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EFFECT OF HELIX ANGLE IN CROSS-ROLL ARRANGEMENTS OF BAR STRAIGHTENING PROCESS WITH KINEMATIC REVERSE BENDING

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Abstract: *Round bars produced in industries are often found compromised with degree of straightness. In many small or medium size industries the problem of straightness is often addressed somewhat manually, which is indeed a slow and cumbersome process and lacks quality and precision. To speed up the process, it is necessary to go for mechanized system i.e. deployment of straightening machine. However, straightening machine indeed helps in perfect processing of operation and quality aspects which can be systematically controlled through various parameters involved in the process. An attempt has been made in this paper to look into the effect of helix angle of the cross-roll arrangement in the process based on the equations developed by former researchers in this field.*

Key words: *Kinematic loading, residual curvature, straightness, rollers, helix angle.*

Efekat ugla zavojnice u pokretnim rasporedima procesa ispravljanja šipke sa kinematičkim obrtnim savijanjem. *Okrugle šipke proizvedene u industriji često su izložene pogoršanju stepena ravnosti. U mnogim malim ili srednjim industrijama problem ravnosti se često rešava pomoću ručne dorade, što je zaista spor i glomazan proces i nedostaje mu kvalitet i preciznost. Da bi se proces ubrzao, potrebno je ići na mehanizovani sistem, odnosno uvođenje mašine za ravnanje. Shodno tome, mašina za ravnanje zaista pomaže u savršenoj obradi i sa aspekta kvaliteta koji se može sistematski kontrolisati kroz različite parametre uključene u proces. U ovom radu je učinjen pokušaj da se sagleda efekat ugla spirale na raspored poprečnih valjaka u procesu na osnovu jednačina koje su razvili bivši istraživači u ovoj oblasti.*

Ključne reči: *Kinematsko opterećenje, zaostala zakrivljenost, ravnost, valjci, ugao zavojnice.*

1. INTRODUCTION

Straight bars are general requirement as input materials for many manufacturing industries. Straight steel round bars are extensively required in civil constructions. Among the various types of bar straightening process cross-roll straighteners are largely in use as a mechanical process of straightening. Two-roll and six-roll straighteners shown in Fig. 1 and Fig. 2 [1,2] are quite common in re-rolling industries as they are used for straightening of slightly bent or distorted which are straightened to specified degrees.

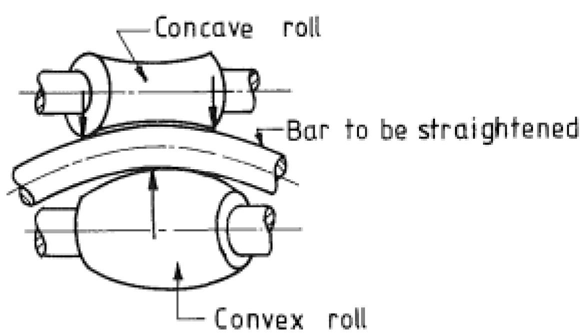

Fig. 1. Bar Straightening in a two-roll "Air- Bend" machine

Cross-roll straighteners are quite popular due to its speed of operation and reduction of curvature simultaneously. These machines are used in industrial applications for improving degree of straightness. In a large-scale production, various machineries with different set ups are used. Straightness is often achieved by virtue of operators' skill and experience since perfect application of theoretical part of moment-curvature relationship is extremely difficult. It also requires to be commercially viable. To combat this problem researchers are deeply involved in finding out viable solutions. Viability of deployment of straightening machine will depend on economic order quantity (EOQ) also. For practical purpose, quality control of bar curvature will depend upon many aspects of bar straightening. However, main feature remains to be final mean curvature in an acceptable range after reduction of initial curvatures. The final mean curvature is important as roller setting shall require a value for which arrangements will be done.

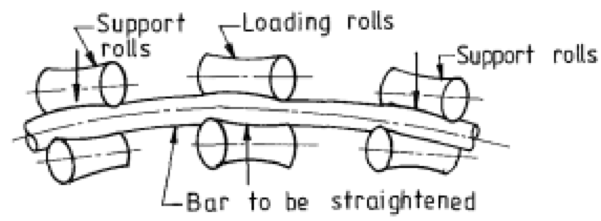

Fig. 2. Bar straightening in a six-roll straightening machine

Positioning of rollers play a vital role in setting up of cross-rolls for bar straightening. Roller positioning with different arrangements particularly the angle of roller with respect to bar's axial motion (called helix angle) may provide different curvature changes leading to final curvature. In the present study effect of helix angle on the cross-roll arrangement of bar straightening process has been investigated to keep high speed of operation.

