tag{4}$$

Because $z_0 = -0.56$, P-value is $P = 1 - \Phi(z) = 1 - 0.28 = 0.72$, so we cannot reject H_0 at the $\alpha = 0.05$ level. We conclude that the wave amplitude averages have no difference and this is a strong conclusion.

3) Average Wavelength Statistic

$$z_0 = \frac{895.99 - 880.33 - 0}{\sqrt{\left(\frac{52,169.08}{441} + \frac{60,288.65}{90}\right)}} = 0.56 \tag{5}$$

Because $z_0 = 0.56$, P-value is $P = 1 - \Phi(z) = 1 - 0.72 = 0.28$, so we cannot reject H_0 at the $\alpha = 0.05$ level. We conclude that the wavelength averages experience no significant difference.

4. CONCLUSIONS

The flatness averages change from 14.47 to 30.43 i-units confirmed the effectiveness of the insertion of centre buckles into the strip at the Cold Mill. The Inspection Line results showed that there wasn´t statistically significant flatness difference between historical records and the experimental lot, but the quarter-buckles were successfully eliminated by the technique. The Temper Mill was able to correct the lack of flatness purposely inserted into the strip, which did not cause any additional damage to the quality of the product.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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7. RESPONSIBILITY NOTICE

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