We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

154
Countries delivered to

Our authors are among the

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities

CLARIVATE ANALYTICS
BOOK CITATION INDEX
INDEXED

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Finite element analysis of strip and rolling mills

Jian-guo CAO, Jie ZHANG, Ning KONG and Kai-fu MI

School of Mechanical Engnieering, University of Science and Technology Beijing

P.R.China

1. Introduction to rolling process of strip

In metalworking, rolling is a metal forming process in which metal stock is passed through a pair of rolls. Compared with forging, extrusion, drawing and other processes, rolling has been more widely applied by high productivity, variety, continuity of the production process, easy mechanization and automation and information advantages.Steel is the largest consumption metal materials. Currently, about 90% of the steel is rolled into strip, section, tubes and wires and so on. As the backbone of steel products, strip that is so-called "universal steel" has widely been used in national economic departments of major products. Rolling of strip is classified according to the temperature of the metal rolled. If the rolling temperature of the metal is above its recrystallization temperature, then the process is termed as hot rolling. If the temperature of the steel is below its recrystallization temperature, the process is termed as cold rolling. In terms of usage, rolling processes of strip play an important roll in the manufacturing industry.

1.1 Hot rolling process

The whole hot rolling process is shown in Fig.1. This casting slab is room temperature in common and when it is taken into the hot rolling process, it should be heated in the heating furnace. In this stage, the slab must be heated to the temperature between 1050 and 1280℃. The temperature must be monitored to make sure it remains up to the temperature required, and then it will be taken out of heating furnace by slab extractor and moved to the next stage called descaling by high pressure water. When the slab is moved to the descaling box by roll table, the high pressure water flushes the slab so as to remove the iron oxide skins and avoid scratching the rolls and strip. The following stage is rough rolling process. It often contains one or two roughing mills in which the slab is hot rolled reversibly. When the slab arrives, it will be rolled 5 or 7 times repeatedly to reach the thickness requirement. What is also worth mentioning is that the roughing mill contains edger rolls which are used to roll the edge of slab and center it. After rolled by the roughing mill, the slab is called transfer bar

Jian-guo CAO; Ph.D.; Professor; Tel.+86-10-62332835; **E-mail:** geocao@ustb.edu.cn

in common and it goes to which can uniform the temperature and decrease temperature drop of the whole transfer bar. Then the transfer bar will be cut the front and end by flying shear. The later stage is finishing rolling process which is the most important and complex process in hot rolling. This part contains seven 4-high rolling mill stands from F1 to F7, which contains kinds of effective control methods such as shifting and bending of work rolls. Transfer slab is rolled by the seven mill stands so as to reach the strip control requirements and then goes to the laminar cooling section. In this section, the strip will be cooled to the required temperature according to mechanical properties needed. The last stage is coiler, and then the strip will be sent to the product room. Also, some strips should be rolled by temper mill if needed and after that the whole hot rolling process is finished.

Hot rolling is used mainly to produce hot rolling strip steel, which provides to the raw material of cold rolling and to the process of equipment such as container.
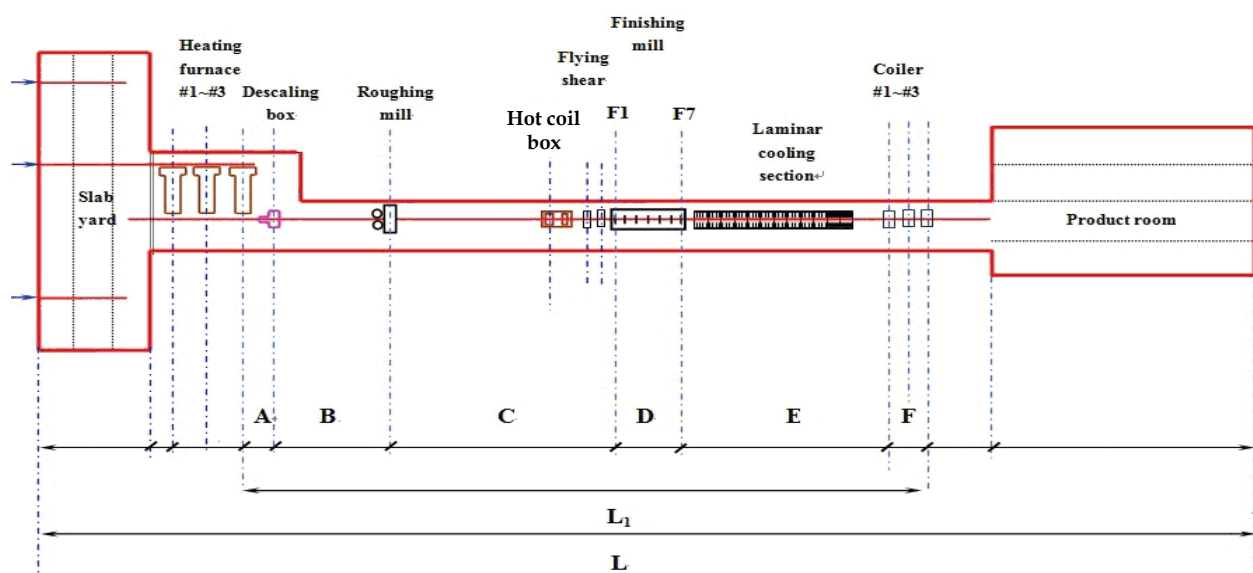

Fig. 1. Layout diagram of main equipment in hot rolling process

1.2 Cold rolling process

Cold rolling occurs with the steel below its recrystallization temperature (usually at room temperature), which increases the strength via strain. It also improves the surface finish and holds tighter tolerances. Commonly cold-rolled strips are usually thinner than the same products that are hot rolled. Because of their smaller size and greater strength, as compared to hot-rolled strips, 4-high, 6-high or reversing mills are used. But cold rolling cannot reduce the thickness of strips as much as hot rolling process. The whole cold rolling process reveals as follows.

Raw material of cold rolling is Hot-rolled strips. Steel strips are welded one after another by welder so that they are linked together. This is so called continuous rolling. These continuous strips are then sent to the pickling section for removing the iron oxide skins by sulfuric acid or hydrochloric acid in common. After that, the strips will be cleaned, dried, cut edge and sub-volumed. After acid washing machine, in order to roll the strips to final thickness and required strip profile and flatness, strips should be rolled by 4-high or 6-high tandem cold rolling mill of five stands named from S1 to S5 while generally without any intermediate annealing. In this stage, it takes into account of strip quality, rolling force,

allocated reduction and other factors for this tandem rolling process. The following stage is annealing used to eliminate cold hardening and soften the recrystallization strip steel so as to acquire the good ability of plasticity. The next stage is rolling the strip by temper mill. The last stage is galvanizing, tinning or colour coating of the cold-rolled strips, according to the requirements. Then these strips will be cut and packaged and the whole tandem cold rolling process is finished.Cold rolling is used mainly to produce cold-rolled strip, which provides to the production of auto sheet, home appliances sheet, electrical steel pieces and so on.

The main deformation processes of wide strip are rough and finishing rolling process of hot strip mills, tandem cold rolling process. New generation high-tech mills for profile and flatness control in wide strip rolling, such as 4-high or 6-high CVC (continuously variable crown) mill, SmartCrown mill,K-WRS(kawasaki steel work-roll shifting) mill,ASR(asymmetry self-compensating rolling) mill, UCM(universal crown mill),UCMW mill includes an work roll shifting system in addition to the strip profile and flatness functions that are provided in the UCM mill, ECC(edge drop & crown compact) mill, T-WRS&C(taper work roll shift and cross) mill(Ginzburg V. B.,1993; Chen X.L. 1997;Cao J.G.,2006), have been developed and applied to the production of strip.

2. Finite element analysis of spalling on the backup roll of a roughing mill for stainless steel

Rolls are the important consuming parts that affect the efficiency of large industrial mills and the quality of mill products. The accidents of rolls, such as spalling, cracks and roll breakage, may happen during the service period, in which spalling is the primary form of damage(Li, H.C.,2007). There are a lot of factors that could lead to roll spalling including thermal shock loads, unreasonable distribution of roll surface pressure , rolling accidents, and inadequate cooling and so on(Ray, A.K.,2000;Chen, S.G., 2006).

2250 HSM(hot strip mill) of TISCO (Taiyuan Iron & Steel (Group) Co. LTD.) in China put into operation on June 29, 2006. The annual capacity of 2250 HSM is 4 million tons including 2 million tons of stainless steel, which is the largest stainless steel production equipment, and is the most advanced technology and most complete hot rolling production line in the world. This strip mill just set up a roughing mill for adapting to the stringent requirements on the temperature when rolling stainless steel slab, which leads to harsh conditions of rolling process, rolling difficulty, the complex mechanical behavior during service periods and less stable rolling process control performance. This roughing mill Occurred continuously 3 spalling accidents in a month, and each accident not only causes direct economic losses but also incident handling time is up to 2h even 5 ~ 6h, which directly threat to a long-term stable and normal operation of the 2250 HSM production line. So the study of spalling on the backup roll of a roughing mill for stainless steel sheet has important theoretical significance and engineering applications.

2.1 Backup roll spalling of 2250 roughing mill

3 spalling accidents occurred continuously in this roughing mill within a month of 2250 HSM on March 8, April 4 and April 8 , 2008, e.g., the roughing rolls diameter of which is 1552mm occured serious edge spalling in the April 4,2008, the circumferential length of spalling is 4023mm(reached more than 82% of perimeter), the axial width is 1250mm(reached half of the length of roll body) and the maximum radius depth is

185mm(far more than the use range of the layer radius thickness 80mm of the new backup roll). The actual spalling fracture appearances are shown in Fig.2.

Fig. 2. Spalling of backup rolls in roughing mill of 2250HSM

A lot of tracking tests on the work roll and backup roll wear contours of the roughing mill have been finished. In general,work roll wear contours are the U-typed wear and the partial peak exists. Backup roll wear is generally non-uniform along the entire length of the roll barrel and there are overall and local backup roll wear contours, i.e. "cat ear" near strip edges.

Through the above analysis shows:(1)The alternating shear stress of A certain depth from the roll surface caused by roll contact pressure is the key reason of the backup roll spalling;(2)Spalling usually occurs in the maximum contact pressure area. The U-typed wear of conventional rolls makes contact stress between the edge of backup and work rolls increase significantly, contact stress between rolls in the middle of the roll had little change and spalling in the edge of the roll occurs sometimes. So the ideal solution is obtains uniform axial contact pressure distribution by improved backup roll and work roll contours(Cao, J. G.,1999).

