THE DAVID W. TAYLOR MODEL BASIN

UNITED STATES NAVY

EFFECT OF WELDING CONDITIONS ON THE WARPING OF GIRDERS WITH OFF-CENTER WELDS

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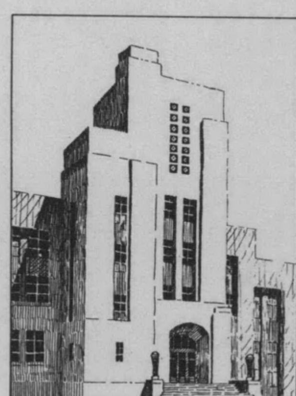

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EFFECT OF WELDING CONDITIONS ON THE WARPING OF GIRDERS WITH OFF-CENTER WELDS

(EINFLUSS DER SCHWEISSBEDINGUNGEN AUF DIE TRÄGERKRÜMMUNG BEI AUSSERMITTIGER SCHWEISSUNG)

by

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EFFECT OF WELDING CONDITIONS ON THE WARPING OF GIRDERS WITH OFF-CENTER WELDS*

When off-center longitudinal welds are applied to girders, warping, shrinking, and internal stresses result. It is desirable to be able to predetermine the type and magnitude of these phenomena. This would achieve the result that in planning and construction measures could be adopted to minimize harmful effects or even to eliminate them completely. The following paper reports tests intended to contribute to this result.

The lack of adequate data on deformation of girders when welded longitudinally gave rise to a systematic investigation of all the effects due to welding conditions. To this end beads were deposited by every conceivable method on a large number of I 16 girders (12 pounds per foot I beams), and the resultant deformations were measured.

1. MATERIAL

All the girders were taken from the same shipment. A test of the material gave the following values: Chemical composition in per cent - 0.075 C, 0.014 Si, 0.53 Mn, 0.054 P, 0.050 S; ultimate strength 39.7 kg/mm² (56,466 lb/in²), elastic limit 28.2 kg/mm² (40,109 lb/in²); strain δ_{10} = 26.3 per cent. Before being welded the girders were first annealed until free of strain by heating to 650 degrees Centigrade and slowly cooling in the furnace.

2. TEST SET-UP

The first tests were carried out with girders 2.5 m (8.2 feet) in length, freely supported at two points 1 m (3.28 feet) apart, while a dial micrometer with 1/100-mm (0.0004-inch) graduations was attached to the bottom of the girder at each end and at midpoint.

Thus five points were available for measuring the warping of the girder. After the form of the warping had thus been determined in 12 girders, the set-up was simplified. In the subsequent tests, girders 1.6 m (5.25 feet) in length were laid across two

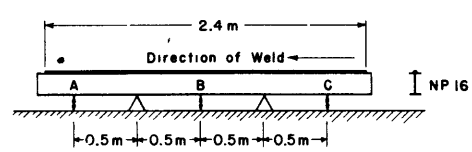

Figure 1. Set-up for warping tests

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* The present paper is an excerpt from Part 1 of a treatise by the author, titled "Deformations in Steel Girders due to the Warping Effect of Arc Welds applied Longitudinally," Mitteilungen der Forschungs Anstalt GHH-Konzern 8 (1940), Heft 1/2. The tests were carried out by the Esslingen Machine Shops. Bibliographical citations are given at the end of the detailed treatise.

supports. Deformations were measured only in the middle of the girders. The test conditions were exactly the same as those for the middle dial gage in the preceding tests.

With this set-up the dial gages were not affected by the welding heat.

3. GROUPING OF THE TESTS

The tests are numbered in chronological order and divided into groups for analysis. Each group serves to solve a given question in connection with the deformation of girders due to the deposition of longitudinal beads.

Group I - Time-deformation curve
II - Shape of deformation curve after shrinking
III - Effect of bead cross section, type of electrode, and diameter of electrode
IV - Effect of welding current
V - Effect of a second weld on the opposite side of the girder
VI - Interruptions during welding process
VII - Multiple-layer welding
VIII - Behavior of clamped girders.

