A Probabilistic Approach on the Estimation of Residual Curvature of Round Bars in Straightening Process with Cross-Roll Arrangements

Sanjib Roy[1], Arun Kiran Pal[2]

Abstract: ***There have been various research works in the field of bar straightening in last several decades, but somehow probabilistic approach of various process parameters of bar straightening has practically not been deeply looked into. This paper has made an effort to discuss mainly on probabilistic approach on the estimation of curvature of round bars along with brief narration of bar straightening process. Bar straightening involves various parameters like bar size and speed, helix angle, roller speed, pitch length, bending moments, residual curvatures. Statistical concept has been applied through these parameters to estimate final mean residual curvature of the processed bar.***

Keywords: Straighteners, Residual Curvature, Reverse Kinematic Bending, Bending Moment

1. Introduction

Production of round bars of various sizes and lengths are common requirements in many industries, since round bars are used directly as raw materials in structural work or for fabrication purpose as per users' specification. In the event of such cases where material shall be considered as input material to produce some value added designed industrial product like machined rods, shafts, mechanical links, sliding rods in the machines where some material movement shall take place, then bar straightening plays very significant role as straightening of bar will save raw material from machining and also valuable standard time of machining process. Round bars so produced need to meet quality requirements which are sometimes stringent based on applications. Straight rods are in use as components of machines or as raw materials for machinery parts. In wire production industry, straightening of wire is a general requirement after de-coiling. In fact, there is a requirement of continuous straightening in case of wire. Ferrous and non-ferrous both types of wires require straightening before application.

Bar straightening through cross-roll arrangement enables straightening of bars and tubes in continuous manner. However, both the ends still call for further processing since terminal ends usually don't get straightened up easily to acceptable range. Needless to mention that curved bars come with residual curvatures. Even after straightening process elimination of residual curvatures at both ends are extremely difficult. Sometimes, multi-step straightening control system (MSSC) helps in reducing residual curvatures [1].

The bar when is chosen for straightening usually has some residual curvature which is actually the final output of previous process. It is indeed necessary that bars produced in hot rolling shall require straightening process depending on nature of applications. Probabilistic approach shall therefore be quite useful in choosing a production lot or a batch of such products which are considered as straight rods or tubes. Present paper is primarily focused on round bars or tubes which are subjected in cross roll straightening machine for straightening purpose under reverse kinematic bending. Cross rolls are set at an angle called helix angle which actually enables the bar to move ahead in the straightening machine.

2. Types of Cross-Roll Straighteners

Various types of cross-roll straighteners are available in industries based on number of rollers, arrangements of rollers, types of rollers etc. In all the rotary straighteners, the rollers are usually of concave hyperbolic contour [2]. Each type has superior advantage in specific circumstances. Cross-roll straightening machine or reeling machines being most popular have several combinations of idle and driven roll arrangements.

2.1 Cross-roll straightening machines

Cross-roll straightening machines are designed for straightening of both tubes and bars of circular cross section. The rolls are mounted at an angle to the line of pass. The material or bar rotates as it proceeds through the machine. Although there are several types, but generally four basic types of cross-roll machines are in use which may be put as below [3]:

1) Two-roll Straighteners or Reeling machines
2) Six-roll types (six rolls which are mounted in a set of three pairs).
3) Multi-staggered roll types having five, seven or even ten rolls
4) Cluster-roll machines having seven rolls. A set of two-clusters each cluster is made of three-rolls and another roll at centre i.e. deflecting roll.

2.1.1 Two-roll Bar Straighteners or Reeling machines

Two-roll Bar Straighteners or bar straightening machines comprise of one convex roll and one concave roll. The ends of concave roll act as horns while the convex roll can exert reverse load at centre of the bar where bending takes place. Reeling machines are classified again into two types which are as below:

(a) Free-bend straighteners or Air-bend straighteners
(b) Line-contact type rolls straighteners.

