The Mechanical Properties of Welds in Zinc Coated Steel

The tensile, bend and impact properties of sound welds made with the covered electrode, shielded metal arc or submerged arc processes in zinc-coated steel are equivalent to the properties of sound welds in uncoated steel

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SUMMARY. This paper is based on work carried out at the Welding Institute on the ILZRO ZM-115 programme sponsored by the International Lead Zinc Research Organization Inc. (ILZRO), and also includes some data from a parallel program of work on Welding Primed Plate carried out by Drayton.

Work has been completed on the welding of galvanized, metallized and zinc-rich painted steels to $1^3/_4$ in. (44.5 mm) thick by CO_2 welding, shielded metal arc welding and submerged arc welding. The tensile, bend and impact properties of sound welds on zinc coated steel were equivalent to those of welds on uncoated steel. The presence of extensive porosity did not affect the static strength of cruciform tensile test specimens but, according to Drayton's work, caused a reduction in fatigue strength in cases where the fillet welds were small enough for failure to occur through the weld throat. The significance of porosity is considered in relation to the size of the weld and the function of the welded joint.

The presence of zinc penetrator cracks caused by intergranular penetration of zinc also reduced the fatigue strength of welds on galvanized steel. The use of low silicon weld metal which eliminates zinc penetrator cracking in CO_2 welds on galvanized steel produced joints having equivalent fatigue strengths to those of welds on uncoated steel.

The fracture toughness properties of welds and heat-affected zones were determined by crack opening displacement (COD) and drop weight tests on uncoated, galvanized, metallized and zinc-rich painted steel welded with basic covered electrodes, and the risistance to brittle fracture was the same in joints in uncoated and coated steels.

Introduction

A considerable amount of work has been carried out over many years on the mechanical properties of welds on zinc coated steel made by CO_2 welding, shielded metal arc or submerged arc welding. Reported results [1-10] indicate that tensile, bend and impact properties of welds on galvanized, metallized or zinc-rich painted steels are equivalent to the properties of welds on uncoated steels.

The tests reported in the above literature were carried out on butt welds which are less prone to defects than fillet welds even when the prepared edges are coated with zinc. Fillet welds on zinc coated steel can under certain conditions contain porosity, and the effects of this on static, fatigue and impact strength are discussed in this paper.

Fillet welds on galvanized steel can, under conditions of high restraint, contain zinc penetrator cracks caused by the intergranular penetration of molten zinc. Tests were carried out to determine the effect of this defect on fatigue strength and its effect on static strength is also considered.

The Charpy impact test is useful as a quality control test for comparing different materials. However, a more realistic test to determine the resistance to initiation of brittle failure is a slow bend test on a notched specimen in which the movement of the faces of the notch before fracture of the specimen is measured. Measurements were carried out of the critical crack opening displacement (COD) at fracture of notched bend specimens from welded Stelcoloy S steel* 1 in. (25.4 mm) thick coated by galvanizing, metallizing, or zinc epoxy primer before welding with basic covered electrodes.

The second aspect of brittle fracture is the propagation of a crack which can be determined by the Drop Weight Test which establishes the Nil Ductility Transition (NDT) temperature. Drop Weight Tests were carried out on butt welds made with basic coated electrodes on both uncoated and zinc coated Stelcoloy S plate.

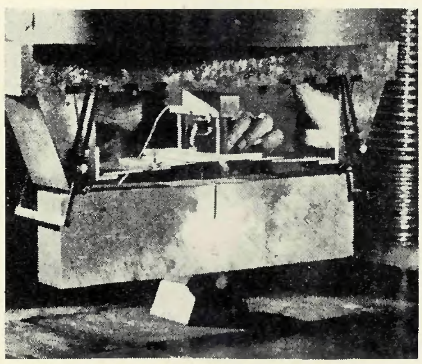

Fig. 1—Arrangements of a notch bend test which is used to measure crack opening displacement

Properties of Sound Welds on Zinc Coated Steel

When welding conditions are chosen to give sound welds on galvanized, metallized or zinc-rich painted steels, the tensile, bend, and impact properties are equivalent to those of welds on uncoated steel.[1-10] This applies to butt joints in which the prepared edges of the plate are zinc coated. It is normal practice in the production of all weld metal test specimens (e.g., tensile test specimens machined longitudinally from the weld or Charpy impact specimens with the notch in the weld metal) to use a wide root gap of $^1/_4$–$^3/_8$ in. (6.4–10 mm) so that the specimens are not affected by dilution of base metal into the weld. This practice would also tend to reduce the effect of any surface coating

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Paper sponsored by the International Lead Zinc Research Organization for presentation at the AWS 52nd Annual Meeting held in San Francisco, Calif., during April 26-29, 1971.

