WORK-ROLL PROFILE EFFECT ON COLD ROLLING SHEET FLATNESS*

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Abstract
Quality criteria in cold rolled sheets have been continuously increased due to a highly demanding and competitive marketplace. Motivated by the Lean manufacturing movements and sustainable projetcs development, which reinforces the need for otimization of resourses, the flatness effects in cold rolled steels plays an important role in meeting the narrowest quality requirements. Flatness is a requirement of cold rolled steel that guarantees the final product aplicability. Furthermore, into finishing process, this feature is strongly attached to a good material performance during its processing, avoiding downtime and reducing scrap generation. The present work shows a case of study within the flatness universe, which investigation was motivated by the occurrence of a shape defect, that showed up a decentralized waves aspect on metalic sheet. It was investigated the correlation between this occurrence and the work-roll gap profile. The analysis was embased comparing both symmetric and assymmetric work-roll profile in a real five tandem cold rolling mil process, shifting the last two stand work-roll profile.
Keywords: Flatness, cold rolling process, rolling mill, work-roll profile, quarter buckle, wave-edge, flatness control.

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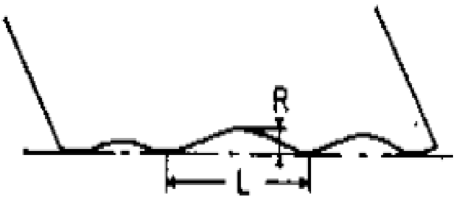
1 INTRODUCTION

According to Roberts [1], the term flatness is the material ability of the strip to be flat when lie on a horizontal surface. For commercial use of steel product, flatness control is important to avoid visual distortion when applied on household appliance, automotive industry and so on.

The unit used to describe flatness is the I-units, that consist, according to figure 1, a relationship between wave amplitude and the wave length. The measurement control system of flatness, during cold rolling mill, is called Shapemeter. That system generate data which can be graphically represented and it's obtained through a tension-input roll that it converts tension into Iunits.



$$I - units = \frac{R}{L} x\ 100\%$$

R = wave height
L = wave lenght

Fig 1 – I-units determination (Yarika et al. [2])

Another flatness parameter is the shape of the strip. It's observed that different flatness shape is produced, during cold rolling mill process. This phenomena impacts, depending on quantitative analysis (Iunits) and asymmetric feature, in processing performance at continuous line. Figure 2 exhibit two flatness shape produced by a five tandem four-high mill at CSN.

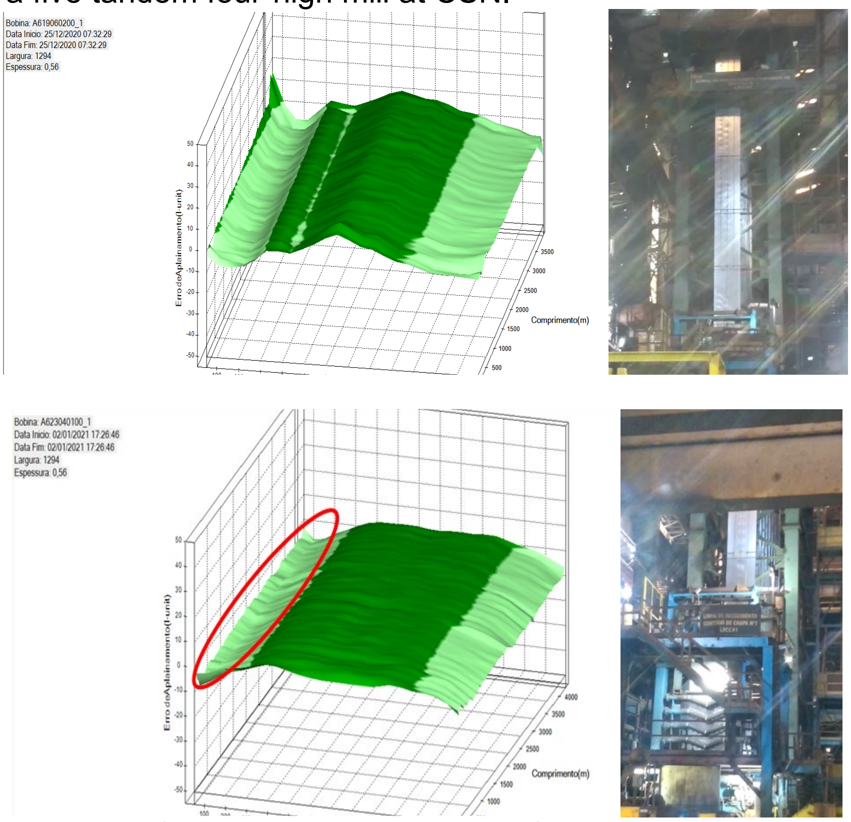


Fig. 2 – Flatness shape: at left, shapemeter graphic generated after rolling process, at right real strip flatness processing in a continuous line First shapemeter graphic representes a non-symmetric curve, called Quarter-Buckle [3], the second curve, represent a parabolic shape profile.