2. PROBLEM STATEMENT

A sketch of round bar's motion in cross-roll arrangement has been described below. In Fig. 3(a) cross-rolls are set at helix angle $\pm\alpha$, w.r.t. bar's axial motion and throughput speed, v_x. The bar rotates about its own axis at an angular velocity $\dot{\theta}$ as shown in Fig. 3(b). Radius of bar and rollers are *r* & *R* respectively.

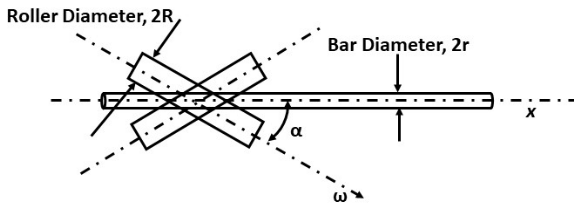

Fig. 3(a). Round bar's motion through Cross-Rolls

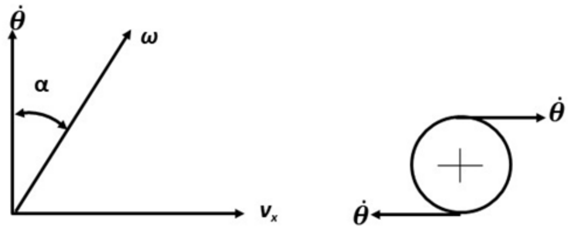

Fig. 3(b). Bar's rotation and angular velocity

3. ANALYSIS OF THE STRAIGHTENING PROCESSES

Non-dimensional form on the relationship of moment-curvature is described [3]:

$$\bar{M} = \bar{\kappa} \qquad 0 \leq \bar{M} \leq 1,$$
$$\bar{M} = \bar{M}(\bar{\kappa}) \qquad 1 \leq \bar{M}, \tag{1}$$
where, $\bar{M} = M/M_y$, and $\bar{\kappa} = \kappa/\kappa_y$

M_y is the yield moment and κ_y is the yield curvature for a section considered. $\bar{M}(\bar{\kappa})$ is a function of $\bar{\kappa}$, which depends on the stress-strain relationship of the material beyond the yield point. For convenience purpose, Curvature and moment of resistance in reverse loading will be taken as positive. Considering a bar to be straightened is having initial curvature, $-\bar{\kappa}_r$. The length of the bar should be subjected to loading in the reverse direction. The loading should be kinematically either by applying a known moment or a known curvature.

If the loading is kinematic and the curvature to which the bar length is subjected is $\bar{\kappa}_f$, then, in order to leave no final residual curvature on unloading, the curvature change $\Delta\bar{\kappa}$, as illustrated in Fig.4 [1].

$$\Delta\bar{\boldsymbol{\kappa}} = \bar{\boldsymbol{\kappa}}_f + \bar{\boldsymbol{\kappa}}_r \tag{2}$$

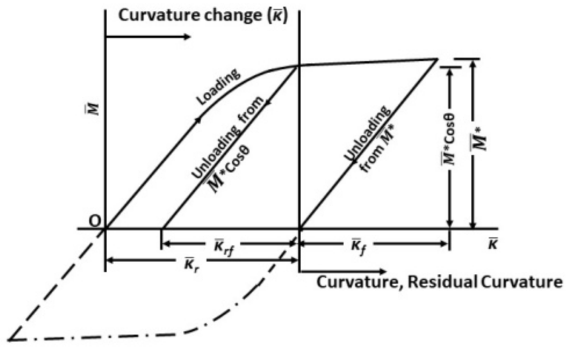

Fig. 4. Relationship between curvature change and resisting moment developed in the bar.

Considering plane of loading as vertical in this analysis, and osculating plane enclosing an angle $\boldsymbol{\theta}$ between them, the effective bending moment will be the component of the bending moment in the loading plane, along the osculating plane [4].

$$\bar{m} = \bar{M}cos\theta, \tag{3}$$

where $\bar{\boldsymbol{m}}$ is the effective bending moment and $\bar{M}$ the bending moment in the plane of loading at the section considered.

