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SUBJECT: Pressure Vessel Fabrication Using T-1 Steel

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A number of pressure vessels have already been successfully constructed using T-1 (see Table I) material. The design of such pressure vessels, and the use of T-1 steel in their construction, in addition to the material's properties have been treated by L. P. Zick¹, L. C. Bibber², and W. D. Doty³. To date, no trouble has been encountered with T-1 steel, although some trouble has cropped up during welding, in the form of transverse cracking of weldments made in the field under conditions of high restraint and unfavorable weather. It has been established that, with the proper use of available low-hydrogen electrodes, (see Table II) sound welds in T-1 can be obtained.

Welding Problems

The fabrication of two 110 ft. 6 in. diameter welded Hortonspheres in Tokyo of 0.73 in. thick T-1 gives a good example of the difficulties to be encountered in welding the material. The resolution of these difficulties has resulted in a suitable welding procedure for T-1 steel.

The building of the spheres proceeded by ground assembly of large sections, which were then erected with welded closing joints. All welding was done with a-c machines using E12016 nickel, molybdenum, vanadium electrodes, and an ASME qualified procedure. The electrodes were stored in a drying oven at 300 to 400°F, and welding was done without preheat and an interpass temperature of 75°F.

Rather widespread transverse cracking was encountered in the circumferential closing welds, which were made under conditions of high restraint. These cracks were felt to be extensions of microfissures which always had their origin, and were normally contained, in the heat-affected zone resulting in the underlying weld metal when a weld bead was placed on top of another weld bead.

Solution of Welding Problems

An experimental program carried out by U. S. Steel determined the causes of, and the cure for, the cracking discussed above. The proper welding procedure is thus based on the results of this experimental program.

It was found that crack-free welds could consistently be produced with an E12015 electrode, whose coating contained only 0.03% moisture, substantially less than the 0.20% normally found in other electrodes. When the 0.20% moisture content of E12016 electrodes was reduced to 0.10% by baking at 850°F for 4 hr, cracking was greatly lessened, but not completely eliminated. The procedure which was found to produce consistently sound

TABLE I

CHEMICAL REQUIREMENTS

	<u>Per Cent</u>
Carbon	0.10/0.20
Manganese	0.60/1.00
Phosphorus, max	0.035
Sulfur, max	0.040
Silicon	0.15/0.35
Nickel	0.70/1.00
Chromium	0.40/0.80
Molybdenum	0.40/0.60
Vanadium	0.03/0.10
Copper	0.15/0.50
Boron	0.002/0.006

TABLE II

ELECTRODE CLASSIFICATION

AWS-ASTM Classification Number	Type of Covering	Usable Welding Positions ^a	Type of Current
E120 Series. Minimum Tensile Strength of Deposited Metal in Stress-Relieved Condition 120,000 psi.			
E12015	Low hydrogen sodium	F, V, OH, H	dc, reverse polarity (electrode positive) only
E12016	Low hydrogen potassium	F, V, OH, H	ac or dc, reverse polarity (electrode positive)

^a The abbreviations F, H, V, OH and H-Fillets indicate welding positions as follows:

F = Flat
H = Horizontal
H-Fillets = Horizontal Fillets

V = Vertical
OH = Overhead

} For electrodes 3/16 in. and under except in classifications EXX15 and EXX16, 5/32 in. and under.

welds with E12016 electrodes was to use rebaked electrodes with a preheat and interpass temperature greater than 150°F.

The rebaking of electrodes must be done with caution. For low-hydrogen electrodes, containing most of the alloys in the coatings, the tensile strength of the deposited weld metal from the rebaked electrodes could be greatly altered by the temperature and time bake cycle. A recommended bake cycle is 500°F for 24 hr, and in no case should baking exceed 900°F for 1 hr.

Further Welding Considerations

T-1 steel is a quenched and tempered material, and thus, steps must be taken to see that the welding procedure does not impair the tensile and toughness properties of the steel.