4. TIME-DEFORMATION CURVE

The time-deformation curve is shown in Figure 2. The result is directly traceable to the process of thermal expansion and contraction during welding, and for the moment has no bearing on further analysis. The maximum bending of the girder due to heating and the warping in the opposite direction due to cooling are of greater interest for the various welding conditions than the warping pattern.

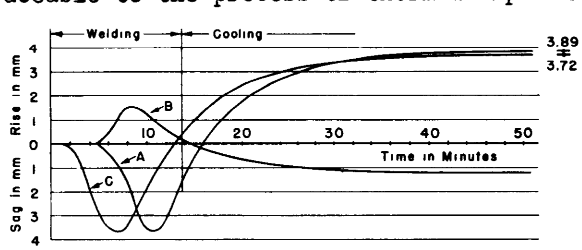

Figure 2. Curve of deformation of the girder

This was determined from the rise and sag of the test Points A, B, and C (Test 5)

5. SHAPE OF DEFORMATION CURVE AFTER SHRINKING

Since every cross section of the girder with the exception of the ends beyond the test Points A and C, Figure 1, was subject to the same conditions with respect to heating and cooling, the originally straight girder must form an arc after shrinkage has occurred. The circle through the two points of support and test point B must therefore likewise pass through points A and C. Calculation of this first gave certain deviations from measured values, which were traced to non-uniform deposition of the beads. Greater precautions to lay a uniformly thick weld resulted in very good agreement of the deformation curve of the girder with an arc.

6. EFFECT OF BEAD CROSS SECTION, TYPE OF ELECTRODE, AND DIAMETER OF ELECTRODE

Since the quantity of weld metal deposited undoubtedly has a considerable effect on the deformation of the girder, the cross section of the bead was determined exactly. With allowance for losses due to sputtering, the mean bead cross section was calculated from the amount of welding rod used.

The investigations were intended first to reveal the differences between girder deformation when bare electrodes and when covered electrodes were used. Numerous brands of each of these two types are in use, with certain differences in speed of fusion and in current conditions, which certainly must have some effect on the deformation of the girder. Within the scope of this study, naturally, only a few brands could be selected. The properties of these electrodes which are of importance in deformation of the girder are compiled in Table 1.

TABLE 1

Properties of Electrodes used

Brand	Type	Rod diameter in mm	Sheath thickness in mm	Sputter loss per cent	Fusing speed * cm/min	Welding Current	
						Amp.	Volts
GHH blue	bare	4		11	26.7	155	19
GHH blue	bare	5		12	23.2	190	20
Union P	bare	4		10	23.9	150	19
Siemens 165	sheathed	3.25	0.87	18	30.7	115	27
Siemens 165	sheathed	4	1.5	13	37.9	170	38
Siemens 165	sheathed	5	1.5	10	37.5	225	32
GHH Pan	sheathed	4	1.3	12	29.5	160	36
GHH Pan	sheathed	5	1.5	10	27.9	210	40
Union SH yellow	sheathed	4	1.3	13	31.2	180	32

* Determined from current values in next column.

For all the tests carried out under normal welding conditions (manual operation, direct current at voltages customary in the shop, about ten seconds interruption for each change of electrodes) the greatest rise at the middle of the girder during welding and the sag after cooling have been plotted as functions of the bead cross section in Figure 3. The extent of the rise, it is true, has no practical significance, but it has been included in the plot because presumably it also has an effect on the deformation of the girder.

The chart, Figure 3, yields the following information:

The points of sagging follow a nearly straight line until a given bead cross section has been reached. An extension of this line will pass through the origin. The sag of the middle of the girder, therefore, is within certain limits proportional to the bead cross section.

When 4-mm (0.16-inch) bare electrodes are used this is true only of Tests 19, 18, and 1. When bead cross sections are greater than 20 mm² (0.03 square inch), on the other hand, the sag no longer increases. Presumably the reason is to be found in the given cross-sectional dimensions of the girder. The slow speed of welding when heavy beads are deposited causes almost complete penetration of heat into the upper flange even before shrinkage begins. The resistance of the girder to thermal expansion of the weld zone, and similarly the pushup in this zone, must in this case be less than in a heat zone confined more to the mid-portion of the top flange, such as is formed when beads of smaller cross section are deposited.

