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STRESSES CAUSED BY COLD-ROLLING

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I. INTRODUCTION

Prof. A. E. White [1] held that a given total reduction of the thickness of brass condenser tubes was given better by many light drafts than by a few heavy ones, an opinion as to which so competent an observer as W. R. Webster expressed doubt. Later experiments by Mr. Webster [2] were inconclusive.

In studying the effect of variations in the degree of reduction per pass, we should know, among other things, how they affect the intensity of the stresses set up in the metal by the rolling. To that end we have made the experiments here described. As a matter of convenience we operated on strips of soft sheet steel, both because this is a more important material than brass, and because we believe that what is true of one is true qualitatively of the other, and indeed of most metallic masses which resemble them generally in their mechanical properties.

II. EXPERIMENTAL PROCEDURE

We rolled cold a series of pairs of strips of low-carbon sheet steel as sketched in Figs. 1 and 2, reducing the several strips from their initial thickness of 0.035 to 0.029 inch. We used in some cases 6 heavy reductions or passes, in others 10 passes of intermediate severity, and in still others 31 light passes. We inferred the relative intensity of the residual stresses from the sharpness of the curvature thus induced in the strips, as shown in Fig. 2. Further details of procedure are given in the Appendix.

[1] Proc. Amer. Soc. Test. Mat., 16, Pt. II, p. 151; 1916.

[2] Idem, 17, Pt. II, p. 157; 1917.

III. RESULTS

As shown graphically in Figs. 3, 4, and 5, the spring caused by a given total reduction increases with the amount of reduction per pass. The concordance in these first crude experiments we believe suffices to establish the principle, but more elaborate experiments would be needed to determine the quantitative relations between the effects of light and heavy reductions. In particular, the length of the strips used in the experiments, 3 inches, was too small to enable us to enter them always strictly normally to the vertical plane passing through the axes of the rolls, and

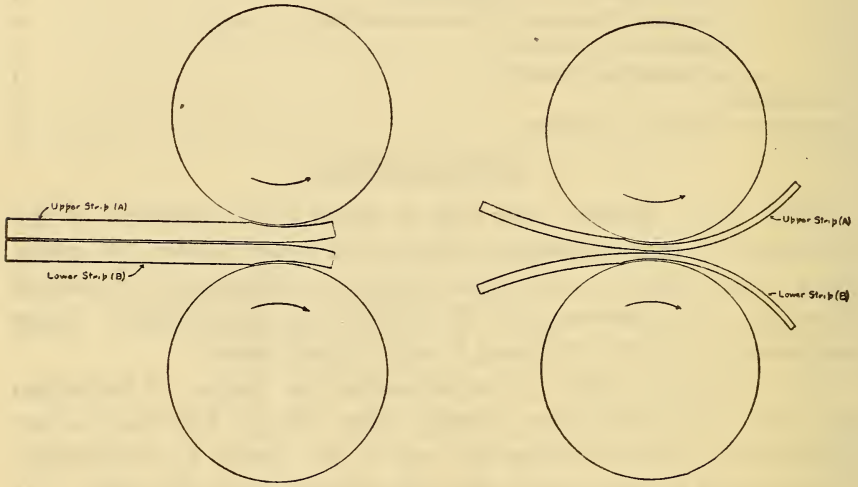


FIG. 1.—*Strips entering the initial pass* FIG. 2.—*A later pass*

Sketches showing how the spring or arching is caused in two superposed strips by the residual stress induced by cold rolling. The thickness of the strips is exaggerated for clearness of illustration

hence the strips tended to roll diamondwise. This tendency was met by entering them slightly obliquely in the following pass.

IV. EXPLANATION

1. FLOW OF METAL DUE TO SKIN FRICTION

We refer the greater stress caused by the heavier reductions to the greater skin friction produced between the strips and the rolls.

To refresh our memory as to what occurs in rolling, let us suppose that a solid bar *OABDHE*, Fig. 6, enters the rolls so that its face *CG* reaches the plane of their axes, and that its segments *ABC* and *HDG* are squeezed away from the original position by the pressure, with the result that the upper surface of the piece takes the shape *OKC* and the lower surface the shape *ELG*. What becomes of this metal initially in *ABC* and *HDG*? It

flows away from the pressure of the rolls. The vertical component of the flow from each roll is in great part neutralized by the resistance of the other roll, so that most of the flow follows the horizontal component and that the metal flows backwards. For simplicity the slight bulging up and down at K and L may here be ignored.