According to Roberts [1], due to the cold rolling process nature, the Full-hard product generated contain residual stresses. These residual stresses when not symmetrical with the central plane of strip (NN' at figure 3) exhibit a tendency to curl or to buckle.

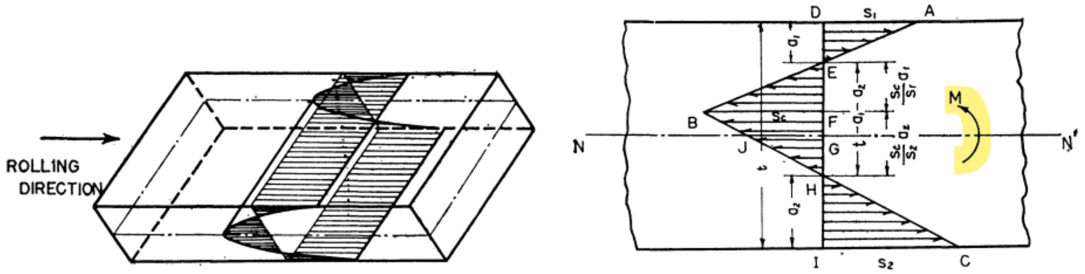


Fig 3 – Schematic Residual Stress distribution in cross section of strip presented by Roberts [1], NN' reffers to central plane of strip, t is the thickness.

Many factors can result in a non-balanced residual stress during cold rolling: non-uniform roll force distribution, friction and cooling. A result of these non-uniform residual stress generation is shown in fig 4. Into roll force distribution, some factors play an important role, mentioning the gap profile configuration as one, which brings to discussion the work roll profile.

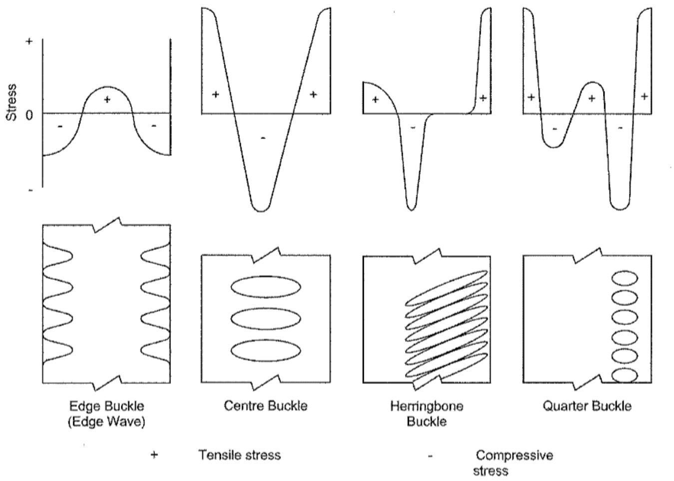


Figura 4 – Schematic indication of principal shape defects and stress distribution (Wistreich, Journal of the Iron and Steel Institute 1203 1968) [3]

According to the Wistreich [3], the flatness effect called quarter-buckle is caused by a high stress on the edge summed with a non-centered compressive stress applied at one quarter on the transversal strip profile. He et al [4], classified the quarter buckle as a high order wave curve effect. For continuous production line is center buckle (parabolic strip profile) is preferred due to roll adherence at the interface roll-strip.

Zhou et al [5] correlated the quarter-buckle to a non-parabolic bending. According to him, an adverse profile of roll gap would imply in imbalanced stressed sheet profile and, as result, the quarter-buckle would appear. His work was aimed to validate the Wistreich hypothesis for quarter-buckle generation (fig. 4) using FEM.

Chao Liu et al [6] affirmed that the roll profile is an important aspect to be taken into consideration when dealing with high order flatness profile. Despite his analysis was all correlated with hot rolled strip, the writer describes an non symmetrical roll which he called a "S" profile (fig.5), used in CVC method of flatness control by shifting. According to him, the gap formed, will be always a parabola, no matter what roll shifting position is. This fact impacts in a non-adjustment ability face high order flatness curve.

