Residual Stresses in Thick Welded Plates

A study of the cooling and welding residual stresses in heavy plates provides a method for estimating the residual stresses in welded built-up structural shapes

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ABSTRACT. This report presents the results of an experimental investigation of the magnitude and distribution of residual stresses in heavy steel plates. Twenty-six plates were investigated, of which twenty had oxygen-cut (OC) edges, and the remaining six were universal mill (UM) plates with as-rolled edges. The plate width varied from 9 to 24 in. and the thickness from 1½ to 6 in. Some of the plates were studied in the as-manufactured condition, whereas others had weld beads placed along the center or along the edges, so as to simulate the component plates of welded built-up shapes.

It was found that for as-manufactured UM plates, the maximum compressive residual stress could be determined using the width-factor β, a measure of the rate of cooling after rolling, and that it increased with increasing plate size. Comparison with theoretical results showed good correlation between experiment and theory. The variation of the residual stress through the thickness was negligible in plates thinner than one inch. Considerable variation might be expected in thicker plates.

The oxygen-cutting caused a change in the material properties close to the edge. The stresses at such edges often were higher than the yield stress of the plate base metal. The welding had significant effects only in a narrow region around the welds, but increased with decreasing plate size. Heavy edge-welded plates had residual stress distributions closely resembling those of their as-manufactured counterparts.

A comparison with the residual stresses in welded built-up (OC) H-shapes, showed that the center-welded (OC) and the as-manufactured (OC) plate might represent the flange and the web, respectively, of the shape.

Introduction

Over the past twenty years a number of investigations on the distribution and magnitude of residual stresses in steel plates and shapes have been carried out, and the results have contributed significantly to the understanding of the behavior and load-carrying capacity of various types of structural components. The results have had a major impact on the formulation of design rules of many specifications, in particular the criteria governing the design of compression members such as columns.

Most of the research conducted previously was concerned with members of small or medium size, and the information on the residual stresses in such elements may be regarded as essentially complete. In recent years, however, increasingly heavier columns have been utilized in steel structures,[1,2] prompting the question as to whether light and heavy columns actually exhibit similar patterns of residual stress and structural behavior. Previous investigations[3,4] did indeed indicate that important differences might be expected, thus emphasizing the need for a study of these problems.

The investigations that are described in this article formed part of a research program with the aim of studying the residual stresses both in heavy plates and shapes.* One of the heaviest rolled shapes presently in use was included, but most of the effort was directed towards studying welded shapes and their component plates. This was due to the fact that the largest shapes are exclusively welded, that is, built-up from plates, or in some instances from plates and rolled shapes, by welding, since the very process of rolling automatically limits the practical and economical size of rolled columns. The plates studied were all component plates of heavy welded shapes; some were examined in the as-manufactured condition, and the rest simulated actual conditions by having weld beads placed at the appropriate locations.

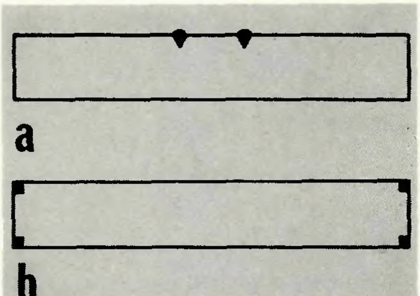

Fig. 1 — Center and edge welded plates, simulating (a) the flange and (b) the web of a welded built-up wide-flange shape

*A plate is defined as heavy when its thickness exceeds one inch. Similarly, a shape is heavy when at least one of the component plates is thicker than one inch.

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Scope of Investigation

Major attention was paid to the investigation of various types of plates, each representing a component plate of a built-up shape. Thus, instead of having a number of different shapes manufactured, for each of which a time-consuming series of measurements would be required, it was intended to find whether measurements taken on a single plate would represent the state of residual stress present in an identical plate when it formed part of a shape. A plate with two centrally located weld beads, as illustrated in Fig. 1(a), may therefore be thought of as the flange of an H-shape, whereas the edge-welded plate in Fig. 1(b) simulates the web of an H-shape or plates of a box-section.

Within the same research program were also studied five complete heavy welded built-up H-shapes and one heavy welded box-shape.[5,6] A direct comparison between the measurements on the single plates and on the plates forming part of a shape was therefore possible.

All plates were manufactured from only one steel grade, ASTM A36. This was on the basis of previous results[3,7] which had indicated that the grade of steel had very little effect on the magnitude and distribution of residual stresses in a shape. ASTM A36 has also been shown to be the steel grade most frequently used for heavy columns in actual structures.[1]

The effects of the following parameters on the residual stress distribution in a plate were studied:

1. plate geometry (width and thickness)
2. manufacturing method (plates with oxygen-cut or as-rolled edges)
3. welding (location, size of weld, and welding parameters).

In order to separate the effects of the welding, some plates were investigated in the as-manufactured condition, that is, without any weld beads.

The influence of varying the welding parameters was studied in another phase of the same overall research program.[8] The welding parameters included were the speed of welding, the number of passes, the voltage of the welding current, and the temperature and extent of preheating. One plate was also annealed, to compare the effects of this type of treatment.

Table 1 gives the appropriate data for all the plates included in the investigation. A total of twenty-six plates was studied, their sizes covering the practical limits of the plates used today for heavy built-up columns. The thickness varied from 1.5 to 6 in., and the width from 9 to 24 in. Twenty of the plates had oxygen-cut (OC) edges, and the other six were universal mill (UM) plates with as-rolled edges.

Table 1 — Summary of Data for Plates Studied

Plate size, in.	Plate condition[a]	Weld location[b]	Weld size in.	Type of shape simulated[c]	No. of Plates
9 x 1.5	OC	AM CW EW	— ¼ ⅜	— — 12H210 (W)	3
12 x 2	OC	AM CW EW	— ¼ ⅜	— 12H210 (F) —	3
12 x 2	UM	AM	—	—	1
12 x 3.5	OC	AM CW EW	— ⅜ ½	— — 24H1122 (W)	3
12 x 3.5	UM	AM	—	—	1
16 x 1.5	OC	AM	—	—	1
20 x 1.5	OC	AM	—	—	1
20 x 2	OC	AM CW EW	— ¼ ⅜	— 20H354 (F) 20□774 ("W")	3
24 x 2	OC	AM CW EW	— ¼ ⅜	— 24H428 (F) 24□774 ("F")	3
24 x 2	UM	AM CW	— ¼	— 24H428 (F)	2
24 x 3.5	UM	AM	—	—	1
24 x 6	OC	AM CW EW	— ⅜ ½	— 24H1122 (F)	3
24 x 6	UM	AM	—	—	1

(a) OC = oxygen-cut plate; UM = universal mill plate with as-rolled edge
(c) F flange; W = web
(b) AM = As-manufactured (no welds); CW = center-welded; EW = edge-welded.

Some typical examples of shapes where some of the plates have been, or might be, utilized are also indicated in Table 1. All of these shapes were fabricated for the research project.

It might be noted that four additional plates 24 by 2 in. (OC) were used for the welding parameter study.[8] The total number of plates included in the project was therefore thirty (24 OC and 6 UM plates).

The sectioning method was employed for the measurement of the residual stresses, utilizing a Whittemore mechanical extensometer with a nominal sensitivity of 0.0001 in.[9] The accuracy in the stress recording is of the order of ± 1000 psi (±1 ksi).

Results from Residual Stress Measurements

Residual Stresses in Universal Mill Plates

Figures 2 through 5 show the residual stress distributions for some typical universal mill plates with as-rolled edges, and Table 2 shows a compilation of the most important data for all six plates. All plates were measured in the as-manufactured condition, except one of the 24 in. plates, which was center-welded.

The five as-manufactured plates all exhibit the typical features of the residual stress distribution in universal mill plates: compressive residual stress occurs in the outer portions, and tensile residual stress in the center region. The open and closed circles in the diagrams represent the stresses measured on the two faces of the plates, and it may be noted that the points lie close together for all the plates measured. This is an indication of the accuracy of the results obtained, and that the plates have cooled uniformly after rolling. A third curve, representing the average values of residual stress in each plate, has been included in the diagrams.

The magnitude of the maximum compressive residual stress in the as-manufactured universal mill plates varies from a low of -16 ksi in the 12 by 2 in. plate, to a high of -28.5 ksi in the 24 by 6 in. plate. Maxi-

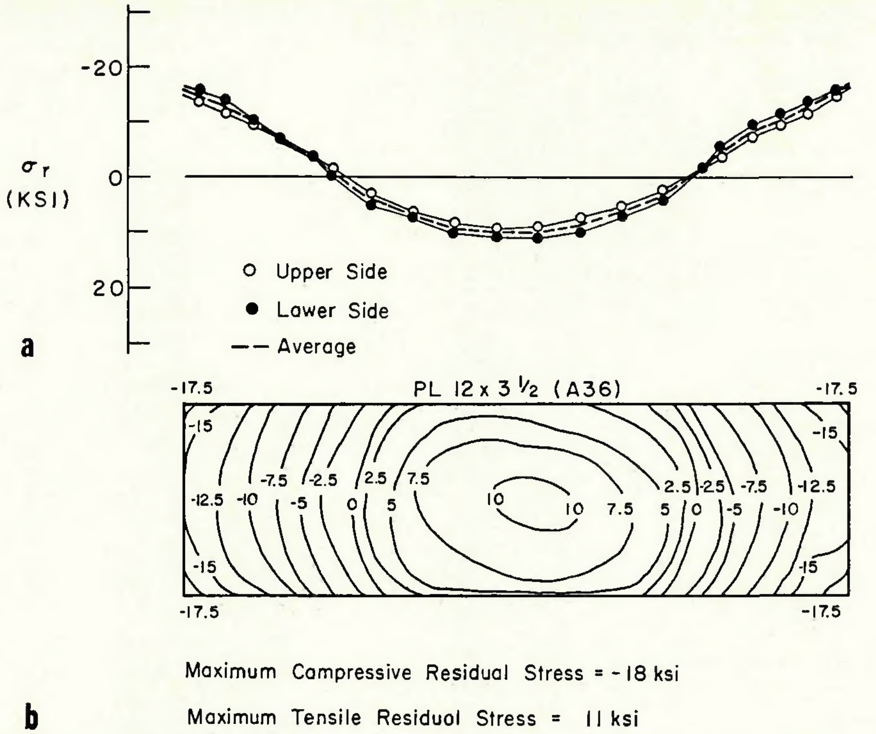

Fig. 2 — (a) Residual stress distribution in a 12 by 3.5 in. universal mill plate with as-rolled edges. (b) Isostress-diagram for the residual stresses in the same type plate (1 ksi = 1000 psi)

mum tensile residual stresses vary from 8 ksi in the 24 by 2 in. plate to 13.5 ksi in the 24 by 6 in. plate. The distribution of residual stress across the plate width essentially is parabolic.

