# Reducing thickness variation of hot rolled steel strip by non-circular back-up roll geometry

**T. Widmaier*[1], T. Salmela[1], P. Kuosmanen[1], J. Juhanko[1], P. Kärhä[2] and J. Uusimäki[1]**

Typically, back-up rolls in hot strip mills are equipped with sliding bearings and it is common to use a key that prevents relative motion between the conical sleeve and the roll shaft. The key groove causes deformation of the sleeve under load. This sleeve 'spring' is observed as rolling force variation, which causes systematic thickness variation of the steel strip. Although there is a keyless bearing construction on the market, an alternative solution was studied. A non-circular camlike geometry that compensates the sleeve spring was ground on the back-up rolls by a three-dimensional grinding method. As a result, ~50% of the rolling force and the thickness variations, which were synchronised with the back-up rolls of the mill stand studied in the present paper, were reduced.

**Keywords:** Non-circular grinding, Rolling mill, Back-up roll, Rolling force variation, Steel strip thickness variation, Roll eccentricity

## Introduction

### Background

At present steel mills operate in a global market in which increased competition from developing countries has created a new situation. This competition has forced the existing mills to focus on producing steel of an improved and more even quality at a higher speed. The tolerances of steel strip profiles have become tighter. At the same time, the increased running speed brings out possible vibration problems in the rolling process, especially in a cold strip steel mill. If the thickness variation of the hot rolled steel strip can be reduced, it will be possible to increase the production speed of the cold strip mill. New harder steel alloys require increased rolling force, thus making the process more sensitive to rolling force variations. These claims set new demands on the acceptable rolling force and steel strip thickness variation levels in the milling roll stands.

The steel mills built in the 1960s and 1970s and even later are looking for cost effective means to meet the new demands. The present study discusses a method of improving the quality of the end product without the need for major investments.

### Research problem

The thickness variation of the rolled steel strip is mainly caused by the force variation during the rolling process. Other causes of the variations should also be visible in the rolling force measurements such as temperature differences and steel quality changes. In the present study, the authors try to understand the phenomena behind the rolling force variations seen in the rolling force measurements and to develop methods to reduce the force and thickness variations.

A measurement of the rolling force during the rolling process of a steel strip of a mill stand is shown in Fig. 1*a*. The level of the rolling force varies during the rolling process. In the beginning the level changes are quite large. The active control system of the rolling force reduces the level changes after a short period (here after ~20 s). In addition, as mentioned before, changes of temperature or steel quality can cause variation to the rolling force level.

Other variations seen in Fig. 1*b* and especially in Fig. 1*c* can be synchronised to the rotational speeds of the back-up rolls in the mill stand. This means that they are probably caused by the eccentricity of the rolls. A closer look at the structure of the studied mill stand can provide an answer to the observed phenomenon. Typically a rolling mill consists of 1–7 rolling stands. There are usually two, three or more rolls in each stand. In the studied hot strip steel mill, all six stands consist of two working rolls and two back-up rolls. The working rolls, through which the strip passes, are relatively small in diameter and have back-up rolls of a larger diameter above and below to reduce the mill spring. A mill stand with two back-up rolls is shown in Fig. 2.

In the mill stand under study, the back-up rolls have a key type sliding bearing construction, as seen in Fig. 3. It is known that a key type sliding bearing construction of back-up rolls causes a periodic rapid drop in the

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[1] Helsinki University of Technology, Machine Design, PO Box 4100, FI 02015 TKK, Finland
[2] Helsinki University of Technology, Metrology Research Institute, PO Box 3000, FI 02015 TKK, Finland

*Corresponding author, email Thomas.Widmaier@tkk.fi

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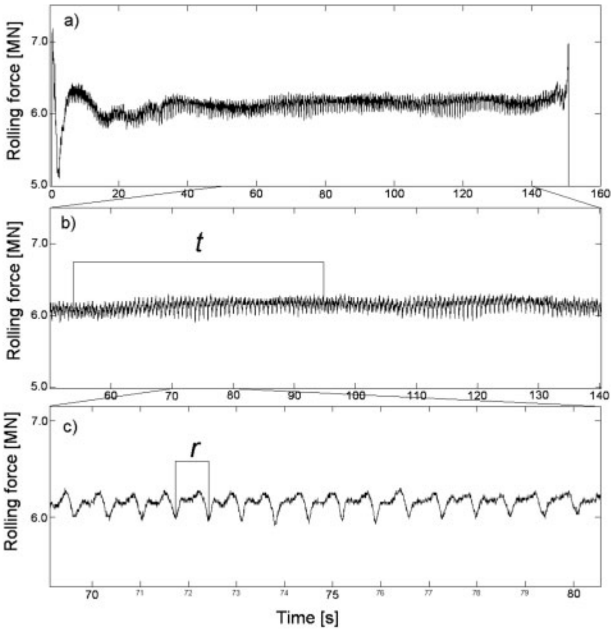


**1 Rolling force variation consists of changes of *a* rolling force level, *b* rolling force fluctuation and *c* drop of rolling force once in back-up roll revolution**