The friction of the faces of the rolls impedes the backward flow of the metal in immediate contact with them, with the result that the rate of backward flow increases from the upper and lower surfaces of the piece AB and HD toward its axis PN. In a solid

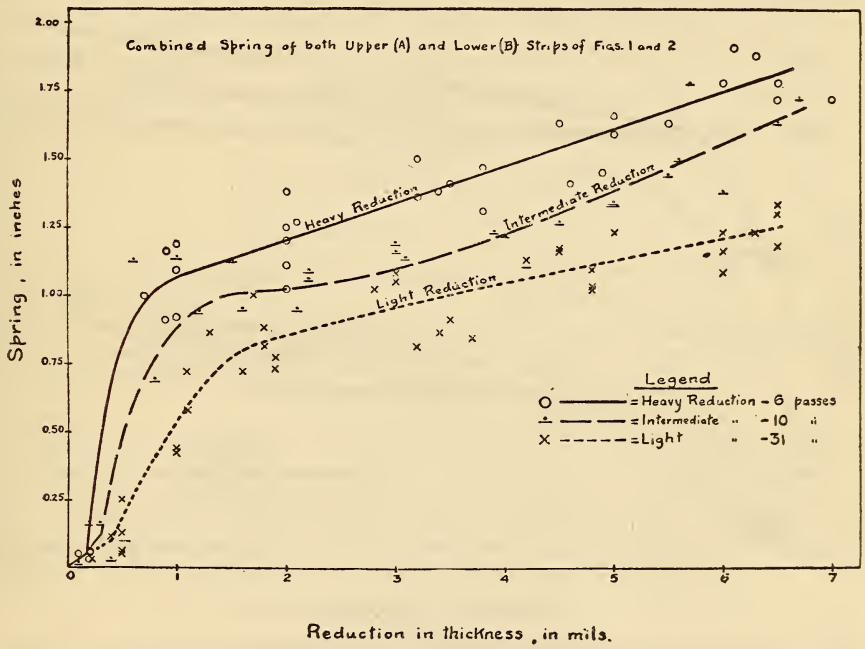
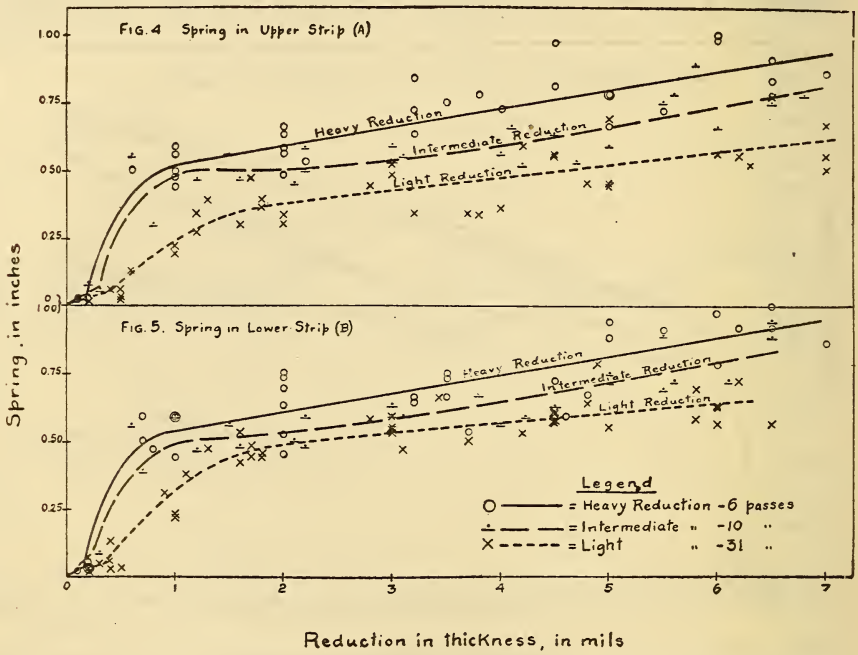


FIG. 3.—*Increase in combined spring produced in both strips of each pair of superposed strips by successive passes.* (*See Fig.* 7)

bar thus rolled cold this progressive difference in the degree of backward flow from surface to axis results in residual stress. But if we suppose that this solid bar $OBDE$ is slit in two along PN so as to give the conditions of our experiments, this same progressive difference causes each of the two strips to bend, so that its face which is next to the roll becomes concave, and that which originally lay along PN becomes convex. The degree of this convexity measures roughly the excess of backward flow along PN over that at the upper and lower faces OAB and EHD.

