1-1-2012

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Abstract

The mathematic model of CVC-Plus work roll curve is built. The ratio of the initial shifting value to the target crown is determined, and the mathematical model considering the relationship between the coefficients A2, A3, A4, A5 and is established. According to the theoretical analysis, the distance between the maximum or minimum point of the high order equivalent crown for work roll with CVC-plus roll curve and the rolling central point is the times of the roll barrel length. In general, the initial shifting value of the CVC-plus roll curve is not equal to the initial shifting value of the 3-order CVC roll curve . The coefficient A1 can also be obtained by optimizing the target function with minimizing the axial force.

Keywords

design, model, mechanics, development, curve, cvc, plus, roll

Disciplines

Engineering | Science and Technology Studies

Publication Details

Xu, J., Gong, D., Jiang, Z., Liu, X. & Wang, G. (2012). Mechanics of design and model development of CVC-plus roll curve. Advanced Materials Research, 418-420 1158-1166.

Mechanics of Design and Model Development of CVC-Plus Roll Curve

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Abstract The mathematic model of CVC-Plus work roll curve is built. The ratio of the initial shifting value s_0 to the target crown is determined, and the mathematical model considering the relationship between the coefficients A_2, A_3, A_4, A_5 and s_0 is established. According to the theoretical analysis, the distance between the maximum or minimum point of the high order equivalent crown for work roll with CVC-plus roll curve and the rolling central point is the $\sqrt{2}$ times of the roll barrel length. In general, the initial shifting value s_0 of the CVC-plus roll curve is not equal to the initial shifting value of the 3-order CVC roll curve s_0'. The coefficient A_1 can also be obtained by optimizing the target function with minimizing the axial force.

Keywords CVC mill, quintic roll curve, crown ratio, axial force, mathematical model

Excellent profile and flatness are always targets of the modern rolling technology of hot rolled strip. The roll curve is a key factor of strip crown, the creation of roll curve can make the progress of strip profile and flatness control technology. Using the shifting of the upper and lower work rolls, the target work roll crown can be obtained, which is a key approach to control the strip profile and flatness. CVC, CVC-plus and Smart Crown have the function to control the strip profile and flatness. Previous researchers have conducted the study in the area [1-4], however, there is no systemic or detailed investigation. In this study, the method to design CVC-plus roll curve and the relationship between coefficients of roll curve were built.