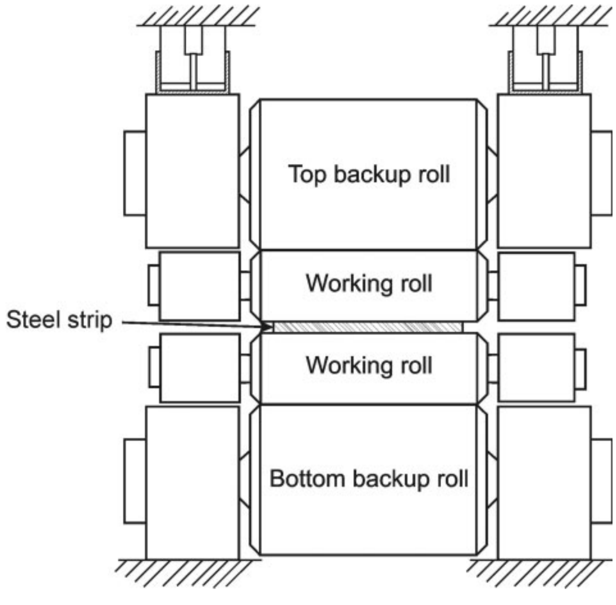
rolling force.[1] The key groove is always made with a clearance in the radial direction. The clearance guarantees that there is no radial force from the key that would deform the sleeve geometry. The key groove clearance is the main cause of the rapid force drop observed once per roll revolution (referred to as *r* in Fig. 1*c*). This phenomenon can clearly be seen in the same figure of the rolling force measurement.

The fluctuation of the rolling force (referred to as *t* in Fig. 1*b*) is caused by the slow change of the relative key groove positions in the bottom and top back-up rolls (Fig. 4). The change of the positions is caused by different rolling speeds of the rolls. The rolling speeds are relative to the diameters of the rolls comparable with different sized gearwheels in a gearbox. In the case of this mill stand, the diameters of the working rolls have no effect on the rotational speed of the back-up rolls, because the surface speed of the rolls is dependant only on the speed of the strip. Thus the frequency of the fluctuation can be calculated from the relation of the diameters of the back-up rolls and the rolling speed. Both the rapid drop of the rolling force and the rolling force fluctuation cause thickness variation to the steel strip.

A keyless bearing construction reduces the run-out of rolls as compared with a key type arrangement. Since the majority of the world's steel works built in the 1960s and 1970s continue to use a key type construction, solving the problem would have a major economic significance. Key type bearings are also still used in new cost effective mill stands. Different systems utilising active control of hydraulic cylinders to compensate for the roll eccentricity have been introduced by, for example, Ginzburg[1] and Kugi *et al.*[2] The dynamics of these active control systems is not enough to compensate for the rolling force variation caused by the key groove.

## Aim and scope of research

The aim of this research was to reduce the periodic rolling force variation caused by the eccentricity of the back-up rolls and to study how this affects the thickness variations of the steel strip. It is assumed that the magnitude of the thickness variation should decrease together with the rolling force variation. The exact relation between the rolling force and thickness variation was not known. In the present work the special case of the eccentricity caused by the sleeve spring of a key type bearing has been studied.



**2 Rolling mill stand unit design**

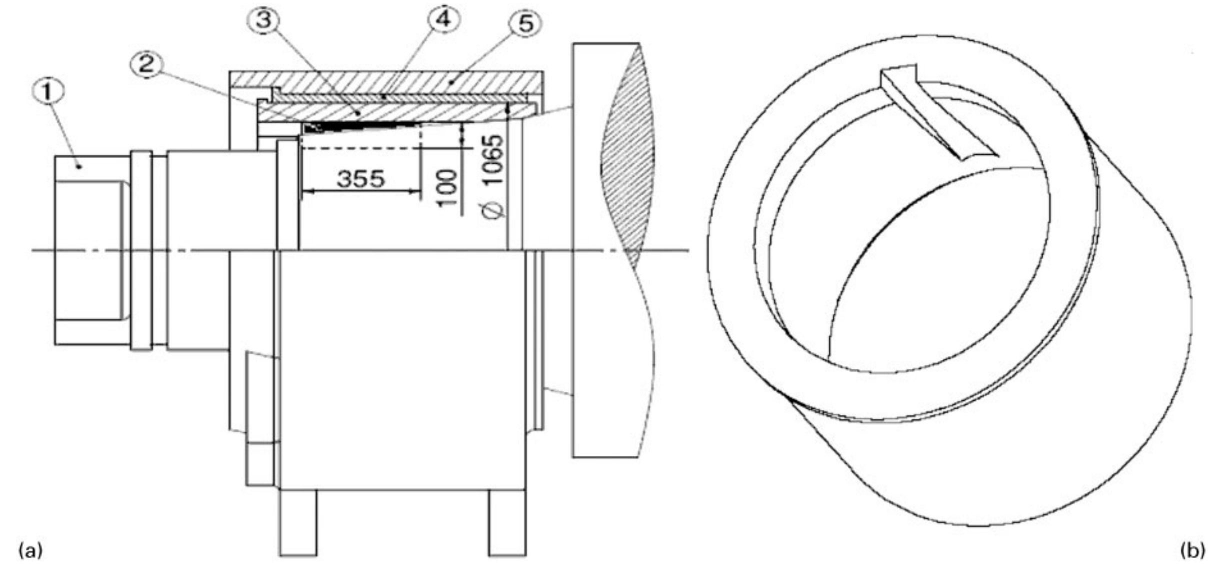
The empirical research took place at a hot strip mill. The three-dimensional (3D) grinding was applied to the back-up rolls at the last (sixth) mill stand. The rolling force and the steel strip thickness variations caused by the key groove were examined. Non-systematic error sources, resonance vibrations and changes to the strip temperature, for example, were excluded from the present study. In addition, systematic run-out errors such as non-circularity of the neck or non-circularity of the bearing bush were not examined. Three-dimensional grinding was applied to the back-up rolls of the mill stand studied.

