# Property Evaluation of Electroslag Remelted A533B Plate

*Tests on ESR plate material show significant improvements in ductility-dependent properties and a marked reduction in directional variation*

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ABSTRACT. Increasing demands upon material performance have promoted the trend toward higher purity steels for pressure vessel use. Technical factors responsible for this trend include concern about the effects of impurities on notch toughness and recognition of the role of inclusions on the anisotropy of mechanical properties. These factors assume additional significance in weldments where toughness degradation of the HAZ or lamellar tearing at mid thickness may be encountered. That the higher level of cleanliness and homogeneity necessary to minimize such problems is obtained by electroslag remelting is indicated by this evaluation of A533B plate steel. Data generated include tensile, Charpy, compact tension, fatigue, and creep-rupture tests.

## Introduction

Steel of the 1½% Mn-½% Mo type in plate form has been broadly used in the pressure vessel industry for decades. Various improvements and modifications have been made through the years to keep pace with the advanced properties and fabricating characteristics demanded. Today, the basic composition in the normalized condition is detailed by ASTM Specification A302B and by ASTM A533A in the quenched and tempered condition. In situations where an additional measure of toughness and hardenability is indicated, an addition of ½% nickel is made. These nickel-containing versions are described by ASTM A302C (normalized) and ASTM A533B (quenched and tempered).

For critical applications, even further enhancement of properties is sought. When such requirements relate to the basic ductility and isotropy of the steel, a higher level of cleanliness, soundness, and homogeneity is the logical route to their satisfaction. While various refining techniques can effect the necessary improvements, the electroslag remelting process provides additional advantages in terms of favorable economics, size availability, and rectangular section capability.

Electroslag remelting of steels is basically a large scale adaptation of the electroslag welding process. The features of this modification for large rectangular remelts (Lukens Lectrefine Process) are shown in Fig. 1. The current availability of product plate to 12 in. thickness and 36,000 lb is indicative of the size of the facility. As in electroslag welding, oxygen and sulfur are reduced significantly. In contrast with other refining techniques, contamination from refractories and oxidation during pouring are avoided. Additionally, the progressive solidification promotes soundness, chemical uniformity, and wide dispersion of the few inclusions remaining.

Extensive quality assessments of the product have confirmed the achievement of the noted benefits. These evaluations included macroetch tests, ultrasonic testing to stringent standards, magnetic particle tests, and metallographic investigations. Consequently, superior ductility-related mechanical properties of reduced anisotropy were anticipated. While much of the data presented here is on base metal properties, the implications for improved weldments is clear. The importance of the Mn-Mo family of steels warranted its selection for initial determination of property levels.

## Material Description

The steel used in this program came from a 100 ton vacuum degassed electric furnace heat that was produced to the chemical requirements of ASTM A302C and A533B. One ingot of this heat was electroslag remelted (Fig. 1) and processed by standard procedures to a single 6 in. gage by 88 in. wide by 102 in. long plate weighing approximately 15,000 lb. The plate was austenitized at 1650 F (¾ h/in. of thickness), dip quenched in agitated water, tempered at 1280 F (¾ h/in. of thickness), and air cooled. To simulate the extensive stress relief that a heavy plate might encounter during fabrication, test sections were held at 1150 F for 40 h followed by air cooling.

## Quality Assessment

Initial assessment of plate quality was made by longitudinal wave ultrasonic testing of 100 % of the plate surface with a 25 % overlap. A 1⅛ in. diameter crystal at 2-¼ Mc was used in conjunction with a reference block made from the same plate and containing 5/64 in. flat bottomed holes

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at depths of ¼, ½, and ¾ gage. Using. 50 % of the response of the reference block to the 5/64 in. holes as a criterion, no reportable indications were observed.

