# DESIGN AND PERFORMANCE OF TANDEM COLD-ROLLING MILLS WITH 6-HIGH AND 4-HIGH TECHNOLOGY[1]


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**Abstract**

Cold strip producers are permanently seeking for mill equipment, which ensures the most efficient rolling operation and fulfils the demands of the future market in terms of strip quality, dimensional performance and steel grade mix to be produced. In recent years a number of new continuous cold-rolling mills have been installed and this trend is still ongoing. There is an obvious dispute over whether the 6-high technology is required to meet the future quality and product mix targets. Some steel producers trust in the 4-high technology, while others are not even willing to discuss the option of 4-high mill stands and swear by the 6-high mill technology. VAI has carried out extensive modelling work to compare the critical parameters of 4-high and 6-high cold-rolling tandem mills. The comparison includes several mill configurations, for example with two 6-high and three 4-high mill stands or four 6-high mill stands and one 4-high mill stand. The aspects of flatness control based on VAI's SmartCrown® system, the flatness performance in the strip transition area, the stiffness of the mill stands and its influence on the thickness performance as well as edge-drop control and its necessity for the automotive industry are discussed.



**Key words:** Tandem mill; Flatness control


[1] *43rd ABM Rolling Seminar, October 17–20, 2006, Cutitiba/Brazil*


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## INTRODUCTION

Cold strip producers are permanently seeking for mill equipment, which ensures the most efficient rolling operation and fulfils the demands of the future market in terms of strip quality, dimensional performance and steel grade mix to be produced.
In recent years a number of new continuous cold-rolling mills have been installed and this trend is still ongoing. There is an obvious dispute over whether the 6-high technology is required to meet the future quality and product mix targets. Some steel producers trust in the 4-high technology, while others are not even willing to discuss the option of 4-high mill stands and swear by the 6-high mill technology.
VAI has carried out extensive modelling work to compare the critical parameters of 4-high and 6-high cold-rolling tandem mills. The comparison includes several mill configurations, for example with two 6-high and three 4-high mill stands or four 6-high mill stands and one 4-high mill stand.
The aspects of flatness control based on VAI's SmartCrown® system, the flatness performance in the strip transition area, the stiffness of the mill stands and its influence on the thickness performance as well as edge-drop control and its necessity for the automotive industry are discussed.

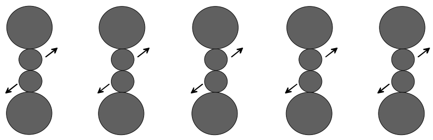
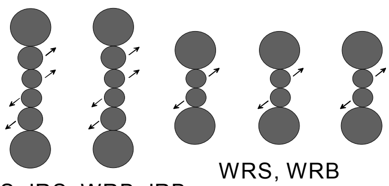
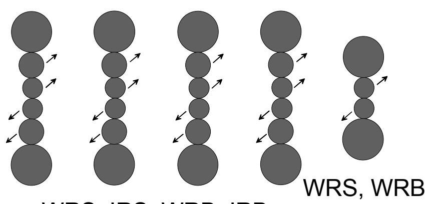
## TARGETS OF THE INVESTIGATION

- This analysis was the basis for a proposal for a new continuous tandem cold mill, which should be capable of rolling advanced high-strength steel grades (AHSS) up to a tensile strength of 1300 MPa. In terms of strip dimensions, the product mix should fit automotive applications (Table 1).
- From existing linked tandem cold mills with five mill stands in 4-high configuration it is well known that there exist distinct reduction limits when rolling AHSS, which should be extended for the new tandem cold mill.
- It was therefore decided to investigate a hybrid mill type No.1 with mill stands No.1 and 2 in 6-high configuration to ensure a larger thickness reduction range and superior flatness control capabilities as well as the ability of edge-drop control.
- Additionally, the hybrid mill type No.2 with mill stands No.1-4 in 6-high configuration and No.5 in 4-high configuration was compared to a mill comprising five 4-high mill stands with tapered work rolls to elaborate the optimum configuration in terms of edge-drop control capability (Table 2).
- For all investigated mill stand configurations, the last mill stand was of 4-high type in order to ensure optimum surface quality for automotive exposed applications.

