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Bowing of Cold-rolled Strips by Multi-slitting*

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Synopsis

The relation between the cross sectional configurations of cold-rolled thin strips and the diameters of bowed strips after slitting has been investigated. When a cold-rolled strip is multi-slitted, an edge-rippled or a center-buckled strip will bow in its plane by the widthwise variation both in elastic strain and in plastic strain. The diameters of bowing due to both effects can be calculated by the equations (6), (11) in edge-rippled strips, and (10), (12) in center-buckled strips respectively. These results have been ascertained by the slitting experiment of some cold-rolled strips.

I. Introduction

When center-buckled or edge-rippled strips are multi-slitted, "bowing" phenomenon may be observed and slitted strips bow toward the inner or the outer side in its plane. This bowing will disturb smooth sending of the strip to a punching press or well-ordered assembling. Consequently, the straightness of multi-slitted strips is of utmost importance for economical production and easiness of the subsequent operations. Hence, in the present investigation, the causes of bowing of cold-rolled and multi-slitted strips and several formulae concerning bowing curvature were examined, and the results were checked by experiments.

II. Bowing

In practical rolling, strips are often edge-rippled or center-buckled by re-rolling, even if they are "flat" when annealed, because of the variation of the rolling reduction in the direction of width after annealing. In such cases, residual stresses will be nonuniformly distributed along the direction of the width.

By slitting these strips the balancing of residual stresses will be lost and strips bow in their planes toward either inner or outer side. Still more, edge-rippled or center-buckled strips have a very slight difference in longitudinal length along the widthwise direction continuously. Before slitting, this is compensated by periodic buckling, but when they are slitted, buckling will vanish and the strips bow toward either side in their planes. This phenomenon is called "bowing". British Standards specify the straightness of rolled strips and qualify the "error of

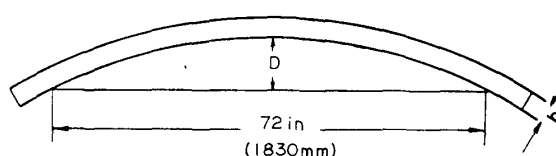
* The 1107th report of the Research Institute for Iron, Steel and Other Metals. Published in Japanese in the Journal of the Japan Institute of Metals, 26 (1962), 117.

straightness' on each range of strip width.⁽¹⁾ Table 1 shows the ASTM specification on bowing (edgewise curvature).⁽²⁾

Table 1. ASTM specifications on edgewise curvature.

b in (mm)	D in (mm)
1/4 (6.35) – 1/2 (12.7)	1 1/2 (38.1)
1/2 (12.7) – 1 (25.4)	3/4 (19.1)
1 (25.4) – 2 (50.8)	5/8 (15.9)
2 (50.8) –	1/2 (12.7)

b: strip width D: maximum edgewise curvature
depth of arc over 72in (1830 mm) length



III. Radius of curvature of bowing

As stated above, bowing will occur by the widthwise variation both in elastic strain and in plastic strain. The former results in the difference in residual stress, and the latter results in the difference in longitudinal (rolling directional) length. When the widthwise variation in reduction is slight, these differences will not come out on the appearance of the strips before slitting, but when the variation grows comparatively large, the difference in plastic strain will be seen as "waving" on the appearance even before slitting.

Residual stresses calculated by Baker's empirical formula⁽³⁾ will not be the cause of bowing, for the stresses remain in a completely balanced state on each longitudinal cross-section.

Hereafter, bowing will be classified into two items according to its cause as follows:

(i) Bowing due to the difference in elastic strain (the difference in residual stress).

(ii) Bowing due to the difference in plastic strain (periodic waving).

In addition, theoretical formulae calculating the bowing curvature will be introduced. For the convenience of calculation, the difference in longitudinal length or plastic strain will not be considered in the case (i), and the difference in residual stress or elastic strain will be neglected in the case (ii).

Comparatively thin strips will bow by the difference in longitudinal length

(1) G.G. Hoare, Sheet Metal Ind., **32** (1955) 325.