The component $\bar{M}sin\theta$ of $\bar{M}$ mostly produces elastic deformations, hence of no consequence in the analysis. Therefore, a section which is subjected to curvature $\bar{\boldsymbol{\kappa}}_f$ in the vertical plane and a resisting moment in the loading plane of $\bar{M}^*$, the effective resisting moment developed in the section is given by,

$$\bar{m} = \bar{M}^* cos\theta, \tag{4}$$

and when unloading takes place from the loading curvature there will remain a final residual curvature in the bar length of $\bar{\kappa}_{rf}$ as illustrated in Fig.4.

In the cross-roll straightening machine, the rolls are set at angles $\pm\alpha$ with the axis of the bar of radius $\boldsymbol{r}$ as illustrated in Fig.3(a). Cross-rolls actually cause bars to rotate about its own axis as the bar progresses forward through the rolls. If ω is the angular velocity of the rolls of radius R, throughput velocity $\boldsymbol{v}_x$ and the tangential velocity is $\boldsymbol{v}_t$ of a point on the surface of the bar Fig. 3(b) then

$$v_x = \omega R sin\alpha, \quad \text{and} \tag{5}$$
$$v_t = \omega R\ cos\alpha \tag{6}$$

The pitch length of the bar can be expressed in terms of helix angle α as below:

$$p = 2\pi r tan\alpha$$

In non-dimension form,

$$\bar{p} = \frac{p}{l} = 2\pi\bar{r}tan\alpha, \tag{7}$$

where, l is the beam length and r is the radius of bar and $\bar{r} = \frac{r}{l}$.

If moment developed at the mid-section of the of the bar at any instant be $\bar{M}^*$ in the plane of kinematic loading, then the bending moment $\bar{M}_x$ in the same plane at any other section will depend on the distance of the section from the mid-section and the type of loading. As a section considered progresses through the rolls, the enclosed angle θ for that section varies continuously due to the rotation of the bar.

Thus, if at a generic section $\bar{x}= x/l$ and $\theta=\theta_x$, then the effective bending moment $\bar{m}_x$ at the section will also vary continuously and will be given by

$$\bar{m}_x = \bar{M}_x \cos\theta_x \qquad (8)$$

If y is the lateral displacement of the section of the bar then,

$$\cos\theta_x = y/r = \bar{y}, \qquad (9)$$

From Eq.5, we get $x = (\omega R \sin\alpha).t$

and $\qquad y = \omega R \cos\alpha .t \qquad (10)$

Also, in non-dimensional form $\bar{x} = \frac{x}{l}$, $\bar{p} = \frac{p}{l}$

Since, pitch length,

$$p = 2\pi r \tan\alpha = 2\pi r \sin\alpha / \cos\alpha$$

Therefore, $\qquad \cos\alpha = 2\pi r \sin\alpha / p \qquad (11)$

Substituting cosα in Eq.10,

we get $\qquad y = \omega R \cos\alpha.t$

$$= \omega R(2\pi r \sin\alpha).t/p \qquad (12)$$

Since, $x = (\omega R \sin\alpha).t$, then by substituting in Eq.12, we get

$$y = 2\pi x\, r/p \qquad (13)$$

Again, $\qquad \bar{y} = y/r$

$$= 2\pi x/p$$

$$= 2\pi\bar{x}/\bar{p} \qquad (14)$$

From Eq.10,

$$y = r \sin(t.\omega R \cos\alpha / r)$$

therefore, $\qquad \bar{y} = \sin(2\pi\bar{x}/\bar{p})$

Hence, $\qquad \bar{m}_x = \bar{M}_x \cos\theta_x$

$$= \bar{M}_x \sin(2\pi\bar{x}/\bar{p}) \qquad (15)$$

From above equation, it can be seen that $\bar{m}_x$ is an oscillating function of $\bar{x}$ with the curve $\bar{M}_x$ as its envelope.