Further evaluations of quality were confined to critically located test sections, specifically at the mid-width of both top and bottom of the plate (melt). Both longitudinal and transverse macroetch tests (50% HCl, 30 min, 160 F) showed no evidence of inclusions, segregation, or other deficiencies, Fig. 2. Metallographic investigation disclosed a uniform bainitic structure, minimal alloy banding, negligible microporosity at mid-gage only, and an ASTM grain size of 7 (Fig. 3). To quantify the cleanliness of the material, quarter gage J-K ratings were made in accordance with ASTM E-45 using Plate III which is intended for vacuum processed materials. The results (Table I) which define the worst area of each type of inclusion are noteworthy and comparable to those of vacuum arc remelted steel. Additionally, other procedures which take both number and size of inclusions into account demonstrate additional benefits from electroslag remelting.

## Chemical Analysis

The chemical analysis of the plate that was evaluated is given in Table 2. Noteworthy features of the analysis are the top-to-bottom uniformity and the low sulfur; both of which are characteristic of electroslag remelts. The small predictable amount of oxidizable elements removed by the remelting is normally offset by selection of an appropriate electrode analysis. An ideal electrode composition was not available for this early remelt and thus the final silicon analysis approached the lower end of the specification.

## Tensile and Creep Tests

The various series of tensile tests conducted in the course of this evaluation are combined in Table 3. The first series, conducted to check mill treatment, demonstrates conformance to the requirements of ASTM A533B, near-equivalence of longitudinal and transverse results, and a high level of ductility.

The second series of tests are conducted after the 40 h stress relief at 1150 F. It includes surface and quarter gage locations in longitudinal and transverse directions, plus mid gage location in all three principal directions. Comparison of quarter gage tests indicates little effect from the stress relief treatment. The minor reduction in strength at center gage is not unexpected in this grade. The uniformity of center gage properties in all three directions, combined with excellent ductility should be important in weldments where complex stress systems are operative. This is particularly critical where lamellar tearing is a potential problem.

The third series of tests span the temperature ranges of -315 to 950 F. These were performed as prerequisites for fracture toughness and creep property determinations. No unusual results were obtained. Strength and ductility varied with temperature in the normal fashion.

Creep tests were performed on material from the quarterline of the plate and were oriented parallel to the rolling direction. Figures 4 to 6 contain the rupture, creep rate and rupture ductility data. Also included in the curves are data for an electric furnace (EF) Heat (1) with comparable strength, although slightly lower, at both room temperature and elevated temperatures.

The rupture data in Fig. 4 shows an apparently better strength for the ESR (Electroslag Remelt) material than for the EF material. This can be explained by the slight strength advantage of the ESR steel. Although the advantage amounts to less than 10 % at all temperatures, it could be sufficient to explain the apparent better rupture strength for ESR A533B.

The creep rate data in Fig. 5 show a similar trend. At both 850 and 950 F, the ESR material has the superior creep resistance. Most noteworthy in the data is the discontinuity in creep rate vs stress in both curves for the 950 F tests. This indicates that the cause for the apparent metallurgical instability responsible for the discontinuity is not removed by the additional step of electroslag remelting. The inflection in the 850 F curve for ESR material may be indicative of a metallurgical instability, but this is unlikely because both the 850 F EF curve and 900 F curve show no inflections. Usually such instabilities occur at temperatures where changes in precipitate composition occur. Therefore, it is not likely that the ESR 850 F curve is representative, but rather it may be the result of experimental scatter.

The higher strength of the ESR processed A533B is reflected in the rupture ductility. The reduction in area as a function of rupture time is shown in Fig. 6. The ESR material has a slightly lower rupture ductility than does the EF material. Differences of this magnitude are easily explained by differences in strength: the higher the strength, the lower the rupture ductility (Ref. 2).