## Research methods

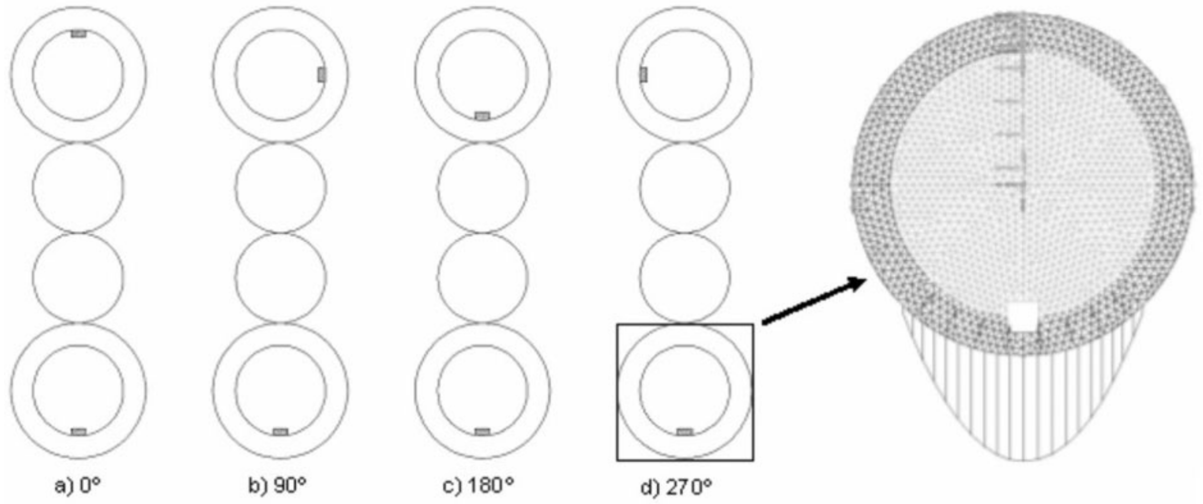
Based on previous research, non-circular roundness profiles, 30 μm (top back-up roll) and 50 μm (bottom back-up roll) in height, were ground on the back-up rolls in order to compensate for the rapid drop in the rolling force.[3]

Triggering sensors were installed on the back-up roll chocks to indicate the key groove. The rolling force and the strip thickness were measured using both conventional and 3D ground back-up rolls. The analysis was carried out by using synchronous time averaging. Measuring data, which consisted of several strips, were divided into periods that represent one revolution of back-up roll. Equivalent measuring points were combined with averaging. Finally, all the steel strips were combined again with averaging. This method is called synchronised time averaging.[4]

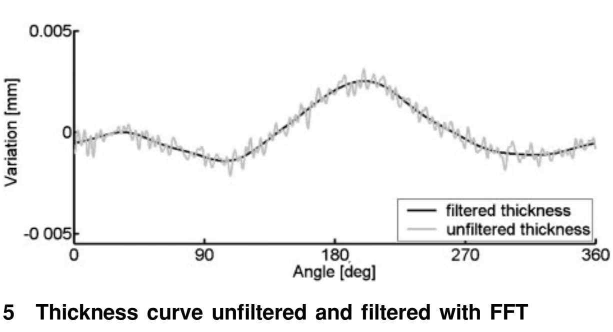
The result graphs of thickness variations are also filtered with a fast fourier transform (FFT).[5,6] The effect of the FFT filtering is shown in Fig. 5. The first 16 terms in the Fourier domain, representing the first 16 multiples



3 ***a*** **key type bearing assembly with *1* roll, *2* key, *3* conical sleeve, *4* bearing bushing and *5* bearing housing and *b* conical sleeve with key groove**



4 **Rolling force fluctuation depends on relative positions of key grooves: estimated two-dimensional (2D) load distribution of back-up roll is shown on right side**



5 **Thickness curve unfiltered and filtered with FFT**

of rotational frequency, also called harmonics, are used in the filtered result curve, as in the real results of the present study.