* Produced by The Steel Company of Canada. Conforms to ASTM A242. Typical composition (%): C—0.15 max., Mn—1.35 max., P—0.03 max., S—0.04 max., Si—0.15–0.30, Cu—0.20–0.50, V—0.01 min., Cr—0.25–0.50, Ni—0.20–0.50.

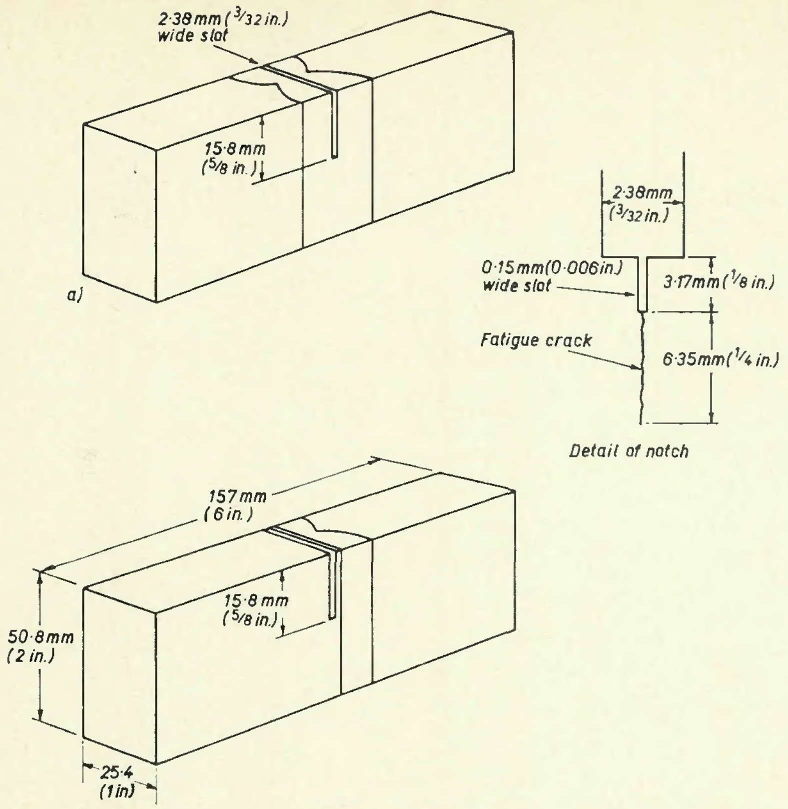

Fig. 2—Details of notch bend test specimens for measurement of crack opening displacement in (a) weld metal, (b) heat-affected zone

so the tests reported in the ILZRO work[5-9] were carried out on specimens made with a small root gap of $^3/_{32}$ in. (2.4 mm) so that any effects of the zinc coating on the properties of the weld would be determined.

The microstructures of the above welds were similar to those of welds on uncoated steels. There is a slight difference in chemical composition because of zinc pick-up which varies from a trace in welds on zinc-rich painted steels to approximately 0.16% in welds on galvanized steel. The presence of zinc in the weld metal was not found to have any effect on the tensile, bend or impact properties.