Figure 2(b) illustrates the isostress diagram for the 12 by 3½ in. plate, which provides an indication of the amount of variation of the residual stress through the thickness of the plate. The data for the isostress diagram are obtained by slicing the plate horizontally in addition to the regular sectioning procedure.[9] It may be noted from Fig. 2(b) that the maximum difference between the surface stresses and the interior stresses amounts to approximately 6 to 7 ksi (in a small part of the center region). In most of the plate, however, the variation through the thickness never exceeds 3 ksi.

Slicing of the plates with thickness less than 3½ in. was not performed, since it could be expected that the through-thickness variation in these plates would be smaller than in the thicker 12 by 3½ in. plate. Although the data from the slicing operation of the two heaviest plates are not yet available, previous investigations[4,10] have indicated that a significant variation of the residual stress occurs through the thickness of the plate when it is as large as 6 in. The isostress-data for the 24 by 3½ in. plate will be comparable to those of the 12 by 3½ in. plate, even though a more accentuated variation through the thickness probably will prevail in the larger plate, due to the increased width.

The residual stress distribution in Fig. 5 for the center-welded universal mill plate exhibits a feature that is typical for all welded plates, regardless of manufacturing method. This is the very high tensile residual stresses that occur in the region around the welds. Also notable is the difference between the values of the residual stresses measured on the two faces of the plate. This is due to the fact that the welds are located only on one side of the plate, which causes an uneven and very localized distribution of the heat input from the welding process; it has a major effect only on the stresses in the relatively small area around the welds. The welding has also enlarged the proportion of the plate subjected to compression, as compared to the as-manufactured plate, and it occurs so that overall equilibrium of the residual stresses in the plate is maintained.

The high tensile residual stresses in the welds are accounted for by the fact that the weld electrodes used were of the grade E7018,[2] with a specified minimum yield strength of 70 ksi.[11] The heat input due to the welding, together with the depositing of the higher strength electrode metal, give rise to material properties in the zone around the welds that are different from the base metal of the plate.[8] An increased yield strength in this zone is one of

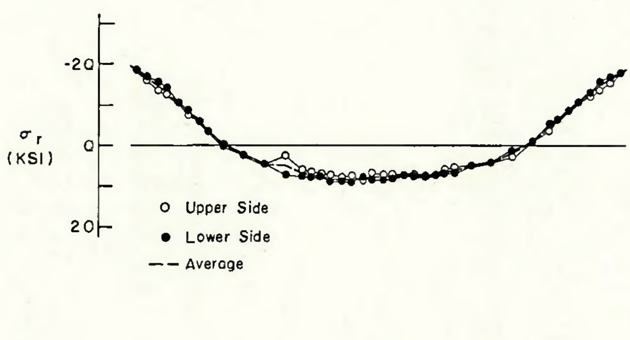

Fig. 3 — Residual stress distribution in a 24 by 2 in. universal mill plate with as-rolled edges.

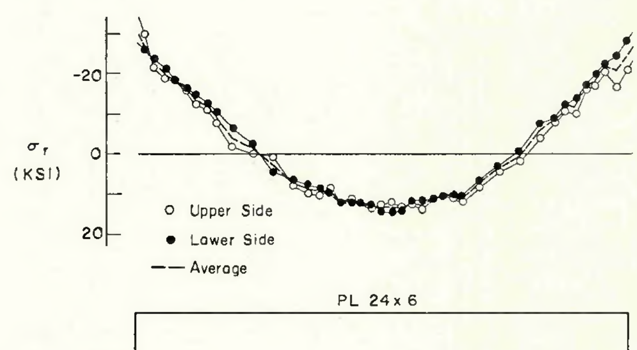

Fig. 4 — Residual stress distribution in a 24 by 6 in. universal mill plate with as-rolled edges

the results, which thus explains why the residual stresses are higher than the yield strength of the base metal. (ASTM A36).

Residual Stresses in Oxygen-Cut Plates

The results from the measurements on plates with similar manufacturing method are described together, to focus attention on particularities relating to the manufacture. The plate categories are therefore (1) as-manufactured plates, (2) center-welded plates, and (3) edge-welded plates.

As - manufactured oxygen - cut plates. Figures 6 through 8 show the residual stress distributions for three typical as-manufactured oxygen-cut plates included in the study, and Table 3 summarizes the most important data for all eight plates.

The residual stress distributions reveal properties that are typical for all oxygen-cut plates, namely, a high tensile residual stress at the oxygen-cut edge which decreases very rapidly with increasing distance from the edge. The stress at the edge is usually substantially higher than the yield strength of the parent material of the plate, because the oxygen-cutting has caused a change of the material properties of the plate in a narrow region close to the edge. The rapid cooling of this region after cutting accounts for a fine-grained material with high hardness and yield strength, and this has been substantiated by the results from tension tests with small specimens cut from the edges of such plates.[8]

The width of the heat-affected region at the edge is very small, a fact which is further illustrated by the high gradient of the residual stress in this area. The data in columns 7 and 11 of Table 3 indicate that the width is less than 3 to 10% of the plate width, depending on the plate geometry, the heat input created by the oxygen-cutting operation, and the residual stresses that existed in the plate prior to the cutting. For example, Fig. 6 shows that for the 12 by 2 in. plate the residual stress has decreased to a value less than the yield strength of the base metal of the plate at a distance of about ⅛ in. from the edge.

The magnitude of the average tensile residual stress at the edge varies from 30.5 ksi to 63 ksi, and the average maximum compressive residual stress from -7.5 ksi to -16 ksi. Columns 5 and 6 of Table 3 indicate that the maximum compression occurs at a distance from the plate edge between approximately 7 and 19% of the plate width. The distance depends on the same factors that control the width of the heat-affected zone at the plate edge.

The stress at the center of the as-manufactured oxygen-cut plates may be either compression or tension, de-

Table 2—Stress Diagram and Average Residual Stresses in As-Manufactured Universal Mill Plates

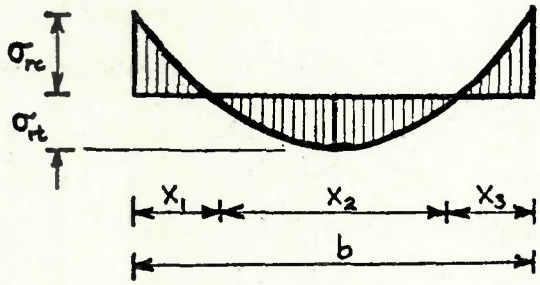

Plate Size, in.	Residual stresses ksi σ_{rc} (a)	σ_{rt} (b)	Non-dimensionalized distances x_1/b	x_2/b	x_3/b
12 x 2	—16.0	8.5	0.23	0.54	0.24
12 x 3.5	—16.0	10.0	0.23	0.53	0.24
24 x 2	—19.0	8.0	0.19	0.61	0.20
24 x 3.5	—23.0	12.5	0.20	0.58	0.22
24 x 6	—28.5	13.5	0.25	0.53	0.22

(a) Extrapolated value at plate edge; average of the two edges.
(b) Taken at center of plate.

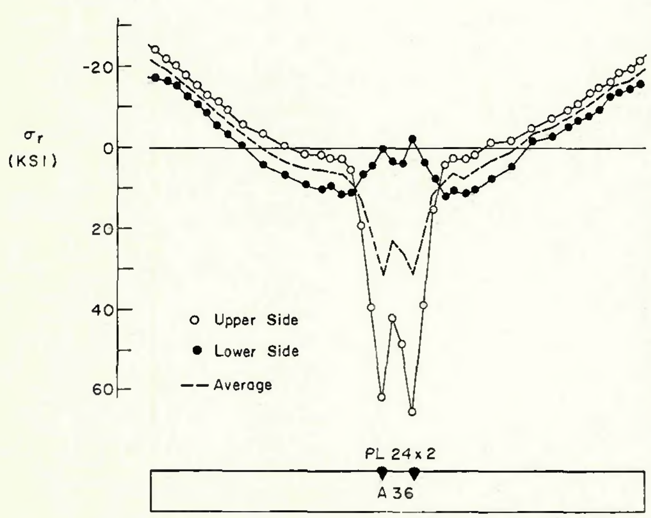

Fig. 5 — Residual stress distribution in a 24 by 2 in. center-welded universal mill plate with as-rolled edges

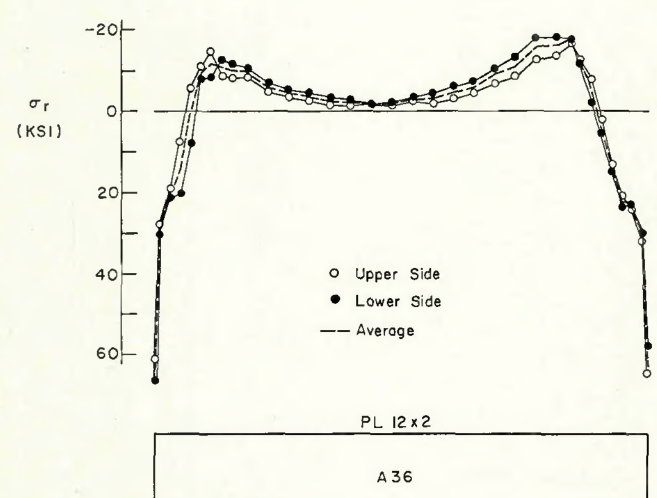

Fig. 6 — Residual stress distribution in a 12 by 2 in. plate with oxygen-cut edges (oxygen-cut plate)

pending on the plate geometry, the oxygen-cutting heat input, and the prior residual stresses. Thus, four of the eight plates exhibit tension in a certain region around the center of the plate, indicating that the combination of oxygen-cutting heat input and plate geometry has not been such that the tensile residual stress, present before the cutting, could be reversed. For the other four plates, compressive residual stress prevails in this zone, but the magnitude of this stress is not more than -3.5 ksi. It is also interesting that for some of the plates, a condition of practically zero residual stress exists in a significant portion of the plate.