1. CVC-plus unload roll gap function and equivalent crown of work roll

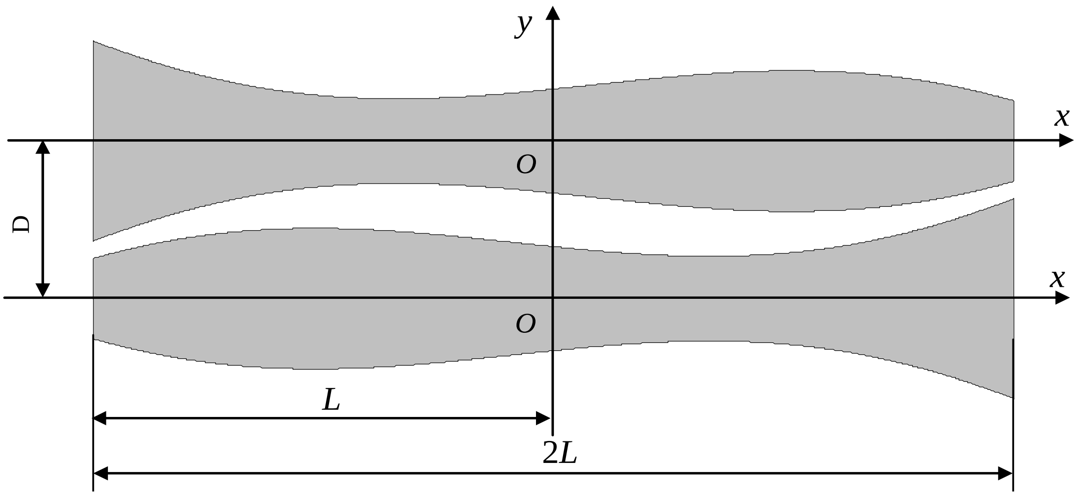


Figure 1 Coordinate system of CVC-plus roll curves

The strip shape defects content not only the central buckle and edge buckle, but also the 1/4 buckle and edge-central composite buckle as well. These shape defects are related to the high order roll gap shape, so the high order roll gap shape tuning should be used to eliminate or improve the shape problems. The roll gap of CVC-plus roll consists of both quadratic and high order components. Therefore, the CVC-plus roll can tune the quadratic shape defects, as well as the high order shape defects. The relationship between the roll gap crown and roll shifting value is nonlinear, however, the roll gap crown and high order crown have a linear relationship with the work roll shifting value.

1.1 Equations of CVC-plus roll curves

The coordinate system as shown in Figure 1 is selected in this study. *L* is a half of the roll barrel length (mm), *D* is the distance between the roll axes. CVC-plus curve is a quintic curve, and the equation of the upper roll curve is listed in Equation (1). As the upper and lower roll curves are anti-symmetric, the CVC-plus roll curve of the lower roll is shown in Equation (2).

$$y_1(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 + A_4 x^4 + A_5 x^5 \tag{1}$$

$$y_2(x) = A_0 - A_1 x + A_2 x^2 - A_3 x^3 + A_4 x^4 - A_5 x^5 \tag{2}$$

1.2 Models of unloaded roll contour, work roll equivalent crown and crown ratio

When the upper roll shifts to right for a distance of s, at the same time the lower roll shifts to left for a distance of *s*, the equation of the upper and lower work roll curves, unloaded roll contour and work roll equivalent crown are shown in Equations (3) - (5).

$$\begin{cases} y_1(x,s) = A_0 + A_1 \times (x-s) + A_2 \times (x-s)^2 + A_3 \times (x-s)^3 + A_4 \times (x-s)^4 + A_5 \times (x-s)^5 \\ y_2(x,s) = A_0 - A_1 \times (x+s) + A_2 \times (x+s)^2 - A_3 \times (x+s)^3 + A_4 \times (x+s)^4 - A_5 \times (x+s)^5 \end{cases} \tag{3}$$

$$\begin{cases} G(x,s) = D - y_1(x,s) - y_2(x,s) = D - 2\times(A_0 - A_1 \times s + A_2 \times s^2 - A_3 \times s^3 + A_4 \times s^4 - A_5 \times s^5) \\ \qquad -2\times(A_2 - 3\times A_3 \times s + 6\times A_4 \times s^2 - 10\times A_5 \times s^3)\times x^2 - 2\times(A_4 - 5\times A_5 \times s)\times x^4 \\ \bar{G}(x,s) = G(x,s) - G(L,s) \\ \qquad = 2\times(x^2 - L^2)\times[(10\times A_5 \times s^3 - 6\times A_4 \times s^2 + 3\times A_3 \times s - A_2) - (A_4 - 5\times A_5 \times s)\times(x^2 + L^2)] \end{cases} \tag{4}$$

where $G(x,s)$ is the roll contour, $\bar{G}(x,s)$ is the function of the roll crown distribution.

$$C_r(s) = -\bar{G}(0,s) = 2\times L^2 \times[(10\times A_5 \times s^3 - 6\times A_4 \times s^2 + 3\times A_3 \times s - A_2) - (A_4 - 5\times A_5 \times s)\times L^2)] \tag{5}$$

As indicated in Equation (5), when s = 0, the equivalent crown of the work roll is not equal to 0, this means that there is initial shifting value. To assume the initial shifting value is S_0 when the equivalent crown is 0, and introduces S_0 into Equation (5):

$$(10\times A_5 \times s_0^3 - 6\times A_4 \times s_0^2 + 3\times A_3 \times s_0 - A_2) - (A_4 - 5\times A_5 \times s_0)\times L^2 = 0 \tag{6}$$

