Producing Strong Welds in 9% Nickel Steel

ABSTRACT. The shielded metal arc welding of 9% nickel steel was investigated using a nickel-base weld metal, and the influences on weld strength of the more controllable variables were studied. Weld metal composition proved important, as higher carbon levels raise the proof stress but also reduce the ductility and impact strength. This inverse relationship was the main problem with most of the elements which raised strength significantly.

Fast cooling of the weld was beneficial. Low interpass temperatures as well as large heat sinks and low heat inputs contributed to strength. Further significant improvements were obtained by employing a high degree of restraint, and increasing the weld thickness proved advantageous.

Position of welding influenced the strength of the weld, but heat input alone did not explain the results. With normal technique, downhand welds were stronger, but welding at a constant heat input favored the vertical-up welds.

X-ray crystallography has shown that the solidification structure leads to anisotropy in the tensile properties of the weld metal. Attention to joint design and welding procedure can turn this anisotropy to advantage.

Introduction

The use of 9% nickel steel for cryogenic storage vessels has been common for some years and, in Britain, this steel has normally been welded with a nickel-base filler metal. Tank construction in accordance with API 620 Appendix Q, which has applied to most of the land-based storage tanks, places limits on design loads based on a minimum specified weld metal strength. Occasionally, fabricators have had difficulty in obtaining the required strength level in procedure tests.

The study reported in this paper began as an attempt to isolate the factors responsible for such unexpectedly low strengths. As the work progressed, however, it became clear that the results obtained depended not only on how the weld was made, but also on how it was tested. Consequently, the work was expanded to study the anisotropy of the welded joint.

Experimental Work

The weld metal under study was that deposited by a commercially available covered electrode with a typical deposit analysis of 63% Ni, 13% Cr, 11% Fe, 6% Mo, 3% Mn, 1% W, 0.3% Si, 0.1% C. The electrode uses a nickel core wire and a heavily alloyed coating.

Varying Weld Metal Composition

To determine whether or not this was the optimum composition, experimental electrodes were made with modifications to the coating to permit variation of most of the alloying elements from virtually nil to about double their normal levels. In each case the 0.2% proof stress, ultimate tensile strength (UTS), % elongation to fracture and Charpy V-notch values were obtained at room temperature, and Charpy results were also measured at -196 °C (-320 °F).

Normal Test Conditions

In all cases of procedural variation, production batches of the electrode were used, the same batch being used throughout any series. Welding was normally carried out with the joint fully restrained and with the maximum interpass temperature limited to 100 °C (212 °F). Two main types of weld were used:

1. 70° V butt welds in 12 mm (½ in.) thick 9% nickel steel plate—Fig. 1A. Hounsfield No. 14 tensile test pieces were machined from these.

2. All-weld-metal joints, normally in 19 mm (¾ in.) thick mild steel plate with a 20 deg included angle and a backing bar—Fig. 1B; 10 mm (0.4 in.) diameter tensile test pieces to BS 2926 were machined from these.

Varying Interpass Temperature

The effect of interpass temperature was investigated by carrying out two identical butt welds using 2.5 mm (½ in.) diameter electrodes, welding vertically up in six passes with a full weave. The control weld (V1) had a 100 °C (212 °F) maximum interpass temperature while the test weld (V2) had a 250 °C (482 °F) preheat maintained throughout welding. Two longitudinal and two transverse tensile test pieces were presented at the AWS 59th Annual Meeting held in New Orleans, Louisiana, during April 2-7, 1978.

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A) 12mm

Fig. 1—The two main weld preparations used: A—V-butt preparation; B—All weld metal preparation

Varying Heat Sink and Restraint

The effects of heat sink and restraint were determined from four welds at constant heat input and interpass temperature. An all-weld-metal preparation was used with 5 mm (\(\frac{3}{32}\) in.) diameter electrodes. Two of the welds had only a thin backing bar, while the other two used a heavy backing plate, 150 mm (6 in.) deep. Two welds were made with the plates unrestrained, while the other two used heavy restraint. Thus the four possible combinations of heat sink and restraint were covered (Fig. 2), and a longitudinal tensile test piece was taken from each weld.