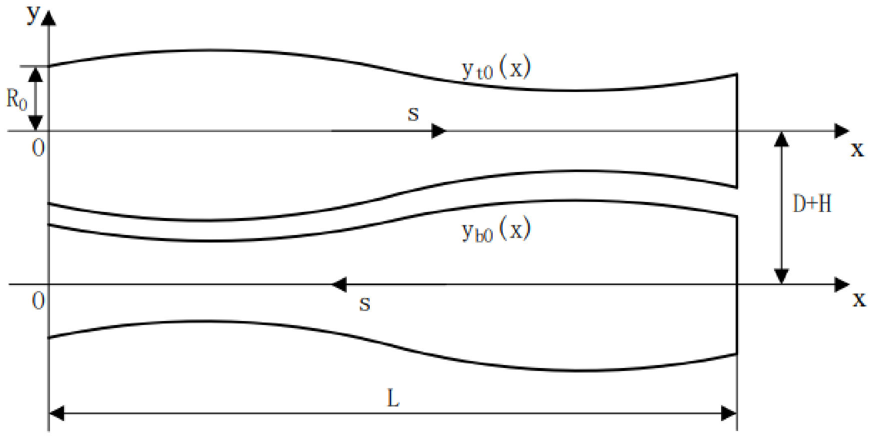


Fig. 5 – Roll profile of a CVC system - Li et al, 2012 [7]

In this papper, it will be explored, in a practical manner, the non-parabolic gap ("S" profile) in comparison with a parabolic one, related to an asymmetrical flatness curve, in general, and a quarter-buckle profile production. The mill process observed, is a five tandem four-high mill, with the last stand designated to flatness control. It does not have a shifting control system, so it's expected that "S profile" has a worse condition than the parabolic one.

2 DEVELOPMENT

This present work was realized in a cold rolling tandem four-high mill with 5 stands, which four stands are designated to thickness reduction and the last one is responsible for flatness correction and roughness printing. It counts with a shapemeter roll, which control the refrigeration nozzles, depending on the flatness response obtained during process. The gauge control is automatic (AGC – Automatic Gauge Control).

In the roll shop, it was measured the work-roll profile using a profile gauge. This is a manual instrument, which detects the shape of roll, related to eccentricity. It was chosen two pair of work-rolls with a "S" profile and two pair of work-roll with a parabolic profile, according to figure 6 and 7, to fill up the 4th and 5th stands separately, and then analyzed the type of flatness shape produced during the cycle.

The 5th stand work-roll texture is an EDT roughness configuration with roughness around 220 micro inch.

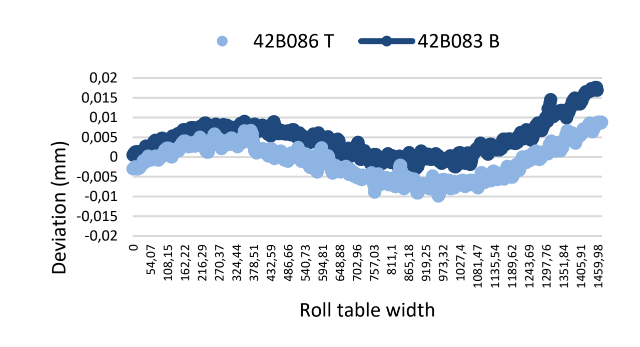


Fig. 6 - "S" profile work-roll, T = Top roll and B = Bottom roll

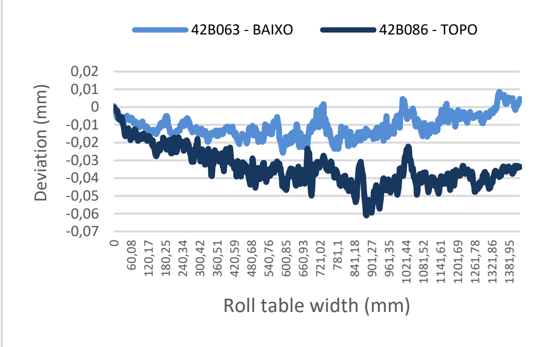


Fig. 7 - Parabolic profile work-roll - T = Top roll and B = Bottom roll

Firstly, there was a need to understand the differences between the rolling gap formed by a “S” profile work-roll and a parabolic profile. It was used the software MATHLAB to find out the equation which describe each one of the work-rolls. It was assumed the gap with no charge applied and disregarded the work-roll elastic effect.