The isostress diagram for the 24 by 2 in. plate (not shown here), further illustrates the high gradient of residual stress adjacent to the oxygen-cut edge. The variation of the residual stress through the thickness in most of the plate is less than 2.5 ksi, and thus rather insignificant. Similar investigations on 16 by 2 in. and 24 by 3½ in. oxygen-cut plates have, however, indicated a much more pronounced variation through the thickness, illustrating the great importance of the plate geometry on this property.[10]

Center-welded oxygen-cut plates. Figures 9 through 11 show the residual stress distributions for three center-welded oxygen-cut plates and Table 4 gives a compilation of the most significant results for all plates.

Similar to the center-welded universal mill plate described above, these plates exhibit the typical high tensile residual stresses at the welds, and there is a marked difference between the stresses measured on the two faces of the plate. Average tensile stress in the welds (column 4, Table 4) vary between 11.5 ksi and 30 ksi, and the surface stresses in the welds attain values between 30 ksi and 63 ksi.

Due to the heat input created by the welding, the tensile residual stress at the plate edge in the center-welded plates is in most cases substantially lower than the edge-stress in the as-manufactured plates (cf. Tables 3 and 4). This is also the reason for the higher compressive residual stresses in the center-welded plates. Both of these changes have occurred in order that equilibrium of the stresses in the plate be maintained. The average tensile residual stresses at the edges vary from a low of 24.5 ksi to a high of 58 ksi, and the average maximum compressive stresses vary from -14 ksi to -18.5 ksi. The width of the region subjected to compression (columns 8 and 10, Table 4) amounts to 50 to 70% of the plate width; the smaller of the two values being applicable to the thicker plates.

Comparing the residual stress distributions for the six plates, it may be seen that the welding operation has the most significant effect on the plates whose thickness and/or width are small. An indication of this is illustrated by the decreasing difference between the residual stresses on the two faces of the plates for increasing size of plate. Thus, for the 24 by 6 in. plate (Fig. 11) the major changes are confined to a relatively small area around the welds; whereas for example for the 9 by 1.5 in. plate, the entire plate has been subjected to severe alteration of the residual stress that existed prior to the welding. The decreasing influence of the welding as the plates become heavier can probably be attributed to the smaller ratio of heat-affected zone width to plate thickness.

Edge-welded oxygen-cut plates. Figures 12 through 14 show the residual stress distributions for some

Table 3 — Stress Diagram and Average Residual Stresses in As-Manufactured Oxygen-Cut Plates

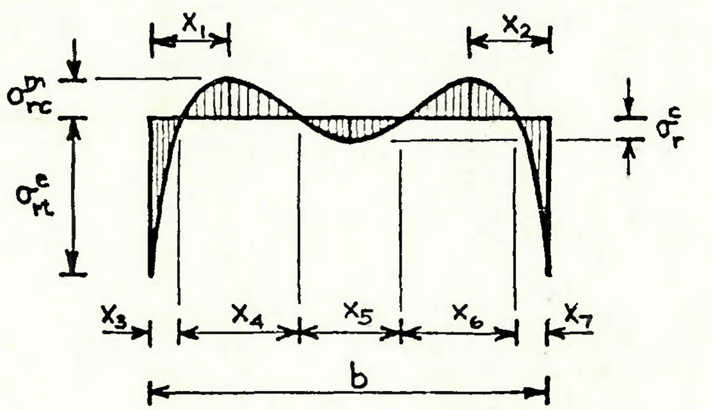

Plate Size in.	Res. stresses ksi $\sigma_{rt}^{e(a)}$	σ_{rc}^{m}	$\sigma_{r}^{c(b)}$	Non-dimensionalized distances x_1/b	x_2/b	x_3/b	x_4/b	x_5/b	x_6/b	x_7/b
9 x 1.5	48.0	-13.5	1.0	0.16	0.13	0.12	0.37	0.14	0.31	0.07
12 x 2	63.0	-14.0	-2.5	0.12	0.16	0.07	0.82[c]	—	—	0.11
12 x 3.5	51.5	-10.5	-3.5	0.19	0.19	0.10	0.80[c]	—	—	0.10
16 x 1.5	50.5	-11.5	-1.0	0.11	0.09	0.07	0.85[c]	—	—	0.07
20 x 1.5	30.5	-16.0	3.5	0.07	0.09	0.04	0.24	0.43	0.24	0.06
20 x 2	49.5	-15.0	3.0	0.11	0.14	0.07	0.26	0.37	0.24	0.07
24 x 2	44.0	- 7.5	-1.0	0.08	0.10	0.05	0.29	0.06	0.54	0.06
24 x 6	46.5	-13.5	3.5	0.14	0.16	0.07	0.28	0.27	0.28	0.08

(a) Extrapolated value at plate edge; average of the two edges.
(b) Taken at the center of the plate.
(c) $x_4 = x_4 + x_5 + x_6$ in this case (compression over the entire region).

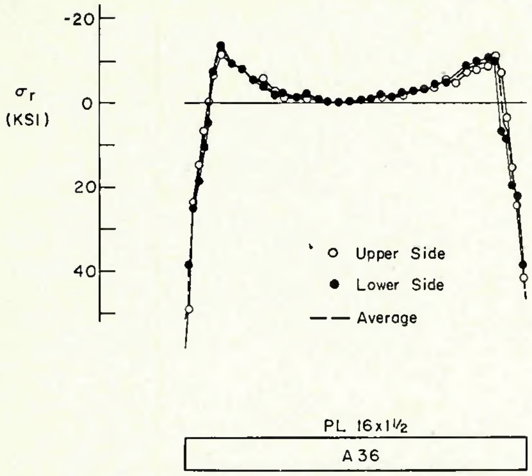

Fig. 7 — Residual stress distribution in a 16 by 1.5 in. oxygen-cut plate

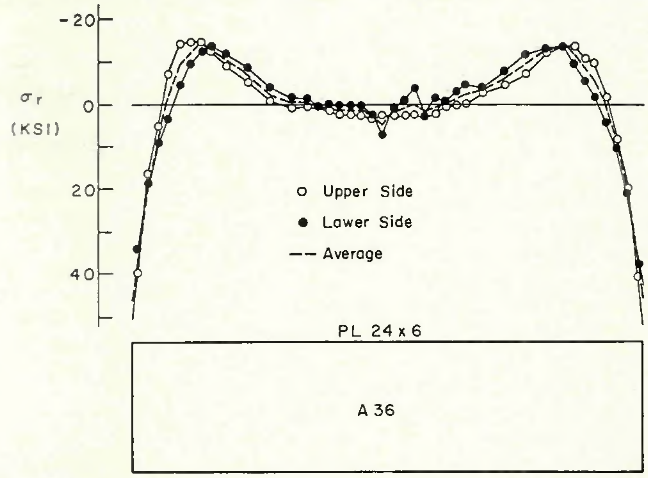

Fig. 8 — Residual stresses in a 24 by 6 in. oxygen-cut plate

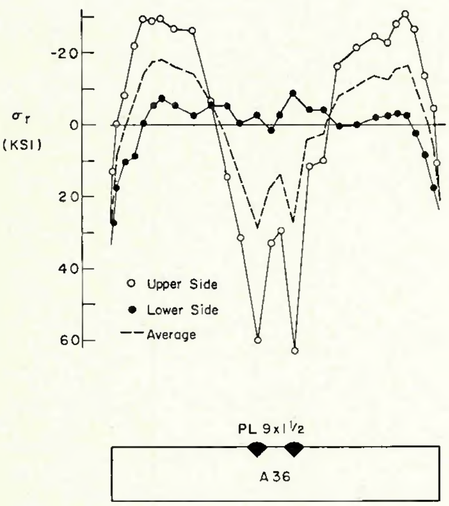

Fig. 9 — Residual stress distribution in a 9 by 1.5 in. center-welded oxygen-cut plate

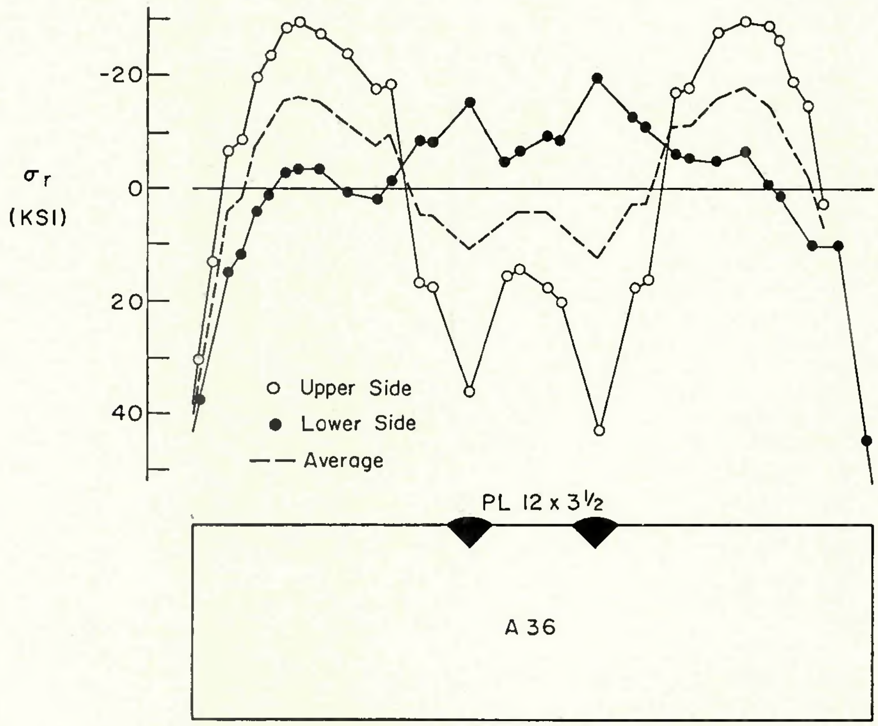

Fig. 10 — Residual stress distribution in a 12 by 3.5 in. center-welded oxygen-cut plate