2.2 Finite element analysis of backup roll spalling

A 3D FEM model of the rolls system should be modeled for the full analysis to 2250 wide strip roughing mill. The finite element model based on ANSYS softpackage(specific unit allocation of finite element model is shown in Table 1) is shown in Fig.3 (Yang, G.H., 2008). Axial distribution of contact stress between work roll and backup roll could be influenced by strip width, unit width rolling force and wear in different service period, and the above factors are analyzed individually by this model.
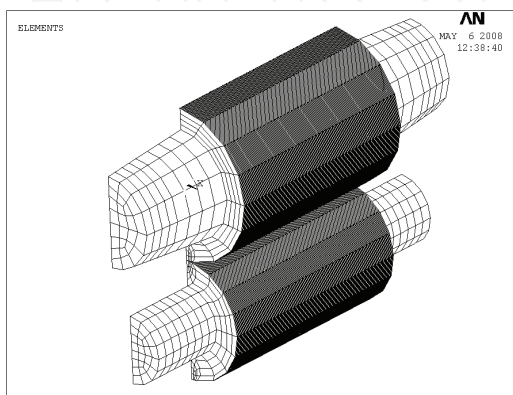

Fig. 3. Three-dimensional finite element roll system model of a 4-high mill

Work Roll	Number of solid elements	20184
	Number of contact elements	900
Backup Roll	Number of solid elements	15684
	Number of contact elements	900
The total number of units		35868
The total number of nodes		68814

Table 1. Unit allocation of finite element model

Fig.4 shows the axial distribution of contact stress between rolls of different strip width when unit width rolling force is 25kN/mm, and adopts the backup roll contour provided by SMS group. It could be known by comparative analysis: the peak of contact stress between rolls gradually increases with the increase of strip width. When the strip width B changes from 1010mm to 2050mm, the peak of contact stress between rolls increase 106.3%. Distribution trends of contact stress between rolls are the same for different width strips, and the non-uniformity coefficient of contact stress distribution between rolls are respectively 1.36, 1.38 and 1.41. It could be seen by analysis of contact pressure between rolls that the peak position of contact stress between rolls is essentially the same which is about 200mm from the edge side of backup roll barrel.
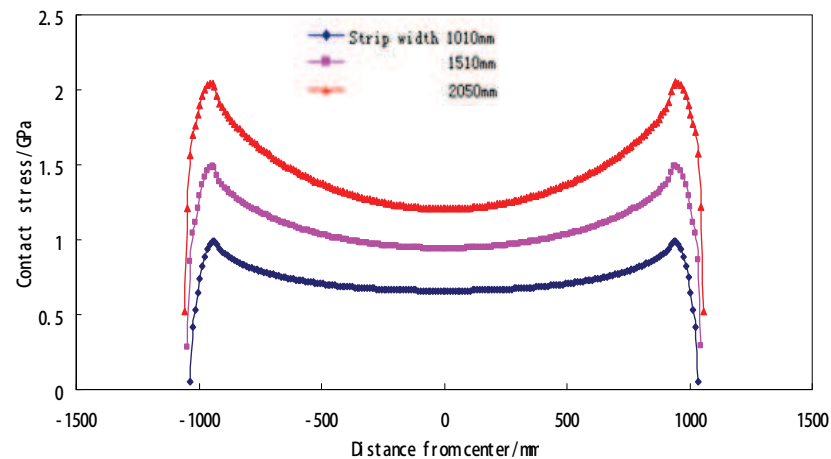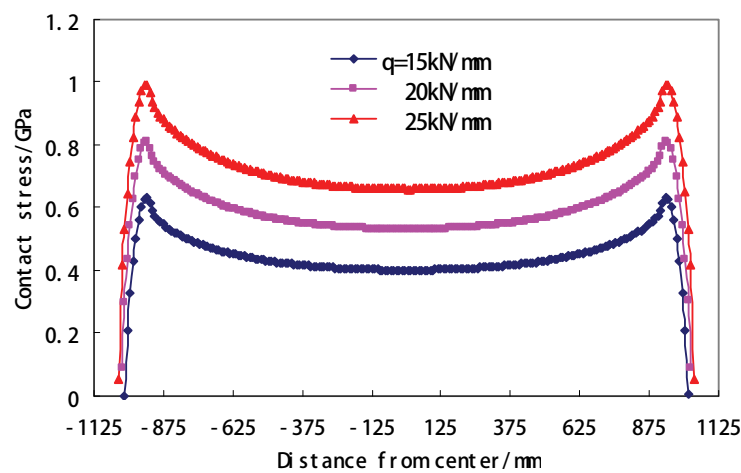

Fig. 4. Contact stress distribution of different strip width（q=25 kN /mm）

Fig. 5 shows the axial distribution of contact stress between rolls for the strip width 1010mm, 1510mm, 2050mm, when rolling force per strip width is 15kN/mm, 20kN/mm and 25kN/mm, and adopts the backup roll contour provided by SMS group. It could be known by comparative analysis: when the rolling force per strip width changes from 15kN/mm to 25kN/mm, the peak of contact stress between rolls increase respectively by 56.8%, 60.7%, 59.3% for the strip width 1010mm, 1510mm and 2050mm, the non-uniformity coefficient of contact stress distribution between rolls decreases with the increase of the unit width rolling force, the non-uniformity coefficient decreases respectively from 1.42 to 1.36, from 1.41 to

1.38, from 1.45 to 1.41 for the strip width 1010mm,1510mm and 2050mm. Distribution trends of contact stress between rolls are the same for different rolling force per strip width, and the peak position of contact stress between rolls is essentially the same which is about 200mm from the edge side of backup roll barrel.

Fig. 6 shows the axial distribution of contact stress between rolls when the rolling force per strip width is 25kN/mm, work roll and backup roll are at different wear periods and adopts the backup roll contour provided by SMS group. WR signifies work roll, BR signifies backup roll, G signifies the roll contour in the early service period, W signifies the roll contour in the late service period. The three conditions in this figure is respectively: work roll adopts the contour in the early service period and backup roll adopts the contour in the late service period; work roll and backup roll both adopt the contour in the early service period; work roll and backup roll both adopt the contour in the late service period. It could be known by comparative analysis: when work roll is in the early service period, the peak of contact stress between rolls is slightly increases but not significantly as backup roll is in the late service period than in the early service period for the strip width 1010mm, 1510mm and 2050mm, and the asymmetry degree of contact pressure distribution between rolls basically
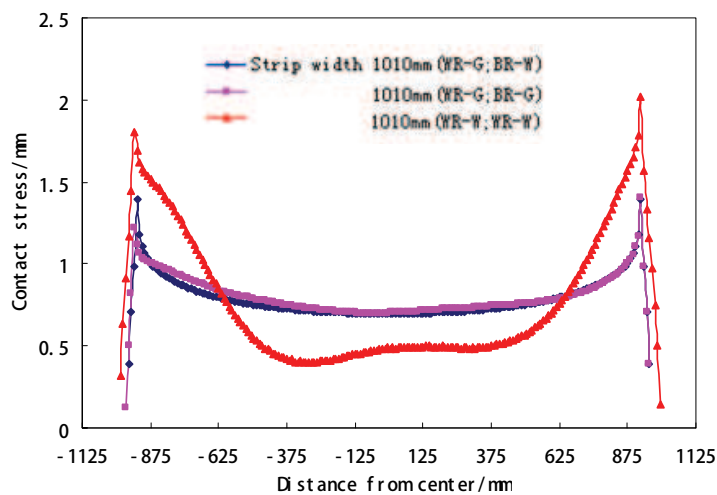
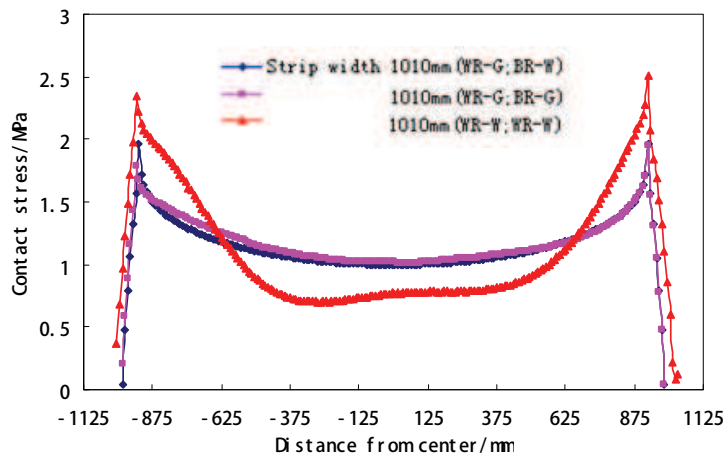

(a) Strip width 1010mm
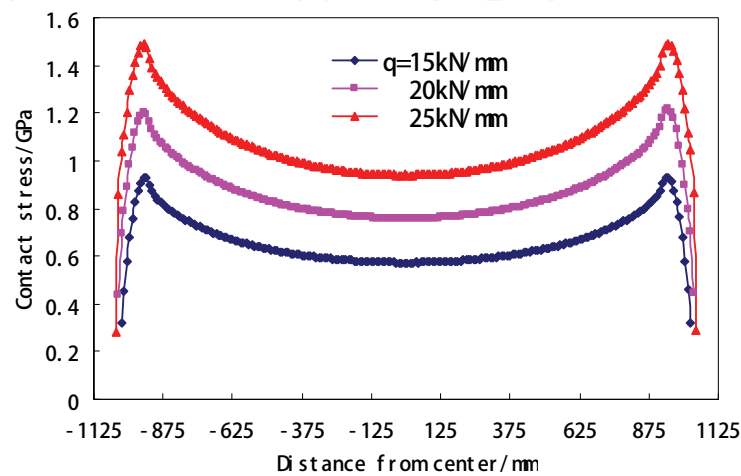
(b) Strip width 1510mm
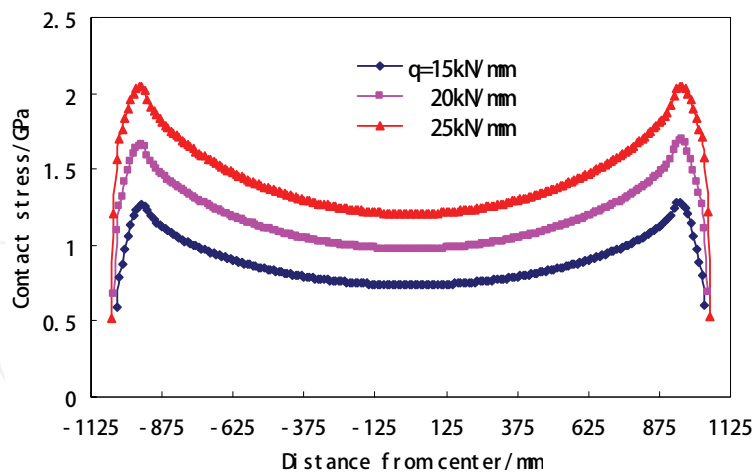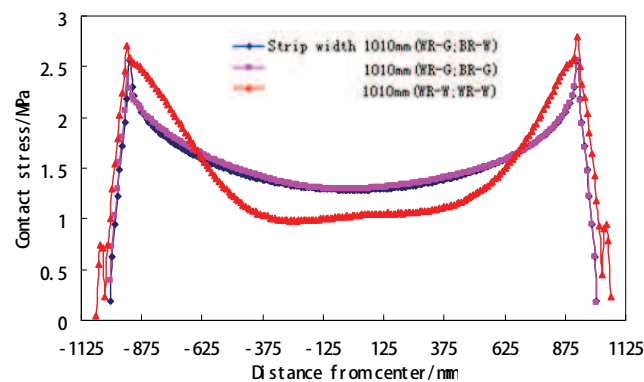
(c) Strip width 2050mm

Fig. 5. Contact stress distribution of different rolling force

(a) Strip width 1010mm

(b) Strip width 1510mm

(c) Strip width 2050mm
Fig. 6. Contact stress distribution of different service period

unchanged. When work roll and backup roll both are in the early service period, the peak of contact stress between rolls increase very significantly, the range of which is respectively 43.7%,28.5% and 9.2%. The asymmetry coefficient of contact stress distribution between rolls increases respectively from 1.76 to 2.61, from 1.68 to 2.26, from 1.66 to 1.95. In comparison, there is greater impact by the wear when rolling narrow strip.

2.3 Simulation Conclusions

The simulation results show: the peak of the roll contact stress increase sharply when strip width and rolling force per width changing. And the peak and the dissymmetry of the roll contact stress increase when the work rolls and backup rolls are at the middle and late stage of the rolling campaign. Further more, there exists peak stress at the edge of backup roll at a distance of 200mm, which closes to actual experiences. Based on this study, according to the principle of varying contact rolling (Chen, X.L. ,1994,2000),The SCR (smart contact backup rolls) and matching work roll contours for different stage of rolling campaigns technology have been developed and applied to the 2250 hot strip mill at TISCO of China and gains a good result without spalled backup rolls during the continuous production of 6.082 million tons and more from July 4, 2008 until now.