## Toughness Tests

Base metal and heat-affected zone Charpy V-notch impact tests were performed on this plate. The base metal tests consisted of material in

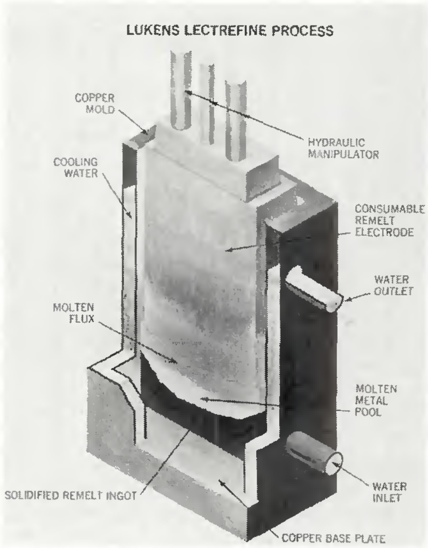


*Fig. 1 — Schematic electroslag remelting furnace*

**Table 1 — Inclusion Count — JK Ratings for Vacuum Processed Steel ASTM E45 Plate III**

| | $A_T$ | $A_H$ | $B_T$ | $B_H$ | $C_T$ | $C_H$ | $D_T$ | $D_H$ |
|---|---|---|---|---|---|---|---|---|
| Top mid width of plate | .1 | 0 | .3 | .3 | 0 | 0 | 1.3 | 1.5 |
| Bottom mid width of plate | .5 | 0 | 1 | .3 | 0 | 0 | 1.5 | 1.5 |

**Table 2 — Check Chemistry [a]**

| | C | Mn | Si | P | S | Ni | Mo |
|---|---|---|---|---|---|---|---|
| Top mid width of plate | .25 | 1.47 | .13 | .013 | .005 | .52 | .59 |
| Bottom mid width of plate | .24 | 1.46 | .14 | .011 | .004 | .52 | .59 |
| ASTM A533B check range | .25 max | 1.10/ 1.55 | .13/ .32 | .035 max | .040 max | .37/ .73 | .41/ .64 |

(a) % by weight. C and S by combustion method. All others by vacuum spectrograph.

both the mill treated and stress relieved conditions. Locations and directions of test specimens correspond to tensile tests previously reported. The HAZ tests were performed on through-gage specimens with the notch ½ in. below the fusion line of a submerged arc weld deposited with 78 kJ/in. and parallel to the final rolling direction (Ref. 3). In addition, drop weight NDT tests were performed on stress relieved base metal.

The results of the impact tests are contained in Table 4. All tests are characterized by high upper-shelf energies. This is characteristic of steels with low sulfur levels. The tests performed on the stress relieved plate material includes through-gage tests. These data compare favorably with the transverse and longitudinal data. An apparent improvement in through-gage impact properties is realized during welding. The HAZ data indicate that the through-gage impact properties are comparable to center line transverse or longitudinal.

The NDT data in Table 4 show results that would be expected based upon CVN data. In addition to NDT, the energy absorption and laterial expansion at NDT + 60 F is shown. According to the Summer 1972 Addenda to Section III of the ASME Boiler Code (Ref. 4), a steel must have at least 50 ft-lb and 35 mils lateral expansion at NDT + 60 F. This heat surpasses that requirement easily.

Another evaluation of toughness is the $K_{Ic}$ This is more critical than the Charpy test, and is also more useful. $K_{Ic}$ is a material property that depends upon heat treatment, test temperature, and fracture orientation. It does not depend upon section size since it measures the energy required to propagate a unit elastic crack. However, in order to meet the requirements for a valid $K_{Ic}$, the various criteria outlined in ASTM E399-72 (Ref. 5) must be satisfied.

Compact tension tests were performed on 2 in. thick specimens removed from the quarter line of the plate. The orientation was T-L. Test temperatures ranged from -200 F to -50 F. Using the criteria contained in E399-72, no valid $K_{Ic}$ values were obtained as shown in Table 5. The tests failed the validity tests because either $K_f$, the maximum fatigue precracking stress concentration, was too high or the plastic zone size at the tip of the crack was too large.