The 3D grinding method introduced in the present study is a method to grind different predefined geometries to cylinders, e.g. back-up rolls. This method is mainly used for compensating measurable systematic geometry errors, i.e. run-out, roundness errors and diameter variation of a roll. The tool path to obtain the desired geometry can be based on measurements, on mathematical analyses or on a combination of these, as in the present study.

## Methods and materials

### Measuring systems

The rolling force of the mill stand was measured from the drive and operator sides of the mill by Millmate PFV100 pressductor, the resolution of which is 24·4 kN (12 bit AD converter, measuring range from −50 000 to +50 000 kN).[7] Several measurement cycles were averaged. The noise of the measuring device together with the averaging enhances the resolution of the measurement.[8] The resolution of the averaged force variation measurement depends on the number of measurements $N$. With $N=100$, the uncertainty ($k=2$ indicating 95% confidence level) caused by the resolution is 1·4 kN.

Strip thickness was measured 4415 mm after stand no. 6 by an SSMC profile gauge, the resolution of which was 15·2 μm (Ref. 9). The total accuracy of the measuring system is ±43 μm at the complete measuring range 1–25 mm. The statistical noise given in the technical data of the measuring device is $<0{\cdot}1\%$ ($<24$ μm). The resolution of the strip thickness is also enhanced due to noise and averaging. With $N=100$, the uncertainty ($k=2$) caused by the resolution is 0·87 μm.

The data sampling rate of both systems was set to 300 Hz. Triggers on both back-up rolls are used to indicate the key groove so that the measuring data from the rolling force and the thickness gauges can be synchronised with each back-up roll.

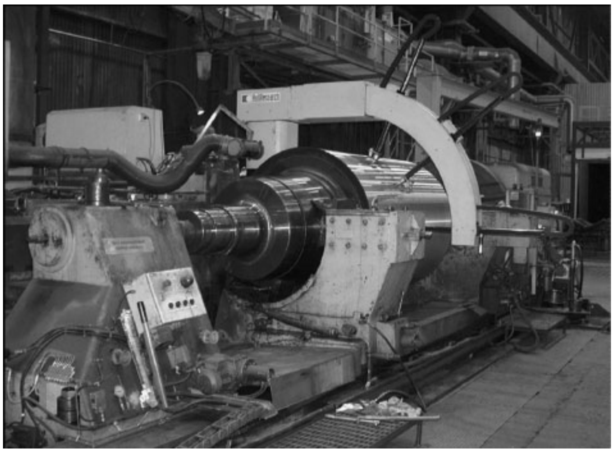
## Grinding system

The grinding machine (Fig. 6) in the present study had been upgraded with a 3D grinding system and a four point measuring system for large scale rotors. The installed control and measurement systems are based on prototypes developed in the Laboratory of Machine Design at the Helsinki University of Technology. The grinding machine can grind large scale back-up rolls up to ~100 tons. The maximum length of these rolls can be ~5 m and the maximum diameter ~2 m. In both traditional and 3D grinding, normal operating parameters of the grinder were used.

The accuracy of the grinding process is heavily dependent on the accuracy of the control system, which gets the feedback from the information gained through the measurements. The manufacturer of the grinding control system has announced accuracy values for the hard roll grinding. Accuracy in cross direction (CD) compensation (diameter variation) is ±2·5 μm and in machine direction (MD) compensation (roundness profile) ±2 μm.

To achieve the above accuracy there are prerequisites for the proper grinding conditions. The most important is the stability of the environmental and coolant temperatures within ±0·5°C and the absence of direct sunlight and large temperature differences. Before grinding, the temperature of the roll and the grinding machine must be stabilised.[10]

The grinding machine is equipped with an automated roll geometry four point measuring device. The four point measuring method uses four sensors in combination of a three point method and a two point method. The two point method has been used in, for example, caliper rules or measuring devices for conventional roll grinders and lathes. The three point method can be used for roundness measurements.[11] The four point method combines them in a more accurate way.[12]



6 Three-dimensional grinding machine used in present study

The measuring device is capable of measuring the diameter variation (CD profile) and the roundness profile (MD profile) of a large scale cylinder, a back-up roll, for example. The measuring accuracy is ±1 μm. According to the manufacturer, the optical length gauges in the device have a measuring accuracy of ±0·2 μm.

For data acquisition, the measurement system acquires and stores the raw measurement data in a database. The measurements can be accessed, filtered and displayed on a computer display or printer, or used for geometry error compensations while grinding.

## Calculation of sleeve spring compensation profile

The compensation profile for the 3D grinding is based on four separate finite element models of the bearing arrangement to study the shape and the order of magnitude of the spring as a function of the rotational angle of the roll. A simple model of the sliding bearing was used to determine the load distribution. A load of 10 MN was applied for each bearing. A load value of 10 MN was given from the operators of the mill as a typical load in the mill stand. Two of the four finite element (FE) models were 2D models and two were 3D models. The parabolic tetrahedron element type was used in the 3D models. Plane stress linear triangle elements were used in the first 2D model and plane stress linear quadrilateral elements in the second.