(2) H.H. Scholefield and J.E. Riley, Sheet Metal Ind., **32** (1955) 445.

(3) R. Baker, R. Ricksecker and W. Baldwin, Trans. AIME, **175** (1948) 337.

along widthwise direction. Therefore, the above will be a practical approximation.

(1) Bowing by elastic strain

Before calculation, the following assumption will be proposed: the contour of a widthwise directional cross-section is of quadratic curve and the compressive stress-strain curve is approximated as straight line. In this case, the widthwise variation in reduction will induce the difference in elastic strain between slitted plane and edge plane.

(a) Slitting edge-rippled strips

Tensile residual stress will be induced in a cold-rolled strip in the direction of thickness due to elastic recovery and, at the same time, compressive residual stress will be induced in longitudinal direction as shown in Fig. 1. Elastic compressive strain of longitudinal direction of the strip will first be calculated by referring to the rectilinear stress-strain curve Fig. 2.

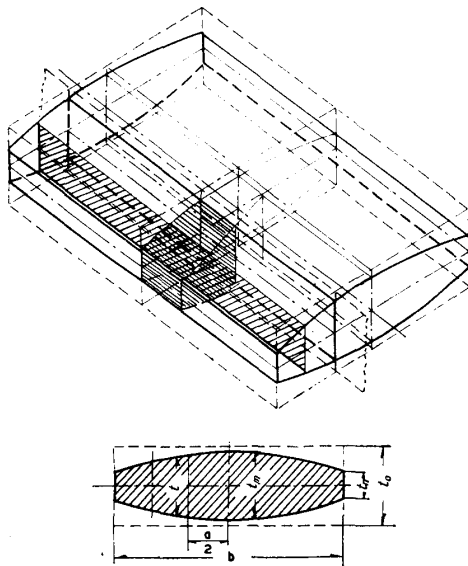


Fig. 2.

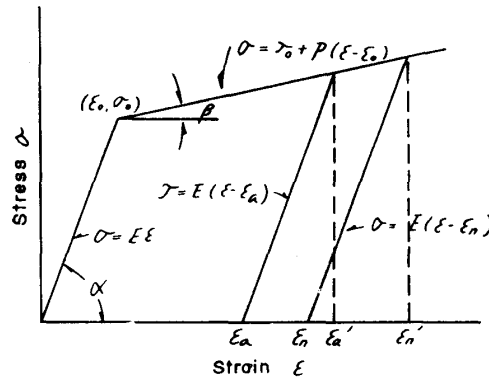


Fig. 1.

Fig. 1. Residual stress distribution of edge-rippled strip.

Fig. 2. Rectilinear stress-strain curve $E = \tan a$, $P = \tan \beta$

Letting E_n , E_n , E_a , and E_a , be the plastic strains and the total (elastic + plastic) strains in the edge plane and the slitting plane of a strip respectively, the total strain (thickness direction) in the slitting plane of the strip will be

$$\epsilon'_a = \frac{\sigma + E \epsilon a - P \epsilon_0}{E - P}, \tag{1}$$

where E and P denote the gradients of the rectilinear stress strain curve in elastic and plastic region respectively. Consequently, the elastic compressive strain

(longitudinal direction) in the slitting plane of the strip will be, by using Poisson's ratio,

$$\begin{aligned}\varepsilon &= \varepsilon a' \gamma - \varepsilon a \gamma \\ &= \varepsilon_0 \gamma + \frac{P}{E-P} \varepsilon a \gamma\end{aligned}\quad (2)$$

Bowing will occur by the difference in this elastic compressive strains both in edge plane and in slitting plane of the strip.