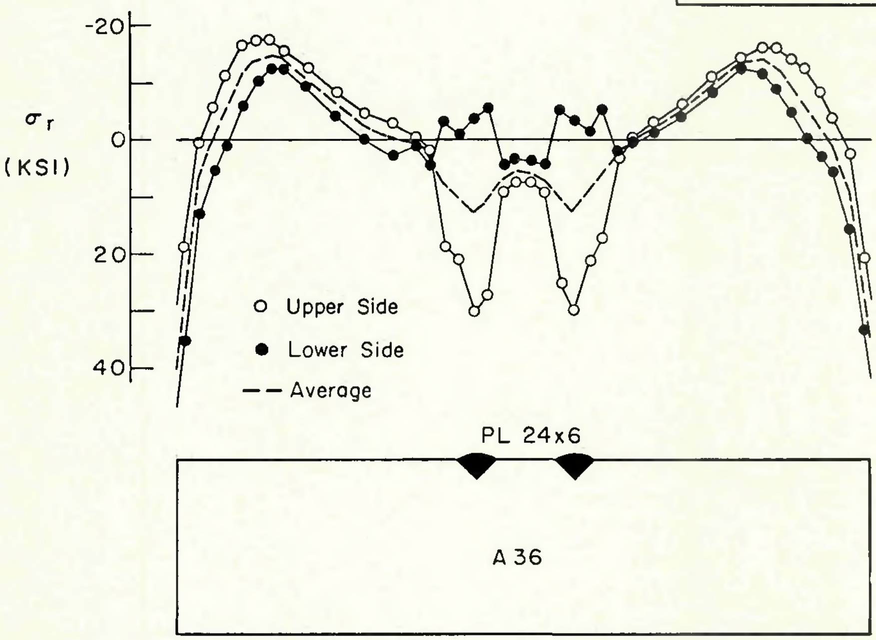

Fig. 11 — Residual stress distribution in a 24 by 6 in. center-welded oxygen-cut plate

typical edge-welded oxygen-cut plates included in the investigation, and Table 5 summarizes the most important data. It will be seen in general that, apart from smaller areas, the distribution in an edge-welded plate resembles very much that of an as-manufactured oxygen-cut plate.

The average tensile residual stress at the edge, that is, in the weld, varies from 40 ksi to 61 ksi. In all except two of the plates (12 by 2 in. and 12 by 3.5 in.), these stresses are higher than those exhibited by the corresponding unwelded plates. It is believed that the welding along the oxygen-cut edge has completely eliminated the effects of the cutting operation, although the two materials may resemble each other in grain structure and mechanical properties.

The maximum compressive residual stress attains values between -12.5 ksi and -16 ksi, and occurs at a distance of 10 to 20% of the plate width from the edge. The residual stress at the center of the plate is compressive for all the plates except the 24 by 6 in. plate. This indicates that the additional heat input due to the edge-welding has caused a reversal from tension to compression of the residual stresses that existed in the plate prior to the oxygen-cutting and the welding. This does not hold true for the heaviest plate, where evidently the volume receiving the heat input is large enough to prevent the welding from having a really significant effect. The data in column 4, Table 5, which illustrate the width of the region of the plate subjected to compression, support the conclusion that the welding has the most pronounced effect on the smallest plates.

The data-points in Figs. 12 to 14, representing the measurements on the two faces of the plates, lie relatively close together. This is explained by symmetry; the welds are equidistant from the center of the plate, giving an even, although localized, heat input.

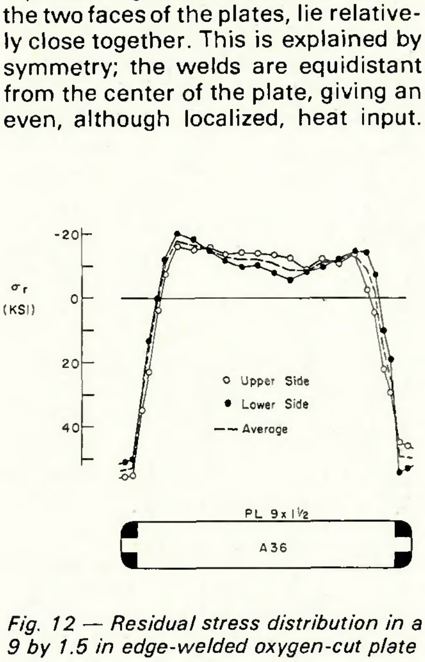

Fig. 12 — Residual stress distribution in a 9 by 1.5 in edge-welded oxygen-cut plate

Measurements and Machining Time

A brief account of the number of measurements made and the time spent on the execution of the investigation may be of interest. A total of approximately 70,000 readings were taken with the Whittemore extensometer, and about 3500 man-hr were spent, on all phases of the study. The 3500 hr include approximately 2400 hr machining time, that is, time needed by the machine-shop to cold-saw the plates for the sectioning and slicing operations. The remaining 1100 hr were used for the actual measurements, the preparation of drawings, the evaluation of data, the preparation of specimens, and so on.

An example will be given by considering the time and number of measurements needed for the 12 by 3.5 in. (UM) plate. The sectioning operation for this plate involved 400 measurements, and an additional 2600 measurements were needed for the slicing procedure, giving a total of 3000 measurements. The time for sawing the plate for sectioning was 50 hr

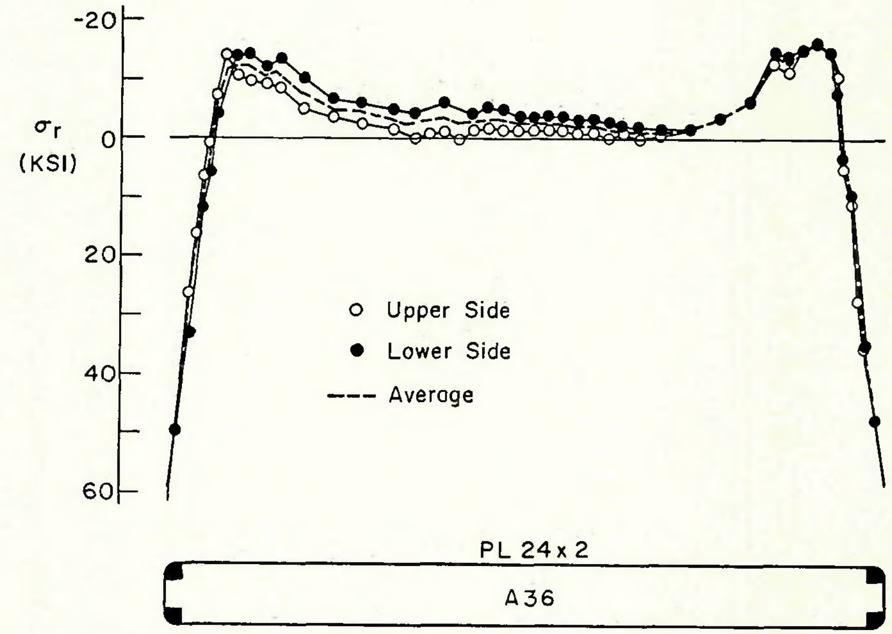

Fig. 13 — Residual stress distribution in a 24 by 2 in. edge-welded oxygen-cut plate

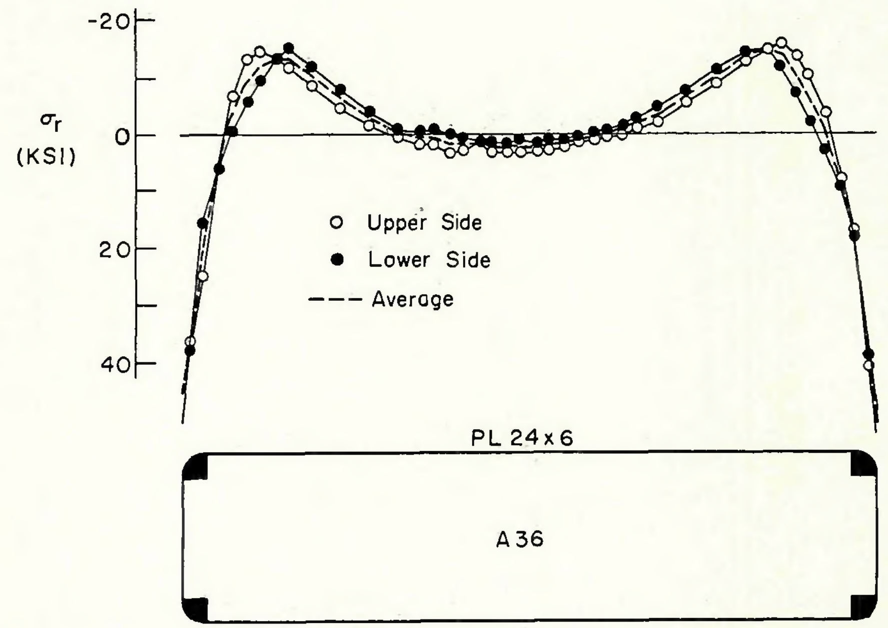

Fig. 14 — Residual stress distribution in a 24 by 6 in. edge-welded oxygen-cut plate

Table 4 — Stress Diagram and Average Residual Stresses in Center-Welded Oxygen-Cut Plates

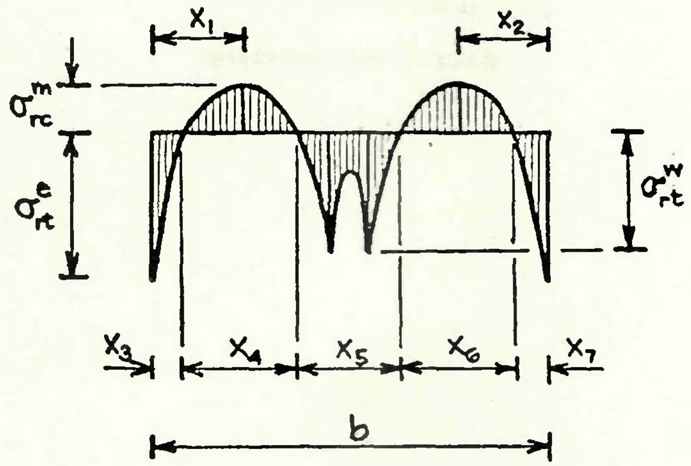

Plate size ins.	$\sigma^{e(a)}_{rt}$	σ^{m}_{rc}	$\sigma^{w(b)}_{rt}$	x_1/b	x_2/b	x_3/b	x_4/b	x_5/b	x_6/b	x_7/b
	Res. stresses ksi			Non-dimensional distances						
9 x 1.5	24.5	-17.5	28.5	0.15	0.10	0.04	0.33	0.33	0.31	0.03
12 x 2	58.0	-18.5	22.0	0.13	0.16	0.06	0.31	0.27	0.29	0.09
12 x 3.5	40.0	-17.0	11.5	0.16	0.19	0.08	0.25	0.35	0.24	0.09
20 x 2	49.0	-14.5	24.0	0.14	0.12	0.08	0.32	0.31	0.24	0.06
24 x 2	25.5	-14.0	30.0	0.10	0.10	0.04	0.36	0.21	0.38	0.02
24 x 6	38.0	-14.5	13.0	0.14	0.16	0.05	0.27	0.34	0.28	0.06

(a) Extrapolated value at plate edge, average of two edges.
(b) Average value of the residual stresses in the two welds.