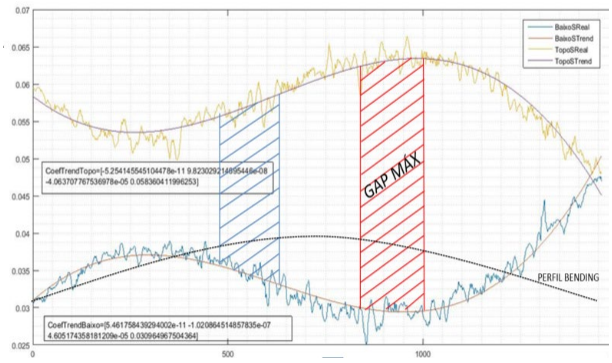


Fig 8 – “S” profile curve determined at MATLAB which:

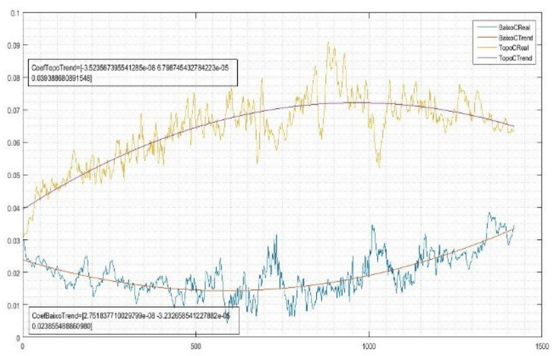


Fig 9 – Parabolic Curve determined at MATLAB, which;

$$f_{ST}(x) = Top\ \text{"S"}\ profile\ work - roll\ curve$$
$$f_{SB}(x) = Bottom\ \text{"S"}\ profile\ work - roll\ curve$$

$$f_{ST}(x) = 4.10^{-10}x^3 - 4.10^{-7}x^2 + 8.10^{-5} + 0{,}06$$
$$f_{SA}(x) = 4.10^{-10}x^3 - 4.10^{-7}x^2 + 9.10^{-5} + 0{,}03$$

$$f_{PT}(x) = Top\ parabolic\ profile\ work - roll\ curve$$
$$f_{PB}(x) = Bottom\ parabolic\ profile\ work - roll\ curve$$

$$f_{ST}(x) = 1.10^{-7}x^2 - 0{,}0001x + 0{,}0393$$
$$f_{SB}(x) = 1.10^{-7}x^2 - 6.10^{-5}x + 0{,}0239$$

The rolling gap can be determined, calculating the area shaped by the superposition of the top and bottom work-roll profile.

$$A_{GAP\ parabolic} = A_{PT} - A_{PB}\,|_{19}^{21} \qquad (1)$$

Where,

$$A_{PT} = Parabolic\ profile\ work - roll\ \ shaped\ area - Top\ work - roll$$
$$A_{PB} = Parabolic\ profile\ work - roll\ \ shaped\ area - Bottom\ work - roll$$

Using partial integer differences over the equations of fig.9 to determine roll profile asymmetry ratio, with zero mark taken as the midline of work-roll body, the rolling gap area to drive side (DS) and operator side (OS):

$$A_{GAP\ parabolic,DS} = A_{ST} - A_{SB}\,|_{19}^{21} \qquad (2)$$

$$A_{GAP\ parabolic,DS} = \int_{19}^{21} f_{ST}(x).dx - \int_{19}^{21} f_{SB}(x).dx \quad (3)$$

$$A_{GAP\ parabolic,DS} = 9{,}4530 - 2{,}0854 \quad (4)$$

$$A_{GAP\ parabolic,DS} = 7{,}3676\ umed^2 \quad (5)$$

For operator side:

$$A_{GAP\ parabolic,OS} = \int_{12}^{14} f_{ST}(x).dx - \int_{12}^{14} f_{SB}(x).dx \quad (6)$$

$$A_{GAP\ parabolic,OS} = A_{ST} - A_{SB}\,|_{12}^{14} \quad (7)$$

$$A_{GAP\ parabolic,OS} = 10{,}3566 - 2{,}4355 \quad (8)$$

$$A_{GAP\ parabolic,OS} = 7{,}9212\ umed^2 \quad (9)$$

So, the total parabolic work-roll profile is calculated throught the (9) relation:

$$A_{GAP\ parabolic} = A_{GAP\ parabolic,DS} + A_{GAP\ parabolic,OS} = 15{,}28\ umed^2 \quad (10)$$

The result above allows to determine the different constriction between drive side and operator side.

$$Constriction\ ratio = 1 - \frac{A_{GAP\ DS}}{A_{GAP\ OS}} = 0{,}0698 \quad = 6{,}98\% \quad (11)$$

The drive side is more constrict 6,98% than the operator side.