Resistance to Brittle Fracture

The impact properties of sound welds on zinc coated steels cited in the references above were determined by Charpy impact tests. The Charpy impact test is useful as a quality control test for comparing materials; it can be stated that, in general, a Charpy V-notch impact strength of 20 ft lb (27J) at the minimum temperature expected in service should ensure freedom from brittle fracture of 1 in. (25.4 mm) thick plate. A more realistic test to determine the resistance to initiation of brittle failure is a slow bend test on a notched specimen in which the movement of the faces of the notch before fracture of the specimen are measured—Fig. 1. Fracture initiation from a welding defect such as a crack depends upon various factors which determine whether the region of material at the tip of the crack will fracture in a brittle manner. If there is a high resistance to initiation of brittle fracture, then the crack will open, i.e., the crack surfaces will separate to a greater extent before fracture is initiated than in the case of material with low resistance to fracture initiation. The opening of the crack at fracture is a measure of the notch ductility of the material and can be determined in the laboratory.

Measurements were carried out[7] of the critical crack opening displacement (COD) at fracture of notched bend specimens from welded Stelcoloy S steel 1 in. (25.4 mm) thick coated by galvanizing, metallizing, or zinc epoxy primer before welding with basic covered electrodes. Details of the specimens for the measurement of crack opening displacement in the weld metal or the heat-affected zone are shown in Fig. 2. The purpose of the fatigue crack which was propagated for 0.25 in. (6.4 mm) was to provide a sharp notch from which a brittle crack could be initiated during bend testing at temperatures from 20 to −40° C. As reported[7] the COD values were measured by means of a clip gauge and were also calculated as detailed by Nicholls *et al.*[11] The results of these tests showed that the fracture toughness properties of welds on zinc coated steels were equivalent to those of joints in uncoated steel—Fig. 3.

The second aspect of brittle fracture is the propagation of a crack which can be shown by the Drop Weight Test which establishes the Nil Ductility Transition (NDT) temperature. Drop weight tests were carried out in accordance with ASTM E208-66T in order to determine the NDT temperature of weld metal from basic coated electrodes in butt joints in 1 in. (25.4 mm) Stelcoloy S, uncoated and coated by galvanizing, metallizing or with zinc epoxy primer. The butt joints were made between Stelcoloy S plates 24 x 7 x 1 in. (610

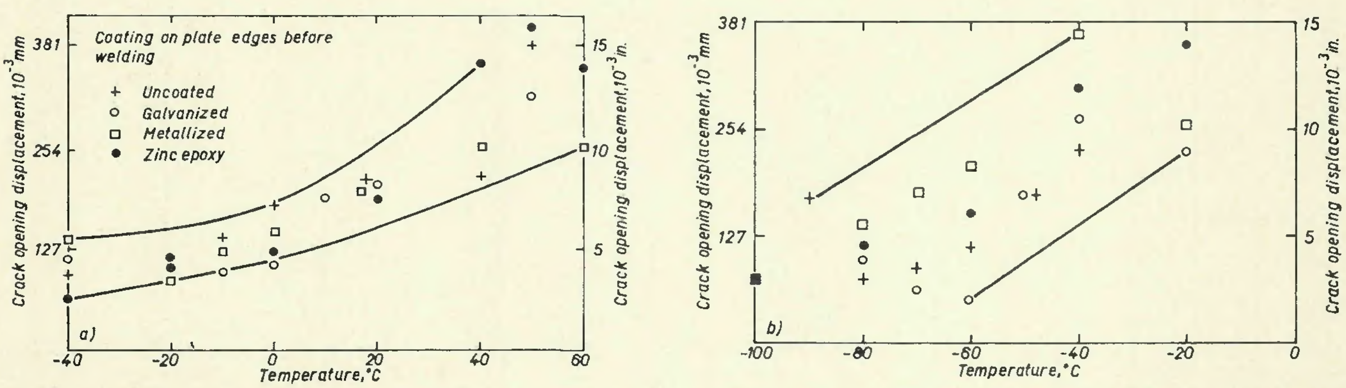

Fig. 3—Results of COD tests—25.4 mm (1 in.) Stelcoloy S plate, uncoated, galvanized, metallized, and zinc epoxy primed. Welded with basic covered electrodes. Left (a)—COD tests in weld metal; right (b)—COD tests on heat-affected zones