3. Finite element analysis of roll contour configuration on the flatness control performance of non-oriented electrical steel sheets in hot strip rolling mills

Cold-rolled non-oriented electrical steel sheet, widely used as an iron core in electric devices, automobile motors and reactors, is given priority to development by China. National key production base of cold-rolled non-oriented electrical steel sheet, i.e. WISCO(Wuhan Iron & Steel (Group) Corp.),Baosteel(Shanghai Baosteel Group Corp.), TISCO(Taiyuan Iron & Steel (Group) Co. LTD.), and ANSTEEL(Angang Steel Co. LTD.), are expending production capacity of cold-rolled electrical steel sheet and other backbone enterprises which have the potential productivity are to plan and prepare production lines of cold-rolled electrical steel sheet. Recently with the automation level and energy requirements improvement of industrial users, the precision of profile and flatness of cold-rolled non-oriented electrical steel sheet is becoming an important factor in determining strip quality and mill

productivity. According to industrial tracking test results and theory study, we found that the finishing rolling process of HSM is the critical procedure of profile and flatness control performance of non-oriented electrical steel sheets(Cao, J. G. & Ou, Y.Y., 2005; Cao, J. G.,2006). In the chapter, we investigated the 1700mm hot rolling mill in WISCO that have produced the largest amount and the most comprehensive available cold-rolled electrical steel sheets in China. The finite element models were developed to calculate the profile and flatness control performance of different typical roll contours configurations in 1700 HSM.

3.1 Roll contour configuration and variety on electrical steel sheets in hot rolling

The 1 700 mm hot strip mill at WISCO was designed and built by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) and was commissioned in 1978. From 1992 to 1994, the mill completed a series of upgrades,i.e the profile and flatness control system and mathematics model of high precision, on the finishing mill supplied by SIEMENS VAI CLECIM. The mill is one of the largest hot strip mills in China with a capacity of 3.45 Mt/y. The control system has the following characteristics after a series of upgrades: F4 through F7 apply K-WRS with a long stroke work roll shifting system (±150mm), work roll heavy-duty bending system(200t/chock), conventional backup and work rolls. From 1997 to 2000, VCR (varying contact backup rolls) technology developed by USTB and WISCO has applied to F1 through F7 of 1700mm HSM(Chen, X.L.,2000). The rolling period of a newly ground backup roll set in hot strip mills exceeds two weeks,the varying contact backup rolls,being geared to different steel kinds and sizes,only go halfway towards solving the problem of significant transverse thickness profile difference by wear contour patterns of conventional work roll contours. From 2003 to 2008, the developed ASR (asymmetry self-compensating work rolls) technology has applied to to the production of 2.3 mm×1 050 mm conventional width electrical steel sheets rolling campaign successfully since November 2004 (Cao, J. G.,2006) and 2.3 mm×1200-1300 mm wide electrical steel sheets rolling campaign since October 2005 (Cao, J. G.,2008). The 4-high ASR mill with work roll shifting devices is functionally superior to other mills,such as CVC mill,SmartCrown mill and K-WRS mill, when they have ability of both wear control and overall profile control covering the strip crown, edge drop and high spot in downstream stand and suitable to the schedule free rolling of hot strip mills. The ASR work roll contours for stand F5 of 1700 hot strip mill with a 72-coil elertrical steel rolling campaign is shown in Fig.7.
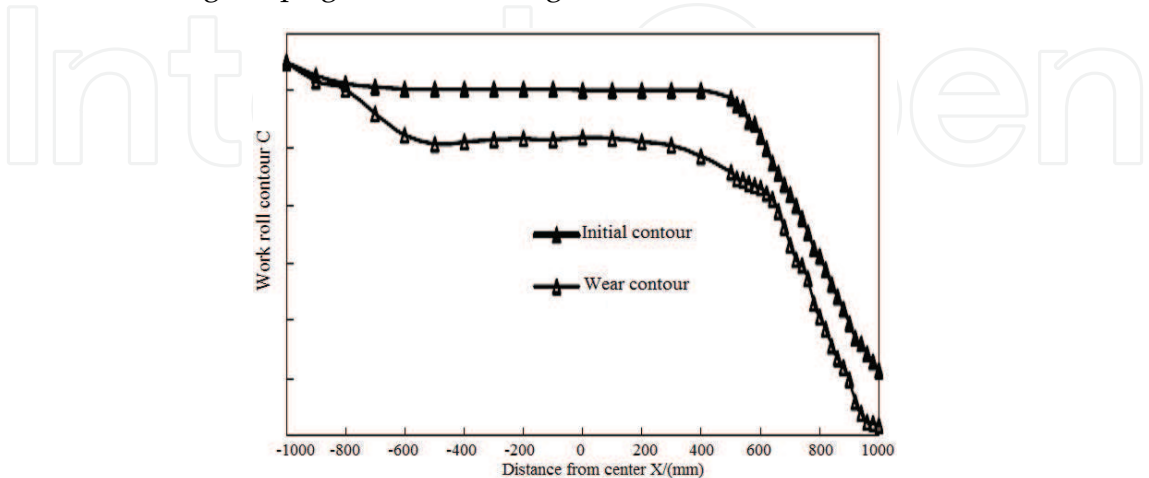

Fig. 7. ASR work roll contours for stand F5 of 1700 hot strip mill with a 72-coil elertrical steel rolling campaign(2.55mm×1280mm)

During rolls servicing period, the change of work roll and backup roll contours which are resulted by wear and thermal expansion are important conditions that determine the mill type and control ability. The CVC and SmartCrown mill can provide a wide crown control range that is incapable of the wear control. The severe wear of work roll in downstream results in the failure and distortion of crown control ability for CVC, SmartCrown and CVC plus mills. The K-WRS mill is an effective way to alleviate the severe work roll wear contours by application of long stroke work roll shifting system with conventional work roll contours that is incapable of the crown control. In this chapter, we investigated three typical roll contour configurations of hot rolling mills in downstream stands for non-oriented electrical steel sheets in 1700 mm HSM, i.e. conventional backup/work rolls of K-WRS mill, VCR/conventional work roll contours, and VCR/ASR contours of ASR mill.

Fig. 8 shows the work roll contours measured in the conventional work roll (initial and wear contours) on the F5 stand in the rolling of the non-oriented electrical steel sheets and the match temperature of the work rolls. Conventional backup roll contours of 145 rolls, VCR of 94 rolls, conventional work roll contours of 37 rolls and ASR of 14 rolls that were used in WISCO 1700mm hot finishing mill have been measured. According to the large amount of comparison of work roll and backup roll (initial and wear contours), the following conclusions can be concluded: (1)The roll wear contour did not come out the "cat ear" roll contour from F1 through F3, but the roll wear contours, i.e. "cat ear" near strip edges(about -500m to 500mm near strip edges), were significant from F4 to F7; (2) A maximum value of the work roll wear appears in stand F4, whereas the rolls in stands F1 and F3 show a very small increase in roll wear and the rolls in standsF5, F6 and F7 wear rapidly but smaller than those in stand F4; (3) Comparing to conventional strip, the value of work roll wear contour of non-oriented electrical steel sheets was larger, even reached to two times or three times larger; (4) If the conventional backup roll was applied, it would cause uneven wear resulting in bad self-maintenance of the roll contour from the top to the end stands; (5)If VCR was applied, the work roll wear is generally uniform along the entire length of the roll barrel.
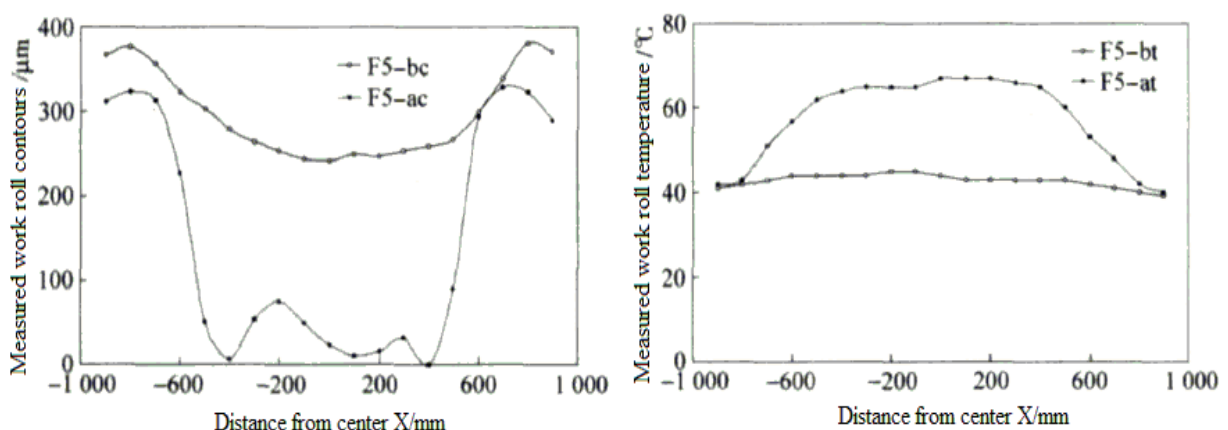

Fig. 8. Measured work roll contours and surface temperatures of non-oriented electrical steel sheet rolling campaign

3.2 Finite element analysis model of the roll stacks

In order to analyze the effect of roll contour configuration on the profile and flatness control performance of non-oriented electrical steel sheets in hot rolling, the two-dimensional finite

element analysis model with varying thickness of the 4-high hot finishing mill system,as shown in Fig. 9, was developed for effect of typical roll contour configuration on the
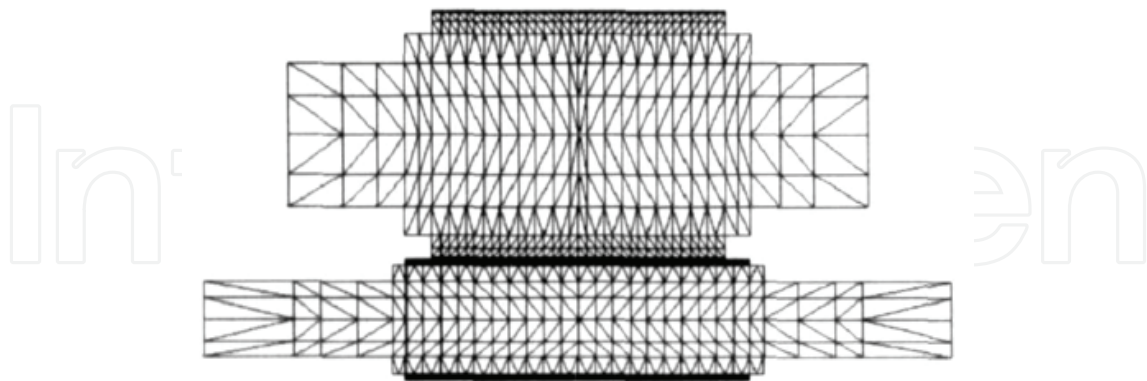

Fig. 9. Two-dimensional finite element model with varying thickness of roll stacks in 1 700 mm hot strip mill

characteristics of roll gap profile. In the model, adaptive contact elements are set at the contact interface between rolls, equivalent thickness on theory are set according to the equal principle of anti-flattening, and the thickness of physical units in each layer of the rolls is set by the equivalent principle of anti-bending modulus. The model has characteristics of high accuracy, fast calculating speed and a wide range engineering applications.