When slitting a strip of width b at the distance of $a/2$ from the center line as shown in Fig. 1, bending moment M which results in bowing will be (the moment acting on the strip to bow toward the outer side in its plane is treated as positive)

$$M = \int_{-\frac{b-a}{4}}^{\frac{b-a}{4}} t \sigma y dy \quad (3)$$

Here,

$$\begin{aligned}t &= t_m - \frac{4(t_m - t_n)}{b^2} y^2 = t_m - 2P y^2 \left(\text{letting } P = \frac{2(t_m - t_n)}{b^2} \right) \\ \sigma &= -E\varepsilon = -\frac{E\nu}{E-P} \left\{ \varepsilon_0 (E-P) + \left(\frac{2P}{t_0} y^2 + 1 - \frac{t_m}{t_0} \right) P \right\}\end{aligned}$$

Substituting them for t and σ , the above equation will be

$$\begin{aligned}M &= \frac{E \gamma P (a+b) (b-a)^3}{480 t_0 (E-P)} \\ &\quad \times \left[\left\{ 10 t_m - 2 (2 m^2 + m + 2) (t_m - t_n) - 5 t_0 (1 - \varepsilon_0) \right\} P - 5 t_0 \varepsilon_0 E \right]\end{aligned}\quad (4)$$

where $m = \frac{b}{a}$

From this equation, if

$$P > (<) \frac{5 t_0 \varepsilon_0 E}{10 t_m - 2 (2 m^2 + m + 2) (t_m - t_n) - 5 t_0 (1 - \varepsilon_0)},$$

then

$$M > (<) 0,$$

then which implies that the strip bows toward the outer (inner) side.

The moment of inertia of the cross-section about the neutral axis of the slitted strip will be

$$I = \frac{(b-a)^3}{480} \left\{ 5 t_m - (2 m^2 + m + 2) (t_m - t_n) \right\} \quad (5)$$

From (4), the formula for calculating ρ becomes,

$$\rho = \frac{b^2 t_0 (E-P) \{5t_m - (2m^2 + m + 2)(t_m - t_n)\}}{2\nu(a+b)(t_n - t_m) [2\{5t_m - (2m^2 + m + 2)(t_m - t_n)\}P - 5t_0\{\varepsilon_0(E-P) + P\}]} \quad (6)$$

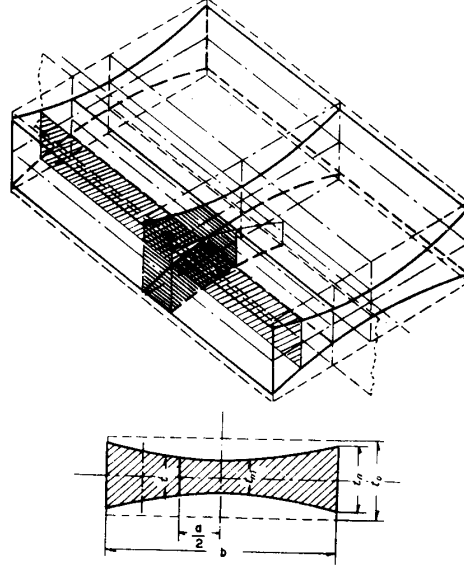


Fig. 3. Residual stress distribution of center-buckled strip

(b) Slitting center-buckled strips

In this case, M and I will be, referring to Fig. 3,

$$M = \frac{E \nu P (a+b) (b-a)^3}{480 t_0 (E-P)} \times [10 t_m + 2 (2 m^2 + m + 2) (t_n - t_m) 5 t_0 (1 - \varepsilon_0)] P - 5 t_0 \varepsilon_0 E$$

$$I = -\frac{(b-a)^3}{480} \{5 t_m + (2 m^2 + m + 2) (t_n - t_m)\}$$

Consequently, the bowing curvature will be

$$\rho = \frac{b^2 t_0 (E-P) \{5 t_m + (2 m^2 + m + 2) (t_n - t_m)\}}{2 \nu (a+b) (t_n - t_m) [2\{5 t_m + 2 (2 m^2 + m + 2) (t_n - t_m)\} P - 5 t_0 \{\varepsilon_0 (E-P) + P\}]} \quad (7)$$

(2) Bowing by plastic strain

Buckling and waving of the edge in edge-rippled strips and the middle in center-buckled strips correspond to this case.

In calculation, the effect of residual stress will not be considered as stated before, and the following assumptions will be proposed: the contour of a widthwise directional cross-section is of quadratic curve and no volumetric variation on longitudinal cross-section is allowed.