Table 5 — Stress Diagram and Average Residual Stresses in Edge-Welded Oxygen-Cut Plates

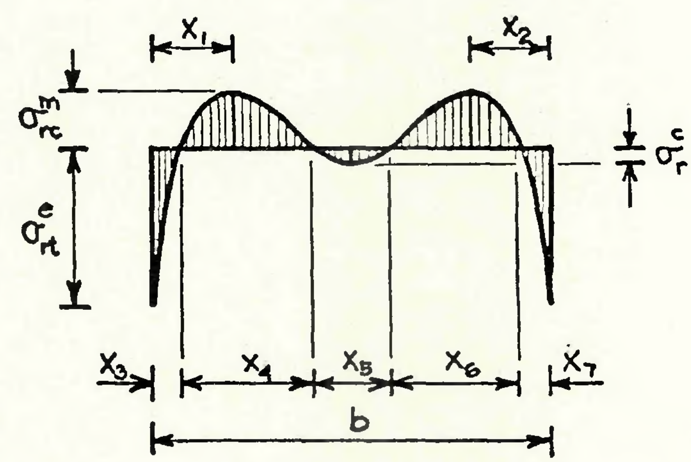

Plate size in.	$\sigma^{e\,(a)}_{rt}$	$\sigma^{m\,(b)}_{rc}$	σ^c_r	x_1/b	x_2/b	x_3/b	x_4/b	x_5/b	x_6/b	x_7/b
	Res. stresses ksi			Non-dimensional distances						
9 x 1.5	52.0	-16.0	-11.5	0.19	0.19	0.13	0.75c	—	—	0.12
12 x 2	57.5	-15.5	- 4.0	0.13	0.14	0.10	0.80c	—	—	0.10
12 x 3.5	40.0	-13.0	- 2.5	0.12	0.19	0.10	0.80c	—	—	0.12
20 x 2	61.0	-12.5	- 1.0	0.14	0.14	0.09	0.83c	—	—	0.09
24 x 2	58.5	-14.0	- 2.5	0.10	0.10	0.06	0.88c	—	—	0.06
24 x 6	48.5	-13.5	2.5	0.16	0.16	0.07	0.25	0.31	0.31	0.07

(a) Extrapolated value at plate edge; average of the two edges.
(b) Average value of maximum compressive residual stress, measured at the two locations given by x_1 and x_2.
(c) The entire region $x_4 + x_5 + x_6$ is subjected to compression.

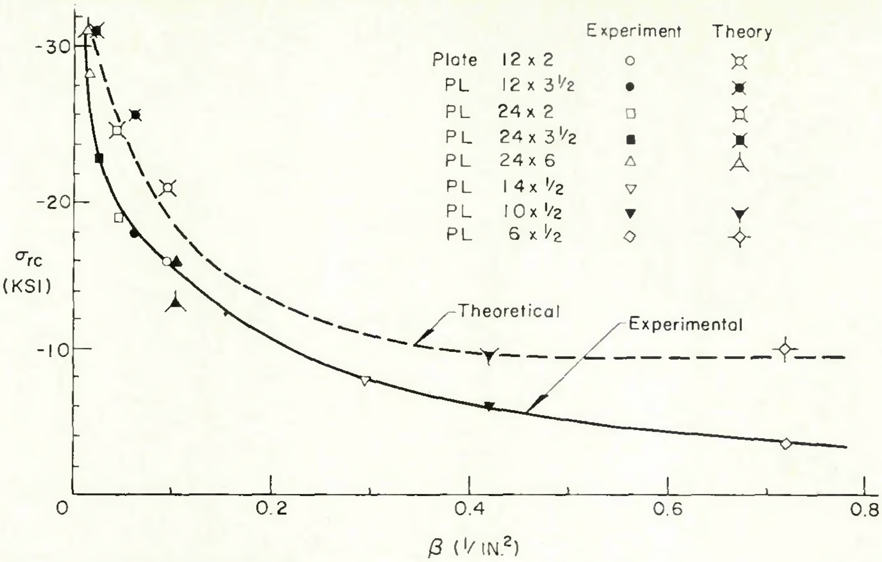

Fig. 15 — The relationship between the width-factor β and the maximum compressive residual stress in as-manufactured universal mill plates

and for slicing 51 hr, leading to 101 hr machining time. Adding the time used for measuring, data evaluation, and so on, gives a final number of approximately 140 hr spent on this particular plate.

Discussion of Results

Universal Mill Plates

Additional meaningful information may be obtained by considering together the various residual stress distributions in the as-manufactured plates. No such comparison can be made for center-welded universal mill plates, since only one is included in this study.

It was found that the maximum compressive stress, occurring at the edge of the plate, is directly dependent on the thickness of the plate. The 24 by 6 in. plate exhibits the highest compressive stress, and the magnitude of this quantity decreases in the order 24 by 3.5 in., 24 by 2 in., 12 by 3.5 in. and 12 by 2 in.; although the two smallest plates have practically the same residual stress distribution. This indicates that the width of the plate also has a significant influence.

A simple measure for the differences between the residual stresses in various as-manufactured universal mill plates is the width-factor β. Denoting the following ratio of the plate surface to the plate volume by α

$$\alpha = \frac{\text{Surface area/unit length}}{\text{volume/unit length}}$$

$$= \frac{2(b+t)}{bt} \qquad (1)$$

the width-factor is given by the expression

$$\beta = \frac{\alpha}{b} = \frac{2(b+t)}{b^2 t} \qquad (2)$$

where b denotes the width of the plate and t the thickness. α is therefore given in units $(\text{length})^{-1}$, and β in units $(\text{length})^{-2}$.

The plate-factor α is a direct measure of the rate of cooling of the plate after rolling, by considering the surface area through which the heat stored in the volume dissipates. The width-factor β is a measure of the same, but it also takes into account the fact that the width has a substantially larger influence on the rate of cooling than the thickness.

Corresponding values of the maximum compressive residual stress, σ_{rc} and the width-factor have been plotted in Fig. 15. The solid line in the figure represents an empirical relationship between σ_{rc} and β, which has been developed using a low-order polynomial of the form

$$\sigma_{rc} = a_1 + \frac{a_2}{\beta} + \frac{a_3}{\beta^2} \qquad (3)$$

where a_1, a_2, and a_3 are constants. A piecewise continuous function has been fitted to the experimental data, giving the following empirical relationship between σ_{rc} and β:

For $\beta > 0.1$:

$$\sigma_{rc} = \frac{2.85}{\beta} - \frac{0.135}{\beta^2} \qquad (4)$$

and for $\beta \leq 0.1$:

$$\sigma_{rc} = 10.2 + \frac{0.566}{\beta} - \frac{0.0048}{\beta^2} \qquad (5)$$

Note that a minus-sign should be attached to the value of σ_{rc} found from equations (4) and (5), using the regular sign-convention with plus for tension and minus for compression.

The empirical equations have been compared with other test data in order to include plates with high β-values. The points representing the maximum compressive residual stresses in plates 20 by 1 in., 14 by 0.5 in., 10 by 0.5 in., and 6 by 0.5 in.

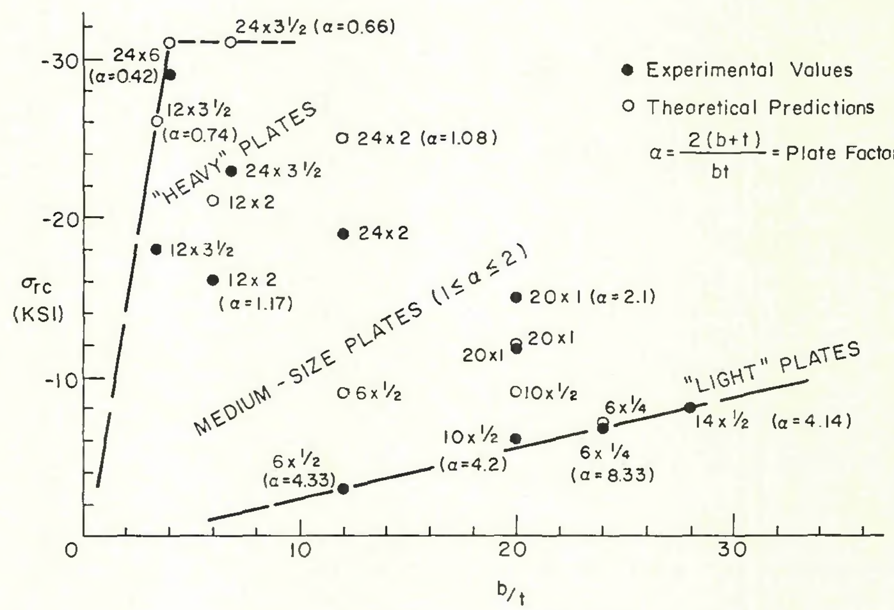

Fig. 16 — Comparison of experimentally and theoretically obtained values of the maximum compressive residual stress in as-manufactured universal mill plates