For "S" profile work-roll, it's repeted the same procceding to determine the roll gap area and the constriction ratio:

$$A_{GAP\ "S"\ PROFILE,DS} = A_{AT} - A_{AB}\,|_{19}^{21} \quad (12)$$

$$A_{GAP\ "S"\ PROFILE,DS} = \int_{19}^{21} f_{ST}(x).dx - \int_{19}^{21} f_{SB}(x).dx \quad (13)$$

$$A_{GAP\ "S"\ PROFILE,DS} = 3{,}17\ umed^2 \quad (14)$$

For operator side:

$$A_{GAP\ "S"\ PROFILE,OS} = \int_{12}^{14} f_{AT}(x).dx - \int_{12}^{14} f_{AB}(x).dx \quad (15)$$

$$A_{GAP\ "S"\ PROFILE,OS} = 4{,}78\ umed^2 \quad (16)$$

$$A_{GAP\ "S"\ PROFILE} = A_{GAP\ "S"\ PROFILE,OS} + A_{GAP\ "S"\ PROFILE,DS} = 7{,}95\ umed^2 \quad (17)$$

The constriction ratio for "S" work-roll profile is determined:

$$Constriction\ ratio = 1 - \frac{A_{GAP\ "S"\ PROFILE,DS}}{A_{GAP\ "S"\ PROFILE,OS}} = 0{,}3368 = 33{,}68\% \quad (18)$$

The drive side is more constrict 33,68% than the operator side.

Based on (10) and (17) relationship, it's possible to calculate the divergence of constriction ratio, now, comparing the "S" work-roll profile with parabolic work-roll profile:

$$Constriction\ ratio = 1 - \frac{A_{GAP\ "S"\ PROFILE}}{A_{GAP\ PARABOLIC\ PROFILE}} = 0{,}4797 = 47{,}97\% \qquad (19)$$

Based in (17), it's recognizable that the work-roll gap of "S" profile is 47,97% more constrict than the parabolic work-roll gap.

2.1 Work-roll profile and Flatness impacts

According to Chao Liu et al [6], in your research the work-roll described as "S" profile is adjusted by a cubic curve, and this kind of profile is unable to better a quarter buckle profile. Analyzing the quarter buckle in flatness profile, with materials rolled with "S" shaped work-roll in 4th and 5th stand, it's observed (fig 10), that the occurrence happened in both work-roll profile installed, but "S" profile probability of quarter buckle occurrence in drive side is worse. Such fact can be related to a summed factors acting in both conditions but showing worse when using a constricted work-roll gap, causing an excessive imposed charge over the region mentioned.

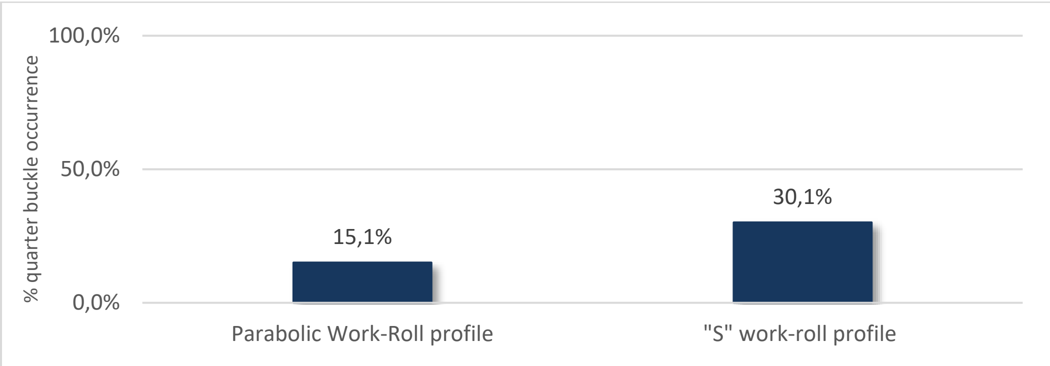


Fig. 10 – Quarter buckle flatness profile occurrence with different 4th and 5th stand work-roll installed – Drive side occurrence

Then, when operator side was analyzed, where the problem was concentrated, the diferences between both profile was negligible not showing a clear relation between roll profile and the ocurrence. This non-correlation can be explained by the variety of phenomenas which quarter buckle can be correlated with. Hui Li et al [7], oppened the buckle causes correlating since emulsion properties till roll wear and grinding error of the roll contour . The present study was strictly to verify the correlation between the "S" shaped work-roll and it's effect in flatness shape.