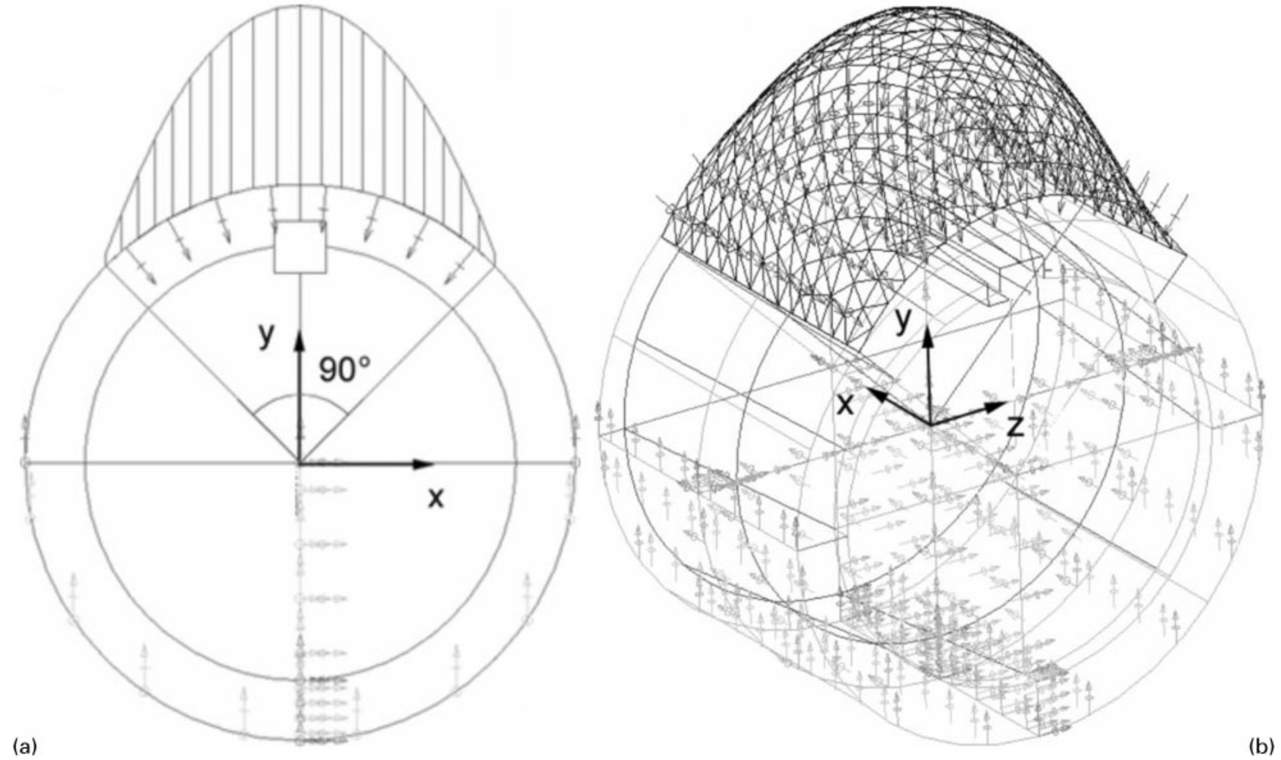
The results from the FE models were analysed. The result from the model with the plane stress triangle elements was chosen as the basis of the sleeve spring compensational profile (Fig. 7*a*). This result was chosen because it has no points of discontinuity, and it is therefore most suitable for grinding. The result, as shown in Fig. 8, was transformed to a control curve by filtering, inverting and expanding the results to cover the whole perimeter of the roll shaft. The procedure is described by equation (1).

$$y_c(c)=\begin{cases} -y_{fe}(c)\frac{S_c}{S_{max}} & (c_c-60^\circ\leqslant c\leqslant c_c+60^\circ) \\ 0 & (c<c_c-60^\circ, c>c_c+60^\circ) \end{cases} \qquad (1)$$

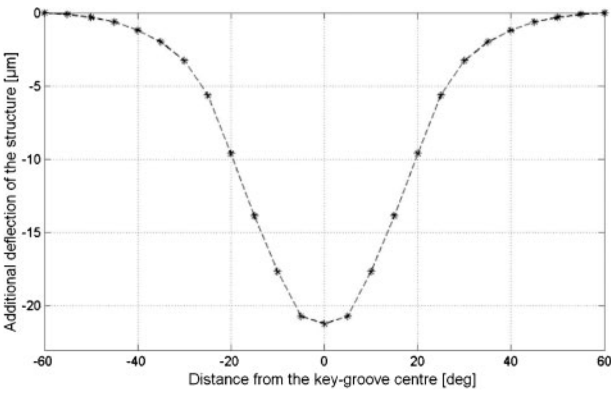
where $c$ is the rotational angle of the roll in degrees, $y_{fe}(c)$ is the result from the FE model (Fig. 8), $y_c(c)$ is the correction profile (Fig. 9), $S_c$ is the desired scale of the curve in μm, $S_{max}$ is the maximum of $-y_{fe}(c)$ in μm, $c_c$ is the angular position of the key groove centre.