In one subsidiary experiment, all-weld-metal preparations were used—first, with 12 mm (\(\frac{3}{8}\) in.) thick plate, a thin backing bar and no restraint; second, with 12 mm plate, a heavy backing plate and full restraint; and, finally, in 19 mm (\(\frac{3}{4}\) in.) plate with a heavy backing plate and full restraint. In the other subsidiary experiment, full restraint and heat sink were covered (Fig. 2), and a longitudinal tensile test piece was taken from each weld.

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Varying Heat Input

Heat input—or, more accurately, heat input per unit length of weld—often has an influence on the properties of weld metal. Here it has been calculated as current \(\times\) arc Voltage + travel speed and is thus measured in joules per unit length. The effect of heat input was measured using four vertical butt welds (V5 to V6) made with 2.5 mm (\(\frac{3}{32}\) in.) electrodes in 12 mm (\(\frac{3}{8}\) in.) plate. By varying the run-out length per electrode it was possible to complete the weld in 6, 4, 2 and even 1 pass, and thus to vary the heat input across the range 1 to 6 MJ/m (20 and 46 kJ/in.) was achieved (welds D1 and D2). Two vertical-up welds were carried out similarly: the first (V7) at a heat input of 1.8 MJ/m (46 kJ/in.), the second (V8) at 21 MJ/m (530 kJ/in.). (Although this is an unrealistic procedure for shielded metal arc welding, this weld was thought likely to produce an extreme in tensile results.)

Varying Weld Position

The effects of welding position and testing direction were assessed in two series of welds. In the first series 2.5 mm (\(\frac{3}{32}\) in.) electrodes were used to make fully restrained butt welds in the downhand, horizontal-vertical and vertical-up (1G, 2G and 3G) positions (welds D3, HV1 and V9). Two longitudinal (all-weld-metal) and two transverse tensile pieces were taken from each weld.

For the second series a horizontal-vertical weld (HV2) at 1.8 MJ/m (46 kJ/in.) was compared with welds D2 and V7 (made at the same heat input) from the second heat input series. One longitudinal and one transverse tensile test piece were taken from each weld, and the remainder of the weld (as with D1 and V8) was used for x-ray crystallography.

Results

The Effect of Weld Metal Composition

It was observed that compositional influences on proof stress or impact strength were easy to identify. However, the strong correlation between % elongation and UTS (or, particularly, UTS-Proof Stress) made it difficult to determine whether low values of either were due to composition, or to some unsoundness, inhomogeneity or embrittlement.

The results suggest that a high proof stress is favored by high levels of carbon and molybdenum and by low nickel levels. The only notable influence on UTS or elongation was that low chromium levels reduced them both, possibly indicating an imbalance in deoxidation under these circumstances. At both of the test temperatures, impact strength was favored by low levels of carbon, silicon, molybdenum and niobium (and high levels of nickel).

The Effect of Interpass Temperature

The use of a high interpass temperature reduced the longitudinal yield.
stress by 15 MPa (2,175 psi) and the UTS by 20 MPa (2,900 psi), but had little effect on ductility or impact strength. The transverse yield stress was about 5 MPa (725 psi) higher, but the transverse UTS was 5 MPa lower with the higher interpass temperature.

The Effects of Heat Sink and Restraint

It was found that restraint had a beneficial effect on strength, while a large heat sink was also advantageous. The results of the primary experiment (Table 1) show that, while the effects on UTS were minor and may not be significant, the elongation values are noticeably less where heavy restraint was applied. More significantly, the combination of restraint with a large heat sink has raised proof stress by 8%.

The subsidiary experiments (Table 2) show a similar trend, the restraint

<table>
<thead>
<tr>
<th>Table 1—The Effects of Heat Sink and Restraint</th>
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<tbody>
<tr>
<td>Backing bar</td>
</tr>
<tr>
<td>Effects on proof stress, MPA (ksi)</td>
</tr>
<tr>
<td>Effects on UTS, MPA (ksi)</td>
</tr>
<tr>
<td>Effects on elongation, %</td>
</tr>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2—The Effect of Restraint on Tensile Properties</th>
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</thead>
<tbody>
<tr>
<td>Thickness (mm) or test position</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>19</td>
</tr>
<tr>
<td>Top of weld</td>
</tr>
<tr>
<td>Center of weld</td>
</tr>
</tbody>
</table>

Fig. 3—The effect of heat input on mechanical properties: solid symbols—longitudinal; open symbols—transverse
factor being of major importance. Even the additional restraint resulting from a thicker joint, or more runs on top of the test area, has increased strength.