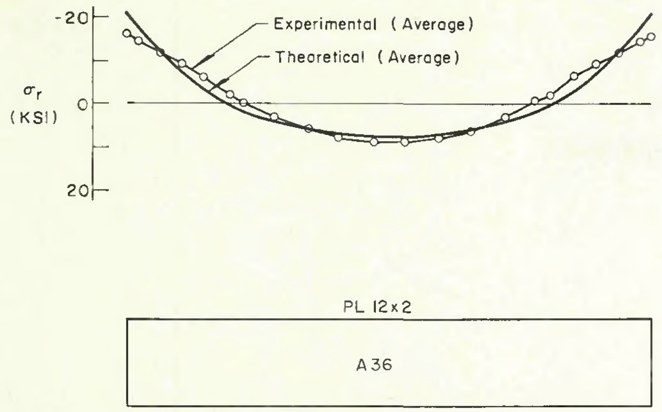

Fig. 17 — Comparison of theoretically predicted and experimentally found average residual stresses in a 12 by 2 in. universal mill plate

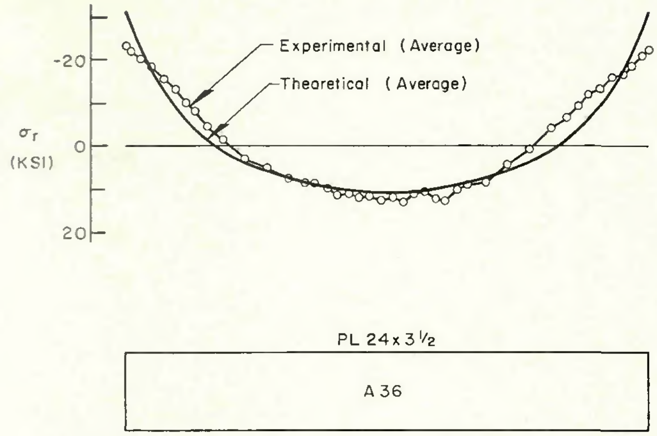

Fig. 18 — Comparison of theoretically predicted and experimentally found average residual stresses in a 24 by 3.5 in. universal mill plate

are seen to fit well. Equations (4) and (5) should not be used for plates with β-value larger than approximately 1.0, because for these the width plays an even more dominant role in the cooling process than that expressed in Eq. 2.

Observing the limitations of Eq. 4 and 5 as far as the magnitude of β is concerned, and utilizing the knowledge that the residual stress distribution takes on the shape of a parabola, the complete distribution may be determined, knowing the width and the thickness, and maintaining equilibrium of the stresses.

A comparison between the theoretically determined values of σ_{rc} [4] and the experimental results, is provided by the inclusion of the additional data points in Fig. 15. The dashed line gives the approximate theoretical relationship between σ_{rc} and β. The fact that the theoretical predictions exhibit somewhat higher values of σ_{rc} than the test results does not imply that the theory is erroneous. It rather emphasizes that the test results are based on one-specimen data only, and significant variations might be expected,[13] due to variations in the yield strength, thermal properties and cooling conditions.

The diagram in Fig. 16 underlines the fact that the test results will form a scatter band instead of indicating a mathematical curve. Both theoretical and experimental data are plotted in this figure, which relates σ_{rc} to the width-thickness ratio b/t.

A more rational basis for the comparison of experiment and theory is provided by a study of the complete residual stress distributions for a plate. Examples of such information are given in Figs. 17 and 18, where the experimental and theoretical residual stress distributions for two plates are shown. It may be seen that in both plates, the largest deviation between theory and experiment occurs at the plate edge. In the remainder of each of the plates, the correlation between experimental and theoretical results may be regarded as satisfactory.

An indication of the effect of the welding on the cooling residual stresses in universal mill plates may be seen from Fig. 19, where the distributions for the as-manufactured and the center-welded 24 by 2 in. plates are drawn in the same diagram. For this particular plate the only major changes have occurred in a relatively small area around the welds, and in the rest of the plate the differences in residual stress do not amount to more than about 2 to 3 ksi. It is expected that the changes will be more severe for smaller plates, and the opposite for heavier plates. These effects are considered in greater detail for the oxygen-cut plates, where it is possible to make several more comparisons.

Oxygen-Cut Plates

The data in Table 3 indicate that the two smallest oxygen-cut plates, that is, the 9 by 1.5 in. and the 12 by 2 in. plate, exhibit the highest tensile residual stress at the edge, which indicates that the heat input due to the oxygen-cutting process has the greatest effect on the smallest plates. The smallest tensile stress at the edge occurs in the 24 by 6 in., the 24 by 2 in., and the 20 by 1.5 in. plate. Whereas the 20 by 1.5 in. plate has the highest tensile stress at the center of the plate, which was to be expected, the other two plates fall in the middle of the band of values for all plates. This shows that the heat input has been so large as to create a significant change of the stress at the center of the plate, but also important for the 24 by 6 in. plate is its large volume. Likewise,

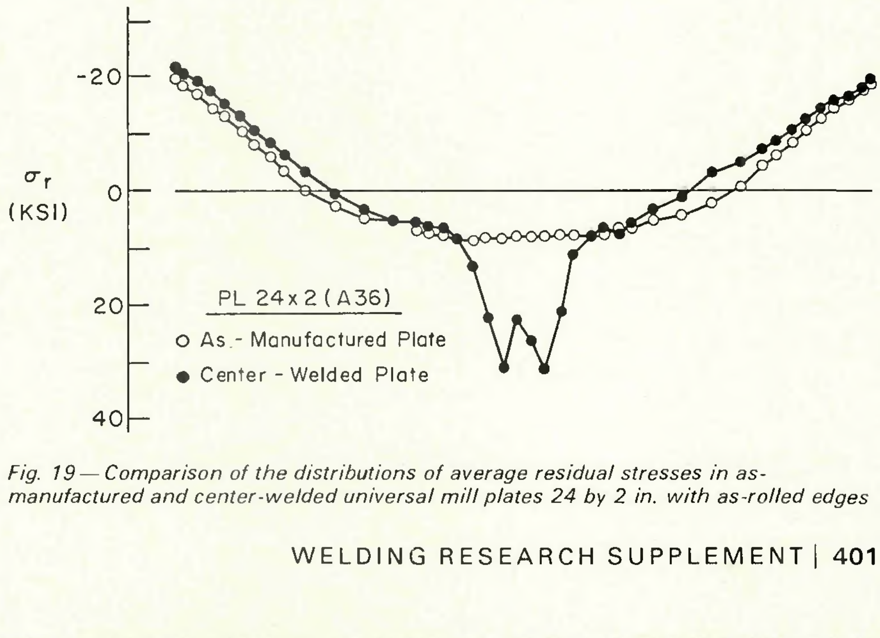

Fig. 19 — Comparison of the distributions of average residual stresses in as-manufactured and center-welded universal mill plates 24 by 2 in. with as-rolled edges

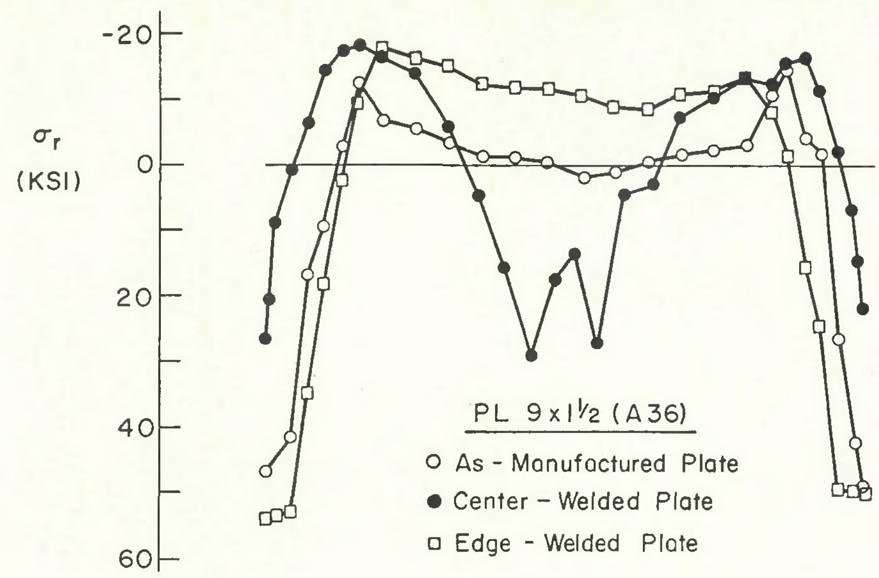

Fig. 20 — Comparison of the distributions of average residual stresses in as-manufactured, center-welded, and edge-welded oxygen-cut plates 9 by 1.5 in.

the 20 by 1.5 in. plate by far exhibits the highest compressive residual stress, whereas all the other plates (except the 24 by 2 in.) are very much alike. The low compressive stress in the 24 by 2 in. plate is consistent with its low values of tensile stresses at the edge and at the center.

There seems to be no simple means of predicting either the stresses occurring in an oxygen-cut plate, or the way they are distributed. This is probably due mainly to factors such as local variations in the heat input during oxygen-cutting, variations in the material structure and properties, and the rate of cooling after cutting. For a plate with a large thickness, the cutting operation will not have effects similar to those in a thinner one, because the heat penetrates the plate to a much smaller distance from the edge. All these factors together constitute a very involved picture, which can not be interpreted by simple, independent observations.

In general, it has been found that welding reduces the tensile stresses at the oxygen-cut edge that existed prior to the welding, and this effect is more pronounced the smaller the plate, provided the size of the weld remains constant. The magnitude of the maximum compressive residual stress does not differ too much from plate to plate, so that the major changes occur in a relatively small area around the welds.

A comparison of the effects of center-welding and edge-welding on the residual stress distribution in some oxygen-cut plates is provided by Figs. 20 through 23. The distributions of corresponding as-manufactured, center-welded, and edge-welded oxygen-cut plates have been drawn in the same diagram, and thus make possible a direct evaluation of the effects of the welding.

It is quite evident that as the size of the plate increases, the changes in the residual stress distribution that are produced by welding at the center or at the edge, become less and less significant. For example, placing welds at the center of the 9 by 1.5 in. plate (Fig. 20) changes the original tensile stress at the edge from approximately 48 ksi to 28 ksi, and welding at the edge of the same plate introduces changes of 10 to 115 ksi throughout the entire plate. On the other hand, the same operations for the 24 by 6 in. plate (Fig. 23) produce almost negligible alterations in the residual stress distribution. Note particularly that for this heavy plate the residual stress distributions for the as-manufactured and the edge-welded condition are practically identical, and also that the only notable changes for the center-welded plate occur in the weld-region.