**Table 1.** Product mix, steel grade overview

| | | |
|---|---|---|
| DP | 260.500 tpy | Up to tensile strength of 1300 MPa |
| MP | 52.500 tpy | |
| TRIP | 87.000 tpy | |
| **DP, TRIP, MP** | **400.000 tpy** | |
| HSLA | 249.500 tpy | |
| HS-IF | 177.000 tpy | |
| Structural | 238.000 tpy | |
| CM, C | 6.500 tpy | |
| **HSLA, HS-IF, Structural, CM, C Steel** | **671.000 tpy** | |
| **Si Steel** | **90.000 tpy** | |
| **IF** | **59.000 tpy** | |
| **Total Annual Production** | **1.220.000 tpy** | |

**Table 2.** Mill configurations and main technical data of the mill stands

| | | |
|---|---|---|
| 4-High Mill | | |
|  WRS, WRB | All mill stands equipped with work roll shifting in conjunction with VAI's **SmartCrown®** system for improved flatness control. | |
| | Work roll diameter: | 470/420 mm |
| | Work roll barrel length: | 2080 mm |
| | Backup roll diameter: | 1550/1400 mm |
| | Backup roll barrel length: | 1880 mm |
| | Shifting stroke: | +/-100 mm |
| | Work roll bending force: | -455/+650 kN per neck |
| | Work rolls are driven. | |
| Hybrid Mill No. 1 | | |
|  WRS, IRS, WRB, IRB / WRS, WRB | The six-high mill stands are equipped with work and intermediate roll bending, intermediate roll shifting with **SmartCrown**® for improved flatness control and with work roll shifting for edge-drop control purposes. | |
| | Work roll diameter: | 470/420 mm |
| | Work roll barrel length: | 1880 mm |
| | Intermediate roll diameter: | 580/520 mm |
| | Intermediate roll barrel length: | 2120 mm |
| | Backup roll diameter: | 1450/1300 mm |
| | Backup roll barrel length: | 1880 mm |
| | Intermediate roll shifting stroke: | +/-120 mm |
| | Work roll bending force: | -455/+650 kN per neck |
| | Intermediate roll bending force: | -455/+650 kN per neck |
| | Work rolls are driven. | |
| | The 4-high mill stands no. 3-5 at the rear of the mill are identical to those of the 4-high mill described above. | |
| Hybrid Mill No. 2 | | |
|  WRS, IRS, WRB, IRB / WRS, WRB | The mill stands feature the same properties as for hybrid mill no.1. | |

## ANALYSIS METHOD

The VAI program “Roll Stack” is a software tool for analysing the forces and displacements in 2-high, 4-high or 6-high rolling mill stands and was used to determine the results presented below.
The theoretical background of the numerical analysis of a mill stand was presented first in a paper by Shohet and Townsend in 1968. This basic concept is still used, although the actual software tool was extended by a number of features to improve the accuracy and information content of this analysis. The most important extension was to add a reliable assessment of the roll flattening behaviour, based on finite element analysis results from a “master” roll, which are projected by means of influence functions and mechanical similarity considerations to the roll to be investigated. Beside others, this added feature allows for highly accurate analysis of “edge-drop” effects as part of the roll-stack deflection calculation, which are of vital importance for cold mill investigations as shown in the following.
Another important addition to the roll-stack software was an improved model describing the interaction between the work roll and the strip, which allows determining the contact pressure distribution across the strip width and particularly the interaction between strip tension and rolling force. This feature provides useful information about the state of flatness of the strip at the exit of the roll gap based on arbitrarily chosen strip entry conditions and all kinds of flatness actuator settings in the stand under consideration.

## FLATNESS ADJUSTMENT RANGE

Today most customers target to run a rolling mill with just a single roll contour per mill stand, provided that the actuators are sufficiently powerful to ensure flatness for the complete production range. This aim can be fulfilled by any of the three configurations under consideration. All variants make use of VAI’s SmartCrown® system (patents AT 410 765 B, WO 03/022470).
The work rolls are employed for flatness control in the 4-high mill stands, whilst the intermediate rolls are utilized in the 6-high mill stands. The basic function principle of **SmartCrown®** is depicted in Figure 1. The main advantages of the **SmartCrown®** system compared to existing systems based on third-order roll contours are the following:

- Increased adjustment range regarding flatness defects of fourth order in combination with work roll bending
- Increased adjustment range regarding flatness defects of second order, especially for narrow strips

In order to homogenize the load distribution between mate rolls, the backup rolls can be equipped with a complementary contour as exemplarily shown in Figure 2. The effect of rolls ground in this way is presented in Figure 3. Figure 4 shows a comparison between the flatness adjustment range of second and fourth order for a 4-high and a 6-high mill stand.
Although the simulated roll crown range for the 4-high mill stand was smaller than for the 6-high mill stand, the attainable control range is considerably larger. This effect is the result of mutual flattening of the work and the intermediate rolls, which causes a drop of the efficiency by about 50 % compared to a **SmartCrown®** application utilizing the work rolls.
This difference is compensated by a larger crown adjustment range, which, however, necessitates a larger shifting stroke in case of a 6-high mill.
Neither of the two systems shows an advantage regarding the total flatness adjustment range; both are capable of covering the complete projected product mix.