The final curve for the top back-up roll was scaled to 30 μm (Fig. 9). The scale value was obtained from previous research.[3] In that study, the camlike profiles machined to the bottom and the top back-up rolls were of the same size. It was seen that the force drop decreased by 40% only. Therefore, the cam size of the bottom back-up roll was increased to 50 μm, which was the largest size accepted by the operators of the mill stand.

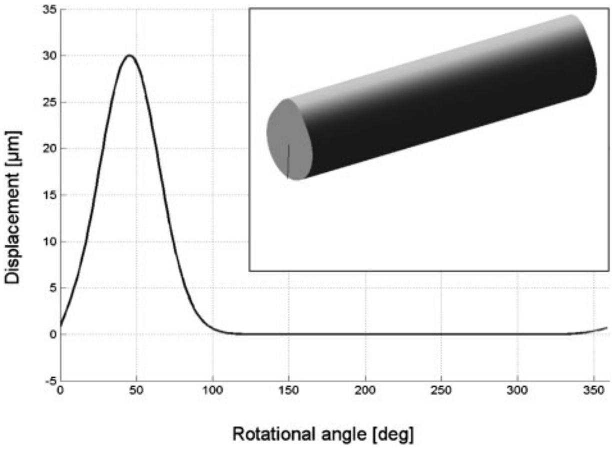
The calculated 3D compensation profile was sent to the numerical control (NC) unit controlling the tool axis and used as a tool path while grinding the roll to achieve the desired camlike geometry of the back-up roll. In Fig. 10, a measurement of the ground profile is shown.



7 Two models in FE analysis: *a* plane stress linear triangle and *b* solid parabolic tetrahedron elements



8 Result from plane stress linear triangle element analysis

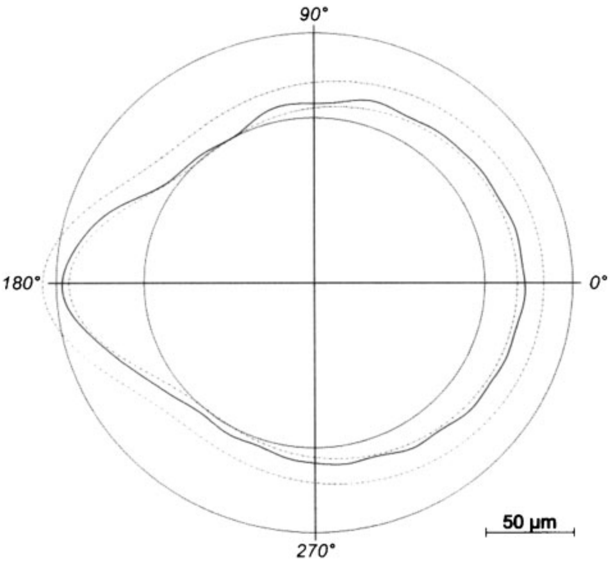


9 Calculated 30 µm 2D correction profile for each cross-section of roll shown on left side: same profile was applied to whole length of back-up roll (smaller picture)

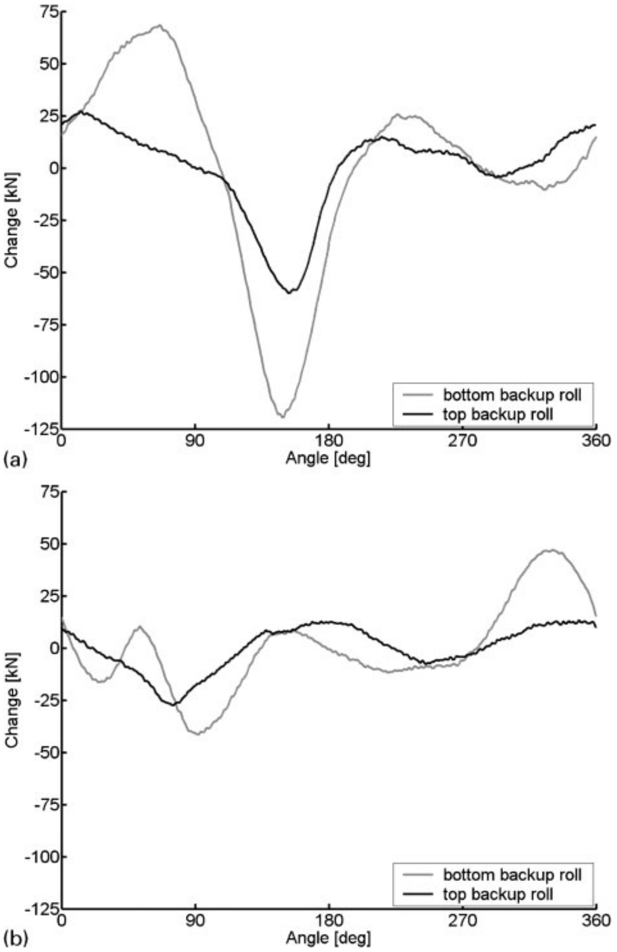
## Results and discussion

Rolling force and strip thickness were measured from typical 2·3 and 8·0 mm thick steel strips. The measuring data were analysed with synchronised time averaging, and thus all the presented results represent variations, thickness or force, synchronised to the back-up rolls.