According to a study reported by McCabe (Ref. 6), no deleterious effects of $K_f$ on $K_{IQ}$ were observed when $K_f$ was 0.77 $K_Q$. The test at -100 F $K_Q$ of 50.8 ksi $\sqrt{\text{in.}}$ has $K_f$ equal to $0.7(\sigma_{YS_1}/\sigma_{YS_2})K_Q$ which is within the bounds described by McCabe. Therefore, if any $K_Q$ is near valid it would be this one. When

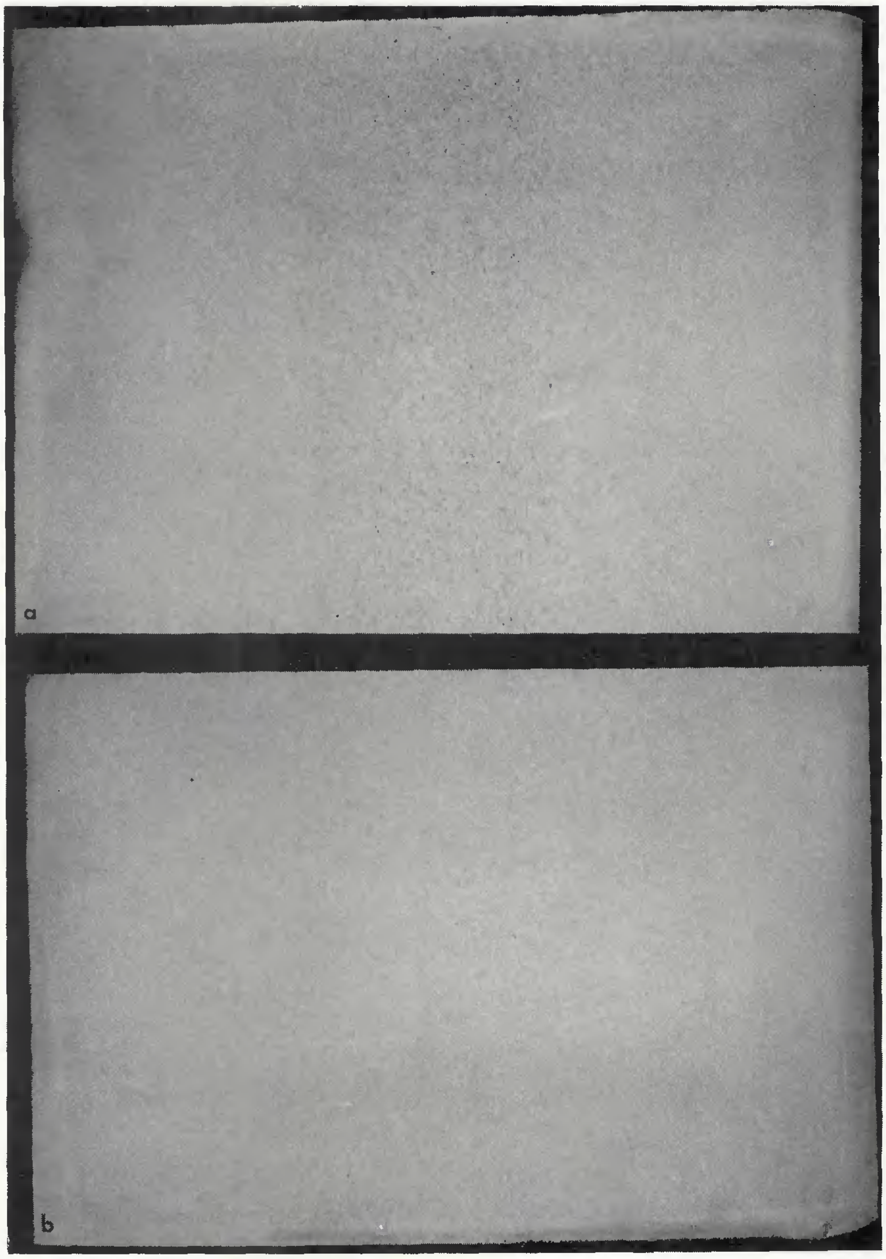

Fig. 2 — Macroetch of cross-sections through 6 in. gage Lectrefine A533B steel, (a) transverse, (b) longitudinal

compared to a $K_{Ic}$ of 40 ksi $\sqrt{\text{in.}}$ generated by the HSST program (Ref. 7), there is a 25 % increase in $K_{Ic}$ (Fig. 7).