This brings us to our explanation of the phenomenon observed, that for a given total reduction the spring increases with the severity

of reduction in the individual passes, or in other words is approximately inversely as the number of passes used to cause the given reduction. The friction of the face of the rolls is due chiefly to their roughness. Each of the thousands of immeasurably small protuberances on the face of the rolls bites into the metal and impedes its flowing past them, impedes it but does not arrest it, as is proved by the progressive lengthening of even the concave faces of the strips. Clearly the greater the reduction in a given pass, the greater is this frictional impediment to the backward



FIGS. 4 *and* 5.—*Increase in spring produced in the individual strips of each pair of superposed strips by successive passes*

flow at the surface, hence the greater is the ratio of the axial to the surface flow, the greater the internal stress in a solid bar thus rolled, and the greater the convexity induced in a pair of strips as rolled in these experiments.

The explanation thus resides wholly in the increase of the ratio of axial to surface flow caused by increase of surface friction due to increased reduction per pass.

2. PROGRESSIVE FLATTENING OF THE CURVES OF FIGS. 3, 4, AND 5

This flattening represents a progressive lessening of the increment of curvature caused in successive passes by the friction of the rolls. A tentative explanation is that, as the strip grows

progressively stiffer because of the plastic deformation, it offers progressively greater resistance to the tendency of the friction of the rolls to increase its curvature.

3. CONFIRMATORY EVIDENCE

E. H. Peirce,[3] of the American Steel and Wire Co., finds that a greater total reduction can be endured without rupture in wire drawing with a larger number of light drafts than with a smaller number of heavy ones. Moreover the tensile strength, the ductility as indicated by the various toughness tests, and the elastic limit as indicated by the ability of the wire when in helical springs to endure compression without taking permanent set, are greater for given total reduction when this is caused by a larger number of light drafts. Since internal stress tends to lessen all three of these properties, these observations are in harmony with ours.

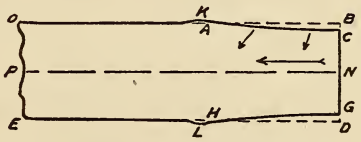


FIG. 6.—*The backward flow of the metal during reduction is greater along the axis than on the surface of the bar and approximately in the directions shown by arrows*

4. EXTRAPOLATION OF RESULTS

It may be assumed provisionally that what is true of cold-rolling is true also of drawing through a die, because the action of the rolls approximates that of a rolling die, the grip which draws the metal forward being given by the surface friction of the rolls instead of by a clutch as in wire, spring, and tube drawing.

V. SUMMARY

1. When the thickness of a pair of strips is reduced by a given amount by cold-rolling, the internal stress, as inferred from the convexity which these strips assume, increases with the amount of reduction per pass. This is ascribed to the skin friction of the rolls.

2. As the rolling progresses the rate of deflection decreases, perhaps because the progressive increase of the stiffness of the strips enables them to resist better the bending effect of the skin friction.

3. The elongation is proportional to the reduction and independent of the number of passes.

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[3] Private communication, Mar. 20, 1919.

APPENDIX.—DETAILS OF PROCEDURE

MATERIAL.—This consisted of common cold-rolled soft sheet steel 0.036 inch in thickness. All the strips were cut from a single sheet. Each of them was 3 inches long and 0.5 inch wide. All were ground to size along the edges, to remove any part that was affected by cutting them from the sheet; they were next annealed at 690–740° C for two hours, and were then ground down to a thickness of 0.035 inch.

THE ROLLS were 2 inches in diameter and 3 inches long.

THE CURVATURE.—The strips were rolled in pairs, one strip being superposed on the other, as in Figs. 1 and 2, and the resultant curvature was determined after each

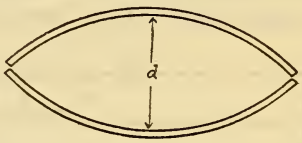

FIG. 7.—*Sketch showing method of measuring the combined spring of the two members of each pair of strips.* (*See Fig. 3*)

pass both by measuring the "rise" or arching of each strip, and also by measuring the total distance between the two members of each pair at their greatest distance apart, *d*, when set together as in Fig. 7.

THE WIDTH of the strips did not change measurably in any case throughout the whole course of the rolling.

THE ELONGATION of the strips as measured along their convex faces was found to be directly proportional to the reduction, and independent of the number of passes by which it was brought about.

THE TOTAL NUMBER OF STRIPS represented by these results was 12 for the heavy, 6 for the intermediate, and 14 for the light reductions.

WASHINGTON, December 4, 1919.