Comparison with Results from Measurements on Shapes

So far the residual stresses found in the various plates have been related only to each other, but a problem of major concern is whether these results are comparable to the data provided by measurements on complete, built-up shapes. Several investigators have studied the distributions of residual stresses in heavy shapes,[3,4,5,6,7,8,10,12] but no comparisons between the results from heavy plate and shape measurements have previously been done. However, the data provided by an in-

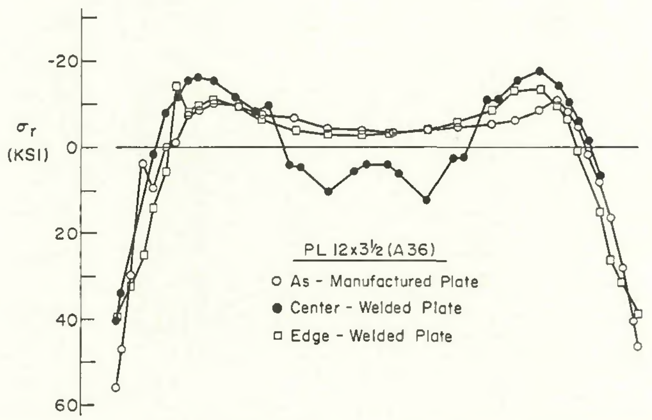

Fig. 21 — Comparison of the distributions of average residual stresses in as-manufactured, center-welded, and edge-welded oxygen-cut plates 12 by 3.5 in.

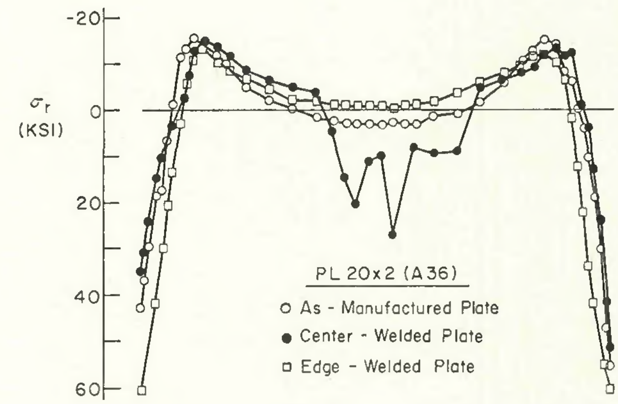

Fig. 22 — Comparison of the distributions of average, residual stresses in as-manufactured, center-welded, and edge-welded oxygen-cut plates 20 by 2 in.

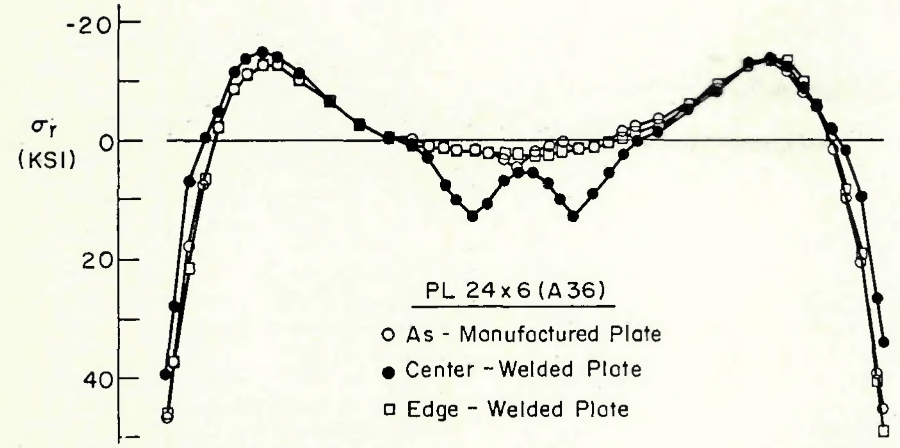

Fig. 23 — Comparison of the distributions of average residual stresses in as-manufactured, center-welded, and edge-welded oxygen-cut plates 24 by 6 in.

vestigation[5] that was conducted within the same research program make such an evaluation possible here.

Figures 24 through 27 compare the distributions of the average residual stresses found in the single plates so as to simulate welded built-up shapes, and relate these results to those given by measurements on complete shapes with component plates of the same sizes. In general, it may be said that the residual stress distribution in the center welded plates represents very well the distribution in the same plates when they form part of welded built-up shapes. The differences that arise are largest for the smallest shapes, which may be seen by comparing, for example, the results given in Fig. 24 and Fig. 27; and they are confined to the areas around the welds and very close to the edges. For the largest shape (24-H1122, Fig. 27), the residual stresses found by plate as well as by shape measurements are almost identical throughout the whole of the plates.

The residual stress distributions in the webs and the corresponding edge-welded plates (Figs 24 and 27) exhibit larger differences than those found for the flanges and the center-welded plates, although the deviation is smaller for the largest shape. The reason for the discrepancies is probably that, even if comparable amounts of heat have been produced by the welding of the shape and the plate, in the shape the heat is stored in a much larger volume, and the rate of cooling after welding therefore will be smaller than in the plates. The significantly higher compressive residual stresses in the edge-welded plates as compared to the webs are indications to this effect.

For two of the shapes (20H354, Fig. 25, and 24H428, Fig. 26) edge-welded plates of the same dimensions as the webs were not included in the investigation. The comparison in Figs. 25 and 26 are therefore based on the results for as-manufactured oxygen-cut plates. An interesting conclusion may be made, namely, that there seems to be better correspondence between the residual stress distributions in the web and the corresponding as-manu-

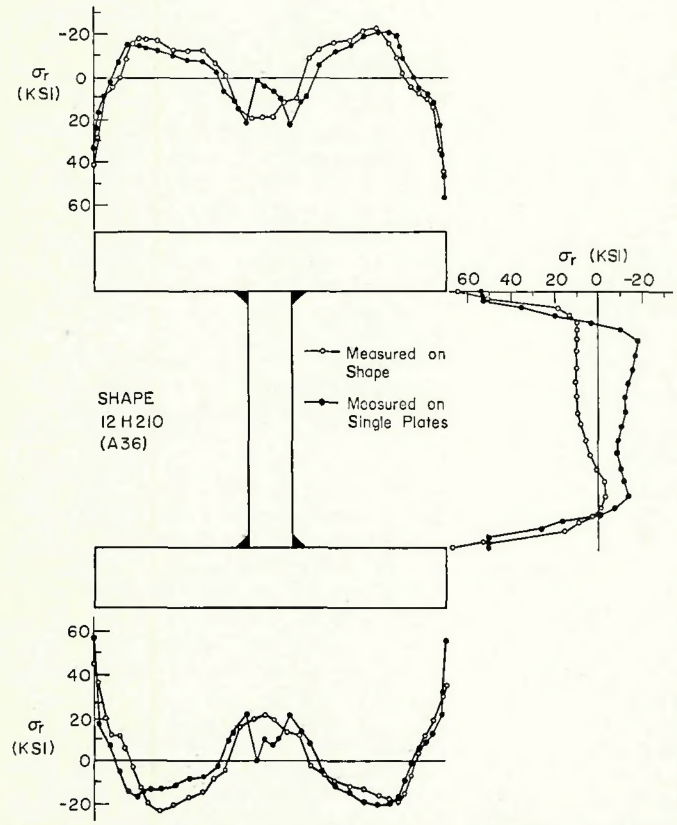

Fig. 24 — Average residual stresses in a shape 12H210, based on shape and plate measurements

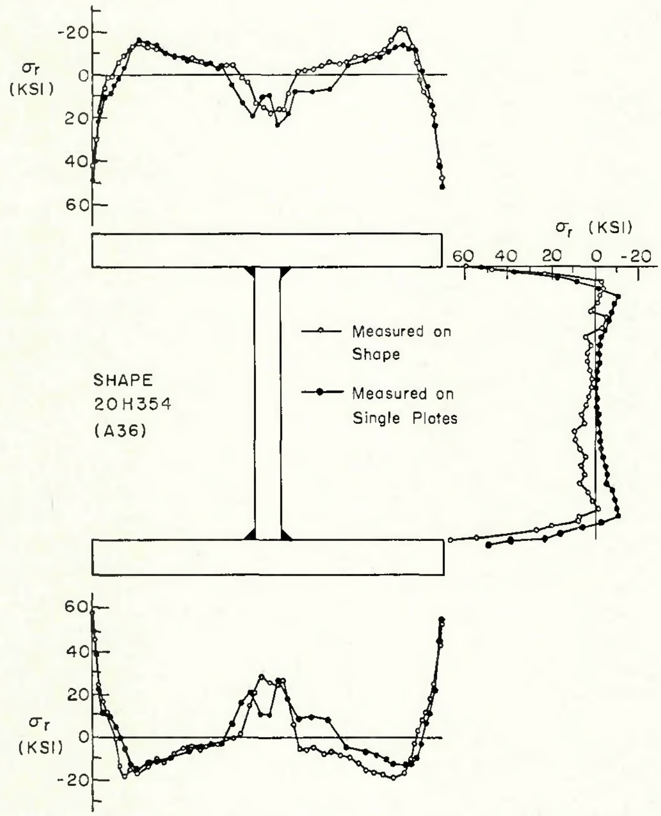

Fig. 25 — Average residual stresses in a shape 20H354, based on shape and plate measurements