There are only two peak values in CVC-plus roll curve which is shown in Equation (1). If the two peak values are $x_1$and x_2, the following equations can be obtained:

$$\begin{cases} y_1'(x_1) = A_1 + 2\times A_2 \times x_1 + 3\times A_3 \times x_1^2 + 4\times A_4 \times x_1^3 + 5\times A_5 \times x_1^4 = 0 \\ y_1'(x_2) = A_1 + 2\times A_2 \times x_2 + 3\times A_3 \times x_2^2 + 4\times A_4 \times x_2^3 + 5\times A_5 \times x_2^4 = 0 \end{cases} \tag{7}$$

Make $y_1'(x_1)$ minus $y_1'(x_2)$, considering $(x_2 + x_1) = -2\times s_0$, the following equation can be obtained:

$$A_2 - 3\times A_3\times s_0 + 8\times A_4\times s_0^2 - 20\times A_5\times s_0^3 - 2\times(A_4 - 5\times A_5\times s_0)\times x_1\times x_2 = 0 \tag{8}$$

Add Equation (6) to Equation (8), Equation (9) is obtained. In general, $(x_2 - x_1)^2 \neq 2\times L^2$, therefore, Equation (10) is true. When A_4 is substituted into Equation (8), the relationship between A_2, A_3, A_5 and s_0 can be shown in Equation (10).

$$(A_4 - 5\times A_5\times s_0)\times[(x_2 - x_1)^2 - 2\times L^2] = 0 \tag{9}$$

$$\begin{cases} A_4 = 5\times A_5\times s_0 \\ A_2 = 3\times A_3\times s_0 - 20\times A_5\times s_0^3 \end{cases} \tag{10}$$

Substituting A_2 and A_4 into Equations (4) and (5), the unloaded roll gap, equivalent crown of work roll and crown ratio of CVC-plus roll curve are shown in Equations (11) ~ (13) respectively. The work roll crown ratio is a ratio of the quadric equivalent crown to the high order equivalent crown. As shown in Equation (12), the distance between the maximum points of the high order equivalent crown and the rolling central point is $\sqrt{2}$ times of the roll barrel length.

$$\begin{cases} \bar{G}(x,s) = 10\times A_5\times(s-s_0)\times(x^2-L^2)\times\left\{x^2 + \left[L^2 + 2\times(s-s_0)^2 + \left[\dfrac{3\times A_3}{5\times A_5} - 6\times s_0^2\right]\right]\right\} \\ \bar{G}_h(x,s) = 10\times A_5\times(s-s_0)\times(x^4 - L^2\times x^2) \end{cases} \tag{11}$$

where $\bar{G}(x,s)$ is the function of roll gap distribution, $\bar{G}_h(x,s)$ is the function of the high order crown distribution.

$$\begin{cases} C_r(s) = -\bar{G}(0,s) = 10\times A_5\times(s-s_0)\times L^2\times\left\{L^2 + 2\times(s-s_0)^2 + \left[\dfrac{3\times A_3}{5\times A_5} - 6\times s_0^2\right]\right\} \\ \dfrac{\partial\bar{G}_h(x,s)}{x} = 10\times A_5\times(s-s_0)\times\left[4\times x^3 - 2\times L^2\times x\right] = 0 \Rightarrow x = \pm\dfrac{L}{\sqrt{2}} \\ C_h(s) = -\bar{G}_h(L/\sqrt{2},s) = \dfrac{10\times A_5\times(s-s_0)\times L^4}{4} \end{cases} \tag{12}$$

$$R_C(s) = \frac{C_r(s)}{C_h(s)} = \frac{4}{L^2}\times\left\{L^2 + 2\times(s-s_0)^2 + \left[\frac{3\times A_3}{5\times A_5} - 6\times s_0^2\right]\right\} \tag{13}$$

where $C_r(s)$ is the equivalent crown of the work roll. $C_h(s)$ is the high order crown of the work roll. $R_C(s)$ is the crown ratio of the work roll.