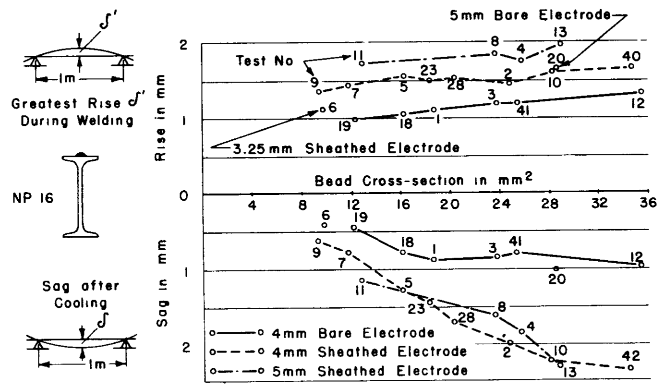

Figure 3. Values of maximum rise and sag of the middle of the girder during deposition of a longitudinal bead

This explanation could be checked by suitable tests of girders with different cross sections, and moreover, the same phenomenon as with bare electrodes would have to occur when covered electrodes are used, but only when heavier beads are deposited, owing to the greater fusing speed. Test 42, which was carried out subsequently, with a particularly heavy bead in one layer, confirms this. Since the phenomenon here involved is based on the choice of girder section, the tests with bead cross sections above the given limits (Tests 3, 41, 12, 42) will be disregarded in further analysis of the results of the sags.

The rising of the middle of the girder is greater than sagging with small bead cross sections, but increases very little with increases in bead cross section, so that with heavier beads, sagging is greater than rising. Rising as well as sagging is greater when covered electrodes are used than with bare electrodes. Tests 18 and 5 permit comparison of the two types of electrodes where the bead cross section was equal (Figure 4). The characteristic of covered electrodes is the greater development of heat resulting from the combustion of the sheath. This is also the cause of the greater rising and

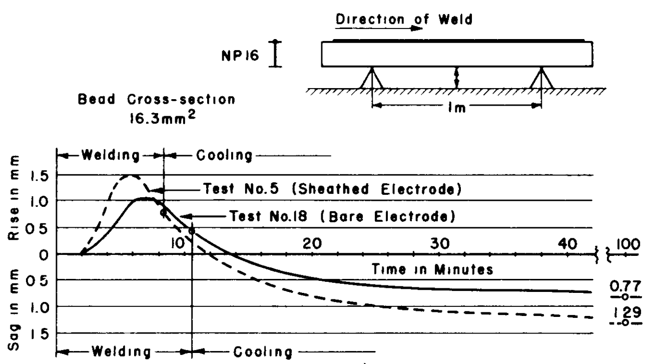

Figure 4. Rising and sagging of the middle of the girder when welded with sheathed and with bare electrodes

sagging. The sags in Test 18 (bare electrode) and Test 5 (sheathed electrode) are in the ratio of 1:1.7.

When the influence of diameter of electrodes is considered it is clearly evident that rising will be greater the greater the diameter, but that with 4-mm and 5-mm (0.16-inch and 0.20-inch) electrodes of the same type and the same bead cross section, there is no difference in sagging (See Tests 10 and 13).

To clear up this apparently paradoxical result, the following theories are presented: The welding process involves a conversion of electrical energy into heat. Heat is the essential factor in the effect on deformation of the girder, but is not susceptible of direct measurement. On the other hand, it is easy to determine the electrical energy consumed in the arc, since the amperage and voltage and the duration of the arc were determined during the course of the tests. The amount of energy used is the product of these three quantities.

Assuming that losses from radiation of heat and light are relatively small, it must be possible to find a relation between the energy consumption and the deformation of the girder. In Figure 5 the calculated energy requirements in the arc, referred to a bead length of 1 m (3.28 feet), are plotted in kilowatt-hours per meter. The energy required to deposit a given amount of weld metal thus will depend only on the type of electrode, and not on the diameter of the electrode. The sheathed electrodes GHH Pan and Union SH yellow require 1.77 times as much energy for deposition of a given amount of metal as the bare electrode GHH blue.