At the beginning and end of the measurement of a strip, there are rapid level changes in the rolling force (Fig. 1*a*), therefore, 5–10 s from the beginning and the end of the measuring data were cut out because of possible interference. Results of the synchronised rolling force variation measurements from the operator side of 2·3 mm thick strips are presented in Fig. 11. Results are presented as a change of the rolling force. The phase shift present in the results in Fig. 11 is caused by



10 Measured cam profile of ground bottom back-up roll



**11 Synchronised rolling force variation of 2·3 mm steel strip measured from operator side *a* before and *b* after 3D grinding**

different placements of the triggering sensors after the 3D grinding.

Rolling force was also measured from the drive side and from the 8·0 mm strips. In Table 1, the results before and after 3D grinding are compared in all cases. In Table 2, the force variation is relative to the mean force level during milling.

The synchronised thickness variation results from the strip thickness measurements are shown in Figs. 12 and 13. In Fig. 12, the target strip thickness is 2·3 mm, while in Fig. 13 it is 8·0 mm. A phase shift is also present in these results because of different placements of the trigger sensors and different positions of the key grooves relative to the strip head. The results are filtered by FFT filtering with 16 harmonics. All the thickness variation results are summarised in Tables 3 and 4.

The study showed that this method can reduce systematic force and thickness variations caused by the key groove. The best results would probably have been obtained if the method had been extended to all the mill stands. If the force and thickness data were analysed in the frequency domain, other systematic variations in the rolling force might have been found, some of them probably caused by the working rolls, which were excluded from the present study. If other systematic variations are found in further research, it should be possible to compensate them by this method.

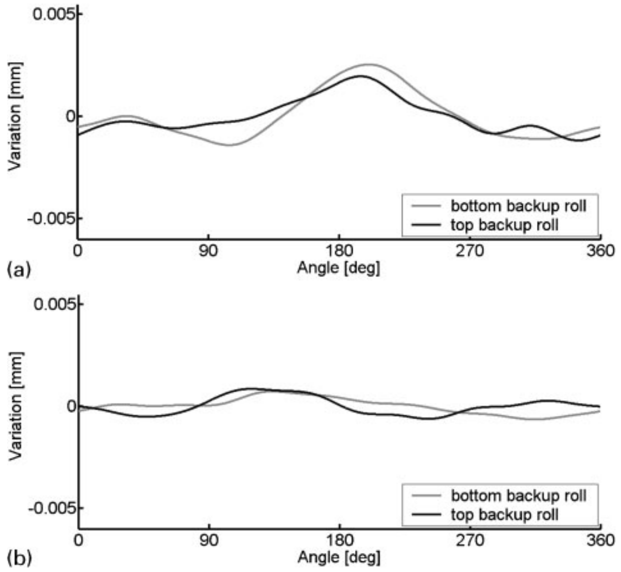
The thickness and the quality of the end product affect the force variation of the mill stand. Thus, to

**Table 2 Synchronised rolling force variation results before and after 3D grinding relative to mean milling force**

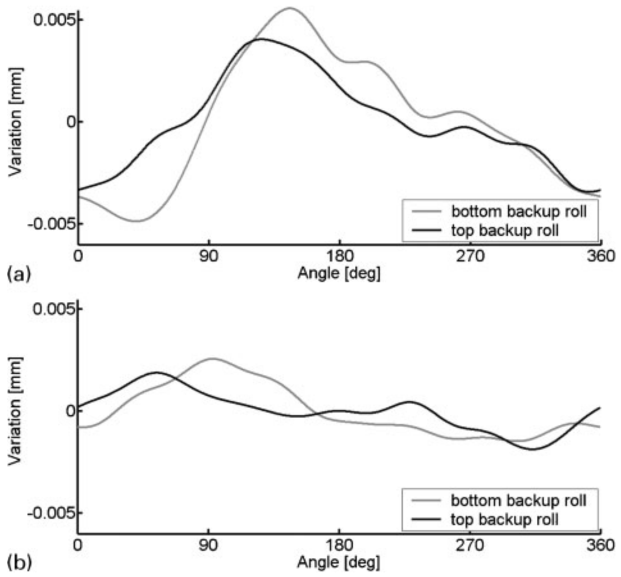
| Side | Back-up roll position | Strip thickness, mm | Force variation, % |  | Reduction, % |
|---|---|---|---|---|---|
|  |  |  | Before | After |  |
|  |  |  | Three-dimensional grinding |  |  |
| Drive | Top | 8·0 | 1·12 | 0·55 | 51 |
| Operator | Top | 8·0 | 1·15 | 0·38 | 67 |
| Drive | Bottom | 8·0 | 1·77 | 0·80 | 55 |
| Operator | Bottom | 8·0 | 1·78 | 1·06 | 40 |
| Drive | Top | 2·3 | 1·20 | 0·56 | 53 |
| Operator | Top | 2·3 | 1·37 | 0·63 | 54 |
| Drive | Bottom | 2·3 | 2·03 | 1·10 | 46 |
| Operator | Bottom | 2·3 | 2·96 | 1·37 | 54 |