2. Models of computational coefficients of CVC-plus roll curves

2.1 Calculation of coefficients A_5-A_2

(1) Relationship between A_2, A_3, A_4, A_5 and initial shifting value

If the minimum and maximum shifting values [s_1, s_2] and the related equivalent crowns [c_1, c_2] are known,

$$\begin{cases} c_1 = 10 \times A_5 \times (s_1 - s_0) \times L^2 \times \left[2 \times (s_1 - s_0)^2 + L^2 + \dfrac{3 \times A_3}{5 \times A_5} - 6 \times s_0^2 \right] \\ c_2 = 10 \times A_5 \times (s_2 - s_0) \times L^2 \times \left[2 \times (s_2 - s_0)^2 + L^2 + \dfrac{3 \times A_3}{5 \times A_5} - 6 \times s_0^2 \right] \end{cases} \tag{14}$$

Coefficient A_5 can be obtained (see Equation (15)). Considering both Equations (10) and (15), the relationship between A_2 , A_3 , A_4, A_5 and initial shifting value s_0 can be obtained, as shown in Equation (16).

$$A_5 = \frac{(c_2 - c_1)/s_2 + (c_2 + c_1)/s_0}{80 \times L^2 \times (s_0^2 - s_2^2)} = \frac{(c_2 - c_1) \times (s_0 - s_0')}{80 \times L^2 \times (s_0^2 - s_2^2) \times s_0 \times s_2} \tag{15}$$

$$\begin{cases} A_4 = 5 \times A_5 \times s_0 \\ A_3 = \dfrac{c_2 - c_1}{6 \times L^2 \times (s_2 - s_1)} - \dfrac{5 \times A_5 \times [L^2 + 2 \times s_2^2]}{3} \\ A_2 = 3 \times A_3 \times s_0 - 20 \times A_5 \times s_0^3 \end{cases} \tag{16}$$

$$s_0 = s_0' = \frac{c_1 + c_2}{c_1 - c_2} \times s_2 \Leftrightarrow \frac{c_1 + c_2}{s_0} = -\frac{c_2 - c_1}{s_2} \tag{17}$$

As shown in Equation (15), if the initial shifting value of CVC-plus roll curve is equal to the initial value of CVC cubic roll curve, which is shown in Equation (17), the calculation result indicates that the coefficients A_5 and A_4 are 0, and the CVC-plus roll curve becomes a cubic CVC curve. It is a special instance of CVC curve for CVC-plus curve when $s_0 = s_0'$, as well as for the quintic CVC-plus roll curve when $s_0 \neq s_0'$. Therefore, how to determine the initial position s_0 and the coefficient A_5 become the key problems in the design and control.

(2) Determination of initial shifting value s_0 and coefficient A_5

Though $s_0 \neq s_0'$, the difference between them is not large. The initial shifting value of the CVC-plus roll curve can be determined according to the target value of the crown ratio $\bar{R}_C$ which can be supplied in plant. From Equation (13), we can know that the relationship between the crown ratio and work roll shifting position are quadratic, and when $s = s_0$ the $\bar{R}_C$ reaches its maximum value. However, the interval of the shifting values [s_1 , s_2] is very small. Therefore, when the shifting value is the maximum value $s_1$and s_2, the target crown ratio $\bar{R}_C$ is shown in Equation (18).

$$\bar{R}_C = \frac{[R_C(s_2) + R_C(s_1)]}{2} = \frac{4}{L^2} \times \left\{ L^2 + (s_2 - s_0)^2 + (s_1 - s_0)^2 + \frac{3 \times A_3}{5 \times A_5} - 6 \times s_0^2 \right\} \tag{18}$$

When $c_1 \times c_2 \neq 0$, from Equations (15) and (16), the following equation can be obtained,

$$\frac{3 \times A_3}{5 \times A_5} = \frac{4 \times (s_0^2 - s_2^2) \times s_0}{s_0 - s_0'} - L^2 - 2 \times s_2^2 \tag{19}$$