3.3 Profile and flatness control performance of electrical steel in hot rolling

As the disturbance variables,such as the change in roll contours,strip width and the roll force fluctuation, exist during the rolling, especially in downstream stands, leading to the variation of the roll gap crown, they are expected that the crown control range by the roll bending force can increase and the roll gap can maintain its crown relatively stable.The roll gap stiffness can be defined as the ratio of the roll force fluctuation to the correspondingly change of the roll gap crown. The effect of roll contours configuration of the ASR mill on characteristic of roll gap profile applied in 1 700 mm hot strip mill (F5) is shown in Fig 10. In Fig.10, CN represents conventional backup and work rolls of the K-WRS mill, 0% of roll bending force; CX represents conventional backup and work rolls of the K-WRS mill, 100% of roll bending force; VN represents varying contact backup rolls and conventional work rolls, 0% of roll bending force; VX represents varying contact backup rolls and conventional work rolls,100% of roll bending force; AN represents varying contact backup rolls and asymmetry self-compensating work rolls of the ASR mill,0% of roll bending force; AX represents varying contact backup rolls and asymmetry self-compensating work rolls of the ASR mill, 100% of roll bending force. It can be seen from Fig.10 that the crown control range
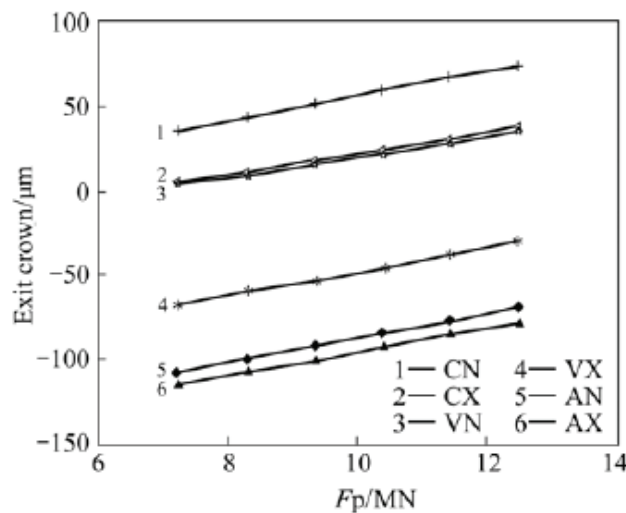
Fig. 10. Effect of typical roll contour configuration of the rolling mill on the characteristic of roll gap profile applied in a 1700mm hot strip mill

by the roll bending force on stand F5 with varying contact backup rolls and conventional work rolls,i.e.the area between the lines VN and VX, is enhanced from 103.5μm before application of varying contact backup rolls to 112.0μm,increased by 8.23% compared with that of the lines CN and CX with conventional backup and work rolls of the K-WRS mill.The crown control range by the roll bending force in the ASR mill, i.e. the area between the lines AN and AX,is 116.7μm, increasing 12.79% greater than that with conventional backup and work rolls of the K-WRS mill.And at the same time the roll gap stiffness shows an increase from 0.1350 MN/μm with conventional backup and work rolls to 0.1578 MN/μm with VCR and conventional work rolls,and to 0.1691 MN/μm by increasing 25.26% in the ASR mill (Cao, J. G.,2008).

The "as-ground" work roll contour is designed by the operators and provides effects on the strip crown magnitude during the initial phase of rolling campaign. The roll thermal contour is a result of thermal expansion during hot rolling that consists of basic and periodic components. Since the periodic component is localized on the roll surface, the roll thermal contour is usually taken into account the basic component only. Based on the statistical analysis of the data obtained during rolling at the 1 700 mm hot strip mill, the roll thermal crown increases rapidly during the first 10 coils in a rolling campaign and amounts to the maximum steady value exceeding 300 μm after rolling 30 coils (about 60 min) during the steady rolling pace that comprises of the rolling time and the idle or gap time between rolling of coils. If there are some changes during rolling, such as rolling pace, variations in strip width and cooling water temperatures, small but rapidly varying changes in the roll thermal contour occur. Work roll wear effect is another major reason for the variation of the roll contour during rolling of a hot strip mill cycle. As can be seen from the collected data, the work roll wear is generally non-uniform along the entire length of the roll barrel. There are different work roll wear contours for different stands. Generally speaking, work roll wear of electrical steel rolling campaign increases greater than that of other rolling campaign. Fig. 11 shows flatness control efficiency curves of typical roll contours configuration applied in F5 in a 1700 mm hot strip mill, in which the rolling force is 10.4 MN and the bending force is 800 kN per chock. In Fig. 11, BW-G represents conventional backup

and work roll inintial ground contours and BW-W represents conventional backup and work roll comprehensive contours including wear contour and thermal expansion after a rolling compaign.VW-G represents VCR and conventional work roll inintial ground contours and VW-W represents VCR and work roll comprehensive contours including wear contours and thermal expansion after a rolling compaign. VA-G represents VCR and ASR inintial ground contours and VA-W represents VCR and ASR comprehensive contours including wear contours and thermal expansion after a rolling compaign.
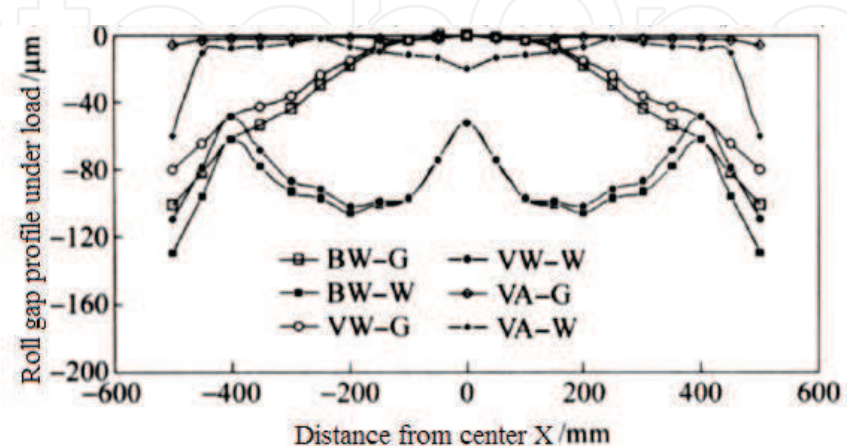

Fig. 11. Flatness control efficiency curves of typical roll contour configuration applied in a 1700mm hot strip mill

It can be seen from Fig. 11 that significant change of roll gap profile with conventional work and backup roll contours in downstream stands of hot rolling lead to non-oriented electrical steel transverse thickness profile difference, i.e. body crown and especially edge drop (Fig.12). It is hard to meet the improvement requirement of industrial users to the quality of
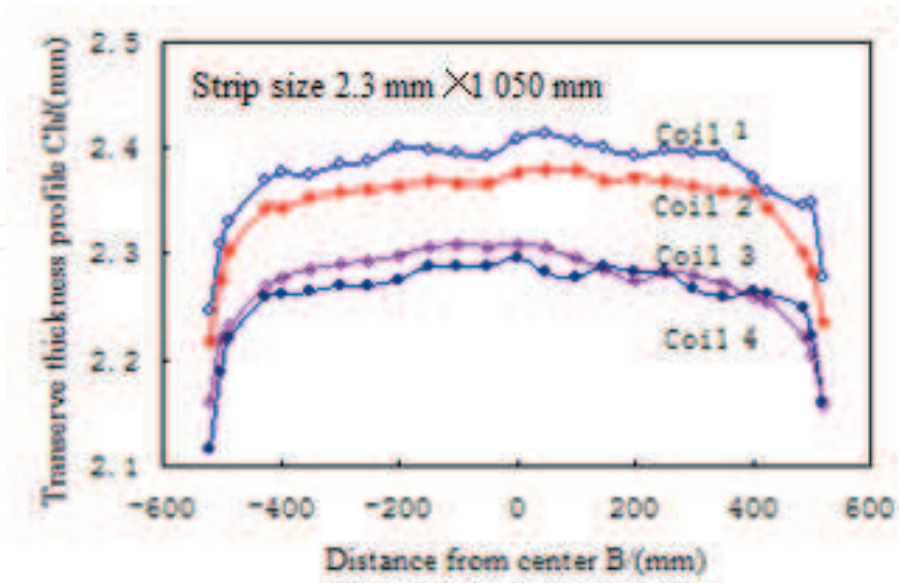

Fig. 12. Measured transverse thickness profile of non-oriented electrical steel strip rolled with long stroke work roll shifting system of conventional work rolls on 1700 mm hot strip mill (2.3 mm×1050 mm)

strip profile and flatness. The rolling period of a newly ground backup roll set in hot strip mills exceeds two weeks, the developed varying contact backup rolls, being geared to different steel kinds and sizes, only go halfway towards solving the problem of significant transverse thickness profile difference by wear contour patterns of conventional work roll contours. A rather smooth local work roll contour near strip edges and an increase in length rolled can be obtained by application of long stroke work roll shifting system with conventional work roll contours that is incapable of the crown control. Having ability of both wear control and overall profile control covering the strip crown, edge drop and high spot in downstream stand and suitable to the schedule free rolling of hot strip mills, the ASR mill with the asymmetry self-compensating work rolls, varing contact backup rolls, corresponding work roll axial shifting strategy and bending force mathematic models have been developed and applied to 1 700 mm hot strip mill at WISGCO. According to the rule of work roll wear contour patterns in rolling process, the wear contour of work rolls with one-side tapered contours in the ASR mill can be change from U-type to L-type by shifting the work rolls to the axial direction with a special shifting strategy. As can be seen from Fig. 7, the work roll wear contours of ASR mill have only one side and open another side of U-type wear, and the hot-rolled strips within an entire rolling campaign can be always in the relatively flat area of work roll contours and remove 'from wide to narrow' constraint of coffin rolling regulations by severe U-type work roll wear. This is the on-line automatic compensation process of work roll wear contours in the ASR mills. It can be seen from Fig. 11 that roll gap profile under load is more flat and controllable by applying VCR/ASR technology in the ASR mill, the strip profile, especially edge drop, and flatness control ability of electrical steel can be enhanced notably, the larger transverse thickness profile difference problem of electrical steel sheets caused by severe U-type wear can be solved efficiently and the proportion of lower crown even "dead flat" electrical steel will raised significantly.

The non-uniformity of distribution of roll contact pressure is the specific value of the maximum value and mean value of the pressure along contact length between rolls. The usual rolling force is 10.4MN and the bending force is 800kN for conventional backup and work rolls, VCR/conventional work rolls, and VCR/ASR on 1700 mm hot strip mill. In this condition, The non-uniformities of distribution of roll contact pressure are 1.97, 1.15 and 1.25 in the early stage of work roll. The non-uniformities of distribution of roll contact pressure are 2.35, 1.40 and 1.48, due to roll contour changing caused by wear and thermal expansion. The distribution of pressure between rolls become smooth by application of VCR/conventional work roll and VCR/ASR configuration in the rolling mill. The peaks of pressure between rolls of the above three roll contours configuration are 14.64, 8.28 and 8.75 kN/mm in the early service stage and the peaks of pressure between rolls of the above three roll configuration are 17.68, 10.22 and 10.36kN/mm in the end service stage. Compared with conventional roll configuration, the peaks of contact pressure between rolls the service stage of VCR/ASR from early to late stage decrease 10.23% and 41.40%. The new ground roll contour in the ASR mill has a well self-maintenance and expresses the ability of strip profile and flatness control steadily within the entire rolling campaign. It also has the ability of avoiding roll spalling and enhancing the service performance.