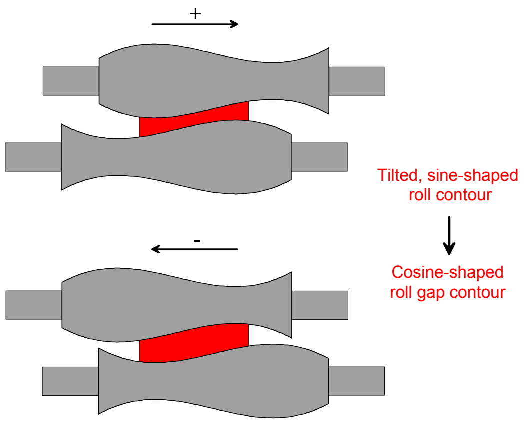



**Figure 1**. Function principle of the **SmartCrown®** system

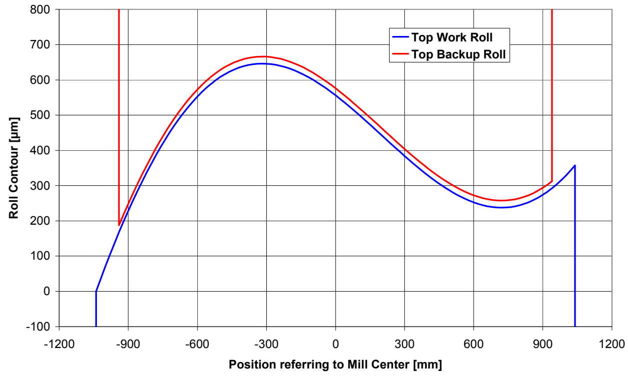



**Figure 2.** Complementary work and backup rolls of a **SmartCrown®** system

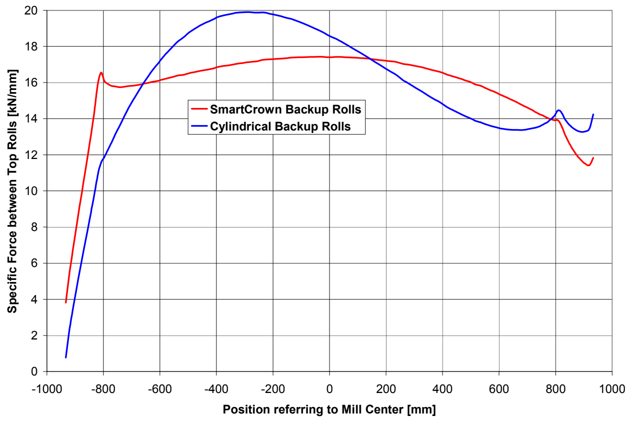



**Figure 3.** Load distribution between upper work and backup roll

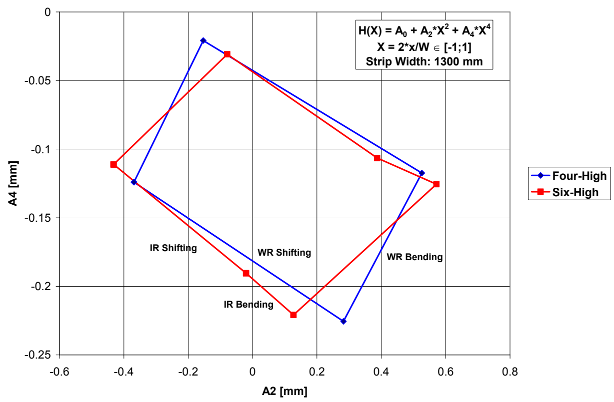



**Figure 4.** Flatness adjustment range comparison between a 4-high and 6-high mill stand

## FLATNESS AROUND WELDED STRIP JOINTS

Proper flatness control around strip joints can only be accomplished by means of roll bending, since the roll shifting speed is a function of the rolling speed and the rolling force for both 4-high and 6-high mill stands.

6-high mill stands are somewhat more advantageous in this respect, because, apart from work roll bending, intermediate roll bending can be utilized as well, which gives an extended flatness adjustment range according to Figure 4.