Substitute Equation (19) into Equation (18), the following equation can be obtained:

$$\bar{R}_C = \frac{16\times s_0\times(s_0\times s_0' - s_2^2)}{L^2\times(s_0 - s_0')} \Leftrightarrow 16\times s_0'\times s_0^2 - [L^2\times\bar{R}_C + 16\times s_2^2]\times s_0 + s_0'\times L^2\times\bar{R}_C = 0 \tag{20}$$

To solve the equation, Equation (21) must be true. When $|s_0'| \le |s_2|$, $\Delta_1 \le 0 \Rightarrow \Delta \ge 0$, so the crown ratio is random. When $|s_0'| > |s_2|$, $\Delta_1 > 0$ .It can be proved that

$$16\times(2\times s_0'^2 - s_2^2 - 2\times|s_0'|\times\sqrt{s_0'^2 - s_2^2})/L^2 > 0,$$

and the maximum value is $16\times s_2^2/L^2 \le 1$. Therefore, the available interval can be seen in Equation (22). The calculation formula of the initial work roll shifting value and coefficient A_5 is shown in Equation (23).

$$\begin{cases} \Delta = L^4\times\bar{R}_C^2 - 32\times L^2\times\left[2\times s_0'^2 - s_2^2\right]\times\bar{R}_C + 16^2\times s_2^4 \ge 0 \\ \Delta_1 = 64^2\times L^4\times s_0'^2\times(s_0'^2 - s_2^2) \\ \bar{R}_C = \frac{16}{L^2}\times\left[2\times s_0'^2 - s_2^2 \pm 2\times|s_0'|\times\sqrt{s_0'^2 - s_2^2}\right] \qquad \Leftarrow |s_0'| > |s_2| \end{cases} \tag{21}$$

$$\begin{cases} \bar{R}_C \ne 0 & \Leftarrow |s_0'| \le |s_2| \\ \left.\begin{aligned} &\bar{R}_C > \frac{16}{L^2}\times\left[2\times s_0'^2 - s_2^2 + 2\times|s_0'|\times\sqrt{s_0'^2 - s_2^2}\right] \\ &\bar{R}_C < 0 \end{aligned}\right\} & \Leftarrow |s_0'| > |s_2| \end{cases} \tag{22}$$

$$\begin{cases} s_0 = \frac{[L^2\times\bar{R}_C + 16\times s_2^2] \mp \sqrt{[L^2\times\bar{R}_C + 16\times s_2^2]^2 - 64\times L^2\times s_0'^2\times\bar{R}_C}}{32\times s_0'} \\ \bar{R}_C > 0 \text{ is “}-\text{”} \quad ; \bar{R}_C < 0 \text{ is “}+\text{”} \\ A_5 = \frac{(c_2 - c_1)/s_2 + (c_2 + c_1)/s_0}{80\times L^2\times(s_0^2 - s_2^2)} \end{cases} \tag{23}$$

When $c_1\times c_2 = 0$ or $c_1 + c_2 = 0$, $s_0 = s_0'$, the coefficient A_5 can be calculated as Equation (24) due to Equations (13) and (14).

$$\begin{cases} s_0 = s_0' = \frac{c_1 + c_2}{c_1 - c_2}\times s_2 \\ A_5 = \frac{c_2 - c_1}{5\times L^4\times s_2\times R_C} \end{cases} \tag{24}$$

2.2 Determination of roll curve coefficient A_1 and the roll diameter peak value

(1) The interval of coefficient A_1

Assume the two peak values of Equation (1) are x_1 and x_2, then,

$$
\begin{aligned}
y_1'(x) &= A_1 + 2\times A_2\times x + 3\times A_3\times x^2 + 4\times A_4\times x^3 + 5\times A_5\times x^4 \\
&= (x-x_1)\times(x-x_2)\times(a\times x^2 + b\times x + c) \\
&= a\times x^4 + [b + 2\times a\times s_0]\times x^3 + [a\times x_1\times x_2 + 2\times b\times s_0 + c]\times x^2 \\
&\quad + [b\times x_1\times x_2 + 2\times s_0\times c]\times x + c\times x_1\times x_2 = 0
\end{aligned} \tag{25}
$$