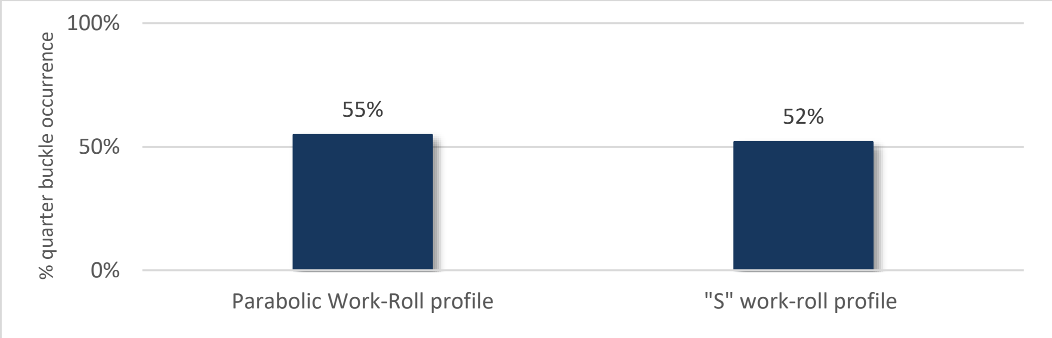


Fig 11 - Quarter buckle flatness profile occurrence with different 4th and 5th stand work-roll installed – operator side occurrence

Lastly, it was analysed the capacity of the work-rolls profile configuration to produce non-assymetric flatness profile. As mentioned in several papers, the "S" work-roll profile is used in rolling mills with CVC (continuous Variable Crown) with shifting control. In this system there is a roll movement that adjusts as the dimensional changes allowing the gap profile to keep parabolic when rolling. As the cold rolling mill studied, does not have this bending system control (the roll are static) some dificulty in keeping the parabolic gap during the process should occur in theory. Anyway, when the comparision was made between these profiles, it was observed that "S" work-roll profile has a tiny better performance when compared with parabolic work-roll profile, being contrary of what was expected in theory. Such result, must be investigated deepen because it contradicts the theory.

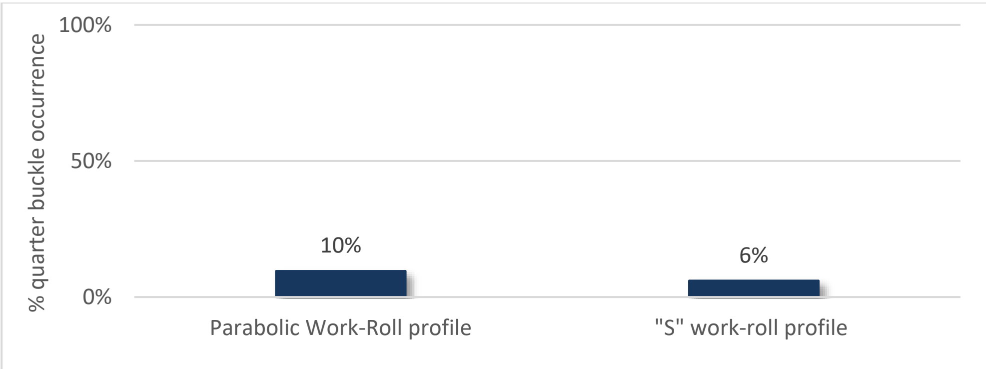


Fig 12 – Work-roll profile capacity of producing non-assymetric flatness profile

3 CONCLUSION

It was presented that the quarter-buckle occurence in drive side exhibit the occurece, as the parabolic profile exhibit it too. The phenomena in drive side is more latent to occur in "S" profile probably due to gap profile, that it has the smaller area. Although, the occurence in operator side can not be explained showing that another cause can be linked to the quarter-buckle effect in that side.

Another aspect analysed was the capacity of producing non-symetrical curves which showed up a unexpected result not correlated to the known theories. Such effect must be deeper studied in other to indentify another aspects that could be resulting in non-assymetric curves even when having a symmetrical work-roll.

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