In practice, however, no problems have to be expected at 4-high mill stands if work roll shifting is already started during rolling of the preceding strip in case the succeeding strip is going to be substantially harder or softer. To illustrate this rolling practice, the following simulation with an extreme change of the work roll bending force was carried out:

The change of work-roll bending forces from -454 kN to +545 kN at a fixed shifting position of +76 mm was applied at the strip joint at mill stand No.1 (4-high mill stand) when rolling the two consecutive strips No.1 and 2 with the following characteristics:

| | Strip No.1 | Strip No.2 |
|---|---|---|
| Steel grade | IF steel | TRIP 800 |
| Width | 1,100 mm | 1,000 mm |
| Entry thickness | 3.00 mm | 3.50 mm |
| Exit thickness | 0.55 mm | 0.90 mm |
| Rolling force | 10,059 kN | 16,592 kN |

It can be seen that even under these unrealistic and extreme assumptions no flatness problems are expected to arise at the strip joint. Moreover, the occurrence of manifest shape problems (waviness) is additionally suppressed by the application of high interstand tensions.

## MILL STIFFNESS

In every tandem mill project, VAI faces the request that, beside excellent flatness performance, tightest thickness tolerances are of paramount importance to the customer. In conjunction with the level 1 control system, mill stands as stiff as possible strongly contribute to realize this task. A comparison of the mill stretch for the same strip rolled at a 4-high and a 6-high mill stand is shown in the Table 3.

**Table 3.** Mill Stiffness - Mill Stretch at a Rolling Force of 25,000 kN

| | 4-high mill stand | 6-high mill stand |
|---|---|---|
| Roll stack (min.) | 2,496 mm | 3,670 mm |
| Roll stack (max.) | 2,729 mm | 4,003 mm |
| Mill housing | 0,909 mm | 0,966 mm |
| Oil column (min.) | 0,532 mm | 0,532 mm |
| Oil column (max.) | 2,011 mm | 2,721 mm |
| Total (min.) | 3,937 mm | 5,168 mm |
| Total (max.) | 5,649 mm | 7,690 mm |
| **Stiffness (min.)** | **4.43 MN/mm** | **3.25 MN/mm** |
| **Stiffness (max.)** | **6.35 MN/mm** | **4.84 MN/mm** |

The total stiffness of a 4-high mill stand is about one third larger than for a 6-high mill stand, which positively affects the thickness control performance. The main reason for the reduced stiffness of a 6-high mill stand can be found in the additional flattening of the intermediate rolls.

## EDGE-DROP CONTROL

The ability to control the edge drop of the strip via work roll shifting is not highest priority for the product mix defined for this investigation. The application of such an operating practice might however be of interest when rolling silicon steel. Therefore, this issue was investigated in more detail.

### Number of active mill stands

The reduction of the edge drop should already start in the first stands of a tandem mill, since the thickness is still large enough to achieve local thickness changes without causing inadmissible tension stresses at the edges, which might lead to strip breaks.
During the investigation regarding edge drop, it became obvious that a major portion of the edge drop reduced in mill stands No.1 and 2 reappears again when applying high reductions in stands

No.3 and 4, Figure 5. This is valid for both 4-high and 6-high mill stands and could only be circumvented by imprinting an excessively high edge rise during the first two passes, which however could lead to the negative effect mentioned above.
The following figure shows the strip cross profile with the first four mill stands actively engaged in edge-drop reduction Figure 6.