$$
\begin{cases}
a = 5\times A_5 \\
b = 4\times A_4 - 2\times 5\times A_5\times s_0 = 10\times A_5\times s_0 \\
c = 3\times A_3 - 20\times A_5\times s_0^2 - 5\times A_5\times x_1\times x_2 \\
A_2 = 3\times A_3\times s_0 - 20\times A_5\times s_0^3 \\
A_1 = [3\times A_3 - 20\times A_5\times s_0^2 - 5\times A_5\times x_1\times x_2]\times x_1\times x_2
\end{cases} \tag{26}
$$

The interval of A_1 is:

$$
\begin{cases}
\dfrac{dA_1}{d(x_1\times x_2)} = 0 \Rightarrow x_1\times x_2 = \dfrac{3\times A_3 - 20\times A_5\times s_0^2}{10\times A_5} = \dfrac{1}{2}\times\left[\dfrac{3\times A_3}{5\times A_5} - 4\times s_0^2\right] \\
A_{1\mathrm{PEAK}} = \dfrac{5\times A_5}{4}\times\left[\dfrac{3\times A_3}{5\times A_5} - 4\times s_0^2\right]^2 \\
-\dfrac{5\times|A_5|}{4}\times\left[\dfrac{3\times A_3}{5\times A_5} - 4\times s_0^2\right]^2 \le A_1 \le \dfrac{5\times|A_5|}{4}\times\left[\dfrac{3\times A_3}{5\times A_5} - 4\times s_0^2\right]^2 \\
\left[3\times A_3 - 20\times A_5\times s_0^2\right]^2 - 20\times A_5\times A_1 > 0
\end{cases} \tag{27}
$$

(2) Determination of coefficient A_1

The coefficient A_1 has a close relationship with the roll diameter peak value, and it determines the axial force of the strip acting on the roll. Considering the strip width, the roll shifting value and the off tracking of strip, using the minimized axial force as the target function, the coefficient A_1 is optimized [5-10].

Assume the off tracking of strip is $t \in [t_1, t_2]$. t_1 and t_2 are the peak values of the off tracking of strip. The axial force on the strip with a width of $2b$ can be obtained by integral calculation.

$$
\begin{aligned}
F_2 &= \int_{y_1(-b+t,s)}^{y_1(b+t,s)} p_0 dy = p_0\times\left[y_1(b+t,s) - y_1(-b+t,s)\right] \\
&= 2\times b\times p_0\times\begin{Bmatrix} A_1 + 2\times A_2\times(t-s) + A_3\times[3\times(t-s)^2 + b^2] \\ +4\times A_4\times[(t-s)^3 + (t-s)\times b^2] \\ + A_5\times[5\times(t-s)^4 + 5\times(t-s)^2\times b^2 + b^4] \end{Bmatrix}
\end{aligned} \tag{28}
$$

where b is a half of the strip width, and $y_1(x,s)$ is the roll curve of the upper roll.

(3) Determination of peak value of roll diameter

When the coefficients are determined, the coordinates of the maximum value can be calculated as follows:

$$
\begin{cases}
x_1 \times x_2 = 0.5 \times \left[\dfrac{3 \times A_3}{5 \times A_5} - 4 \times s_0^2 \right] \mp \sqrt{\left[\dfrac{3 \times A_3}{5 \times A_5} - 4 \times s_0^2 \right]^2 - \dfrac{4 \times A_1}{5 \times A_5}} \\
\overline{R}_C > 0 \text{ is ``}-\text{''} \quad ; \overline{R}_C < 0 \text{ is ``}+\text{''} \\
x_1 = -s_0 - \sqrt{s_0^2 - x_1 \times x_2} \\
x_{12} = -s_0 + \sqrt{s_0^2 - x_1 \times x_2}
\end{cases}
\tag{29}
$$

3 Design of CVC-plus roll curve

According to the condition of a certain steel plant, using the CVC-plus roll curve mathematical model, the quintic CVC roll curve is determined. The parameters needed for the calculation are listed in Table 1. The calculated coefficients are listed in Table 2. The work roll curve is shown in Figure 2. The relationship between the equivalent crown and the shifting value of the work roll is shown in Figure 3. The profile of the roll gap is shown in Figure 4.