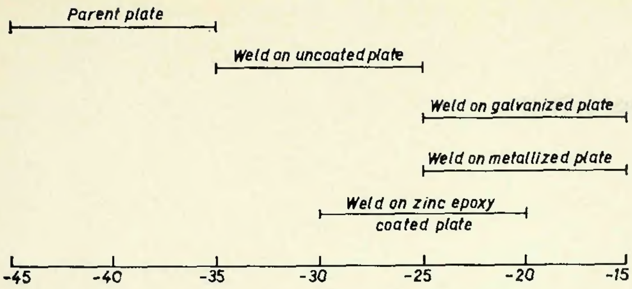

Fig. 4—NDT temperatures (±5° C) of base metal and welds on 25.4 mm (1 in.) Stelcoloy S

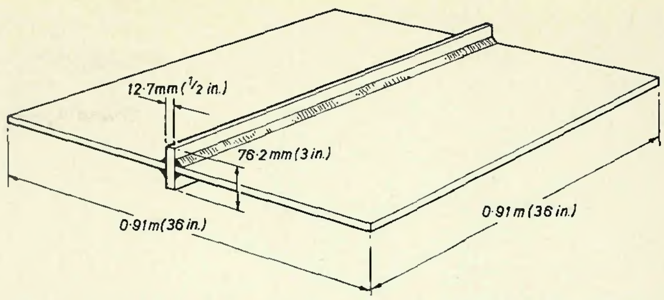

Fig. 5—Details of cruciform joint for production of specimens for fatigue testing

x 171 x 25 mm) having an edge preparation of a double 60 deg V included angle, $^1/_{16}$ in. (1.6 mm) root face and $^3/_{32}$ in. (2.4 mm) root gap. Welding was carried out with 0.192 in. (5 mm) diameter basic covered electrodes at 212 amp.

The welds were machined flush with the plate surface, and six test specimens $3^1/_2$ in. (76 mm) wide were cut from each plate. A weld bead $2^1/_2$ in. (64 mm) long and $^1/_2$ in. (12 mm) wide was deposited from a BOC/Murex Hardex 250 hardsurfacing electrode 0.192 in. (5 mm) diameter at the center of each test specimen transverse to the butt weld.

This crack starter weld was notched in each case and drop weight testing was carried out as specified in ASTM E208-66T. Testing was carried out at progressively lower temperatures until a temperature was attained at which the specimen fractured.

The results of the above tests showed that zinc coatings do not significantly affect the NDT temperature—Fig. 4.

Resistance to Fatigue Failure

Fatigue tests were carried out[7] on fillet welded cruciform joints in galvanized steel 4 in. (102 mm) wide cut from joints 36 in. (910 mm) long (Fig. 5) made by CO_2 welding with low silicon filler metal to AWS E60S-3. The use of this filler metal has been shown[6] to give freedom from zinc penetrator cracking caused by the intergranular penetration of zinc into restrained fillet welds in galvanized steel. Multi-run welds were made in the flat position to give a leg length of 10 mm; this was found by experimentation to give an equal chance of fatigue failure through the base metal or through the throat of welds made either with the shielded metal arc or CO_2 short-circuiting arc process on uncoated steel.

This size of weld was chosen because it would be likely to give results from which any trend in fatigue resistance would be readily shown. For example, any reduction in fatigue strength caused by welding on galvanized steel would result in a greater number of failures through the throat of the weld.

Eight specimens 4 in. (102 mm) wide were cut from each joint and were tested in pulsating tension with the lower limit $f_{min} = 0$. The tests were carried out in a 40 ton capacity Losenhausen hydraulic machine. The results of the above tests (Fig. 6) show that the fatigue strength of the welds on galvanized steel was equivalent to that of the welds made on uncoated steel.

Properties of Welds Containing Defects in Zinc Coated Steel

Porosity

Porosity sometimes occurs in welds on zinc coated steels because of volatilization of zinc or the combustion products of primers. Joint type will affect pore formation because gases can escape more readily from butt joints than from tee or lap joints. In the case of butt joints, a vee edge preparation or square edges with a gap will facilitate the escape of gases more than a close square edge joint. Coating thickness will obviously influence pore formation as will plate thickness because, with thinner sheet, the ratio of coating material to steel is increased.