3.4 Industrial application and its effect

The VCR has been tested in stand F3 of 1700 mm HSM at WISCO since May 1997 and then improved in F6, F4, F5 and applied in all 7 stands with 14 backup rolls since September 1999. The application of VCR enhances the strip control ability and stability of finishing stands in hot rolling and improves the quality of strip profile and flatness distinctly: Through strip profile and flatness production data statistics of 95.2 thousand coils before(50.8 thousand coils) and after (44.4 thousand coils) application of the varying contact backup rolls, the ratio of strip over-limit crown decreased from 33.90% to 13.84%, the ratio of strip flatness overall length over 7 I-units decreased from 19.28% to 6.91%. It can be concluded from the industrial tracking test data that the bakup roll wear contours of VCR is well-distributed along roll barrel which can enhance the self-maintenance of backup roll profile efficiently, ameliorate the change feature of roll profile remarkably. It can not only maintain the stability of strip control effect, but also avoid backup roll spalling, extend life of service from 2 weeks to 3 weeks or even more 5 weeks for test in upstream stands of 1700 mm HSM , increase rolling yield.

In order to verify the performance of ASR mill type and strip control technology and to improve the quality and quantity of electrical steel strip, the ASR has been applied to 1700 mm hot mill at WISCO for test in 2003, 8. According to applied to stands F6, F4, F5 and so on for test and considering edge crack of electrical steel sheets in hot rolling production practice, the ASR applied to downstream stand in rolling service of electrical steel sheets can control edge drop efficiently, but a more serious edge crack maybe caused by stress concentration. Considering the factors as mentioned above, ultimately, the ASR mill has been industrial tested successfully and applied to downstream stand F5 of 1700mm hot strip mill on 1700 hot strip mill in July 2004 and applied to the industrial production of 2.3 mm×1050mm conventional width electrical steel rolling campaign since November 2004 and applied to wide electrical steel rolling campaign since October 2005. The ASR mill can achieve a decrease in the crown of the roll gap and an increase in the roll gap stiffness for the stability of the roll gap profile controllable during rolling, which can better the affection of work roll severe wear to strip profile and flatness control ability of electrical steel sheets edge drop and make a profound contribution to low crown decreasing non-oriented electrical steel sheets production. Measured transverse thickness profile of non-oriented electrical steel strip rolled in the ASR mill is shown in Fig.13, compared with that of long stroke work roll shifting system of conventional work rolls in Fig.12 on 1700 mm hot
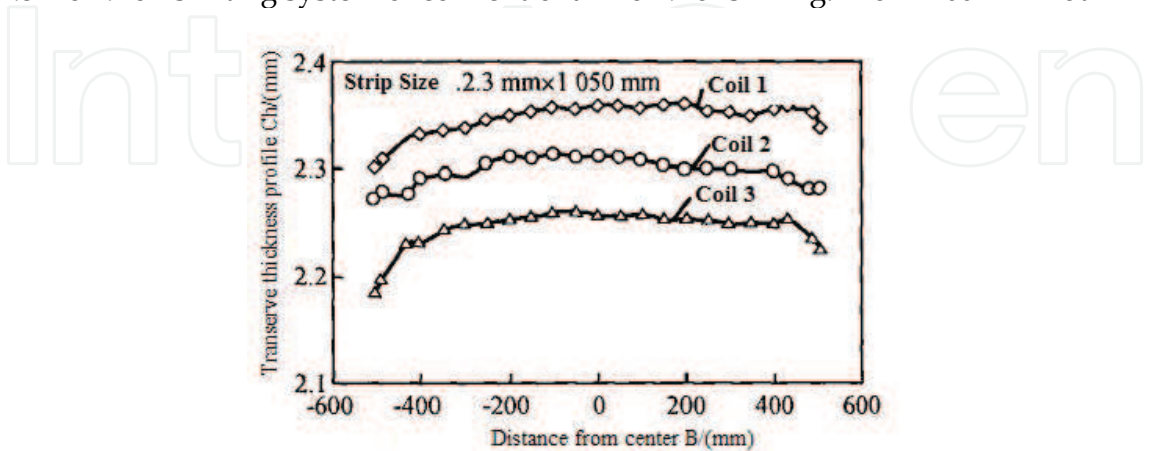

Fig. 13. Measured transverse thickness profile of electrical steel rolled in ASR mill (2.3 mm× 1050 mm)

strip mill(2.3 mm×1050 mm).The industrial results were that the rate of measured crown of the same strip-width 2.3 mm×1 050 mm conventional width electrical steel strips for test less than 52μm was increased from 13.70% to 81.25%, the rate of measured crown less than 45μm is increased to 93.15% by the continuous application, the life of rolls expanded from 60 coils to 80 coils and more, whereas the rate of measured crown of the same width 2.55mm×1200~1300mm wide electrical steel strips for test less than 45μm was increased from 41.8% to 98.2%, the rate was 92.7% for application, the rate of measured wedge less than 22μm was increased from 68.54% to 95.48%, the life of rolls expanded from 40 coils to 70 coils and more.

4. Finite element analysis of shape buckling load for cold-rolled strips

Strip flatness performance obtained during cold reduction is considered to be the main factor in achieving optimum productivity of downstream facilities and final product quality. The distribution of the strip extension along the width direction is usually uneven in tandem cold rolling process. Due to this, the strip after rolled always has internal residual stress distributed unevenly along the direction of strip width, some part of the strip is tensile, and some others is compressive. When the stress of the compression part goes over a certain threshold, strip deformation occurs, kinds of buckle turns up, such as edge wave, center buckle and their compositions. The root causes of strip buckling are that lengths of the longitudinal fibers are different because the strip is unevenly rolled along the width direction and reach the certain threshold.

According to energy principle and variation calculus, using thin elastic small displacement theory, thresholds of strip buckling under every kind of internal stress can be solved without any expression of buckling conditions, numerical method is the effective way to get the value of critical stress under every rolling conditions (Nappez, C., 1997; Fischer, F. D., 2003; Liu,Y.L., 2007). So it's important to ensure the threshold of strip buckling correctly, and this will be the fundamental of establishing a shape control model in cold rolling.

The 1700mm tandem cold rolling mill at the Wuhan Iron and Steel Company (WISCO) was designed and built by SMS and was commissioned in 1978. From 2003 to 2004, the mill completed a series of upgrades on the PL-TCM (pickling line combined with tandem cold rolling mill) etc. supplied by VAI Clecim and SIEMENS. The mill is one of the largest tandem cold rolling mills in China with a capacity of 1.85Mt/y including 500 thousand tons of electrical steel now. The mill still use the previous flatness target model of the automatic shape control system after technical upgradion, which can't reflect actual production in industrial process. With the ANSYS finite element method, a calculated models to analyze and calculate strip buckling was established. With corresponding loads and boundary conditions, the threshold of strip buckling is brought out, which is valuable for the construction of flatness target model in electrical steel rolling.

4.1 Finite element modeling of strip buckling

As the object of study here is wide and thin strip in cold rolling, the thickness of the strip, which is only 0.5 mm, is much less than its width of 1050 mm and more, and length of 1000 km and more, this can be seen as a thin strip buckling problem. So modeling with a two-dimensional element shell63 provided by ANSYS, the value of the strip thickness is imported as a real parameter. The width of the finite element model is the same as that of

the strip, and the length of the model is equal to half wave length L of the buckling strip. The areas of the divided elements is less than 20 mm×20 mm. The detailed parameters of the model: Width b=1 300 mm. The calculated parameters: Young's modulus E=2.1×10^{11}, Poisson's ratio μ =0.28.

Class 1 of Chebyshev polynomial system is adopted to represent the external loads which will be used in the simulation, specific expression are as follows:

$T_1(x)=x$, $T_2(x)=2x^2-1$, $T_4(x)= 8x^4-8x^2-1$. Shape of cold-rolled strip stress is shown in Fig.14.

The external loads is assumed to remain constant in buckling process of strip, i.e. the instability phenomena during stress relaxation is ignored. Different external loads is replaced by different constraint conditions. In addition, try various constraint conditions to each external load. Carrying out a number of calculations to ensure which constraint condition is closest to the actual situation, and use it as the simulation condition. Loads of long center buckle is shown in Fig.15.

4.2. Calculation and analysis

Since the special structure of Cold-rolled wide and thin strip, the buckling has already happened when $\sigma_{cr} << \sigma_s$, so it is unnecessary to take the nonlinear characteristics into account. The main parameters for calculation are strip width, thickness and half wave length L. According to the practical experience and measured data, the half wave length L varies usually between 0.25 and 1.25 times of the width, so the minimum buckling threshold and the length of half wave L can be got by a number of calculations with changes in the parameter range. The method of construction buckling analysis provided by ANSYS is accomplished by increasing the nonlinear load step by step, with which the threshold of the buckling load is brought up. In the calculation, when the initial shape of the strip is flat with a plate load, there would be no deformation or buckling. A reasonable static displacement is needed in order to get predeformation in the strip before calculation, so the model is buckling. Using nonlinear calculation module BUCKLING of ANSYS package, the threshold of buckling will be calculated. Buckling of long center is shown in Fig. 16.
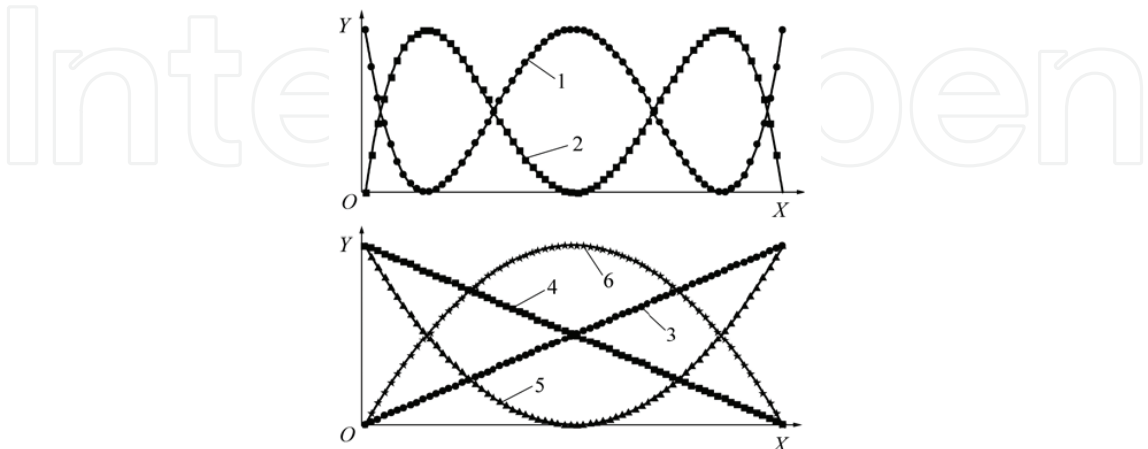
1-1/4 wave, 2- center buckle with edge wave, 3- left side long edge wave, 4-right side long edge wave, 5-center wave, 6-two sides edge wave