Table 1 Parameters needed for calculation

Parameters	**Value**	**Unit**
Work roll barrel length	1650	mm
Work roll named diameter	710	mm
Max. equivalent crown	165	μm
Min. equivalent crown	-245	μm
Shifting area	±100	mm
Strip width	850-1300	mm
Crown ratio	-8.5	-

Table 2 Parameters of roll curve

CVC roll curve parameter	**Calculative result**
A_0	355.00
A_1	-2.264606120865497E-004
A_2	4.248272242897413E-008
A_3	7.088796266017358E-010
A_4	-1.768501519093894E-014
A_5	-1.771761012180488E-016
Initial shifting value S_0	19.963206176632340
Coefficient of axial force Z_E	8.912790141505940E-002
Radius of left end R_{WL}	354.877218672079600
Radius of right end R_{WR}	355.164225753436000
Coordinate of minimum point x_{min}	-354.627623386854300
Radius of maximum point R_{Wmax}	354.954313243425400
Coordinate of extreme point x_{max}	314.701211033589600
Radius of minimum point R_{Wmin}	355.054751093513900

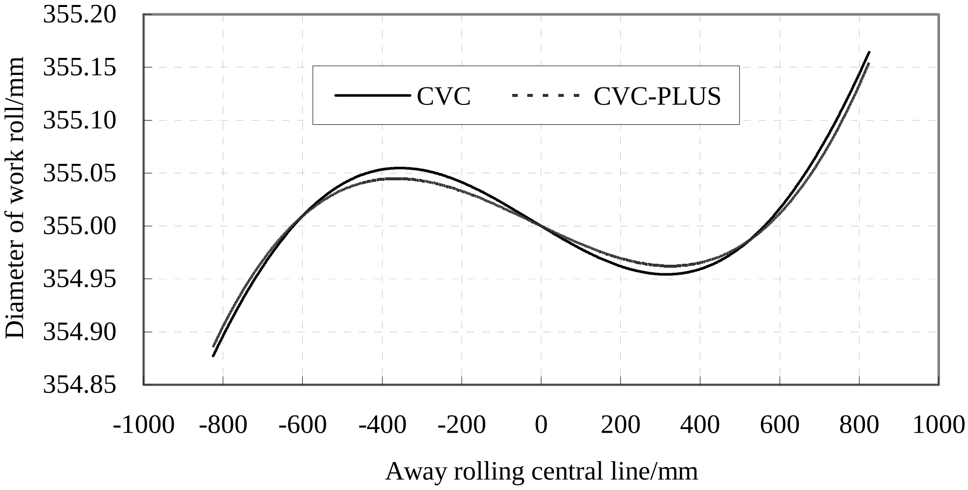


Figure 2 Work roll curves