(a) Slitting edge-rippled strips

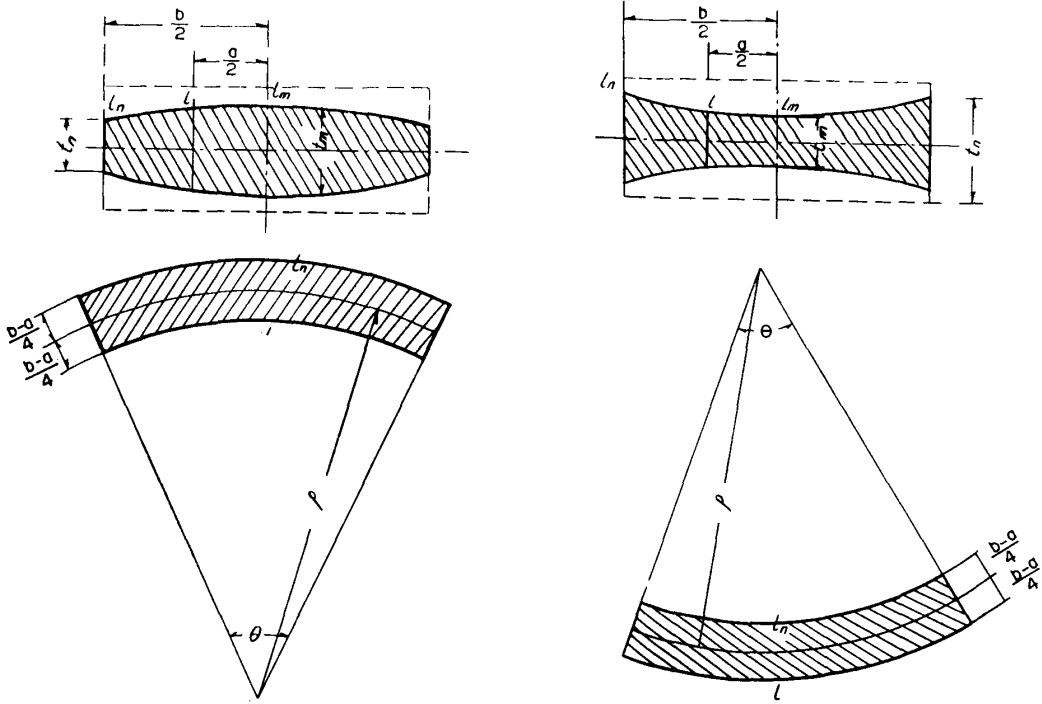


Fig. 4.

Fig. 5.

Fig. 4. Edge-rippled strip and its shape after bowing.

Fig. 5. Center-buckled strip and its shape after bowing.

Letting l_n and l be the longitudinal lengths of the edge and the slitted cross-section respectively, when a strip is cut by the constant length of l_m at right-angle to the rolling direction, the following equations will be obtained.

$$l_n \left(t_m - \frac{P b^2}{1} \right) = l \left(t_m - \frac{P a^2}{2} \right) = C \text{ (const.)}$$

$$\theta = \frac{l}{P - \frac{b-a}{4}} = \frac{l_n}{P + \frac{b-a}{4}},$$

from which, the bowing curvature will be

$$\rho = \frac{(b^2 - a^2) t_m + (a^2 + b^2) t_n}{4(a+b)(t_m - t_n)} \quad (8)$$

(b) Slitting center-buckled strips

In the same way as in the case of edge-rippled strips stated above, the bowing curvature will be, by referring to Fig. 5

$$\rho = \frac{(b^2 - a^2) t_m + (a^2 + b^2) t_n}{4(a+b)(t_n - t_m)} \quad (9)$$

IV. Experiments

The abovementioned results were applied to the rolling-slitting experiments on 7-3 brass and mild steel strips.