The Effect of Heat Input

High heat inputs had a generally deleterious effect on weld strength. In the series of vertical butt welds over a range of heat inputs, the longitudinal yield stress fell by 34% and the transverse yield stress by 25%, while the UTS in both directions fell 8% as the heat input rose. Figure 3 illustrates these values and shows that hardness followed a similar trend, while elongation (%) improved as the weld metal became softer.

Table 3—The Effect of Heat Input on Tensile Properties in All-Weld-Metal Joints

<table>
<thead>
<tr>
<th>Welding position</th>
<th>Heat Input, MJ/m (kJ/in.)</th>
<th>Flat</th>
<th>Vertical Up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal properties:</td>
<td>0.8 (20)</td>
<td>1.8 (46)</td>
<td>1.8 (46)</td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>495 (71.8)</td>
<td>435 (63.1)</td>
<td>465 (67.4)</td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>715 (103.7)</td>
<td>705 (102.2)</td>
<td>745 (108.0)</td>
</tr>
<tr>
<td>Transverse properties:</td>
<td>0.2% Proof stress, MPa (ksi)</td>
<td>505 (73.2)</td>
<td>425 (61.6)</td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>760 (110.2)</td>
<td>735 (106.6)</td>
<td>725 (105.2)</td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>525 (76.1)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Fusion boundary failure.

Table 4—The Effects of Welding Position and Testing Direction on the Tensile Properties of V-Butt Welds

<table>
<thead>
<tr>
<th>Welding position</th>
<th>Heat Input, MJ/m (kJ/in.)</th>
<th>Downhand</th>
<th>Horizontal-vertical</th>
<th>Vertical-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal properties:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>465 (67.4)</td>
<td>440 (63.8)</td>
<td>440 (63.8)</td>
<td></td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>750 (108.8)</td>
<td>720 (104.4)</td>
<td>755 (109.5)</td>
<td></td>
</tr>
<tr>
<td>Transverse properties:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>500 (72.5)</td>
<td>505 (73.2)</td>
<td>445 (64.5)</td>
<td></td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>790 (114.6)</td>
<td>800 (116.0)</td>
<td>740 (107.3)</td>
<td></td>
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</tbody>
</table>

Table 5—The Effects of Welding Position and Testing Direction on the Tensile Properties of All-Weld-Metal Joints

<table>
<thead>
<tr>
<th>Welding position</th>
<th>Heat Input, MJ/m (kJ/in.)</th>
<th>Flat</th>
<th>Horizontal-vertical</th>
<th>Vertical-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal properties:</td>
<td>1.8 (46)</td>
<td>1.8 (46)</td>
<td>1.8 (46)</td>
<td></td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>435 (63.1)</td>
<td>430 (62.4)</td>
<td>465 (67.4)</td>
<td></td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>705 (102.2)</td>
<td>705 (102.2)</td>
<td>745 (108.0)</td>
<td></td>
</tr>
<tr>
<td>Transverse properties:</td>
<td>0.2% Proof stress, MPa (ksi)</td>
<td>425 (61.6)</td>
<td>—</td>
<td>425 (61.6)</td>
</tr>
<tr>
<td>Yield stress, MPa (ksi)</td>
<td>735 (106.6)</td>
<td>—</td>
<td>725 (105.2)</td>
<td></td>
</tr>
<tr>
<td>UTS, MPa (ksi)</td>
<td>735 (106.6)</td>
<td>—</td>
<td>725 (105.2)</td>
<td></td>
</tr>
</tbody>
</table>

The Effect of Welding Position

In the first series, in longitudinal tests, it was observed that the horizontal-vertical weld had a UTS some 30 MPa (4,350 psi) lower than the other two. The downhand weld had a longitudinal yield stress about 25 MPa (3,625 psi) higher than the others. In transverse tests, however, the vertical weld was about 50 MPa (7,250 psi) weaker than the others, both in yield and UTS (Table 4). It can be seen that, while the vertical weld was fairly isotropic, the downhand weld—and especially the horizontal-vertical weld—were very much stronger transversely than longitudinally.