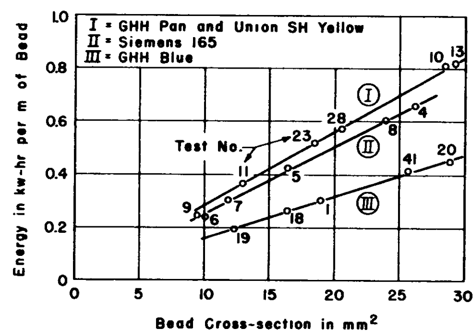

Figure 5. Energy consumed in the arc to weld a bead 1 m (3.28 feet) long

If we now form the ratio of the energy consumption to the measured sags of the middle of the girder we see that, with slight scattering, the sag is proportional to the energy requirement (Figure 6). Type of electrode, diameter of electrode, and cross section of bead have no essential effect in this. Their effect on the sag is governed in the same way by the energy requirement.

In Tests 11, 5, and 28, with greater sags than those shown by the middle curve, a comparatively high amperage was used. Tests 19, 6, 9, and 7, which yielded smaller sags, were carried out with relatively small amperage. Consequently the amperage apparently does affect the girder deformation whenever the amperage deviates from a standard value suitable to the type and diameter of electrode. Therefore a special study will be made of this in the following sections of this paper.

7. EFFECT OF WELDING CURRENT

In Figure 6, Tests 39, 36, and 40 are also plotted. In these tests the electrodes and bead cross sections were the same as in Test 23. But although in Test 23 standard amperage was used, Test 40 was carried out with abnormally high, and Tests 36 and 39 with abnormally low amperage. In these four tests the sags varied in proportion to the product of amperage times voltage.

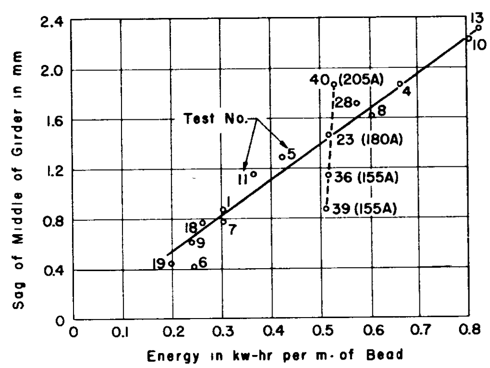

Figure 6. Girder sag as a function of energy consumption in the arc

Calculation of the electrical energy shows that in spite of the greatly varying amperage, the energy consumption does not vary materially when the same electrodes are used, because the speed of fusion increases with the voltage. For amperages that deviate from standard the previously established law therefore does not apply, namely that the sag is proportional to the consumed arc energy. With higher amperages the arc penetrates deeper into the material, and obviously the pushup zone is likewise larger. This causes the greater depression.

Analysis of Tests 7, 9, 10, 28, 5, and 30 with respect to the effect of amperage likewise shows that when the electrodes are the same but are used at different amperages, the sag is approximately proportional to the electrical input (kilowatt, amperage times voltage).

8. EFFECT OF A SECOND WELD ON THE OPPOSITE SIDE

By depositing a bead on the other flange of the girder, further information was sought. The second bead was deposited after the first had cooled. As in previous tests the welding was done from above in horizontal position. The reverse warping of the girder was measured first.

TABLE 2

	First Bead Test 36	Opposite Bead Test 37
Brand of Electrode	Union SH yellow	Union SH yellow
Diameter of Electrode - mm	4	4
Bead Cross Section - mm^2	19.0	19.0
Rise, measured - mm	1.50	1.81
Sag, measured - mm	1.14	0.77
Rise + Sag - mm	2.64	2.58
Rise + Sag per mm^2 of Bead - mm	0.139	0.136