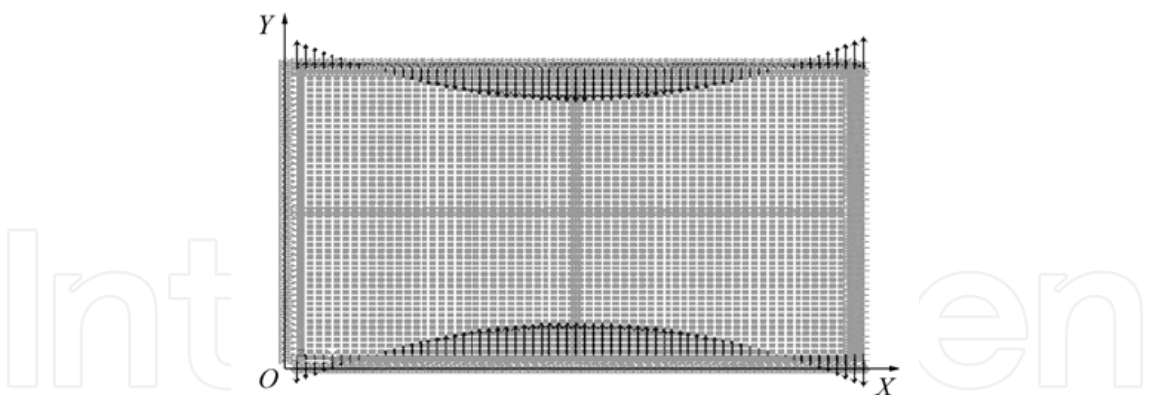Fig. 14. Shape pattern of cold-rolled strip stress
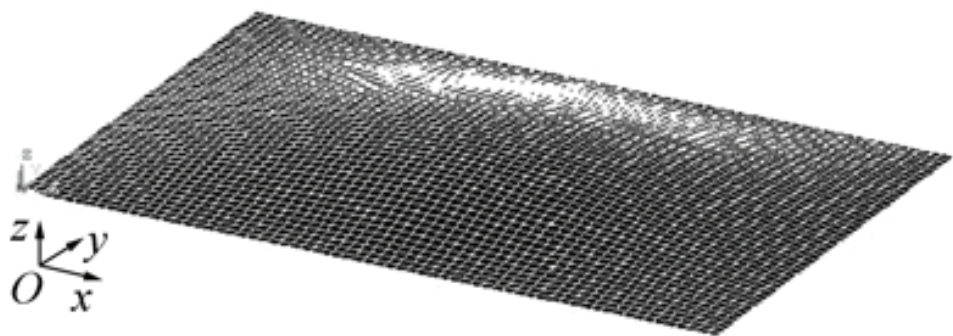
Fig. 15. Loads of long center buckle

Fig. 16. Buckling of long center

The results of strip critical threshold for typical different waves with strip size 0.5 mm×1 300 mm are shown in Table 2 and Fig.17.

Loads of the long edge wave		Loads of the long center wave		Loads of two sides symmetrical wave		Loads of center buckle with edge wave		Loads of 1/4 symmetrical wave	
L/mm	Threshold	L/mm	Threshold	L/mm	Threshold	L/mm	Threshold	L/mm	Threshold
0.80	0.646 95	0.80	0.881 26	0.60	0.592 74	0.30	2.052 30	0.40	1.512 60
0.90	0.634 86	0.90	0.839 76	0.64	0.590 97	0.40	1.818 00	0.46	1.500 50
1.00	0.626 04	1.00	0.814 43	0.70	0.589 86	0.46	1.761 80	0.50	1.497 40
1.10	0.621 20	1.10	0.801 68	0.72	0.589 83	0.50	1.729 70	0.52	1.497 00
1.16	0.620 10	1.16	0.798 90	0.76	0.590 19	0.52	1.733 80	0.56	1.498 10
1.20	0.620 00	1.20	0.798 51	0.80	0.590 99	0.56	1.746 90	0.60	1.500 70
1.26	0.620 66	1.26	0.800 52	0.90	0.594 29	0.60	1.802 10	0.70	1.508 90
1.30	0.621 52	1.30	0.804 08	1.00	0.598 38	0.70	1.899 10	0.80	1.514 90
						0.80	1.975 90	0.90	1.521 00

Table 2. Buckling load results of different strip waves

As can be seen from Fig. 17, different loads lead to different critical thresholds. The biggest buckling load appears in the center buckle with edge wave, the smallest appears in the side long edge, and the long center ranks the middle. Under the same internal residual stress, the edge wave is most easily generated, while it is the most difficult to produce the center buckle with edge wave.
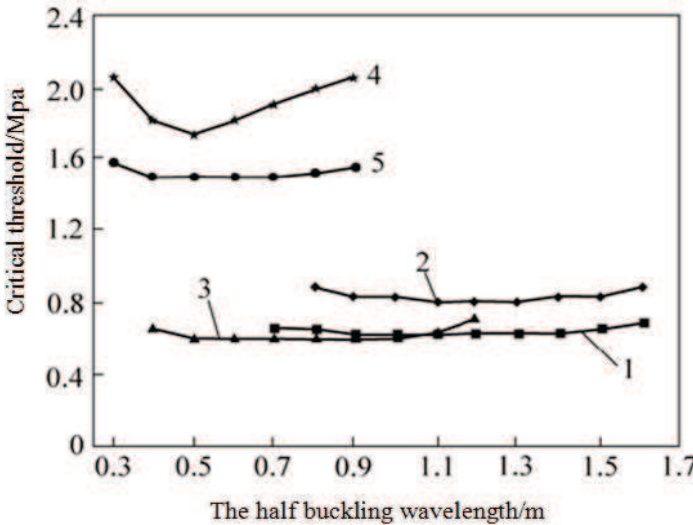

Fig. 17. Buckling load of five typical waves

When the length of edge wave and center wave becomes larger, the half buckling of the center buckle with edge wave is 50%~60% of width, the long center and the single-side long edge is about 80%, the symmetrical dual-side long edge is about 70%. These meet the facts that the center buckle with edge wave is short wave and the long center and the single-side long edge is long wave.

Taking the long edge wave and the center buckle as examples, relationship between buckling load and tensile strain of thin and wide strip is shown in Fig.18. When a tensile strain is applied to the strip, the critical thresholds obviously enlarge with a linear pattern of strain. So a proper tensile stress can prevent the strip from buckling in a cold rolling process.
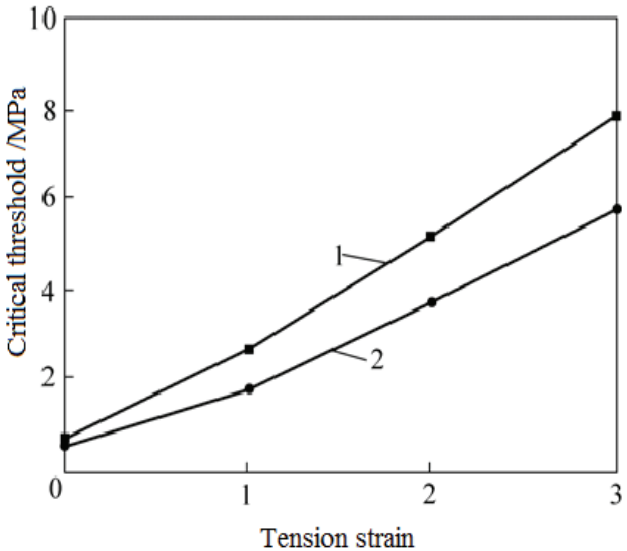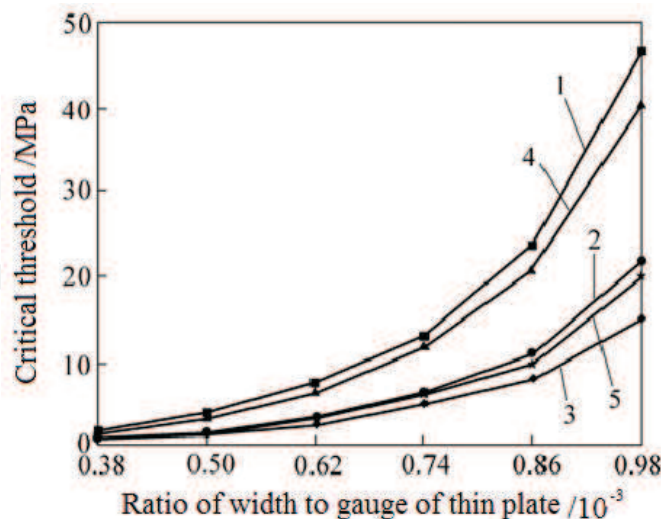

Fig. 18. Relationship between buckling load and tensile strain

The results of critical buckling threshold for 5 typical wave or buckle with different ratio of width to gauge of thin plate are shown in Fig. 19.

1-center buckle with edge wave, 2-center wave, 3-two sides edge wave, 4-1/4 wave, 5-one side long edge wave
Fig.19. Relationship between buckling load and ratio of width to gauge of thin plate

As can be seen from Fig.19, critical buckling thresholds increase significantly with the the increase of ratio of width to gauge of thin plate. And with the same increased ration, the critical buckling thresholds of composite waves increase more quickly than that of simple waves such as center buckle and edge wave, i.e. the slope of the curve is greater than the other two wavy's slope. Therefore, the greater the thickness of the plate, the more difficult buckling.The ratio of width to gauge of thin plate is an important factor to the critical buckling threshold of thin and wide strip. In general, the analysis of strip buckling is valuable for the construction of flatness target model in tandem cold rolling mills.

5. Finite element analysis of comprehensive edge drop control technology of strip in 4-high ECC(edge drop & crown compact) tandem cold rolling mills

Edge drop control is a new research field in the strip profile and flatness control because of the increasing requirements for strip profile and flatness (Campas, J.J.,1995; Wang, J.S. ,2001; Chi, W.M.,2003). Nowadays the main edge drop control technology are applied by the new built 6-high mill type, such as 6-high UCMW developed by Hitachi with tapered work rolls(K-WRS) (Hiruta, T.,1997; Yarita, I.,1998; Lu, H.T. , 2006; Zhou, X.M., 2007)and 6-high CVC with EDC system developed by SMS Schloemann Siemag AG(Hartung, H.G.,1998; Lackinger, C.V.,2002). The 6-high rolling mill in which the edge drop control effect is improved by shifting the intermediate rolls and the work rolls with an effective edge drop control device along the axial direction of rolls and using the smaller diameter of work rolls. For a tandem cold rolling mill composed of conventional 4-high mills is not provided with an effective edge drop control device, the edge drop of cold-rolled strip is maily determinted by the hot-rolled strip profile as shown in Fig. 20. Even taking various measures such as no trimming before rolling and great cutting-edge after rolling, increasing