In free-bend or air-bend straighteners as illustrated in Fig.1, the application of load is concentrated at a point like simply supported beam with a centralised load [4, 5]. On the other hand, in line contact roll straighteners, the bar happens to be deformed between a set of two rolls which is equivalent to conventional simply supported beam with uniformly distributed loading.

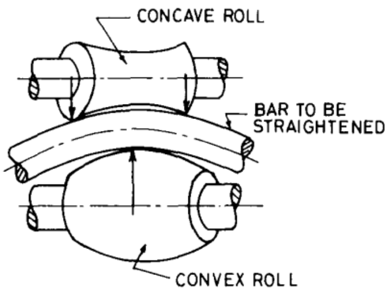

Figure 1: Straightening of Bar in a Two-Roll 'Air-Bend' machine

2.1.2 Six-roll Straighteners

Six-roll straighteners are having six rolls mounted in a set of three pairs as shown in Fig.2. The beam-length is more or larger in case of six-roll straighteners in comparison to free bend or air-bend straighteners. However, loading is distributed but over a span of small length which is in line contact i.e. near mid-span of the bar [4,5].

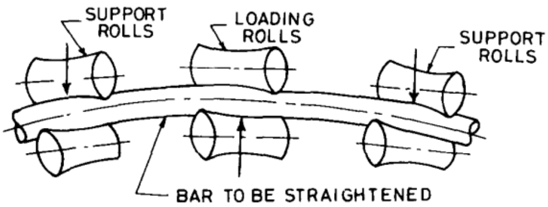

Figure 2: Straightening of Bar in a Six-Roll straightening machine

2.1.3 Multi-staggered roll types having five, seven or even ten rolls

These machines have staggered rolls and number of rolls is five rolls, seven rolls or even ten rolls. The rolls are so arranged that it functions like practically number of "loading bays" and at each loading bay beam length is subjected to a point load or concentrated load and acting at opposite directions at consecutive bays.

2.1.4 Cluster-roll straighteners

In cluster-roll straightening machines, there are seven rolls which are arranged in a set of two-clusters of three-rolls each along with one roll at centre which is for deflecting purpose.

3. Theoretical Analysis of Cross-Roll Straightening Process

An isotropic material if subjected to loading then material undergoes deformation initially up to elastic limit. If loading is beyond yield point, then loading reaches in plastic zone causing permanent deformation. The curved round bars are available with some initial residual curvatures which need to be deformed beyond yield point for straightening. After reaching a certain point while undergoing plastic deformation loading will get released to arrive a new deformation value i.e. a new residual curvature which is expected to be of reduced value under normal circumstances. Based on Moment-Curvature relationship, it can be stated that if reverse kinematic bending takes place with proper value of bending moment, then final residual curvature could be even zero which means bar is fully straightened.

3.1 Mechanics of bar straightening

The theoretical aspects of bar straightening although initiated by Tokunaga [2] but was restricted to preliminary stage. The detailing on theoretical aspects was looked into by Das Talukder & Johnson [4] with their analytical approach which was further enhanced by Yu and Johnson [6]. Moment-curvature relationship was established in non-dimensional form. Detailing on motion of the bar through various roles have been elaborated by Das Talukder et.al. [5] with substantial mathematical treatment. Certain assumptions formed the basis of the mathematical treatment of bar straightening which is put below for ready reference [7,8].

3.2 Assumptions

1) Elastic work hardening is present in the straightened bar.
2) In pure bending condition, round bar's cross-sectional area is circular and neutral axis passes through the centre.
3) Outside shapes of bars and tubing are round and tubing have uniform wall thickness.
4) Cross section remains on a plane at right angles to the axis.
5) Variation of strain is proportional to distance from perpendicular point on neutral axis at any point in bar section.
6) Material is considered as perfectly elastic-plastic, and its stress-strain relations in uniaxial tension is same as in compression. It has same elastic modulus and yield point both in tension and in compression.
7) All stress components other than longitudinal direction is zero.