In the second series, where the heat inputs had artificially been made equal, some of the apparent effects of position disappeared. Table 5 shows the results, the most notable change being that here the vertical-up weld has the greatest longitudinal strength. (The rather unrealistic joint design and welding procedure with the horizontal-vertical weld again led to incomplete fusion at one plate, hence the absence of transverse results.)

X-ray Crystallography of Positional Welds

Pole figures for {200} and {111} planes were produced for five welds in the heat input and welding position series. Each weld showed a “fibre texture” with {200} poles (plane normals) clustered in one direction, the remainder being distributed symmetrically at 90 deg to the cluster. Both downhand welds had poles clustered near the welding plane normal. The three 1.8 MJ/m (46 kJ/in.) welds had their “fibre axes” tilted away, to some extent, from this plane normal. In the downhand weld the tilt was 10 deg toward the welding direction, for the vertical-up weld 15 deg toward the welding direction, but in the horizontal-vertical weld the tilt was 30 deg transverse to the welding direction. In the 21 MJ/m (530 kJ/in.) vertical weld, the fibre axis was tilted 65 deg toward the welding direction (i.e., it was only 25 deg from the line of the weld). Because of the fibre texture, the {111} poles were distributed symmetrically around, and at about 55° from the fibre axis.

Discussion

The Influence of Weld Metal Composition

This is by no means the first study of the influence of composition on properties with this type of electrode. Indeed, any genuine electrode development must involve such a study. Early in the development of the electrode used in this work, Blake et al. looked at the effect of composition. In fact they used only carbon as a deliberate variable, the two levels being 0.07% and 0.10%, but they did analyze the weld metal from which each of their tensile tests was taken. By statistical analysis of their results they produced equations predicting both proof stress and UTS in terms of weld composition. They showed that carbon raised both proof stress and UTS, although it reduced impact strength. They found that tungsten and, to a lesser extent, niobium (i.e., columbium) were also beneficial for raising the UTS.

Following this work, J. P. Turner showed that carbon levels up to 0.19% continued to raise the proof stress of this weld metal. He found a continued reduction in impact strength, and also in elongation. Turner's results do show a slight fall in UTS at high carbon levels. This appears to be a result of the dual effect of carbon on both proof
stress and elongation. Both relationships are approximately linear (Fig. 4) as distinct from the non-linear relationship (Fig. 5) between elongation and work hardening capacity (defined here as the difference between 0.2% proof stress and UTS). As the carbon level rises so the elongation falls, but at high carbon levels the work hardening capacity is rapidly exhausted. Clearly, if this occurs more rapidly than the proof stress rises, the UTS cannot continue to rise; hence the lower UTS values at high carbon levels.

The data of Horii et al., using another nickel-base weld metal, cover carbon levels up to 0.25%. They too show a rise in proof stress over the whole range, but in UTS only up to 0.2%, suggesting that the same mechanism was in operation. They found that molybdenum levels of up to 12% raised both proof stress and UTS. In that series, however, they kept carbon below 0.1% and, although elongation figures are not quoted, it is likely that the low carbon level helped to maintain an adequate level of ductility. They also found a minor benefit adding up to 2% tungsten. Having noted the deleterious effect of carbon on impact energy at any given strength level, they concluded that a low carbon, high molybdenum deposit would provide optimum properties.

The present study used 63 welds of different analyses. When these are plotted on a work hardening capacity vs elongation graph, at least 50 fit within a remarkably narrow band. Of the others, it was found that, for a given work hardening capacity, those with high molybdenum levels tended to give lower than average elongations. Similarly, low silicon or high nickel levels tended to give better than average elongations. Further study showed that lower elongations generally resulted when the weld contained higher than normal levels of carbon, manganese, silicon, molybdenum or niobium, while higher elongations were achieved when levels of nickel, chromium or tungsten were relatively high. Of the nine elements measured only iron proved impossible to classify. For the other elements, as Fig. 6 shows, the distinction was remarkably clear.