the positive bending for center buckle rolling at the expense of flatness control for effects of edge drop, the average edge drop of strip is 15~20μm. The collected measured data of strip which have the different sizes such as 0.5mm×1195mm, 0.5mm×1210mm, 0.5mm×1240mm and etc. show that the average edge drop is 19μm, the proportion of the edge drop less than 10 μm is only 29.2%.The 4-high rolling mill in which the edge drop control effect is improved much by shifting the tapered work rolls (K-WRS) can't meet the required quality nowdays, such as the 1700 tandem cold rolling mill upgraded by VAI CLECIM and SIEMENS on March 2004 (Lu, H.T. ,2006). Generally, the main edge control technology has applied to the new built 6-high tandem cold rolling mills,such as 6-high UCMW mill at yawata works of Nippon Steel in Japan,No.2 silicon steel works of WISCO and No.3 tandem cold rolling mill of Baosteel in China, Gwangyang plant of POSCO in Korea, 6-high CVC mill with EDC work roll and cooling system at Beeckerwerth cold rolling mill of TKS(Thyssenkrupp steel) in Germany, No.2 tandem cold rolling mill of WISCO and Hangang tandem cold rolling mill of HBIS(Hebei Iron & Steel Group Co. Ltd) in China. Based on ANSYS software and industrial rolling of edge drop control, a 3-dimensional finite element model of roll stacks was built for 1700 mm 4-high tandem cold rolling mill. The developed EDW(edge drop control work rolls) and matched VCR (varying contact backup rolls) by integration design thought of roll contours, mathematical model of roll shifting and bending for edge drop control were integrated to the comprehensive edge drop control technology of 4-high ECC mill type developed by the project team of USTB&WISCO(University of Science and Technology Beijing & Wuhan Iron and Steel Company). The comprehensive edge drop control technology has applied to the production of non-oriented electrical steel strip in 1700mm 4-high tandem cold rolling mill at WIS(G)CO of China since August 2006.
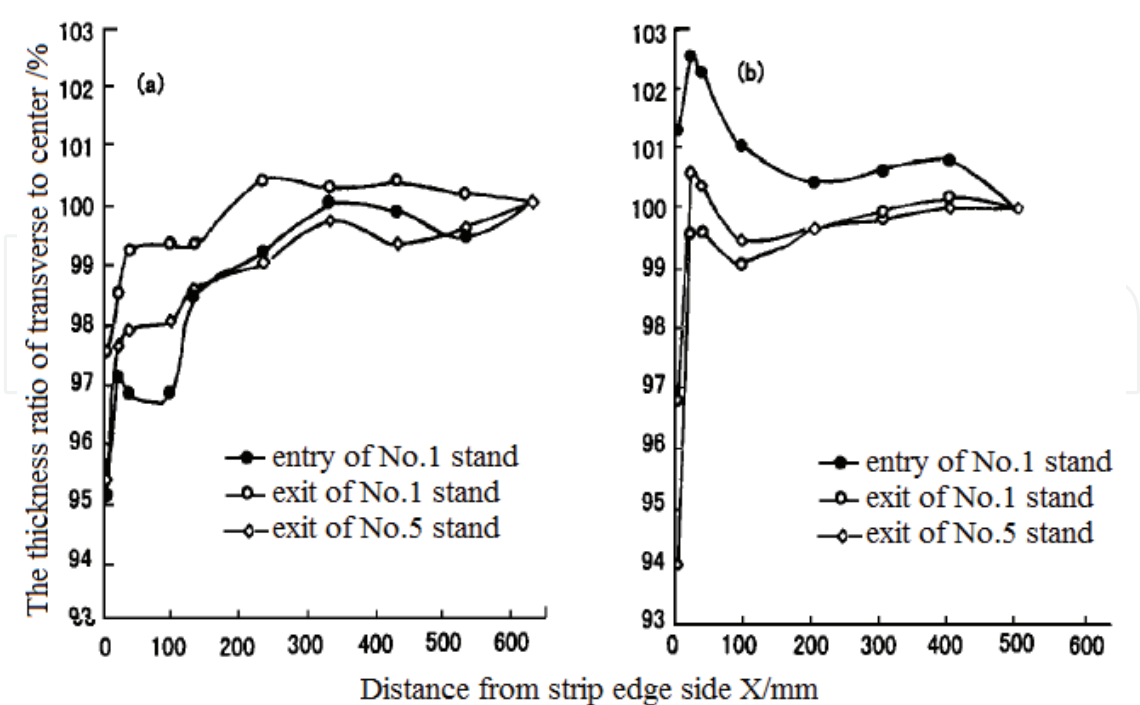

Fig. 20. Edge drop of conventional 4-high tandem cold rolling mills

5.1 FEM for roll stacks and strips

In order to find out the crucial factors which affect the edge drop, an explicit dynamic finite element method was adopted to build a combination simulation model for roll stacks and strip, as shown in Fig. 21. Modeling parameters are shown in Table 3.
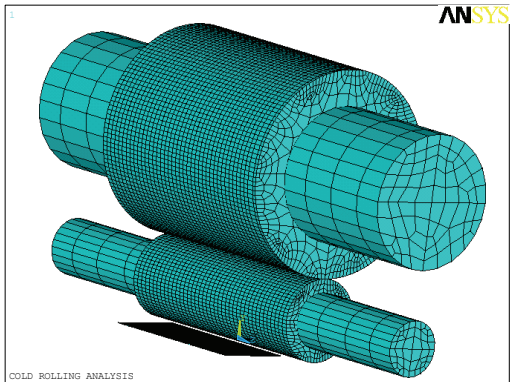
Fig. 21. Finite element model of roll stacks and strip in 1700 tandem cold rolling mill

5.2 The analysis of influencing factor of the edge drop

The main rolling parameters which have a great effect on the strip edge drop are strip width, strip thickness, deformation resistance, friction and roll diameter, etc. Aims at some important parameters such as strip thickness and deformation resistance integrating with the model features, a simulation is finished.

The effect of strip width on the strip edge drop is analyzed by designing three conditions that strip width B is 800mm, 1000mm and 1200mm. The simulation results show that there is a little effect of strip width on the strip edge drop during the process of the cold-rolled strip, the strip edge drop reduces with the increase of strip width, and the rule that the lateral thick difference changes with strip width is invariability after strip thickness reduces, but both of the edge drop are reduced.

Parameter		Value
Measure of the BR body	$D_B \times L_B / mm$	1500×1700
Measure of the BR neck	$D_E \times L_E / mm$	980×520
Measure of the WR body	$D_W \times L_W / mm$	600×1700
Measure of the WR neck	$D_N \times L_N / mm$	406×520
Length of the strip L/mm		500
Width of the strip B/mm		800/1000/1200
Thickness of the strip at maunting side H/mm		1.7/2.3/3.0
The type of the FE		3D Solidl64
The quantity of the strip FE		13158

Table 3. Modeling parameters

The analysis results of strip rolling process thought three conditions that entry thickness was 1.7mm, 2.3mm and 3.0mm separately. The result shows that the strip edge drop is reduced with the reduction of strip thickness. The actual production needs to control the

edge drop ,the width range which is 1000mm∼1200mm and the edge drop which changes with 8μm through simulation calculation. The strip edge drop changes the 36μm when strip thickness reduces from 3.0mm to 1.7mm and the strip edge drop changes the 21μm when strip thickness reduces from 3.0mm to 2.3mm. Therefore, there is a very little effect of strip width on the strip edge drop and the effect of strip width can be ignored during the control of edge drop.

The effect of deformation resistance on the strip edge drop was analyzed by designing three conditions that deformation resistance was 350MPa, 270MPa and 195MPa ,and the effect of deformation resistance with different width on the strip edge drop was analyzed. The simulation results show that there is a great effect of deformation resistance on the strip edge drop and with the increase of deformation resistance, the strip edge drop increases rapidly. The reason is that the increase of deformation resistance leads to the degree of rolling force heterogeneity more serious and makes the roll flattening more heterogeneous, so the strip edge drop increases rapidly.

5.3 Comprehensive edge drop control technology of strip in 4-high ECC mill

Based on the FEM analysis and industrial experiment, the EDW(Edge drop control work rolls) and matching VCR(Varying contact backup rolls) were designed and proposed. In order to control the strip edge drop contiguously, EDW provide a continuously variable taper to compensate for uneven flatten that can also effectively avoid small edge wave and other flatness problems on strip edge. Acoording to the developed shifting strategy and mathematical models,the EDW improve edge drop effect and are suitable for different widths of strip by shifting top and bottom work rolls of multi-stands to the axial oppsiste direction in the 4-high ECC(Edge drop & crown compact) mill(Fig.22). Transverse thickness and profile of the sampling strip is shown in Fig.23 before and after applying EDW technology to No.1 stand of 1700 mm tandem cold rolling mill at WISCO since August 2006 .The rate of edge drop less than 10μ m defined as the difference of thickness of 115 mm and 15 mm from the strip edge side improved from 62.5% of the 4-high tapered work rolls (K-WRS) mills to 91.3% of the 4-high ECC mill with EDW rolls. According to the thoughts mentioned above and the electrical steel production program of PL-TCM(pickling line combined with tandem cold rolling mill), VCR which is compatible with EDW is designed to eleminate harmful contact area between rolls to improve edge drop control effect.
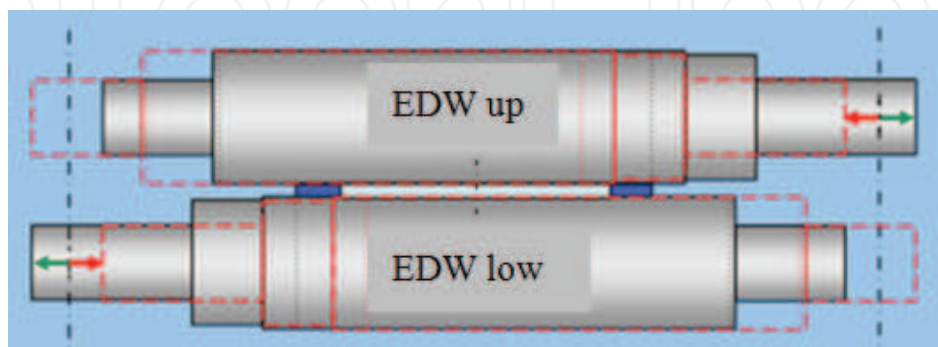

Fig. 22. Principle of EDW(edge drop work rolls) in 1700 tandem cold rolling mill

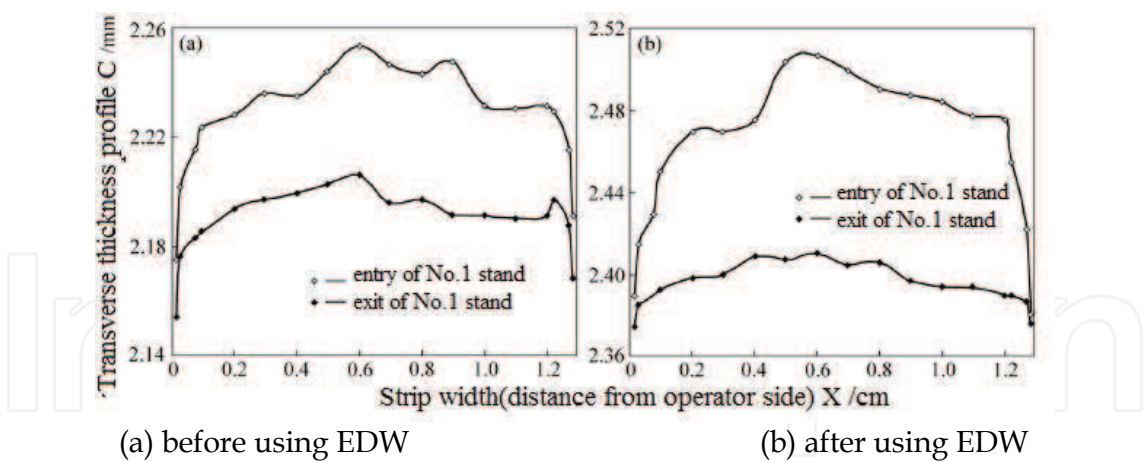(a) before using EDW   (b) after using EDW

Fig. 23. Comparison of strip profile before and after using of EDW(edge drop work rolls) in 1700 tandem cold rolling mill

A finite element model was established to analyze the quantitative relationship between the length of the contact line between the work and backup rolls and the strip width of PL-TCM under different strip width, rolling force and roll bending conditions. According to the properties of roll system deformation, the contact length between rolls can match the strip width automatically under the action of the rolling force, so the harmful contact area is reduced or eliminated, also the bending deformation of roll gap becomes small, reducing the crown of the roll gap, increasing the roll stiffness, raising the control range and efficiency of bending force and improving the flexibility of the roll gap. Under the same roll shifting stroke, roll gap stiffness of the 4-high ECC mill with EDW compatible with conventional backup rolls or VCR was obtained from simulation (Fig.24). The results show that the roll gap stiffness of the configuration roll system of EDW and VCR is 148kN/μm, 19.1% more than conventional back-up rolls 124kN/μm, obviously increasing stability of roll gap control. The roll gap crown adjustable zone of EDW and VCR is 133.1μm, compared with that of conventional back-up rolls 120.2μm, increases 10.7%. This is not only mean an improvement of crown control, but also an increasing of edge control ability. The contact pressure distribution between rolls of EDW with VCR and conventional backup rolls was obtained from simulation and the pressure peak was 21.6% smaller than the former.