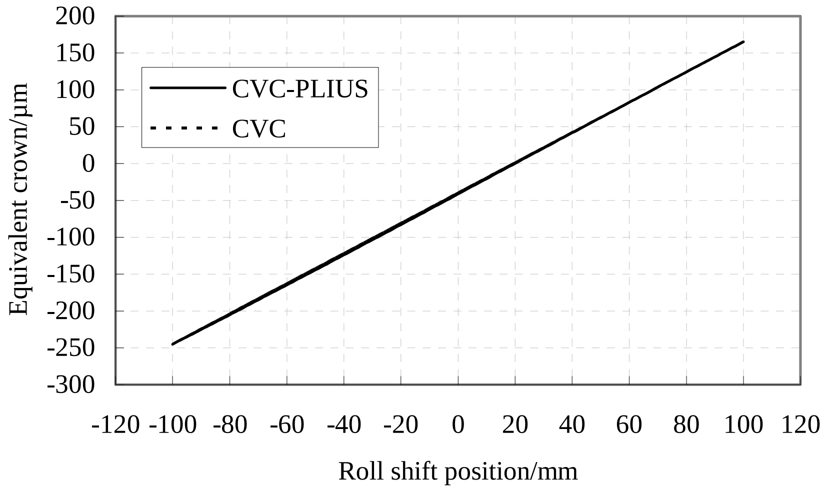
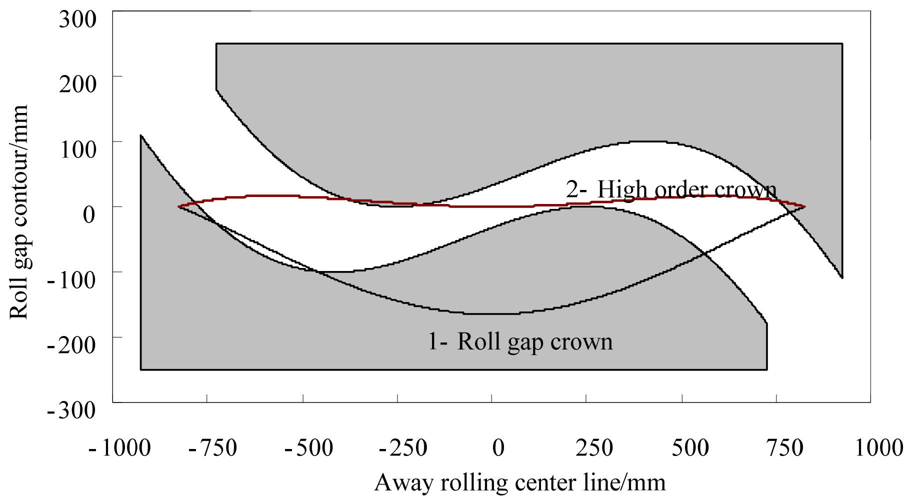
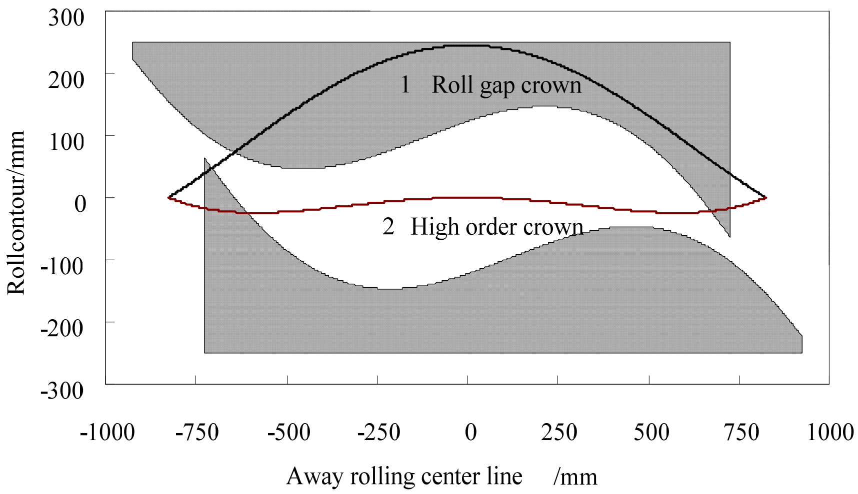


Figure 3 Relationship between equivalent crown and shifting value



(a) Shifting value is 100mm



(b) Shifting value is -100mm
Figure 4 Roll profile of CVC-plus roll

4 Conclusions

1) The distance between the maximum or minimum points of the high order equivalent crown and rolling central point is the $\sqrt{2}$ times of the roll barrel length.
2) In general, the initial shifting value of CVC-plus roll curve is not equal to the initial shifting value of the 3 order CVC roll curve.
3) The relationship between the initial shifting value and the target crown ratio was determined.
4) The relationship between the coefficients A_2, A_3, A_4, A_5 and s_0 was built up.
5) The coefficient A_1 can be obtained by optimization design with the minimized target function of the axial force.

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