As reported in the literature[3-9, 14, 15, 19], close attention to welding conditions can reduce the extent of porosity, but it is not always possible to eliminate this defect completely. Therefore it is essential to consider the significance of porosity in terms of the integrity of a welded joint. Various authorities specify the maximum number of pores of a given size allowed per unit length of weld or total cross sectional area of porosity. These authorities generally have different ideas on the amount of porosity that can be safely allowed in a weld before it has to be gouged out and rewelded.

The differences in opinions arise from the fact that some aspects of the specifications do not appear to be based on any scientific evidence for the effect of defects on the integrity of a structure. As pointed out by Harrison *et al*,[12] porosity—or indeed any type of defect—of such a size or extent that the remaining ligament is

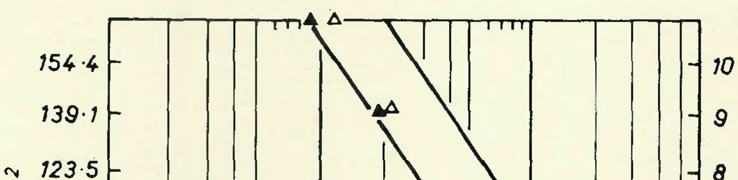

Fig. 6—SN curves showing results of fatigue tests on cruciform joints. CO_2 dip transfer welds on uncoated and galvanized 12.7 mm (½ in.) Lloyds Grade A steel AWS E60S-3 filler metal

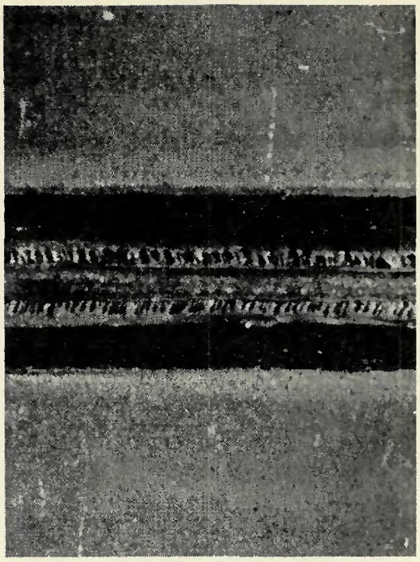

Fig. 7—Broken cruciform tensile specimen. Plate coated with 0.0025 in. (0.001 mm) zinc rich primer. Welded by submerged arc process