The bars on proceeding through cross-rolls set at a helix angle α rotate about its own longitudinal axis with the initial curvature plane which makes different angles at various instants with loading plane and also progresses through the rolls. The pitch, p for one complete rotation of bar of radius r can be equated as below:[4,5]

$$p = 2\pi r \tan\alpha \qquad (1)$$

As bar progresses through the cross-rolls, there will be corresponding variations of effective bending moment. In a span of pitch length, bar's osculating planerotates 360^0. Oscillation of effective bending moment or resisting moment will occur through one cycle [5]. Effective bending moment will have variation which is maximum at half the pitch length as shown in Fig.3.

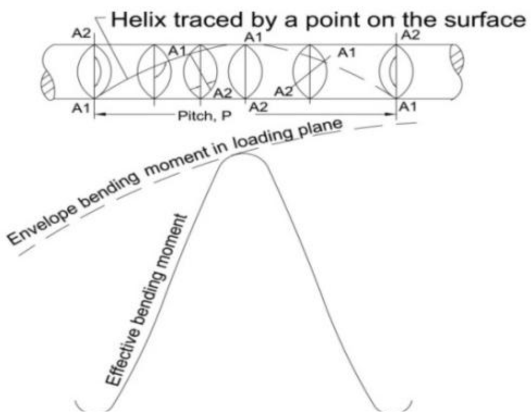

Figure 3: Illustration of variation of resisting moment or effective bending moment in loading plane

The cross-rolls are so staggered that maximum loading moment M^* is developed while passing through the rolls and corresponding curvature change is κ^*. For simplicity, uniform initial curvature of round bar is assumed. The curvature change-resisting moment of a bar can be drawn as indicated in Fig.4.

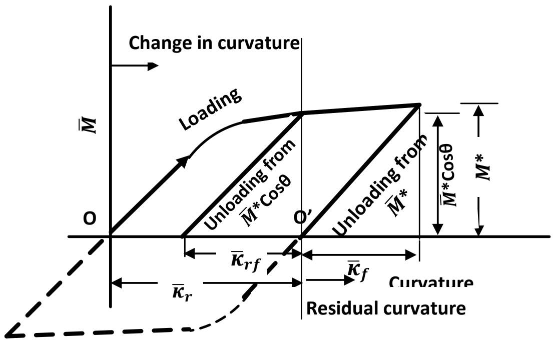

Figure 4: Simplified relationship between resisting moment or effective bending moment in the bar and change in curvature.

Therefore, residual curvature change, $\Delta\kappa_r$ or $\Delta\bar{\kappa}_r$ (in non-dimensional form) can be expressed as,

$$\bar{\kappa}_r = \frac{\kappa_r}{\kappa_y} \qquad (2)$$

$\bar{\kappa}_r$ is equal and opposite to initial curvature [4].Also, $\bar{\kappa}_{rf} = \frac{\kappa_{rf}}{\kappa_y}$ *and* $\bar{\kappa}_f = \frac{\kappa_f}{\kappa_y}$

The non-dimensional form of bending moment, M may be expressed as,

$$\bar{M} = \frac{M}{M_y} \qquad (3)$$

where M_y is bending moment at yield point.

Based on above diagram (Fig.4), effective bending moment will be a component of bending moment which is acting in the plane of loading making an angle θ with osculating plane. Therefore, effective bending moment, $\bar{m}$ can be expressed as,

$$\bar{m} = \bar{M} \cos\theta \qquad (4)$$

M^* is the maximum bending moment due to kinematic reverse bending corresponding to curvature $\bar{\kappa}_f$ which would result into zero or insignificant final residual curvature $\bar{\kappa}_{rf}$ i.e.straight bar without any curvature. From Fig.4 Moment-Curvature relationship it is clearly understood that unloading point is very important to get a desired level of final residual curvature, $\bar{\kappa}_{rf}$. If $\bar{\kappa}_{rf}$ is made to be zero, then unloading needs to start from bending moment level M^*.