The second bead, Test 37, on the opposite side from the first, caused a slighter sag than the first, which was of equal thickness and deposited under the same conditions (Table 2). The phenomenon, frequently observed in practice, that an opposed weld does not completely counteract the warping of the girder caused by the first weld, is confirmed. The tests, by their measured data, furnish a simple explanation for this, i.e., the second bead is deposited on a strip of material affected by internal tensile stress. The thermal expansion (rising) under heat first counteracts this tensile stress without encountering restraint. Beyond this the thermal expansion is free to proceed further than is possible in a weld on unstressed material. The pushup, however, is smaller by the amount of stress relief. Correspondingly, the shrinkage and sag must be smaller than in the case of a weld on an unstressed girder. The test data, Table 2, prove that in the case of the second weld the rising is greater and the sagging less than in the case of the first weld. The sum of rise and sag per 1 mm² (0.0015 square inch) of bead cross section is equal for both welds.

9. INTERRUPTIONS DURING THE WELDING PROCESS

Further tests were planned to determine whether uninterrupted welding or long interruptions during each change of electrodes have an effect on deformation of the girder.

In the tests discussed hitherto every change of electrodes caused an interruption of about ten to twenty seconds. In order to study the effects of interruptions Test 23 was again taken as reference test. Tests 27, 29, 30, 31, and 32 were thus carried out with the same electrodes, the same amperage, and as nearly as possible, the same thickness of bead, but the length of interruption for changing electrodes was different in each test. Seven and one half electrodes were used in each test, and the 1.5 m (4.9-foot) bead was therefore interrupted seven times. In Test 32 an automatic welder, manufactured by Kjellberg, was used which permitted the fusion of all the electrodes without an interruption.

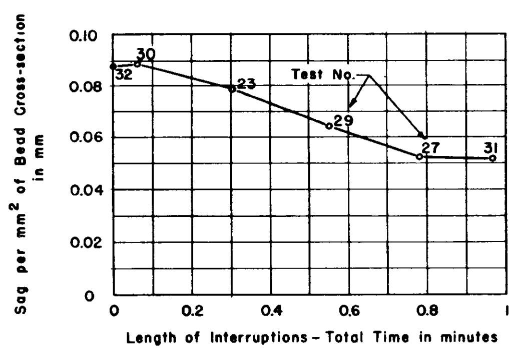

Figure 7. Effect of interruptions in welding on rising of the girder

Sagging of the girder was found to decrease inversely with the length of interruption (Figure 7). Deposition of beads of considerable length (a) without stops, (b) with stops of 10 to 20 seconds for each change of electrodes, and (c) with complete cooling after each electrode, caused sags in the ratio of a:b:c = 9:8:5.

An explanation for these considerable discrepancies may be that at the beginning and the end of each individual section of bead, when there are long interruptions, part of the heat is transfused into the girder in front of and behind the bead and thus is lost for the pushup and shrinkage of the weld zone, whereas in welding without interruption this heat must also contribute to pushup and shrinkage.

The frequently observed fact that in automatic welding there is less warping may be attributed to the circumstance that generally the automatically deposited bead is thinner than that deposited by the less uniform hand method.

10. MULTIPLE LAYER WELDING

In all previous tests the beads were deposited in a single layer. The test data compiled in Table 3 show the behavior of the girder when two or more layers are deposited one over the other.

TABLE 3

Test No.	Electrode		Welding Position	Bead Cross Section	Rise	Sag
	Brand	Diameter mm		mm^2	mm	mm
7	Siemens 165	4	1	11.8	1.43	0.78
15	GHH Pan	4	2	17.7	2.30	+0.64
5	Siemens 165	4	1	16.3	1.53	1.29
17	Siemens 165	4	2	22.0	2.76	+0.48
21	Siemens 165	4	3	21.3	2.97	+0.23
23	Union SH yellow	4	1	18.4	1.49	1.45
24	Union SH yellow	4	2	18.4	2.67	+0.21
25	Union SH yellow	4	3	18.5	2.65	+0.14
26	Union SH yellow	4	4	17.4	2.75	+0.12

The second layer was deposited over the first and in the same direction on the girder already deformed by the initial layer. The amount of rising was found to be considerably greater each time a second layer was deposited. Deformation due to the first layer was overcome, and moreover the middle of the girder rose almost as much as in deposition of the first layer. Therefore the second heating almost wholly eliminates the stress caused by the first layer. Thermal expansion thus has the same ultimate result as though the first layer had not been deposited. The ultimate sagging after the second layer, then, is the result of renewed pushup of the plastic zone.