The other values of $K_Q$ are not valid because the deviation from specification requirements are too great. At -200 F, $K_f$ is equal to $(\sigma_{YS_1}/\sigma_{YS_2})$ $K_Q$. The remaining tests have plastic zone sizes which are too great to allow for plane strain testing. As pointed out by McCabe (Ref. 6), when this particular

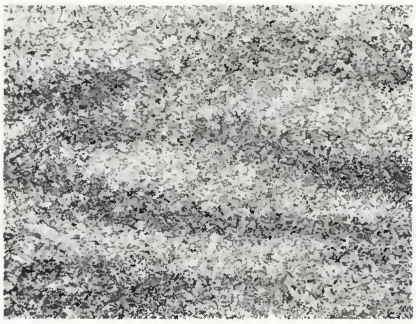

*Fig. 3 — General structure of A533B steel plate at the quarter line*

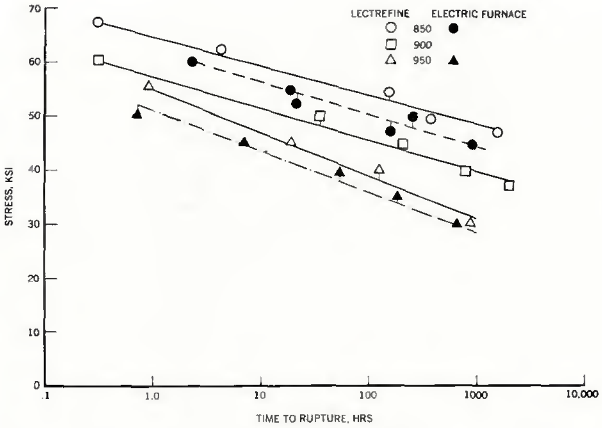


*Fig. 4 — Stress vs. time to rupture for electroslag remelted and electric furnace A533B steel plate (Ref. 1)*

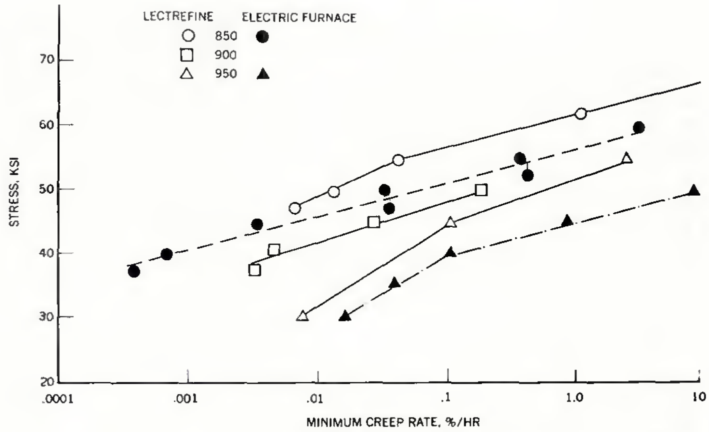


*Fig. 5 — Minimum creep rate data for electroslag remelted and electric furnace A533B steel plate (Ref. 1)*

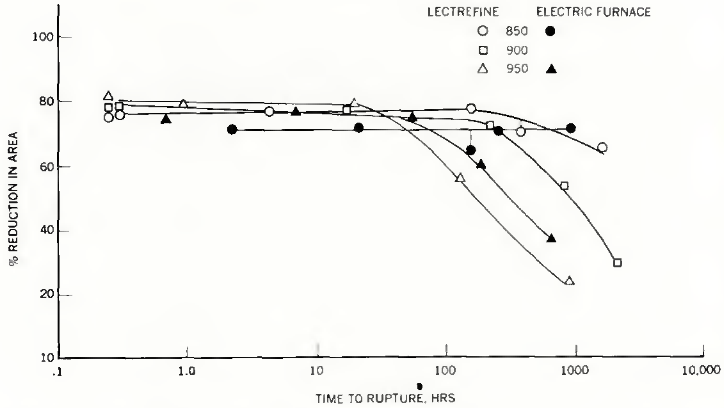


*Fig. 6 — Rupture ductility data for electroslag remelted and electric furnace A533B steel plate (Ref. 1)*