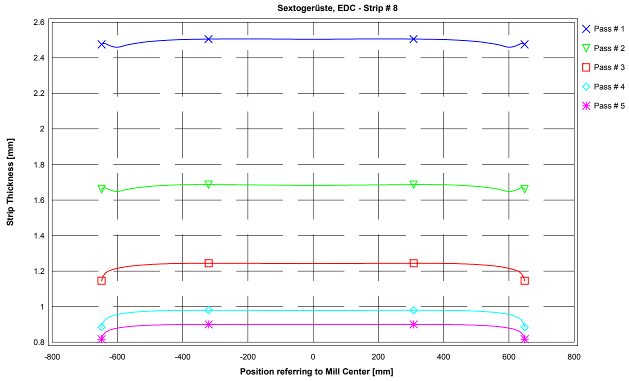



**Figure 5**. Edge-drop control at the first two mill stands (structural steel)

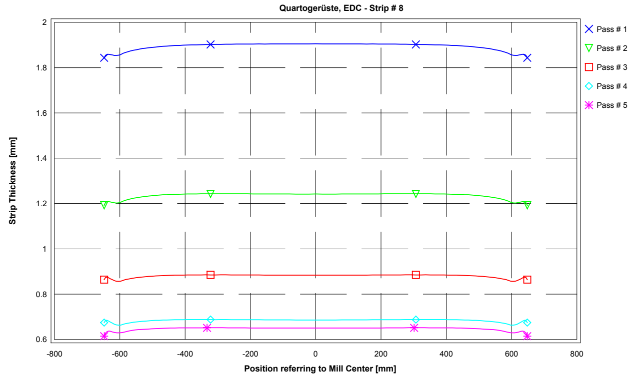



**Figure 6.** Edge-drop control at the first four mill stands (silicon steel)

The achievable value for the edge drop (C5-C40) is in the range of 5 to 10 µm regardless of the mill stand type compared to 40 to 60 µm typically achieved at conventional 4-high mills.
In case of the implementation of such a rolling practice in a 6-high rolling mill, not only the intermediate rolls would have to be equipped with a side-shifting system, but also the work rolls. Edge-drop control would then be possible for all steel grades. According to the defined product mix, which is oriented towards automotive applications, this does not make sense, because those strips would be side-trimmed after rolling anyway.
If edge-drop control was to be applied on a 4-high mill for silicon strips only, this task could be accomplished by means of specially chamfered and cambered work rolls using the - anyhow available - work roll shifting system at stands No.1 to 4. In order to cover the complete product mix for silicon steel ranging from a width of 1200 to 1750 mm, two different work roll contours would be required, since a width range of 400 mm could be covered theoretically with a shifting stroke of ± 100 mm according to the scheme in Figure 7.

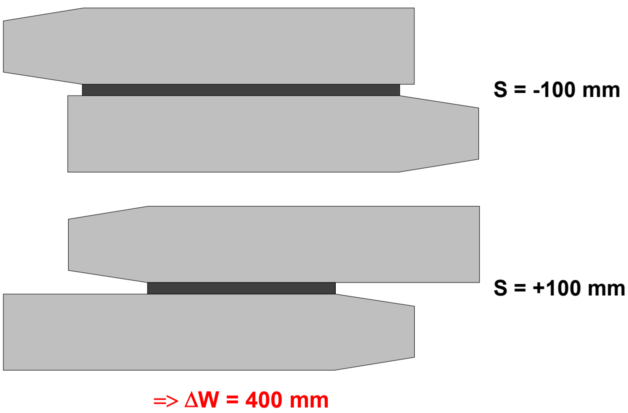



**Figure 7.** Edge-drop control for different strip widths

As the work rolls would only be employed for a limited width range, they could be provided with a custom crown, whereby satisfying shape control would be possible by means of work roll bending only.

## CONCLUSIONS

4-high and 6-high mill stands are equally good in terms of maximum reduction if the work rolls are driven directly.

The required flatness adjustment range can be achieved with all investigated variants, however flatness control is a bit more flexible on 6-high stands due to intermediate roll bending. Since the roll gap adjustment behaviour of intermediate roll bending and intermediate roll shifting is very similar, intermediate roll bending can temporarily compensate for deficiencies due to limited intermediate roll shifting speed during flying gauge or width change operations.

Edge drop control sensibly requires mill stands No.1 - 4 to be equipped with suitable actuators (axial shifting of tapered work rolls, which is feasible in both 4-high and 6-high mill stands). The 6-high technology is the more flexible solution in this respect, since flatness control does not rely on axial work roll shifting.

A 4-high mill stand offers significantly better performance in terms of mill stiffness. The stretch of the roll stack for a 1,300-mmwide strip and a roll force of 16,000 kN is 1,665 mm for the 4-high mill stand compared to 2,602 mm for a 6-high mill stand, which means that the roll stack deflection is more than 50 % higher on a 6-high mill stand.

The contact pressure between mate rolls on 6-high mills (Hertzian pressure) is beyond the normal range, especially when rolling AHSS. Therefore, concerns regarding the proper material selection of work and intermediate rolls and their lifetime still exist.

Finally the investment costs of 6-high mill stands are as a matter of fact higher that of 4-high mill stands, simply because of more equipment to be installed. Roll consumption, however, is remarkably higher on 6-high mills.

The pros and cons of a tandem mill consisting of 4-high or 6-high mill stands can be summarized as follows:

| **Topic** | **4-high mill stand** | **6-high mill stand** |
|---|---|---|
| Flatness control range | When using SmartCrown® work rolls one single contour per mill stand is sufficient cope with the complete product mix. | When using SmartCrown® intermediate rolls one single to contour per mill stand is sufficient to cope with the complete product mix. |
| Flatness around strip joints | Work roll bending sufficient if shifting starts during rolling of preceding strip. | Increased flexibility thanks to work and intermediate roll bending system. |
| Mill stiffness | ~ 5.4 MN/mm | ~ 4.0 MN/mm |
| Edge-drop control | Feasible for silicon steel by means of specially ground work rolls. | Feasible for all steel grades in conjunction with work roll shifting system and specially ground work rolls. |