If too high a preheat temperature is used, some portion of the heat-affected zone may be tempered sufficiently to lower its tensile strength. There is also the possibility that the impact strength of this zone might be impaired. Nippes and Sibley⁴, by using synthetically reproduced microstructures in T-1, have shown that some impairment of the notch toughness can occur from the effect of various peak temperatures and cooling rates. It is a good policy to use preheat only when required to prohibit weld metal cracking, and then to use it moderately.

It has been shown that rebaked electrodes will pick up 0.11% moisture in 30 min. when exposed to 75°F air at a relative humidity of 67%. Further, it was found that a 250°F preheat and interpass temperature was adequate to prevent cracking when using electrodes containing 0.35% moisture. Thus, preheating is a good insurance against microfissuring when there is a chance that the electrodes have picked up moisture from the atmosphere.

Based on the work of Vaughan and DeMorton⁵, it is felt that the hydrogen from the moisture in the electrode coating causes microfissuring. Since heat will rapidly drive off this hydrogen, the value of a preheat is readily seen. In addition, preheating may further serve to prevent microcracking by slowing down the quenching rate of the weld metal, making it more ductile, and at the same time, by lowering the residual welding stresses.

Finally, the ASME Code requires that any T-1 pressure vessels with wall thickness greater than 0.50 in. be stress relieved. This eliminates the use of most of the E12015-16 electrodes that contain vanadium. Stress relief apparently produces embrittlement in weld metal made with such electrodes.

In such a case, a suitable electrode is Ell016, with iron powder added, which deposits a weld metal containing approximately 1.75% Ni, 0.30% Cr, 1.40% Mn, 0.45% Mo, and 0.35% Si. Tests with this electrode showed that, when used rebaked and with a preheat of 250°F, satisfactory weldments in 1-1/2 in. thick plate could be obtained under conditions of high restraint.

Explosion-Bulge Tests

In order to evaluate further the performance of joints made with the Ell016 electrode, the Navy explosion-bulge test, as developed by Puzak and Pellini⁶, was used. Test plates were made under various welding conditions using 1.03-in. thick T-1 and Ell016 electrodes. All samples were in the as-welded condition. Testing was carried out at 30°F, 0°F and -50°F.

The samples showing the best performance were those made under high restraint with rebaked electrodes, and a preheat and interpass temperature of 250°F. In all of the plates a great amount of plastic yielding, as shown by reduction in plate thickness ranging from 8% to 22%, occurred prior to any failure.

Interpretations of ASME Boiler and Pressure Vessel Code

The following are excerpts from cases concerning T-1 steel used in welded pressure vessels. These excerpts seem to be particularly pertinent to the study at hand.

Case 1204:

- (1) The maximum thickness of shell and head plates shall be 2 in.
- (2) The maximum operating temperature shall not exceed 650°F.
- (4) The maximum allowable stress value for use in Table UCS-23 shall be 26,250 psi.
- (6) When the shell or head thickness exceeds 0.50 in., the finished vessel shall be stress-relieved as provided in Par. UCS-56 (c). The stress-relieving temperature shall be between 1000°F and 1100°F (at least 50°F below the minimum tempering temperature).

Cautionary Note: Filler metal, deposited by nickel-molybdenum-vanadium type of electrodes, can become embrittled at the above stress-relieving temperature.

- (a) The qualification of the welding procedure and the welders shall conform to the requirements of Section IX, except

that the radius of the mandrel used in the guided bend tests may be 1-1/2 in. instead of 3/4 in. A separate welding procedure shall be made for this material.

Case 1204-1:

- (12) Structural attachments of other steels shall not be welded directly to shells or heads of material specified in the Inquiry.

Case 1204-2:

- (11) All parts shall be made of the material specified in the Inquiry, except that pipe flanges or pipe of carbon steel may be welded to nozzle necks of the material specified in the Inquiry provided the butt weld is located more than a distance equal to the square root of $r \times t$ measured from the face of the reinforcement, where r = the inside radius of the nozzle neck and t = the thickness of the nozzle neck at the surface of the vessel or reinforcing plate if one is used. The design of the nozzle neck shall be made on the basis of the allowable stress value of the weaker material.