(Experiment 1) Slitting relatively thick strips with widthwise variation in reduction (mild steel). Bowing after multi-slitting was investigated by the mild steel strips which were intentionally rolled with widthwise variation in reduction as shown in Fig. 6. Fig. 7 shows the strip after multi-slitting. Each dismembered

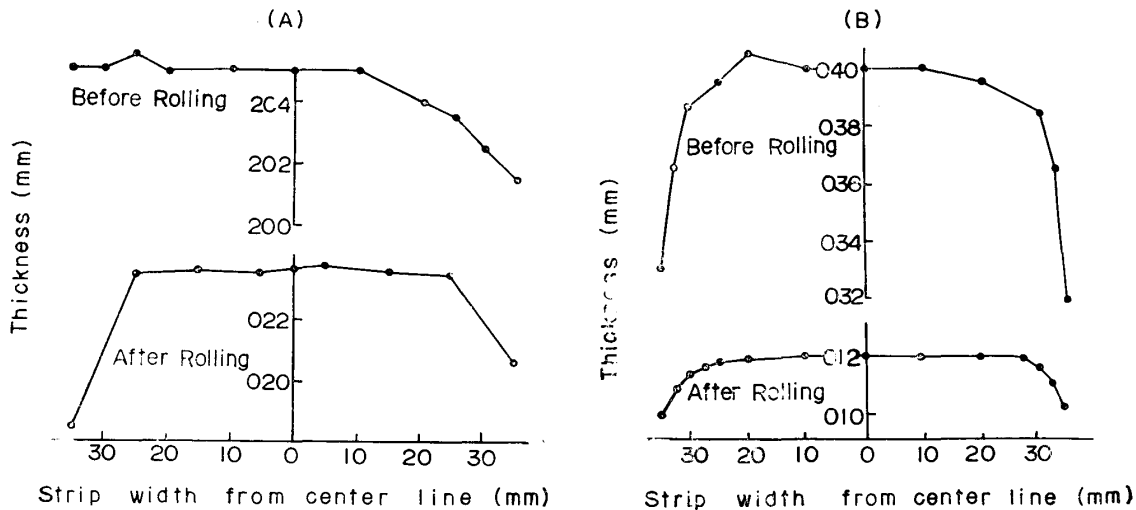


Fig. 6. Thickness distribution of test pieces.

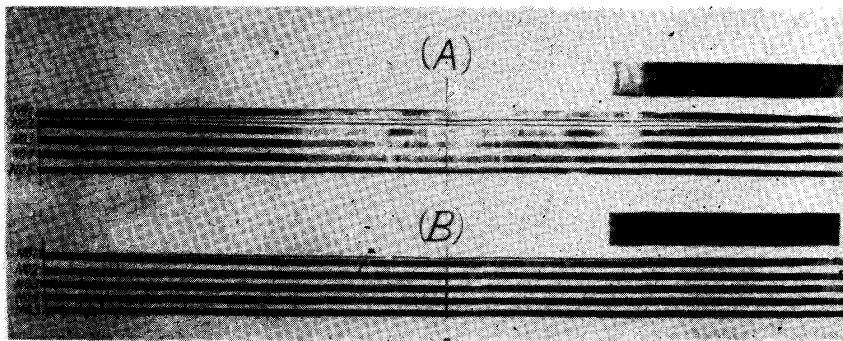


Fig. 7. Experimental results.

strip is to be regarded as almost straight. Approximate calculations on strips No. 1 (A) and No. 1 (B) using the above formulae indicate that the radii of curvature of bowing are $-9.4 \times 10^4 \text{ mm}$ and $-1.8 \times 10^5 \text{ mm}$ respectively, that is, these strips bow toward the inner side in their planes, and the radii of curvature very large (almost straight).

In this experiment, the widthwise variation in reduction was very slight. But, it was practically impossible to give a larger the widthwise direction variation in reduction. It will conclusively be said that if widthwise variation in reduction cannot be seen on the appearance of a strip, the dismembered strips from that

strip do not bow by multi-slitting.