The variation of bending moment in the loading plane and the corresponding variation of effective bending (or resisting) moment as the bar progresses through the rolls is illustrated in Fig. 5 [1]. In a pitch length the osculating plane of the bar rotates through 360°and the effective resisting moment oscillates through one cycle. However, considering Eq.(9)

$$\bar{m}_x = \bar{M}_x \cos\theta_x$$

$$= \bar{M}_x (2\pi\bar{x}/\bar{p})$$

$$= \bar{M}_x (2\pi\bar{x}/2\pi\bar{r}\tan\alpha)$$

$$= \bar{M}_x \bar{x} \cot\alpha / \bar{r}$$

or, $\qquad \bar{m}_x = \bar{M}_x\, x \cot\alpha / r \qquad (16)$

From the above equation, it is clear that theoretically for maximum effective bending moment, helix angle should be kept at lower value and maximum angle can go up to π/4. Beyond π/4 value starts reducing and value becomes zero at angle π/2. Beyond angle π/2, values are in negative which means helix angle cannot be kept more than π/2. There are practical limitations for setting helix angles since roller diameter itself is a constraint which is due to accommodating required space for roller itself. Roller length and diameter along with bar diameter is a concern for accommodation of roller in the setup.

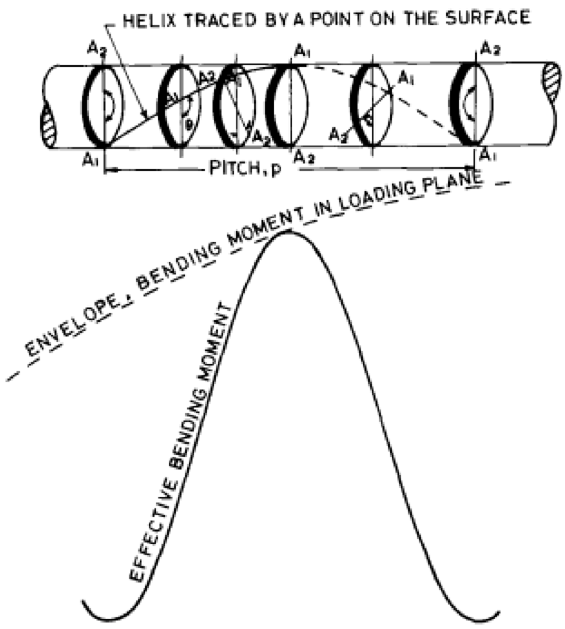

Fig.5. Illustration of bending moment variation in the loading plane and the corresponding variation of effective bending moment in a pitch length as bar rotates through 360° through one cycle.

Considering cotangent graph given in Fig. 6 [5], appreciable high values are available for above purpose when angle is within π/4 which means helix angle to be kept slightly lower than π/4.

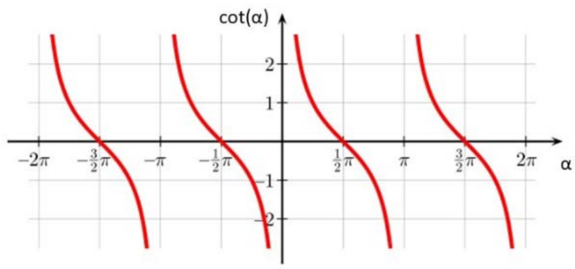

Fig. 6. Cotangent graph showing values along the angle from -2π to 2π.

Throughput speed of bar is given by

$$\bar{v}_x = v_x / (\omega R)$$

$$= [1+(2\pi\bar{r}/\bar{p})^2]^{-(1/2)} \qquad (17)$$

Therefore, it can be seen easily from the above equation that throughput speed of bar can be controlled by controlling helix angle. The bar radius r is constant for a set of bars in a straightening process; hence speed of operation can be controlled by controlling helix angle α. However, if the diameter of bar varies within the length, then throughput speed will change accordingly. It is evident from the above equation that if speed of operation is to be kept high then lower helix angle is essential. However, lower helix angle also means lower pitch length.

4. CONCLUSION

The above analysis indicates that helix angle of the bar straightening process is of considerable importance. It is essential to keep lower helix angle for the purpose of workable throughput speed of the bar. Higher throughput speed definitely causes higher production, but a balance is essential. Also, from the cotangent value of helix angle and practicality of roller adjustment in the machine set up, it is prudent to keep the helix angle slightly lower than $\pi/4$. Since helix angle is related to the pitch length of the bar, lowering helix angle also means lowering of pitch length which is a better option considering standard of straightness. However, it is also possible to increase pitch length keeping the same standard of straightness but with a different roll arrangement.

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