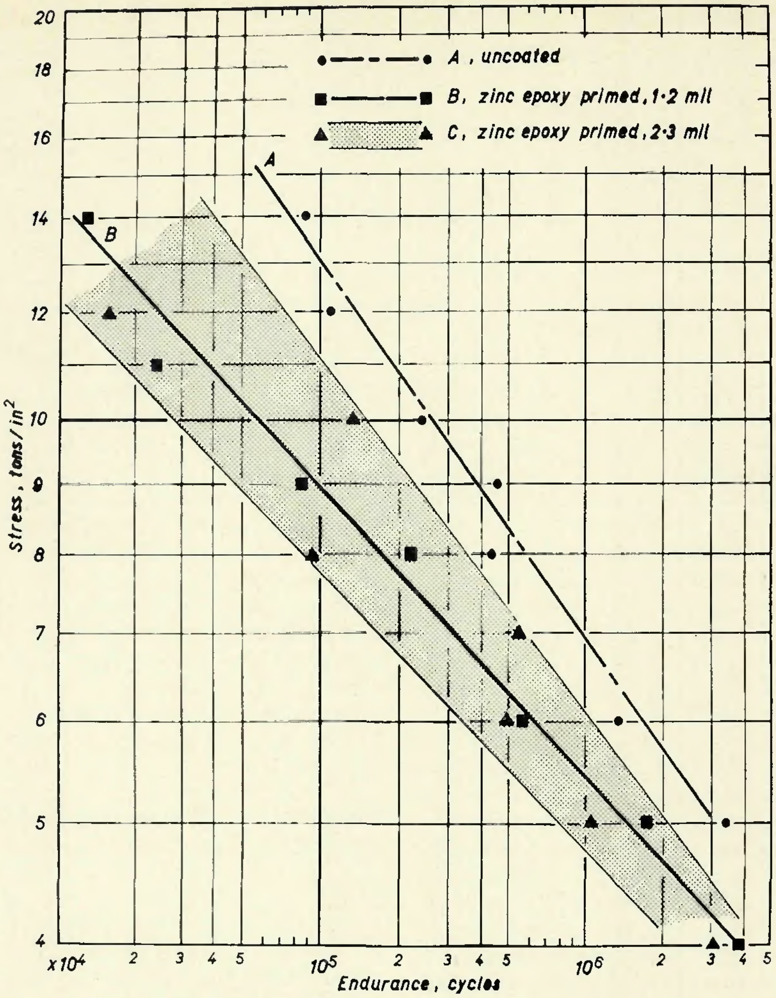

Fig. 8—Results of fatigue tests on cruciform specimens, uncoated or coated with zinc epoxy primer. (After Drayton[15])

loaded to a mean stress level above yield is obviously unacceptable. Furthermore, it has been reported[12, 13] that quite considerable porosity can be tolerated in either butt or fillet welds before there is any deterioration in fatigue strength. This is because fatigue cracking will generally occur at a fillet weld toe or at the edge of the overfill of a butt weld where the stress concentration is greater than that which occurs at quite large internal defects.

Effect of Porosity on Static Strength

The maximum amount of porosity that occurs in twin fillet submerged arc welds on zinc rich painted steel has been shown to cause no deterioration in the static strength of cruciform tensile test specimens.[14] Figure 7 shows a cruciform specimen after tensile testing and indicates the extensive amount of porosity present. This specimen failed in the tensile test at a load 26% greater than that expected for standard mild steel weld metal of satisfactory quality based on shear stresses of 19 tons/in.^{2} (290 N/mm^2:42,560 psi) on the throat of the weld. The results of a series of tensile tests on similar specimens showed no reduction in breaking loads compared with sound control welds on uncoated steel.

Therefore, it is evident that the porosity that may occur in welds on zinc coated steels does not reduce the static tensile strength.

Effect of Porosity on Fatigue Strength

Drayton[15] reported that fillet welded cruciform tensile test specimens made with the submerged arc process on $^1/_2$ in. (13 mm) plate coated with zinc epoxy primers contained porosity in the welds. Moreover, when the welds were small enough to fail by fatigue through the throats of the welds, the presence of porosity caused a reduction in fatigue strength—Fig. 8. In the case investigated, 10 pores in a 6 in. (150 mm) length of weld gave a 10 to 25% reduction in fatigue strength.

The presence of porosity appeared to affect the propagation of fatigue cracks but not the initiation. This means that if a fillet weld is large enough compared with plate thickness to fail by fatigue from the toe of the weld, then the presence of porosity in the weld will not reduce the fatigue strength of the joint. This statement must be qualified by saying that in borderline cases where a weld is just large enough to cause fatigue failure from the weld toe in a sound weld, then the presence of porosity at the root may cause failure to occur through the throat of the weld.

The critical dimensions of welds on various plate thicknesses for transition from root to toe failure have been reported by Harrison.[16] The changeover from root failure to toe failure occurs at a particular weld size and, in the case of a weld containing porosity, the changeover would occur at a slightly larger weld size than for a sound weld. Therefore, in evaluating the effect of porosity on the fatigue strength of a fillet weld, it is necessary to consider both the function of the joint and the size of the weld. The situation is summarized in Figs. 9–11.

Figure 9 shows a fillet weld, which is not a main load, carrying detail; this type of weld detail occurs many times in, for example, a ship where stiffeners are attached to the hull or to the deck plates. The main stresses, indicated by the arrows, are transmitted through the plate and do not go through the welds which attach the stiffeners.