The sagging of the individual layers of weld, therefore, is not additive; the major portion of the sag of the preceding layer is permanently removed by the annealing affect of the next layer.

In Tests 23 to 26 four layers were superposed in beads as nearly as possible of uniform section and under the same welding conditions. The described effect is plainly discernible from the curve of deformation during deposition of the four layers (Figure 8).

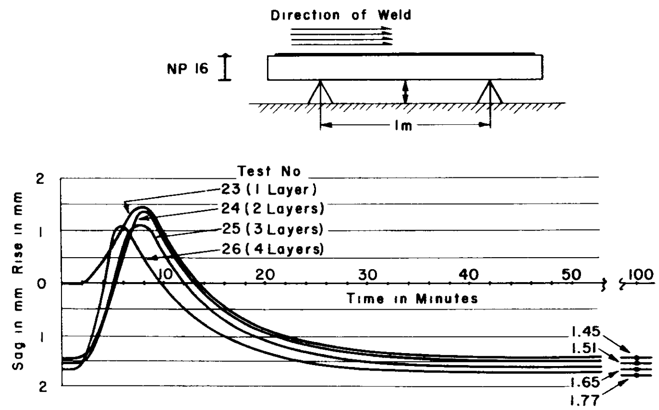

Figure 8. Rising and sagging of the middle of the girder in multiple-layer welding

11. BEHAVIOR OF CLAMPED GIRDERS

When thermal expansion in welding is subjected to additional restraint by clamping the girder, the pushup of the heated part must be greater than in a freely movable girder. Moreover the deformation of the girder must assume a greater value. This statement was given practical support by Tests 22, 33, and 38. The girders were keyed to a rigid support (Figure 9). The keys were so firmly hammered in at intervals of 20 cm (7.9 inches) as to eliminate all possibility of movement of the girders. In this condition a bead was deposited on the girder. Then the keys were removed and the deformation of the girder was measured on surface table.

In Test 22 the brackets for the keys were so lightly welded to the base that the test girder broke loose soon after the welding had been completed, i.e., during the shrinkage. In this case thermal expansion had been restrained, while the greater part of the shrinkage was free to proceed unrestrained. The results of this test give an idea of the effect of increased pushup due to clamping. In this case it amounts to 41 per cent (Table 4).

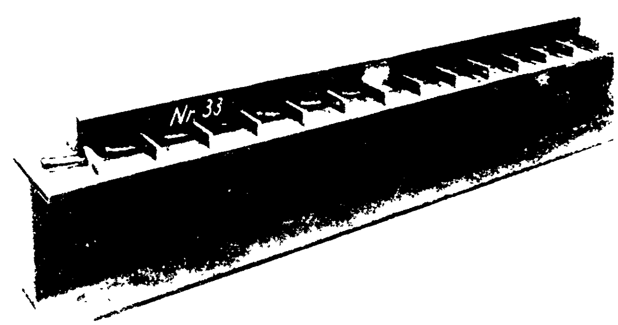

Figure 9. Test with clamped girder

In the other tests the girder remained clamped until cooled. The shrinkage must act as a strain, and if the elastic limit is exceeded, as a plastic extension. Thus part of the previous pushup can be nullified by extension. The deformation of the girder measured after its release from restraint then will be less than that in Test 22, in which the girder was free to deform corresponding to the shrinkage. Thus Test 33 showed an increase in sag of only 34 per cent.