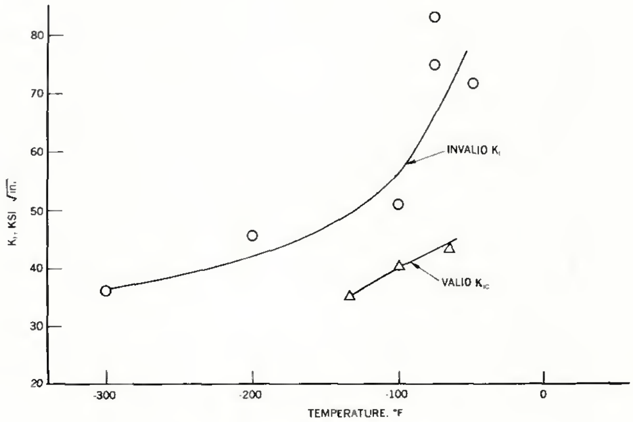


*Fig. 7 — Fracture toughness of electroslag remelted and electric furnace A533B steel plate. Valid $K_{Ic}$ data from Reference 7*

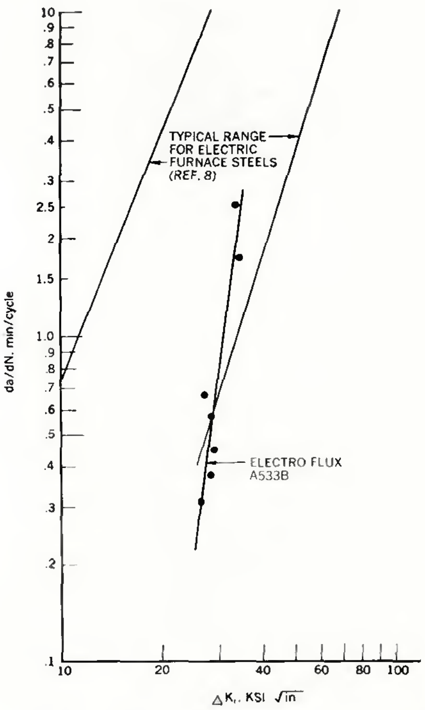


*Fig. 8 — Fatigue crack growth rate of electroslag remelted A533B and low strength low alloy steels (Ref. 8)*