If these stresses are fluctuating and sufficiently large to cause a fatigue failure, failure will be initiated at the toe of one of the fillet welds due to the stress concentration caused by the change in section thickness. A fatigue crack will then propagate through the plate, and the presence of porosity in the weld bead will have no effect on

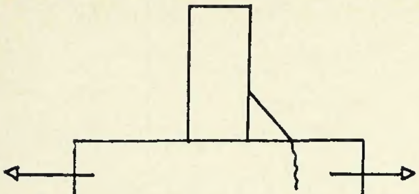

Fig. 9—Non-load bearing fillet weld. Fatigue failure through plate initiated at toe of weld. Porosity has no effect on fatigue strength

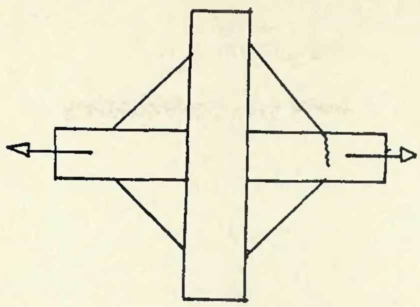

Fig. 10—Load bearing fillet weld—large weld. If weld is large enough, fatigue failure occurs through plate—initiated at toe of weld. Porosity has no effect on fatigue strength

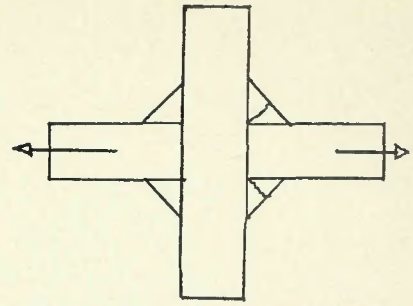

Fig. 11—Load bearing fillet weld—small weld. If weld is small enough, fatigue failure occurs through weld—initiated at root of weld. Porosity can reduce fatigue strength

the fatigue strength of the joint. For a weld that does not transmit the main loads through the structure, porosity is, therefore, unimportant. This was demonstrated by Gonnel[17] who carried out fatigue tests on non load bearing fillet welds some of which contained porosity.

Consider now a main load carrying fillet weld under alternating stresses indicated by the arrows. Here there are two systems which must be considered depending on the size of the welds compared with the thickness of the plate:

Large Welds (Fig. 10). When the ratio of weld leg length to plate thickness is large enough,[16] fatigue failure will again initiate from the toe of the weld. In a border line case when welds are only just large enough to ensure fatigue failure from the toe of the weld rather than its root, then the presence of porosity can cause failure through the weld. However, provided that welds are sufficiently large, fatigue failure will propagate through the base metal and porosity will have no effect.

Small Welds. When the ratio of weld leg length to plate thickness is small enough, fatigue cracks will propagate through the weld from the root—Fig. 11. In this case, as described above, porosity can reduce the fatigue strength—but only, it would appear, by reducing the effective cross sectional area of the weld.

Cracking

The intergranular cracking of fillet welds is sometimes referred to as zinc penetrator cracking and is described in the literature.[18, 19] This may not be detrimental to the integrity of a structure, depending on the extent of the cracks and on the service requirements of the joint. United States Navy Department specification NAV SHIPS 0900-000-1000 Fabrication, Welding and Inspection of Ship Hulls includes qualification procedure requirements for welding galvanized mild and high tensile steels; this involves the welding of a tee assembly which is then fractured through the throat of a single fillet weld 36 in. (974 mm) long by bending. The areas of cracking caused by the intergranular penetration or zinc are identified by heating the standing plate (the web member) in a furnace (oxidizing atmosphere) at 625 ± 25° F for 30 minutes. The surface of fracture representative of sound structure will oxidize and darken (usually to a tan or brown color). The areas of cracking caused by zinc retain their light silvery color.

The welding procedure is considered acceptable by the above specification provided that the total discontinuous length of cracking does not exceed 3 in. (76 mm).

In noncritical joints this extent of intergranular cracking will not significantly affect the strength of the joint. In other cases however, it will be necessary to apply more rigorous acceptance standards. For example, it has been shown[7] that intergranular cracking due to zinc can seriously affect the fatigue strength of a joint. This is shown in Fig. 12 where the fatigue strength of a cruciform joint is reduced progressively depending on the extent of cracking in the particular specimen tested. The gap of $^1/_{16}$ in. (1.6 mm) between the galvanized plates was used because, in many cases, it has been found[6, 18, 19] to be an effective precaution against zinc penetrator cracking. In the present case extensive cracking occurred in some samples, and this was possibly caused by local excessive zinc coating weights on the plate edges. These results indicate the advisability of carrying out procedural tests on material and consumables to be used in critical applications.