**Table 1 Synchronised rolling force variation results**

| Side | Back-up roll position | Mean rolling force level, kN | Force variation, kN | Number of strips (total number of roll revolutions) |
|---|---|---|---|---|
| Before 3D grinding, 8 mm strip thickness |  |  |  |  |
| Drive | Top | 5141 | 57·5 | 3 (172) |
| Operator | Top | 5147 | 59·3 |  |
| Drive | Bottom | 5141 | 91·1 | 3 (169) |
| Operator | Bottom | 5147 | 91·9 |  |
| Before 3D grinding, 2·3 mm strip thickness |  |  |  |  |
| Drive | Top | 6635 | 79·8 | 7 (1355) |
| Operator | Top | 6342 | 87·0 |  |
| Drive | Bottom | 6635 | 134·9 | 7 (1335) |
| Operator | Bottom | 6342 | 187·9 |  |
| After 3D grinding, 8 mm strip thickness |  |  |  |  |
| Drive | Top | 8164 | 44·6 | 6 (201) |
| Operator | Top | 7869 | 29·8 |  |
| Drive | Bottom | 8164 | 65·4 | 6 (202) |
| Operator | Bottom | 7869 | 83·3 |  |
| After 3D grinding, 2·3 mm strip thickness |  |  |  |  |
| Drive | Top | 6873 | 38·2 | 8 (1561) |
| Operator | Top | 6446 | 40·6 |  |
| Drive | Bottom | 6873 | 75·7 | 8 (1588) |
| Operator | Bottom | 6446 | 88·6 |  |



**12 Synchronised thickness variation of 2·3 mm steel strip measured *a* before and *b* after 3D grinding**



**13 Synchronised thickness variation of 8·0 mm steel strip measured *a* before and *b* after 3D grinding**

achieve the best results, the back-up rolls should be ground with an optimised cam profile every time the quality and the thickness of the steel changes. In most cases, this is not possible. In practice, the cam profile could be optimised for the most common steel quality and thickness, while still not negatively affecting other qualities.

**Table 3 Synchronised strip thickness variation results**

| Back-up roll position | Strip thickness, mm | Thickness variation, μm | Number of strips (total number of roll revolutions) |
|---|---|---|---|
| Before 3D grinding | | | |
| Top | 2·3 | 3·1 | 7 (1355) |
| Bottom | 2·3 | 3·9 | 7 (1335) |
| Top | 8·0 | 7·5 | 3 (172) |
| Bottom | 8·0 | 10·4 | 3 (169) |
| After 3D grinding | | | |
| Top | 2·3 | 1·5 | 8 (1588) |
| Bottom | 2·3 | 1·4 | 8 (1561) |
| Top | 8·0 | 3·8 | 6 (201) |
| Bottom | 8·0 | 4·0 | 6 (202) |

**Table 4 Relative strip thickness variation results of nominal thickness before and after 3D grinding with FFT filtering**

| | | Thickness variation, % | | |
|---|---|---|---|---|
| | | Before | After | |
| Back-up roll position | Strip thickness, mm | Three-dimentional grinding | | Reduction, % |
| Top | 2·3 | 0·14 | 0·06 | 53 |
| Bottom | 2·3 | 0·17 | 0·06 | 65 |
| Top | 8·0 | 0·09 | 0·05 | 46 |
| Bottom | 8·0 | 0·13 | 0·05 | 64 |

## Conclusions

A common practice in setting up hot strip mill back-up roll bearings is to attach the conical sleeve of the sliding bearing to the roll's shaft by a key. The key groove required by the key causes deformation of the sleeve under load. This sleeve spring is one of the causes for rolling force and steel strip thickness variations. The obvious solution is to use keyless bearings, but in the present work an alternate solution using non-symmetrical grinding was tested. The proposed method could be used to compensate for asymmetries caused by any other causes as well, not limiting its applicability to compensating effects of key grooves only.

A non-circular, camlike geometry was ground to the back-up rolls to reduce the rolling force variation caused by the key groove. The effect of the reduced rolling force variation to the steel strip thickness variation was examined. The empirical research took place at a hot strip mill. As a result, both the rolling force and the steel strip thickness variations synchronised with the back-up rolls of the mill stand under study were reduced by 46–65%. The effect of extending this method to all the mill stands of a rolling mill, as well as the usefulness of this method to reduce rolling force and strip thickness variations caused by other sources, should be further studied.

With the studied steel qualities and strip thicknesses the achieved reduction of the thickness variation has almost no effect to the processibility of the strips. With thinner steel qualities the reduction of the thickness variation is more important especially with the harder steel alloys. Steel strips with less thickness variation excite fewer vibrations with higher production speeds, thus increasing the runnability and the productivity of a rolling mill stand in the further processing on a cold steel mill.

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