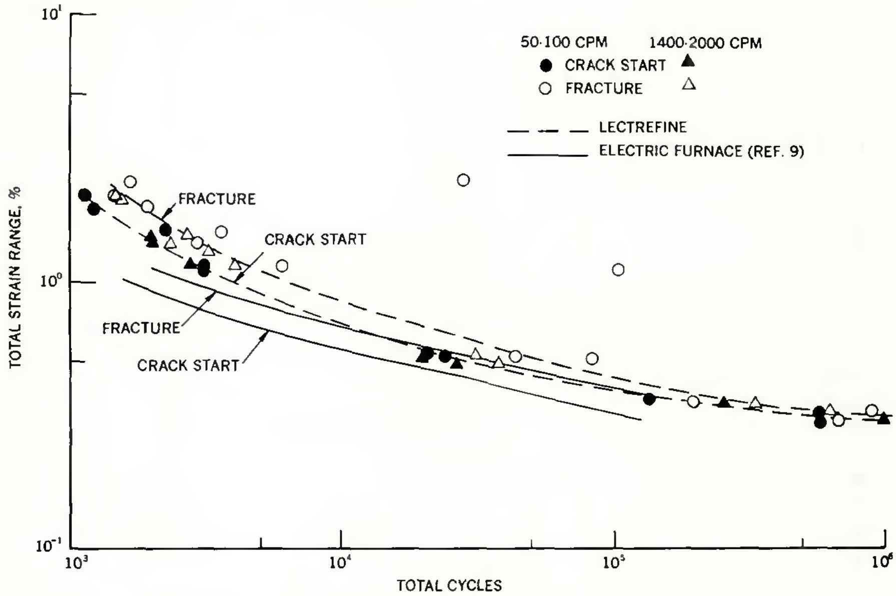


*Fig. 9 — Strain range vs. cycles to future for electroslag remelted and electric furnace A533B (Ref. 9)*

criterion is not satisfied [a, B > 2.5 $(K_Q/\sigma_{YS})^2$] the bias in $K_Q$ is toward higher values.

## Fatigue Tests

In general, there are two types of fatigue data in which designers and users are interested. These are the fatigue crack growth rate (da/dN) and the cycles to failure. The fatigue crack growth rate is generally measured in the elastic region and gives designers an idea of the number of cycles to which a highly restrained structural member can be subjected before a critical size crack forms. The number of cycles to failure, under either constant strain or constant load, is useful in determining the ultimate life of a structural member. Whereas, da/dN can be quantitatively used in design, the cycles to failure can be only qualitatively factored into design.

The fatigue crack growth rate was determined by measuring the growth during fatigue precracking of the compact tension specimens. The data are plotted in Fig. 8. Also included in the figure is a scatter band for electric furnace steels (Ref. 8). The general location of the ESR data with respect to the scatter band suggests a better fatigue resistance for the ESR steel than for EF steels.

Further evidence of this is shown in Fig. 9. These data are the cycles to initiate a 3/16 in. crack and to cause fracture in bending fatigue. Two ranges of cyclic rate were used: 50-100 cycles per minute and 1500-2000 cycles per minute. There is no apparent effect of rate on either the cycles to cause cracking or to cause fracture.

Data for EF A533B are also included for comparison (Ref. 9). At any particular strain range, the ESR steel has at least double the fatigue life for either cracking or failure. The advantage of ESR steel is more pronounced at high strain ranges where the fatigue life is approximately triple the fatigue life of EF steel.

## Conclusions

The minor effect of specimen orientation on the mechanical properties of ESR steels has been demonstrated on mid gage tensile and Charpy tests of 6 in. thick A533B plate. Tensile tests with longitudinal orientation exhibited 25.3% elongation (in 2 in.) compared to 25.0% for through-gage tests. Reduction of area values were similarly high and uniform at 68.9 and 61.6% respectively. Mid gage Charpy V-notch tests, both longitudinal and transverse, had a FATT of 45 F and an energy absorption at 10 F ($E_{10}$) of 70-75 ft-lb. The through-gage tests, sometimes referred to as short transverse, exhibited a FATT of 90 F and an $E_{10}$ of 45 ft-lb. This variation in Charpy toughness criteria is minimal in view of the sensitivity of the test. Charpy tests on welded plate indicated no toughness reduction in the heat-affected zone.