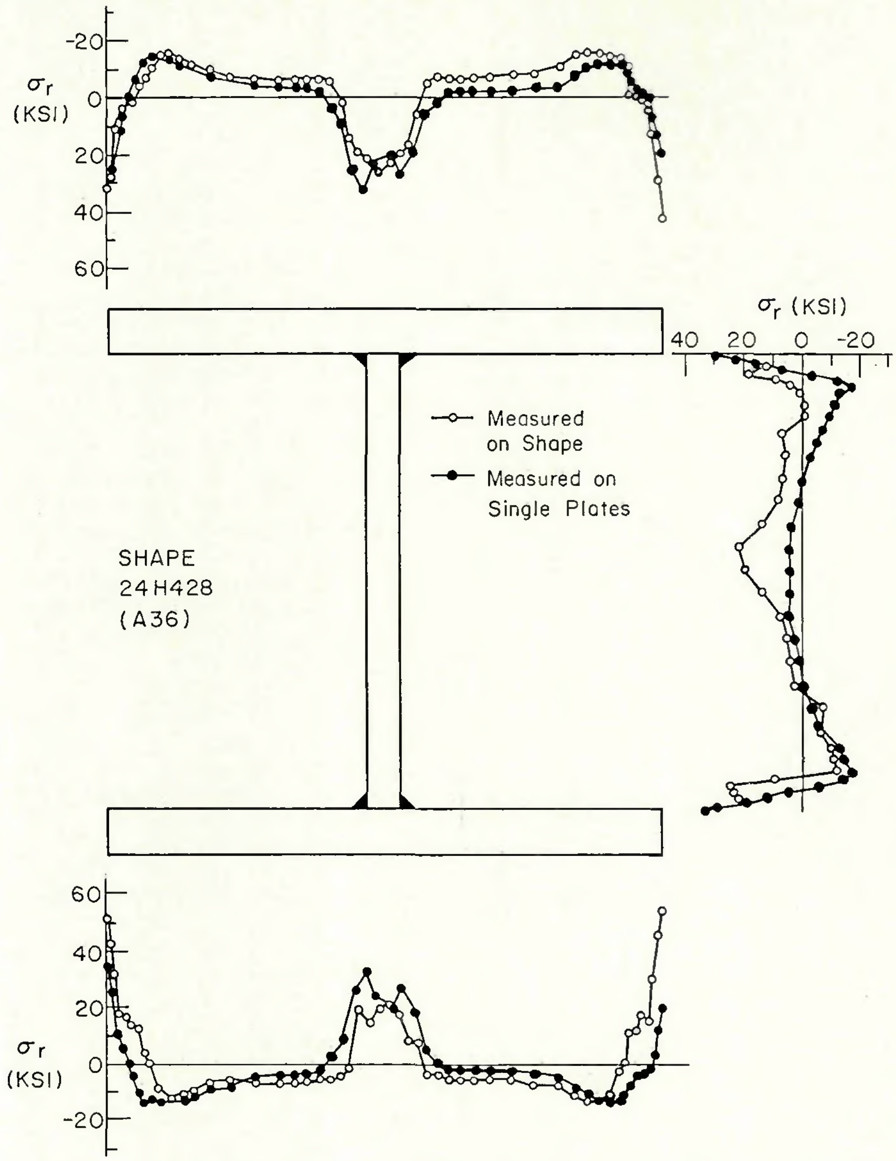

Fig. 26 — Average residual stresses in a shape 24H428, based on shape and plate measurements

factured plate, rather than between the web and the edge-welded plate. The proper simulation of the residual stress distribution in a heavy welded built-up shape therefore may be to assemble the diagrams for center-welded and as-manufactured plates, representing flanges and web, respecitvely.

The conclusions arrived at here are valid for shapes made from oxygen-cut plates. Further studies are necessary in order to substantiate whether or not they hold also for shapes with universal mill plates. It can be stated immediately, however, that the plate simulating the web in such a shape must have some form of edge welds (not necessarily one weld at each of the four corners), in order to introduce the appropriate tensile stresses at the flange-web junction of the simulated section.

Summary and Conclusions

The following conclusions may be drawn on the basis of the results presented in this article:

1. The larger the size of the plate, the larger will be the maximum compressive residual stress in as-manufactured universal mill plates with as-rolled edges. More specifically, the compressive stress increases as the value of the width-factor, $\beta = 2(b+t)/b^2t$, decreases. The width-factor is a measure of the rate of cooling after rolling, and expresses the ratio surface area per unit length of the plate, to volume per unit length times width. This quantity may be used together with the curve in Fig. 15 to determine the maximum compressive residual stress in such plates.

2. The distribution of residual stress in as-manufactured universal mill plates with as-rolled edges generally has the shape of a parabola. This information may be used to determine the complete distribution in a plate given its width-factor . Some deviations from the parabolic shape may be found for plates with high width/thickness ratios.

3. Approximately one-half of the plate width, located centrally in as-manufactured universal mill plates, will be subjected to tensile residual stresses. The outermost one quarter of the plate on either side will exhibit compressive residual stresses.

4. The variation of the residual stress through the thickness normally is negligible in plates with thickness less than about one in., but may be considerable in thick plates.

5. The heat input created by the oxygen-cutting operation causes a change in the material properties within a very narrow region adjacent to the edge, with yield strength significantly higher than that of the base metal of the plate. The tensile stress at the edge, therefore, may become much higher than the yield strength of the plate material itself.

6. Welding at the center of an oxygen-cut plate generally causes a reduction of the tensile stress at the edge prior to the welding. The residual stress in the welds will be very high, and close to the yield strength of the weld metal.

7. The welding of heavy plates usually has its primary effect on the stresses in a relatively small region around the welds, and does not drastically change the stresses in other parts. This effect of the welding will become more and more significant as the size of the plate decreases.

8. The residual stresses in the heaviest (24 by 6 in.) edge-welded oxygen-cut plate are very closely of the same magnitude and distribution as those found in its as-manufactured counterpart. For decreasing plate size, however, the differences between the edge-welded and the as-manufactured plates become more pronounced. In particular, the compressive stresses in the edge-welded plate will be significantly higher than those of the as-manufactured plate.

9. The correlation between theoretical predictions and experimental results of residual stress measurements in as-manufactured universal mill plates may be regarded as satisfactory.

10. Comparison between the residual stresses measured in complete, built-up oxygen-cut shapes and the corresponding single plates, reveal that the flange is accurately represented by a similar, center-welded, plate. The differences in residual stress that do occur are small, and confined to small areas around the welds and very close to the edges. The differences decrease as the size of plate (shape) increases.

11. The residual stress distribution in the web of a built-up oxygen-cut shape seems to be represented better by an as-manufactured plate than by an edge-welded one.

12. The residual stress distribution in a heavy welded oxygen-cut H-shape can be well predicted by using a center-welded (OC) plate as the flange, and an as-manufactured (OC) plate as the web.

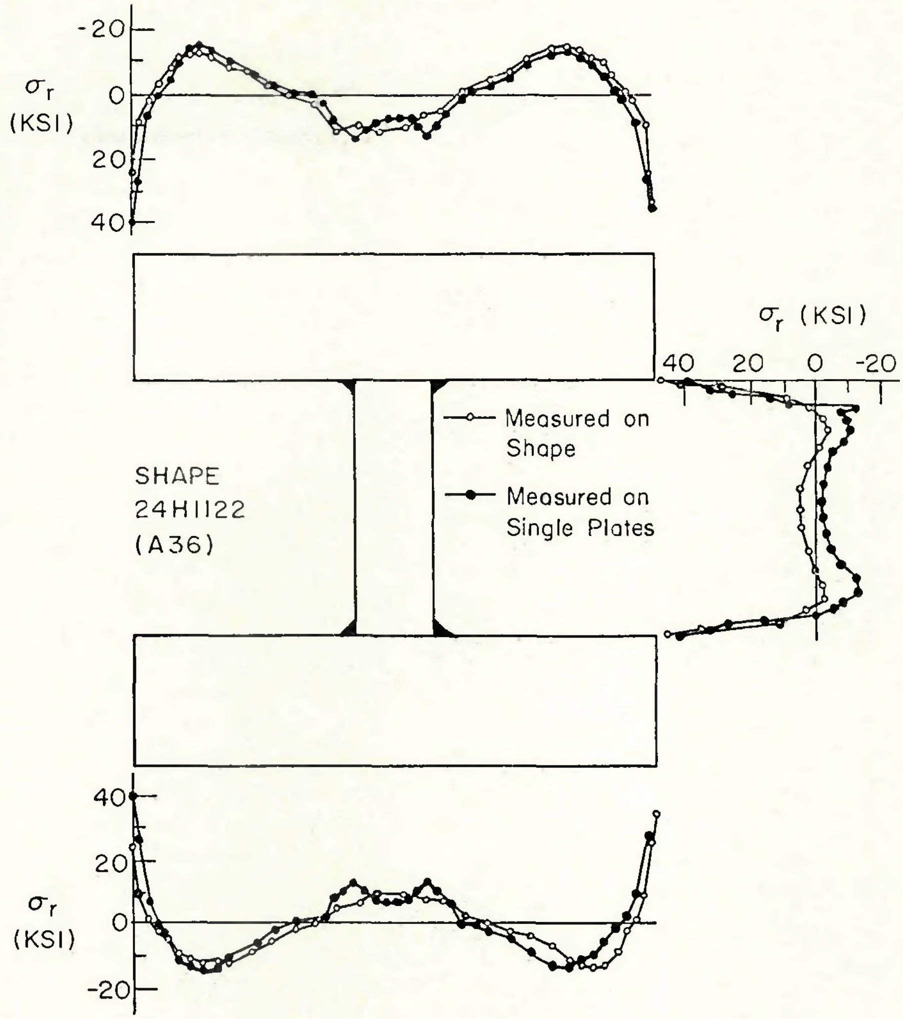

Fig. 27 — Average residual stresses in a shape 24H1122, based on shape and plate measurements

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Appendix

Nomenclature

a_1, a_2, a_3 = constant coefficients, used in polynomials

b = plate width

t = plate thickness

x_1 to x_7 = various distances to important points in the plates, describing the residual stress distribution

α = plate-factor, a measure of the rate of cooling after rolling, given by

$$\alpha = \frac{2\,(b+t)}{bt}$$

β = width-factor, also a measure of the rate of cooling after rolling, given by

$$\beta = \frac{2\,(b+t)}{b^2 t} = \frac{\alpha}{b}$$

σ_r^c = residual stress at the center of an oxygen-cut plate

σ_{rc} = compressive residual stress at the edge of an as-manufactured universal mill plate with as-rolled edges

σ_{rc}^m = maximum compressive residual stress in oxygen-cut plates

σ_{rt} = tensile residual stress at the center of an as-manufactured universal mill plate with as-rolled edges

σ_{rt}^e = tensile residual stress at the edge of an oxygen-cut plate

σ_{rt}^w = tensile residual stress in the welds of center-welded plates