Loading moment is developed at a distance of bar $\left(x - \frac{1}{2}l\right)$, where x is a generic distance at any section along the bar length l. $\bar{M}\ sin\theta$ component of $\bar{m}$ produces mostly elastic component, hence of no consequence in the present analysis.

At the time, when a bar section approaches $x = \frac{l}{2}$, the curvature plane and loading plane may not have any angle or zero angle in between. The effective bending moment as explained in the diagram, will achieve such value only at a few sections. Such sections will be at pitch length distance, p of the bar.

4. Probabilistic approach in the analysis of bar straightening process

A round bar which has some initial residual curvature needs to be straightened with a final residual curvature. The bar in the rollers is moving ahead due to cross-rolls set at an angle, α. It cannot be ascertained that curved portion of the bar will always be subjected to maximum reverse bending as this event will occur only at a particular situation that maximum curvature point during rotation matches with maximum loading arrangement of cross rolls. It was therefore be probabilistic only that to what extent curvature will actually be reduced on each pass of cross-roll arrangement. Various points on outer surface of the rod where curvature lies actually face different effective reverse bending load. The actual frequency distribution can be ascertained only after several experiments and data drawn thereof. However, the change in curvature shall indeed be a function of curvature.

Based on the concept of Das Talukder and Johnson, if a length of bar with initial curvature -κ_{ri} is to be straightened then bar length should be subjected to loading in the reverse direction either kinematically applying a known moment, or kinematically applying a known curvature causing moment by reverse bending[4]. If the loading is kinematic and the curvature to which the bar length is subjected to final curvature on unloading is κ_{rf} , then the change in residual curvature, $\Delta\kappa_r$ is given by

$$\Delta\kappa_r = \kappa_{rf} + \kappa_{ri} \qquad (5)$$

This curvature change can be expressed as a function of curvature $g(\kappa_r)$. We can consider all events of straightening process like rotation of bar, the throughput speed, effective bending moment due to kinematic loading of one complete movement of the bar. Various points of bar's outer surface shall come across different effective bending moment along the bar length. In actual case the bar is continuous and concept of continuous function is applicable.

A small bar segment λ_i is subjected to kinematic reverse bending moment M_i. The initial residual curvature of this small segment is κ_{ri} and final residual curvature after straightening process is κ_{rf}.

A probability P_i is considered of occurring maximum bending moment in the length segment λ_i.. In case of continuous random variable of curvatureκ_r for a beam length (a length between the horns of concave roller), probability density function of curvature change is $f_{\kappa_r}(\kappa_r)$.In such case, probability of occurring maximum bending moment at length segment λ_i can be expressed in terms of curvature

$$P(\lambda_i<\kappa_r<\lambda_{i+1}) = \int_{\lambda i}^{\lambda i+1} f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (6)$$

It follows then that the corresponding distribution function is

$$F_\kappa(\kappa_r) = P(\kappa_r \leq \kappa_i) = \int_{-\infty}^{\kappa_{ri}} f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (7)$$

Accordingly, if $F_\kappa(\kappa_r)$ has a first derivative, then from Eq. (7)

$$f_{\kappa_r}(\kappa_r) = \frac{dF\kappa(\kappa_r)}{d\kappa_r} \qquad (8)$$

A function being non-negative representing probabilistic distribution of a random variable necessarily satisfy the axioms of probability; the probabilities associated with all possible values of the random variable must add up to unity. On further reiteration $f_{\kappa_r}(\kappa_r)$ is not a probability; however, $f_{\kappa_r}(\kappa_r)d\kappa_r = P(\kappa_{ri} <\kappa_r <\kappa_{ri} + d\kappa_r)$ is the probability that values of κ_r will be in the interval $(\kappa_{r\ i}, \kappa_{r\ i}+d\kappa_r)$ [7,8].