Through the fastenings the restrained warping of the girder acts upon the base and exerts forces on it. Therefore the tests at the same time give an idea of the effects of shrinkage on larger girder cross sections. As a result of considerable restraint of thermal expansion, pushup and shrinkage will obviously be greater

TABLE 4

Test No.	Electrode		Bead Cross Section mm^2	Sag *, Girder Free mm	Sag †, Girder Clamped mm	Remarks
	Brand	Diameter mm				
22	Siemens 165	4	21.8	1.8	2.54	Shrinkage without restraint
33	Union SH yellow	4	18.9	1.5	2.03	
38	Union SH yellow	4	19.0	1.5	0.56	About 2 mm of pre-stress in opposite direction

* Assumed on basis of earlier tests

† Measured

in welding large girders than small ones. The widely diffused belief that it is possible by means of clamping to decrease warping in longitudinal welds is therefore fallacious. Welding with the work in clamped condition first causes considerable pushup, and when the clamps are released this is followed by corresponding warping. To decrease warping, therefore, thermal expansion should be permitted to proceed without restraint. It is a different matter, of course, when clamping is combined with a pre-stressing opposed to the direction of shrinkage.

The girder used in Test 38 was precurved in an arc with a sagitta of about 2 mm (0.08 inch) in the direction opposite to that of the shrinkage effect, while it was being clamped in place. The sag measured after its release was only 0.56 mm (0.02 inch) instead of 2.53 mm (0.1 inch) in a girder clamped in plane condition. The weld was deposited on fibers loaded in tension, which has a favorable effect with respect to shrinkage. When the pre-stress is suitably selected, it is possible by this means wholly to prevent deformation of the girder. The internal stresses left in the girder after its release from the clamps no doubt will be less than in a free girder.

12. SUMMARY

By measurement of the curvatures in I-beams of St 37 upon which longitudinal welds had been deposited in various ways, the following effects on shrinking force, or respectively, warping and shortening of the girders, were ascertained:

Cross Section of Bead

In a single-layer weld the shrinking force increases in direct ratio with the bead cross section. Excepted are thick welds on relatively thin girders, for example a bead of 30 mm^2 (0.045 square inch) on an I-beam NP16 deposited with a 4 mm (0.16-inch) coated electrode. In this case the approximate shrinkage force is reached. With increased heating or thinner girders the shrinkage force decreases once more.

Type of Electrode

The shrinkage force increases with the electric energy required to fuse a given volume of a given type of electrode. Thus the girder deformation when coated electrodes of the type Union SH yellow was about 1.7 times as great as that with the bare electrode GHH blue. In both cases amperages standard for the types of electrodes were used.

Diameter of Electrode

Since electrodes of the same type but of different diameters require about the same amount of energy for fusion of a given volume of weld metal, electrodes of 4 mm and 5 mm (0.16-inch and 0.2-inch) diameters give the same shrinkage force, beads being of equal size and deposited in a single layer. In single-layer welding, therefore, it is no advantage as far as deformation is concerned, to select electrodes of smaller diameter than would appear to be technically and economically suitable for the predetermined bead cross section. It is a different matter, however, when several thin layers are deposited with a thin electrode instead of a single layer with a thick electrode.

Amperage and Voltage

In welding with high voltage the shrinkage force is greater than with standard voltage, and with low voltage it is less. The electrodes and bead cross sections being the same, the shrinkage force is in the same ratio as in arc welding (amperage times voltage) when different amperages are used.

Welding Interruptions

Girder deformation can be reduced by interruptions in depositing longitudinal welds with consequent cooling each time. Thus, for example, in long seams complete cooling at every change of electrodes produces only about half the deformation caused by uninterrupted welding.

Multiple-Layer Welding

Deposition of a bead of given cross section in several layers results in a slighter shrinking force than in a single layer. For example, there is a 2.2 mm

(0.09-inch) deformation with a layer 28 mm^2 (0.043 square inch) in cross section, as compared to 1.3 mm (0.05 inch) with two beads of 14 mm^2 (0.021 square inch) each.

Clamping the Girder

Shrinking force is increased by clamping the girder. Thus a clamped girder welded off center shows greater deformation after release than the same girder welded in free condition. A test to determine the difference, for example, showed a 34 per cent increase in deformation.

Pre-stressing

By pre-stressing the girder in the direction opposite that of the expected curvature, a decrease of the shrinking force is achieved. Thus the deformation after release of the girder may be zero if the girder has been welded in a condition of elastic pre-stress. Internal stresses are also diminished materially by this means.