1-bending force is 0 with conventional BR(backup roll); 2- bending force is 0 with VCR; 3-bending force is 0.5 MN with conventional BR; 4- bending force is 0.5 MN with VCR
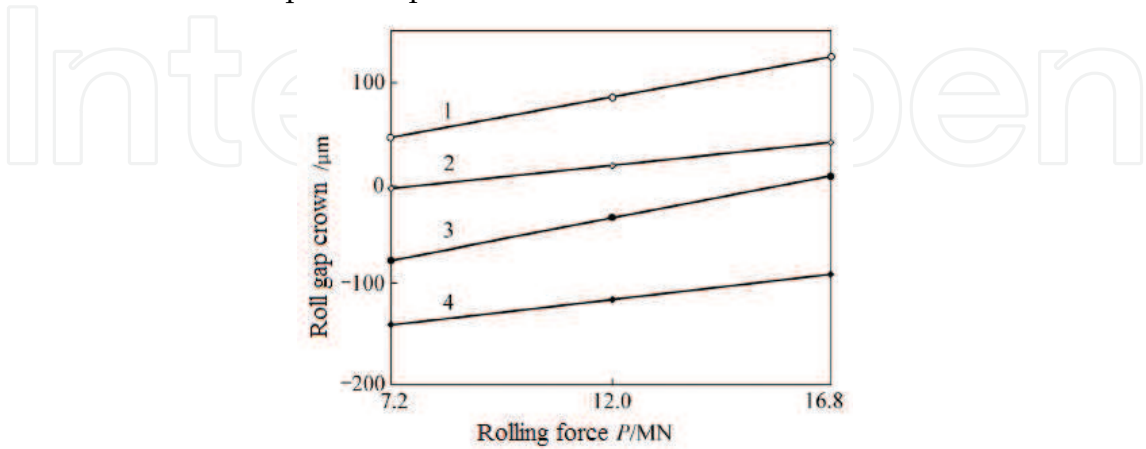
Fig. 24. Roll gap stiffness of EDW compatible with VCR and conventional back-up rolls

An explicit dynamic finite element method is adopted to build a combination simulation model for roll stacks and strip. The area method of edge drop equivalent is put forward to build the shifting mathematical model of edge drop control based on the mechanism of edge drop control and characteristics of the 4-high ECC mill with EDW and VCR. The parameters of model are determined by simulation and industrial experiment (Cao, J. G., 2008).

5.4 Industrial experiment and application

WISCO of China recently established a 4-high tandem cold mill rolling technology that assure excellent profile and flatness by installing ECC(edge drop & crown compact) mill including the comprehensice edg drop technology mentioned above since August 2006. In July 2007,the data which come from the continuous rolling of the total weight of 23266 tons of electric steel with different sizes such as 0.5mm×1150mm, 0.5mm×1195mm, 0.5mm×1240mm show that the proportion of the edge drop less than 10 μm is 100%.According to the user's growing severe demands , the proportion of the edge drop less than 7 μm is 98.22% and the proportion of the transverse thickness deviation along the strip length of the same strip less than 10 μm is 97.25%,this significant performance reaching to the same high precise control level of new-built 6-high 1450UCMW tandem cold rolling mill during the same rolling period.The proportion of the transverse thickness deviation along the strip length of the same strip less than 10 μm is 92.06% by applying this technology on 1700 mm tandem cold rolling mill for the production of 114 800 t non-oriented electrical steel on first half of 2008.

6. Conclusion

Finite element method is an effective way to the behavior analysis of mechanical, thermal, deformation and other characters of strip and rolling mills.With the help of theory research, simulation and industrial experiment, the developed hot strip mill and tandem cold rolling mill which provide both wear control and profile control ability, comprehensive edge drop control ability are applied to the industrial production and gain better strip profile and flatness quality, process improvements and productivity increase.

7. References

Ginzburg, V. B.(1993). *High-quality Steel Rolling: Theory and Practice*. Marcel Dekker Inc, ISSN 0-8247-8967-9,New York

Chen, X.L. (1997). Flatness control in new generation high-tech mills for wide strip rolling , *Journal of University of Science and Technology Beijing*,Vol.19, No.S1, 1-5, ISSN 1001-0521

Cao, J. G., Zhang, J., Song, P., et al. (2006).ASR technology for controlling profile and flatness of non-oriented electrical steel strip in hot rolling. *Iron and Steel*, Vol. 41 , No. 6: 43-46, ISSN 0449-749X

Li, H.C., Jiang, Z.Y., Tieu, A.K., , et al. (2007). Analysis of premature failure of work rolls in a cold strip plant. *Wear*, No.263:1442–1446, ISSN 0043-1648

Ray, A.K., Mishra, K.K., Das, G., et al. (2000). Life of rolls in a cold rolling mill in a steel plant-operation versus manufacture. *Engineering Failure Analysis*, No. 7: 55-67. ISSN 1350-6307

Chen, S.G., Wang J.Z., Kang Y.L., et al. (2006). Barrel spalling analysis of 45Cr4NiMoV forged steel backup roll for hot rolling. *Shandong Metallurgy*, Vol. 28, No. 3: 51-53. ISSN 1004-4620

Cao, J. G., Chen, X.L., Yang Q., et.al. (1999). Preventing method and its effect for roll spalling in hot wide strip mill. *Metallurgical Equipment*, No. 4: 6-9,45. ISSN 1001-1269

Yang, G.H., Cao, J.G., Zhang J., et.al. (2008).Backup roll contour of a SmartCrown tandem cold rolling mill. *International Journal of Minerals, Metallurgy and Materials*, Vol.15,No.3: 357-361. ISSN 1005-8850

Chen, X.L., Yang Q., Zhang Q. D., et.al.(1994/1995). Varying contact backup roll for improved strip flatness. *Steel Technology International*, (yearly): 174−178. ISSN: 0953-2412

Chen, X.L., Zhang, J., Zhang, Q.D., et.al. (2000). Development in profile and flatness control system of hot strip mills. *Iron and Steel,*Vol.35,No.7: 28−33. ISSN 0449-749X

Cao, J.G., Zhang J., Chen X.L., et al.(2002). Control of roll contour for strip profile and flatness in hot rolling, *Proceedings of the 44th Mechanical Working and Steel Processing Conference and the 8th International Rolling Conference*, pp.1001-1010, Florida, Sept. 2002, The Iron & Steel Society, Orlando

Cao, J. G., Zhang, J., Chen, X.L., et al. (2005). Selection of strip mill configuration and shape control. *Iron and Steel*, Vol.40, No.6: 43-46. ISSN 0449-749X

Ou, Y.Y., Cao, J. G., Zhang J., et al. (2005).Relation between profile and flatness control and rolling trait of the hot strip mill for non-oriented silicon steel. *Metallurgical Equipment*,No.1: 6-9. ISSN 1001-1269.

Cao, J. G., Zhang, J., Gan, J.B., et al. (2006).Work roll wear prediction model of non-oriented electrical steel sheets in hot strip mills. *Journal of University of Science and Technology Beijing*, Vol.28, No. 3: 286-290, ISSN 1001-0521.

Cao, J. G., Wei, G.C., Zhang, J., et al. (2008). VCR and ASR technology for profile and flatness control in hot strip mills. *Journal of Central South University : Science &Technology of Mining an Metallurgy* ,Vol.15, No. 3: 264-270, ISSN 1005-9784.

Nappez, C., Boulot, S., McDermott, R.C.(1997). Control of strip flatness in cold rolling: a global approach. *Iron and Steel Engineer*, Vol. 74, No. 4: 42-45, ISSN 0021-1559

Fischer, F. D., Rammerstorfer, F.G. & Friedl, N.(2003). Residual stress-induced center wave buckling of rolled strip metal. *Journal of Applied Mechanics*, Vol.70, No.1: 84-90, ISSN 0021-8936

Liu,Y.L., Fan, J., Mike, L., et al. (2007). Three-dimensional simulation of local shape defects in continuous cold rolling. *Iron and Steel Technology*, Vol.4, No.8: 70-80, ISSN 1547-0423

Campas, J.J., Terreaux, S., Roches,L.V D, et al.(1995). New on-line gage for edge drop measurement and effect of tapered work rolls. *Iron and Steel Engineer*, Vol.72, No.12:27-32, ISSN 0021-1559

Wang, J.S. , Zhao, Q.L., Jiao, Z.J. , et al.(2001). The research on the principle and application for T-WRS&C cold mill . *Heavy Machinery*,No.6:8-11,ISSN 1001-196X.

Chi, W.M., Gao, W., Wu, B., et al. (2003).Cold strip rolling of new technology-edge drop control. *Mining and Metallurgy,* Vol.12, No.2:91-94. ISSN 1005-7854.

Hiruta, T., Akagi, I., Mizushima, N. (1997). Development of advanced transverse thickness profile control of thin hard steel strips at tandem cold rolling mill. *Kawasaki Steel Technical Report*, Vol.37, No.10:19-24, ISSN 0388-9475

Yarita, I., Kitahama, M., Hiruta, T., et al. (1998). Transverse thickness profile control in hot and cold strip rolling by tapered-crown work roll shifting (K-WRS) mill. SEAISI Quarterly (South East Asia Iron and Steel Institute), Vol.27, No.3:26-34,ISSN: 0129-5721

Lu, H.T. , Cao, J.G. , Zhang, J. , et al. (2006).Edge drop control of a taper roll during continuous cold rolling. *Journal of University of Science and Technology Beijing*, Vol.28, No. 8: 774-777, ISSN 1001-0521.

Zhou, X.M., Zhang, Q.D.,Wang,C.S., et al. (2007). Automative edge drop control system of UCMW cold mill and its optimization. *Iron and Steel*, Vol.42, No.9: 56-59. ISSN 0449-749X

Hartung, H.G., Hollmann, F.W., Holz, R., et al. (1998). A new way to reduce the edge drop. *Steel research*, Vol.69, No.4-5: 143-147, ISSN: 0177-4832

Lackinger, C.V.,Nettelbeck, H.J.,Oemkes, H.(2002). The new tandem mill at ThyssenKrupp Stahl's Beeckerwerth cold strip. *Stahl und Eisen*, Vol.122, No.2: 25-32, ISSN 0340-4803

Cao, J.G. , Qi, J.B., Zhang, J., et al. (2008).Backup roll contour for edge drop control technology in tandem cold rolling mill. Journal of Central South University(Science and Technology), Vol.39, No. 5: 1011-1016, ISSN 1672-7207.

Cao, J.G., Mao, N., Zhang, J., et al. (2008). Study on shifting mathematical model of edge drop control in tandem cold rolling mill. Iron and Steel, Vol.43, No.8: 57-60. ISSN 0449-749X.

Finite Element Analysis

Edited by David Moratal

Finite element analysis is an engineering method for the numerical analysis of complex structures. This book provides a bird's eye view on this very broad matter through 27 original and innovative research studies exhibiting various investigation directions. Through its chapters the reader will have access to works related to Biomedical Engineering, Materials Engineering, Process Analysis and Civil Engineering. The text is addressed not only to researchers, but also to professional engineers, engineering lecturers and students seeking to gain a better understanding of where Finite Element Analysis stands today.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Jian-guo Cao, Jie Zhang, Ning Kong and Kai-fu Mi (2010). Finite Element Analysis of Strip and Rolling Mills, Finite Element Analysis, David Moratal (Ed.), ISBN: 978-953-307-123-7, InTech, Available from: http://www.intechopen.com/books/finite-element-analysis/-finite-element-analysis-of-strip-and-rolling-mills

INTECH
open science | open minds