(Experiment 2) Slitting relatively thin strips with variation in reduction (7-3 brass, mild steel). Such edge-rippled and center-buckled strips of 7-3 brass and mild steel that buckling had appeared on the strips caused by the difference in plastic strain due to the widthwise variation in reduction were rolled and subjected to the experiments on bowing with flat rolled strips for reference. In this case, as

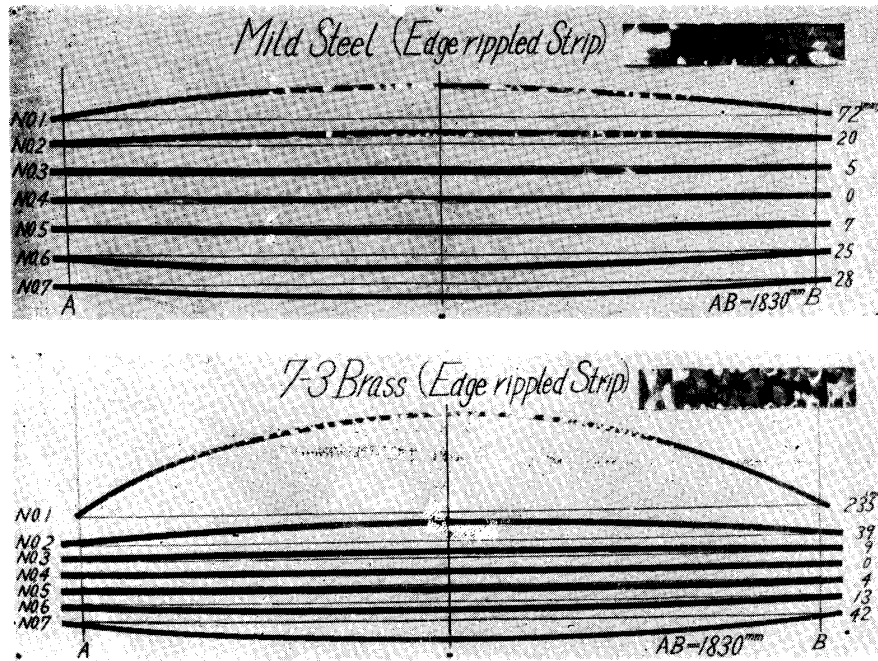


Fig. 8. Experimental results.

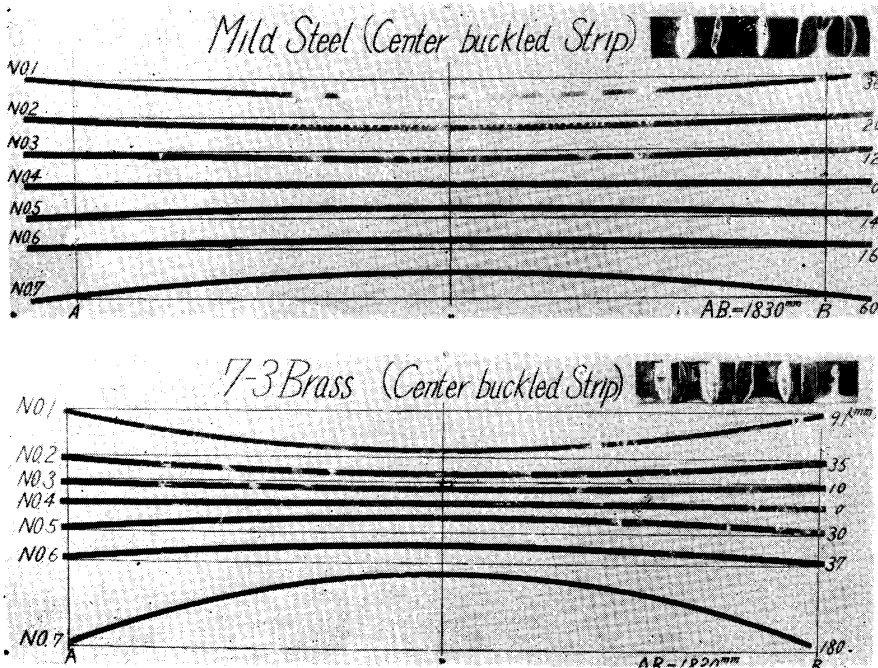


Fig. 9. Experimental results.