Since the normal (nickel plus chromium) level is 76%, with iron making up a further 11%, it is arguable that the apparent influences of nickel and chromium are merely a reflection of the relative absence of the other elements. Since the normal tungsten level is only 1%, however, the same criticism cannot apply. Consequently, this area will be the subject of further study.

The Influence of Interpass Temperature

9% nickel steel is often site welded, and here the interpass temperature is likely to be 100 °C (212 °F) maximum. Although the fall in strength on raising interpass temperature is no surprise (low alloy steel welds behave in the same way), it emphasizes that attention must be paid to interpass temperature during shop welding, particularly of small components. In low alloy steel welds, the transformation products are modified at the higher temperature. However, since nickel based alloys do not transform on cooling, another mechanism must apply. The slower cooling rate may result in carbide growth, but the most likely cause is the influence on solidification rate and thus on grain size or dendrite arm spacing.

The Influence of Heat Sink

The presence of a large heat sink seems to have a small, but positive, effect on weld strength. The mecha-
nism is probably the same as that involved in the interpass temperature effect. Both a low interpass temperature and a large heat sink will assist in speeding up the cooling rate of the weld and weld pool. This will tend to result in closely spaced dendrite arms, small grain sizes and small carbides, all of which will promote strength.

J.C. Thornley has pointed out that the influence of dendrite arm spacing is probably more significant than that of grain size.

The Influence of Restraint

In the work on which their paper was based, Blake and Phelps obtained no benefit when they increased restraint by changing the size of plates they welded. In the present study, however, the levels of restraint involved (Fig. 2) were distinctly different.

Work hardening capacity (MPa)

\[ W = \frac{1}{2}k \sigma^{n+1} \]

Subsidiary experiments showed that thicker welds give better tensile properties and that the center of the weld is stronger than the top. This confirmed the importance of strain due to subsequent thermal cycles. Since this thermomechanical treatment makes subcutaneous beads stronger than those on top, it might reasonably be inferred that, the more runs there are in a joint, the higher the stress it will carry.

The Influence of Heat Input

Blake et al observed that reducing the heat input could enhance the strength of the weld. However, they had found this by changing to a smaller size of electrode, and thus a lower current, as there had been no clear benefit from slight reductions in current or increases in welding speed with a constant size of electrode. They observed no difference in grain size or orientation as a function of heat input, and inferred that carbide precipitation or dislocation density was responsible.

Certainly the 19 mm (¾ in.) thick quality control welds obtained with this electrode show a general trend for smaller electrode sizes to give higher strengths. There is undoubtedly a heat input effect, but the restraint tests suggest that the number of layers in the joint is also significant. Also, the mechanism there does seem to be one of changed dislocation density.

Horii et al showed that heat input could have a marked effect on joint strength. However, this seemed to depend on the consumable used, some being much less sensitive than others. Joint thickness also had an effect. So they proposed that dilution was a major factor responsible for the falls in strength. Their least susceptible joint was that in thickest plate and welded with the consumable with lowest iron content, which would appear to support that thesis.

Thornley found that grain size was relatively insensitive to heat input, whereas dendrite arm spacing changed significantly. He also showed that dendrite arm spacing correlated well with proof stress, and it seems likely that this is a major factor in the correlation between proof stress and heat input. However, since heat input has been varied by changing run length and thus number of runs per weld, the restraint effects on dislocation density can also have had a significant effect.

It is worth mentioning that, since the method of calculating heat input used here takes no account of bead shape, heat input may not be an accurate guide to weld metal cooling rate and dendrite arm spacing. A more useful measure would probably be obtained by working with the fusion boundary area of the bead, rather than just its length. Unfortunately, this would mean cutting up a weld to determine the heat input, so the present calculation is considered satisfactory for most purposes. However, this inaccuracy probably explains why the 0.9 and 1.8 MJ/m (23 and 46 kJ/in.) results in Fig. 3 appear to be in the wrong order. Similarly, the properties of weld V8 are not as poor as might be expected from the calculated heat
input of 21 MJ/m (530 kJ/in.).

The Influences of Welding Position and Weld Metal Crystallography

These two topics are strongly interrelated and thus are discussed together. Blake, Rowntree and Phelps observed that vertical welds tended to have the greatest longitudinal strength. Also, they noted that the grains were then oriented at about 45 deg to the longitudinal axis of the weld.