Based on above, it can be said that, if $F_\kappa(\kappa_r)$ is the distribution function of κ_r, then it must have the following properties:

(i) $F_\kappa(-\infty) = 0$; $F_\kappa(+\infty) = 1$
(ii) $F_\kappa(\kappa_r) \geq 0$, and is non-decreasing with κ_r
(iii) It is continuous with κ_r

For a segmented length λ_i of bar within cross-roller under reverse kinematic bending,

$$P(\kappa_r) \leq \kappa_{ri} = \int_{\lambda i} f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (9)$$

In a length segment of λ_i of a bar in process of straightening, P_i, the probability of occurring maximum reduced *curvature* for a specific pass or final residual curvature κ_{r_f} which may be within acceptable range for industrial purpose. This will occur due to maximum effective bending moment or resisting moment arising out of reverse kinematic loading. However, the least curvature is possible only when that particular length segment of rotating bar, λ_i faces an alignment of $\theta=0^\circ$ with loading and osculating plane so that maximum bending moment is available on that segment.

If κ_{r_i} is the initial residual curvature in the osculating plane, then initial curvature in the loading planeκ_{r_l}can be equated as,

$$\kappa_{r_l} = \kappa_{r_i} cos\ \theta \qquad (10)$$

Needless to say that, both initial residual curvature κ_{r_i} and angle θ are certainly random variables as values of these variables at any instances are not known. This is indeed probabilistic that which segment of bar will be subjected to maximum bending moment. This is due to the fact that various parameters are in use in the process *i.e.* initial residual curvature,κ_{ri}, throughput speed of bar, v_x, radius of bar r, angular speed of bar about its longitudinal axis due to cross-roll arrangement of rollers and roller size with radius, R. As such for practical purpose, speed of the motors causing rotation of cross-rolls is somewhat constant or with insignificant variation. In that case throughput speed, i.e. bar speed can also be considered as constant. Roller size and bar size can be considered as constant since variations are insignificant. Therefore, primarily two random variables are in place i.e. initial residual curvature (κ_{r_i})and angle between loading plane and osculating plane (θ).

Considering random bar segment λ_i with initial residual curvature κ_{ri}, segment λ_i will come across point of reverse bending under some particular set up of cross-roll arrangements. As the bar is having rotation with angular speed, ω based on r.p.m. of cross-rollers, the particular length segment λ_i with an initial residual curvature κ_{ri} may be at any angle of osculating plane and facing the corresponding kinematic reverse bending load. The situation will certainly occur as a point on bar surface which will be within 0° to 360°.

Now, for a length segment of bar, λ_i with initial residual curvature, κ_{ri} shall undergo curvature change, $\Delta\kappa_r$ with effective bending moment ΔM and make new residual curvature or final residual curvature, κ_{rf}.

If the probability density functions of the curvature change is $f_{\kappa_r}(\kappa_r)$ or final residual curvature$f_{\kappa_r}(\kappa_{rf})$for this particular length segment λ_i then, the probability of final residual curvature on that length segment shall be:

$$P(\kappa_{ri}<(\kappa_r)<\kappa_{rf}) = \int_{\kappa_{ri}}^{\kappa_{rf}} f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (11)$$

Similar approach can be considered for each small length segment from beginning till end of the bar. Except the terminal ends of the bar, all such length segments will be somewhat subjected to above.

It can further be said that, after deformation due to reverse kinematic bending for a length segment of bar region from segment $\lambda_i$tosegmentλ_{i+1}, λ_{i+1} tosegmentλ_{i+2},. λ_{n-1} to segment λ_n, probability of occurrence of final residual curvature for entire length of bar can be stated as below:

$$P(\kappa_{\lambda i}< \kappa_r<\kappa_{\lambda n}) = \int_{\kappa_{\lambda i}}^{\kappa_{\lambda n}} f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (12)$$

Hence for all practical purposes, it can be stated that probability of final residual curvature of a bar length, L can be put as below:

$$P(\kappa_r)= \int_L f_{\kappa_r}(\kappa_r)d\kappa_r \qquad (13)$$

Probability density function $f_{\kappa_r}(\kappa_r)$ can be evaluated by virtue of substantial experimental data of the process.