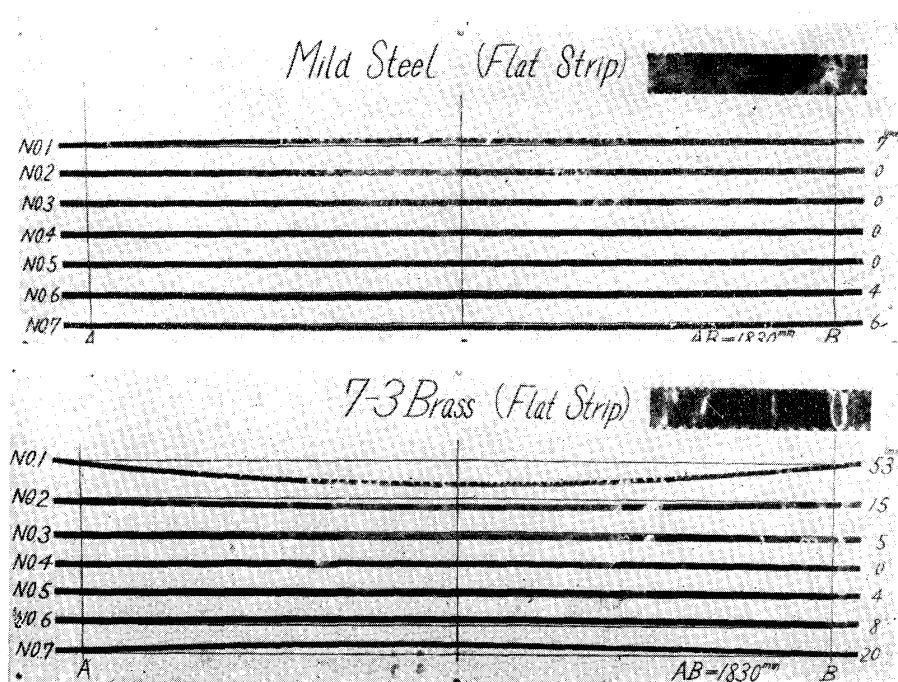


Fig. 10. Experimental results.

it was impossible to measure the thickness distribution of the thin strips, the theoretical formulae could not directly be verified. So, supposing that a measured thickness is that of the middle of the strip, the thickness of the both edges of the strip was calculated from measured radius of curvature of bowing by using the theoretical formula. The results are shown in Figs. 8, 9 and 10.

V. Considerations

According to the calculations and experiments, the very slight difference in thickness will be the cause of bowing.

As shown in Experiment 2, both edges will bow to an excess of ASTM standards by more or less 0.1μ (about 0.2 per cent) of the thickness variation between the middle and the edges. On this standpoint, to manufacture strips as flat as possible, reducing the edge scraps and facilitating the subsequent treatments will be most convenient and economical. In general, the plastic deformation of metals is always accompanied by some elastic deformation, though its contribution is very small. According to the experiments, however, bowing will be caused by the difference in plastic strain — “waving” on the strip — but not so much as by the difference in elastic strain, so far as usual flat strip rolling is concerned.

Conclusions

Summerizing the above-mentioned calculations and experiments, the following conclusions may be obtained:

- (1) Residual stresses calculated by Baker's empirical formula will not be the

case of bowing.

(2) When a cold-rolled strip is multi-slitted, an edge-rippled or a center-buckled strip will bow in its plane by the widthwise variation both in elastic strain (difference in residual stress) and in plastic strain (difference in rolling directional length).

The radii of curvature of bowing for edge-rippled and center-buckled strips will be calculated by the formulae (6), (7), (8), and (9), respectively.

(3) In comparatively thick strips, the difference in elastic strain is not negligible for bowing, but in thin strips, the difference in plastic strain will be the main cause for bowing, and the difference in elastic strain can be neglected.

(4) The direction (inner or outer side) of bowing of multi-slitted strip by the difference in elastic strain will depend on the gradient of the compressive stress-strain curve of the material in plastic region, and edge-rippled strips do not always bow toward the outer side or vice versa.

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