Their horizontal-vertical weld had its grains at about 45 deg to the transverse axis of the joint, while the downhand weld's grains were normal to both axes. To check the significance of this effect they made a thick downhand weld and cut tensiles in two orientations. Cutting a longitudinal tensile gave the normal tensile axis/grain orientation relationship for downhand welds, while cutting the second tensile on a 45 deg tilt gave the same orientation relationship as for a vertical weld. They did find the increased strength they had looked for, and they attributed this to the less favorable orientation for slip to occur in the ‘vertical’ weld.

Horii et al. found that the columnar growth of weld grains was “oblique” to the welding direction in vertical welds, which here too showed relatively high longitudinal strength. They also show the results of tests in a series of inclined horizontal welding positions.

Although the main weld was by submerged arc, the reverse side was shielded metal arc welded, and the paper appears to show transverse tensile test results on this weld metal. The strengths quoted are 706 MPa (102,400 psi) at 70 deg inclination to the vertical (almost fully overhead) and 754 MPa (109,400 psi) at 30 deg inclination (approaching horizontal-vertical). Their result at 50 deg inclination was 761 MPa (110,400 psi), but the heat input was lower (1.1 MJ/m or 27.5 kJ/in. compared with 1.3 MJ/m or 32.5 kJ/in. for the other two). Thus, if it is assumed that downhand and overhead welds will have a similar structure, then the closer one approaches to horizontal-vertical the higher the strength becomes (as was found in the present study).

Figure 7 shows the longitudinal yield or proof stress and the UTS plotted against the appropriate transverse value for all of the welds tested in both directions. The UTS graph shows that vertical values tend to be higher longitudinally, and the same is generally true of yield stresses. The main exceptions are at high heat input (heat input rises from V3 to V6, and V8 was made at 21 MJ/m, i.e., 530 kJ/in.), but high preheat weld V2 is also an exception, probably for the same reason. The downhand welds and the horizontal-vertical weld tend to have a higher transverse strength.

To illustrate the relationship between microstructures and pole data, Figure 8 compares \{200\} and \{111\} pole data for the five welds investigated with their normal sections, both longitudinal and transverse to the welding direction. Because each of the pole datum was built up in four quadrants, measured on different weld sections and because those all showed strong symmetry longitudinally and/or transversely, the appropriate pairs of quadrants have been averaged to give a slightly simpler picture. Shaded areas have more than the average density of poles, while black areas have more than three times the average density.

Comparison of the sections with the pole data shows that the \{200\} pole cluster, or fibre axis, is along the growth direction. Where the fibre axis lies in a plane which is normal to the welding plane but longitudinal or transverse to the welding direction, the growth pattern is clearly visible on the appropriate section (e.g., the growth structure of a downhand weld is seen in both longitudinal and transverse sections, but that of a vertical weld in longitudinal section only). These results are, in fact, similar to those obtained by Baikie et al. on weld pads of Type 316 stainless steel (which, like this material, has a face centered cubic crystal structure). However, no tensile property studies were carried out in their work.

The tensile properties of ductile materials are governed by the resolved shear stress on the slip plane in the slip direction. Because of this, any polycrystalline metal with a strong crystallographic texture (one in which all of the grains are similarly oriented) will...
be anisotropic. This means that the yield stress in particular will depend on the testing direction. The pole figures and sections from the welds considered here show that the welds have a strong texture. So it is reasonable to expect some difference between the longitudinal and transverse properties.

Fig. 8—Microstructures and pole figures for different welding positions (×40 microstructures reduced 59% on reproduction)
The symmetry about the fibre axis means that, to a first approximation, the slip direction can be ignored and plastic property predictions can be made in terms of the slip plane distribution. Thus, since \{111\} is the main slip plane, the \{111\} pole data can be used to estimate the direction in which each weld will be strongest. The resolved shear stress on a slip plane is greatest when that plane is at 45 deg to the stress axis. So, for easy slip and thus a low yield strength, it is necessary to have a high density of \{111\} planes about 45 deg from the tensile axis. Conversely, when few \{111\} planes lie at 45 deg to the tensile axis, a much higher applied stress is necessary to achieve general yielding.