$f_{\kappa_r}(\kappa_r)$ is not a probability; however, $f_{\kappa_r}(\kappa_r)d\kappa_r$= P($\kappa_{ri}$<$\kappa_r$<$\kappa_{ri} + \Delta\kappa$) is the probability that values of residual curvature κ_r will be in the interval (κ_r, $\kappa_r + \Delta\kappa$) [9].

It is now possible to calculate probability density function using computer software like Minitab or any other similar software. It may follow some standard distribution. In that case we can straightway deploy that distribution and make estimation of mean final curvature. The expected value of curvature $E(\kappa\ )$ may be stated as below:

$$E(\kappa\ ) = \int_{-\infty}^{\infty} \kappa_r f_{\kappa_r}(\kappa_r) d\kappa_r \qquad (14)$$

It is customary to designate the expected value as mean which is expressed as μ. Hence, for a random continuous variable of residual curvature in a bar, the mean can be expressed as

$$\mu_\kappa = \int_{-\infty}^{\infty} \kappa_r f_{\kappa_r}(\kappa_r) d\kappa_r \qquad (15)$$

Considering residual curvature as a function of residual curvature, then the expected value, E of curvature may be estimated as

$$E\,[g(\kappa_r\ )] = \int_{-\infty}^{\infty} g(\kappa_r)\, f_{\kappa_r}(\kappa_r) d\kappa_r \qquad (16)$$

where, $g(\kappa_r\ )$ is a function of residual curvature, κ_r .

Hence, for a random continuous variable of residual curvature in a bar, the mean curvature, μ_κ after the rolling process can be expressed as

$$\mu_\kappa = \int_{-\infty}^{\infty} g(\kappa_r) \quad f_{\kappa_r}(\kappa_r) d\kappa_r \qquad (17)$$

In the event, the probability density function of the above equation follows normal distribution then the equation can be expressed as

$$\mu_\kappa = \int_{-\infty}^{\infty} g(\kappa_r) \quad \frac{1}{\sigma_{\kappa_r}\sqrt{2\pi}} \quad e^{-\frac{(\kappa_r-\mu_\kappa)^2}{2\,\sigma_{\kappa_r}^2}} d\kappa_r \qquad (18)$$

The variance of residual curvature after the rolling process may be expressed as Var (κ_r), where standard deviation of the process is σ_{κ_r}.

Therefore,

$$\mathrm{Var}(\kappa_r) = \sigma_{\kappa_r}^2 = \int_{-\infty}^{\infty} (\kappa_r - \mu_\kappa\ )^2 \quad f_{\kappa_r}(\kappa_r) d\kappa_r \qquad (19)$$

$$= E\left[g(\kappa_r\ )\right]^2 - \mu_\kappa^2 \qquad (20)$$

A more convenient measure of dispersion will be standard deviation, σ_{κ_r} ; that is,

$$\sigma_{\kappa_r} = \sqrt{Var(\kappa_r)} \qquad (21)$$

Probabilistic approach in the straightening process has led to arrive into the development of mean residual curvature and standard deviation in the continuous process of reduction of residual curvatures in cross-roll arrangement of bar straightening. Such probabilistic approach has not been dealt so far in bar straightening process in terms of reduction of residual curvatures.

5. Conclusion

It is obvious that probabilistic approach has not been practically looked into in earlier researches. With a help of proper database, a more definitive conclusion can be drawn so as to understand the actual behaviour of reduction of curvatures in cross-roll arrangements, in particular which distribution pattern is followed while reducing the residual curvature in various processes. Now sufficient scope has emerged to understand the process based on statistical approach of residual curvatures. Prediction of number of passes required actually for reducing the residual curvatures to the desired extent so as to meet the required level of straightness will be possible based on generation of statistical data of the process parameters. Statistical process control can now be considered as scope of further research work in the field of bar straightening.

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