In cases where procedural tests show that a gap effectively prevents zinc penetrator cracking, then this technique should be suitable for joints that are to be subject to fatigue loading because the presence of a gap in the uncoated specimen (Fig. 12) did not reduce the fatigue strength. Apart from fatigue failure, the risk of brittle fracture in weld metal may be in-

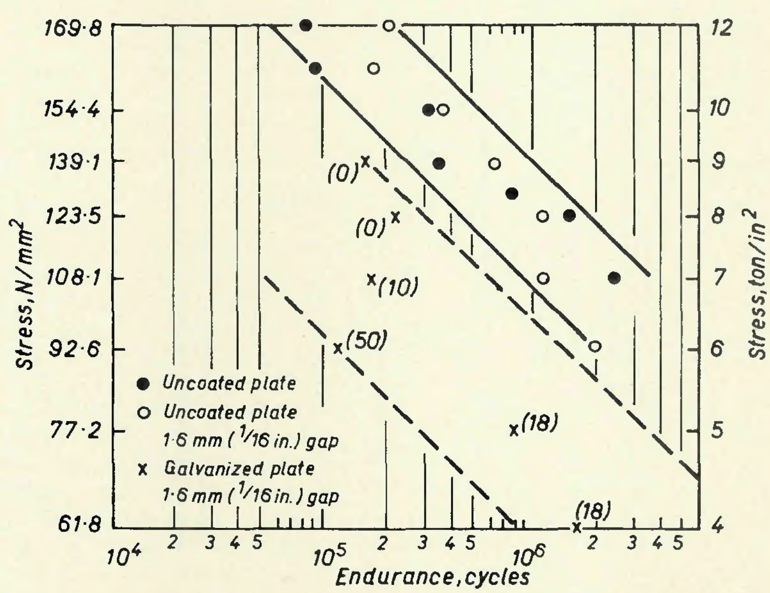

Fig. 12—SN curves showing results of fatigue tests on cruciform joints welded with basic coated electrodes. Uncoated and galvanized 12.7 mm (½ in) Lloyds Grade A steel. Numbers in brackets represent length of weld showing zinc penetrator cracking

creased if cracks are present. Where this risk is present, it is essential to prevent the formation of cracks by the procedures recommended in the literature.[6, 18, 19]

Conclusions

1. The tensile, bend and Charpy impact properties of welds on steel coated by galvanizing, metallizing, or zinc-rich paints are equivalent to those of welds on uncoated steel.

2. The resistance to initiation of brittle fracture of butt joints in 1 in. (25.4 mm) Stelcoloy S, the edges of which were coated by galvanizing, metallizing or zinc epoxy primer, before welding with basic covered electrodes was shown by COD measurements on notched bend tests to be equivalent to that of joints in uncoated steel.

3. Drop weight tests showed that the nil-ductility transition (NDT) temperature of 1 in. (25.4 mm) thick Stelcoloy S plate was −40° C and that of weld metal deposited by basic covered electrodes on uncoated Stelcoloy S was −30° C.

4. The effect of zinc coatings on Stelcoloy S before welding did not significantly affect the NDT transition temperature of welds made with basic covered electrodes.

5. The presence of extensive porosity did not affect the static tensile strength of cruciform test specimens welded by the submerged arc process on plate coated with excessive coating thickness (0.0025 in., 0.001 mm) of zinc epoxy primer.

6. As shown by Drayton[15] the presence of porosity to the extent of 10 pores in a 6 in. (150 mm) length of weld gave a 10–25% reduction in fatigue strength in submerged arc welded cruciform joints on plates coated with zinc epoxy primer.

7. The fatigue strength of a fillet welded cruciform joint made by CO_2 welding galvanized steel with low silicon filler metal was equivalent to that of a joint made from uncoated steel.

8. The fatigue strength of a cruciform joint made by welding uncoated steel with basic covered electrodes was not affected by the presence of a gap of $^1/_{16}$ in. (1.6 mm) between the plates. Therefore this procedure, which in certain circumstances can eliminate defects such as porosity or zinc penetrator cracks will not of itself reduce fatigue strength.

9. Zinc penetrator cracking of fillet welds made with basic covered electrodes gave a marked reduction in fatigue strength of cruciform joints.

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