Figure 8 shows that the downhand welds have their fibre axes at about 90 deg to both the longitudinal and transverse testing directions. Thus, a similar proof stress can be expected in both directions, as is the case (see Tables 3 and 5). The horizontal-vertical weld has its fibre axis tilted transverse to the welding direction. This has not affected the slip plane shear stress in longitudinal tests. However, for transverse tests, the slip planes are less favorably oriented so that the proof stress will be greater. The heat input vertical weld is affected in a similar fashion, except that here the fibre axis tilt is longitudinal. Consequently, the longitudinal strength is raised while the transverse strength is unaltered.

In the high heat input vertical weld the growth direction, and thus the fibre axis, is very close to the welding direction. This is such a large tilt that the slip planes are oriented for slip at a low tensile stress in longitudinal tests, much lower in fact than for the transverse test.

At first sight, the conclusion to be drawn from this work is that all load-bearing joints should be welded in the horizontal-vertical position (although, if the inspection authority insists on all weld-metal longitudinal tensile tests, the advantage lies in welding vertically up). In practice, most of the shielded metal arc welding on cylindrical land-based storage tanks is carried out vertically up. The horizontal-vertical welds, which are often welded automatically, do not use their full strength since these are normally low pressure tanks. As such the main stress is the hoop stress, which loads the vertical seams.

The solution must lie in modifications to procedure which will take advantage of the crystallographic factors. Clearly, one possible solution is the use of a K preparation for vertical welds. A suitably designed welding procedure would ensure that the fibre axis is tilted away from the stress axis normal. A work program, which will test this hypothesis has been started; the results will be reported in due course, and initial results are promising.

Conclusions

1. Carbon is the element most effective in raising the strength of this type of nickel-base weld metal, but it has a deleterious effect on ductility.
2. A high interpass temperature, small heat sink or high heat input will slow the weld metal cooling rate and lead to lower strength levels.
3. A heavily restrained weld will have a higher proof stress.
4. Downhand, horizontal-vertical and vertical-up welds can exhibit different strengths when tested in different directions. With conventional welding procedures, the mean solidification direction tends to give vertical-up welds the greatest longitudinal strength, while horizontal-vertical welds have the greatest transverse strength. Changes in joint design or welding sequence may be used to increase joint strength.

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WRC Bulletin 238  
June 1978  

Plastic Stability of Pipes and Tees Exposed to External Couples  
by J. Schroeder and P. Tugcu  

Experimental results on plastic deformation of four pipes exposed to pure bending and of sixteen tee-intersections of pipes exposed to out-of-plane couples at the branch are given. The test data indicate that both pipes and tees buckle plastically under these loading conditions and that in case of tees exposed to out-of-plane couples the carrying capacity is determined by plastic buckling and not by plastic limit loads for certain geometries.  

Publication of this bulletin was sponsored by the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 238 is $7.50 per copy. Orders should be sent with payment to the Welding Research Council, 345 East 47th St., New York, NY 10017.  

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WRC Bulletin 236  
April 1978  

Determination of Stiffness and Loading in Bolted Joints Having Circular Geometry  
by G. R. Sharp  

A synthesized technique to aid in predicting the overall dynamic or static response of a bolted connection to externally applied dynamic or static tractions is presented. The technique is a synthesis of an existing method for determining stiffness coefficients in a bolted connection together with concepts and analysis techniques presented in this document. The information presented is considered a “first step” in the development of an analytical technique for predicting the overall stiffness of a bolted connection.  

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PVRC/MPC Task Group on Fracture Toughness Properties for Nuclear Components—Final Report  

This publication, dated October 1977, was sponsored jointly by the Metal Properties Council, Inc. and the Welding Research Council.  
The four reports in this 292-page monograph summarize several years work on the analysis and application of fracture mechanics performed under the jurisdiction of the Task Group. The titles of the reports are:  
1. PVRC-MPC Proposed Initial Program on Fracture Toughness Properties of Nuclear Components Material—Report to USAEC.  
The price of the monograph is $25 per copy. Discount prices: 5 to 20 copies, 20% discount; 20 to 50 copies, 33 1/3% discount; over 50 copies, 50% discount. Orders should be sent with payment to the Welding Research Council, United Engineering Center, 345 East 47th St., New York, NY 10017.