Case 1204-3:

- (1) The minimum thickness of shells, heads, and other pressure-containing parts shall be 1/4 in. The maximum thickness of the shell and head plates shall be 2 in.
- (9) The qualification of the welding procedure and the welders shall conform to the requirements of Section IX, except that the radius of the mandrel used in the guided bend tests shall be as follows:

<u>Thickness of Specimen</u>	<u>Radius of Mandrel</u>	<u>Radius of Die</u>
3/8 in.	1-1/4 in.	1-11/16 in.
t	3-1/3 t	4-1/3 t + 1/16 in.

A separate welding procedure shall be made for this material.

- (19) Welds for pads, lifting lugs, and other nonpressure parts, as well as temporary lugs for alignment, shall be made in full

compliance with a welding procedure qualified in accordance with Section IX. Temporary welds shall be removed, the area shall be inspected for damage, and the metal surface shall be restored to a smooth contour. If repair welding is required, it shall be qualified in accordance with Item (16) of the Reply.

Impact Properties

The impact transition temperature, as determined with Charpy keyhole specimens is 62°F for hot rolled T-1 plate, -140°F for quenched plate, and -243°F for quenched and tempered plate. Thus, T-1 steel in the as-received condition will have extremely good impact properties.

However, there are a few factors which might be expected to affect the toughness of the material. These include straining, strain ageing and radiation dosage. Doty³ has shown that a 10% strain (cold reduction) will raise the transition temperature on the order of 20 to 30°F. Straining 10% and artificially ageing for 1 hr at 550°F raised the NDT on the order of 40 to 60°F, while straining 10% and stress relieving for 1 hr at 1100°F lowered the NDT on the order of 5-20°F. Thus, T-1 appears to be relatively insensitive to straining and strain ageing.

R. G. Berggren and J. C. Wilson,⁷ of the Oak Ridge National Laboratory Solid States Division, report on the behavior of T-1 after irradiation by neutrons of greater than 1 mev. energy. The impact specimens were subsize (0.2 in. sq.), Izod-type, with a V-notch, 0.060 in. deep and having an included angle of 45°, and a root radius of 0.005 in. Notch to striker distance was 7/8 in. The change in tensile properties under irradiation was also investigated.

The unirradiated material was found to have a transition temperature of around -200°F. After a neutron dose of 5×10^{18} nvt at 575°F, the transition temperature rose to about -75°F. A dose of 5×10^{18} nvt at less than 200°F brought the NDT to the neighborhood of 0°F, while a dose of 7×10^{19} nvt raised the NDT to 175°F. In addition, irradiation served to lower the fracture energy of the ductile part of the curve from 50 in.-lb. to 25 in.-lb. in the most severe case.

A neutron dose of 1.7×10^{19} nvt raised the yield strength of T-1 from 120,000 psi to 170,000 psi, the tensile strength from 129,000 psi to 171,000 psi, and lowered the elongation from 14% to 4.5% in 8 dia of an 0.180 in. dia specimen. Irradiation of 1×10^{20} nvt further changed the respective

properties to 186,000 psi, 187,200 psi, and 3.8%.

As an interesting sidelight, Berggren and Wilson's investigation includes tests on a weld made in carbon-silicon steel plate with a low-hydrogen E7016 electrode. It was found that the impact properties of both the deposited weld and the heat-affected zone were superior to the base plate before irradiation. Although large changes in properties did take place upon irradiation, the impact characteristics of the weld metal remained better than those of either the base plate or the heat-affected zone at the highest neutron doses.

Fatigue Properties

Doty³ has reported the results of numerous fatigue tests of T-1 steel, both on the base material and on welds. The welds and base material were tested both as rotating beam specimens and in pulsating-tension. In pulsating-tension, the base material showed an endurance limit of from 45,000 to 50,000 psi, while the endurance limit for the welded material ranged from 21,000 to 37,000 psi, depending on welding procedure. For the rotating beam specimens, the endurance limit of the base material ranged from 36,000 to 45,000 psi, while that of the welded material ran from 14,000 to 28,000 psi, depending on welding procedure.

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