Another benefit obtained is the

Table 3 — Tensile Data for Electroslag Remelted A533B

| Temp. F | Location (a) | Orientation (b) | .2% YS, ksi | UTS, ksi | Red. in area, % | Elong. 1 in., % |
|---|---|---|---|---|---|---|
| | | | Mill heat treated material (d) | | | |
| 80 | Q | L | 65.3 | 89.1 | 72.1 | 27.0 (c) |
| 80 | Q | T | 63.9 | 88.9 | 73.0 | 26.8 (c) |
| | | | Stress relieved material (e) | | | |
| 80 | S | L | 69.4 | 91.3 | 72.6 | 27.5 (c) |
| 80 | S | T | 74.9 | 95.7 | 73.7 | 25.3 (c) |
| 80 | Q | L | 65.5 | 88.8 | 70.9 | 25.5 (c) |
| 80 | Q | T | 67.8 | 90.8 | 71.3 | 25.8 (c) |
| 80 | C | L | 65.7 | 88.9 | 68.9 | 25.3 (c) |
| 80 | C | T | 66.7 | 90.6 | 68.9 | 24.8 (c) |
| 80 | C | G | 65.0 | 89.2 | 61.6 | 25.0 (c) |
| -315 | Q | L | 143.0 | 149.3 | ND (f) | ND (f) |
| -225 | Q | L | 105.9 | 119.3 | 64.8 | 27.7 |
| -125 | Q | L | 82.6 | 106.9 | 69.2 | 27.6 |
| -50 | Q | L | 72.1 | 99.6 | 72.3 | 29.0 |
| 0 | Q | L | 70.1 | 96.9 | 72.1 | 26.5 |
| 700 | Q | L | 57.2 | 83.7 | 77.2 | 27.7 |
| 800 | Q | L | 57.7 | 76.2 | 77.9 | 25.1 |
| 850 | Q | L | 54.9 | 70.8 | 80.8 | 26.1 |
| 900 | Q | L | 54.2 | 66.9 | 83.0 | 26.0 |
| 950 | Q | L | 50.8 | 61.0 | 85.6 | 27.3 |

(a) S = surface; Q = quarterline; C = centerline
(b) L = longitudinal; T = transverse; G = through-gage
(c) 2 in. gage length
(d) 1650 F/4 h — water quench — 1280 F/4 h
(e) (d) plus 1150 F - 40 h
(f) ND = not determined

Table 4 — Charpy V-Notch Impact and Nil-Ductility Transistion Data for Electroslag Remelted A533B

| Location (a) | Orientation (b) | $E_{10}$ (c), ft-lb | $E_{US}$ (d), ft-lb | FATT (e) F | NDT (f) F | NDT + 60 F: E, ft-lb | NDT + 60 F: Lat. exp., mils |
|---|---|---|---|---|---|---|---|
| | | | Mill heat treated material (g) | | | | |
| Q | L | 90 | 150 | 25 | — | — | — |
| Q | T | 110 | 135 | 0 | — | — | — |
| | | | Stress relieved material (h) | | | | |
| S | L | 145 | 175 | -50 | — | — | — |
| S | T | 145 | 170 | -75 | -100 | 120 | 77 |
| Q | L | 85 | 160 | 50 | — | — | — |
| Q | T | 75 | 150 | 40 | -10 | 105 | 75 |
| C | L | 75 | 150 | 45 | — | — | — |
| C | T | 70 | 145 | 45 | -10 | 100 | 70 |
| C | G | 45 | 130 | 90 | — | — | — |
| | | | Heat-affected zone — Through-gage, notch ½ in. below weld surface, parallel to rolling direction (i) | | | | |
| | G | 75 | 150 | 20 | — | — | — |

(a) S = surface; Q = quarterline; C = centerline
(b) L = longitudinal; T = transverse; G = through-gage
(c) Energy absorbed at 10 F
(d) Upper-shelf energy
(e) Fracture appearance transition temperature
(f) Nil-ductility transition temperature
(g) 1650 F/4 h — water quench — 1280 F/4 h — air cool
(h) (g) plus 1150 F/40 h — air cool
(i) 1150 F/40 h — furnace cool to 600 F — air cool (Ref. 3)

elevation of the upper-shelf energy of Charpy tests as a result of the sulfur reduction by the refining action of the flux. The reduced amount of MnS thus formed is credited with this enhancement of impact properties in the ductile range. In the case of the 6 in. gage A533B plate, an upper-shelf energy of approximately 150 ft-lb was obtained with material heat treated to 90,000 psi tensile and 65,000 psi yield strength.

The improved toughness is also manifest in the results of compact tension tests. The extreme fatigue resistance and exceptional ductility have precluded obtaining a valid $K_{Ic}$ in a 2 in. thick specimen. In order to propagate a fatigue crack at room temperature, a $\Delta K_f$ of at least 26 ksi $\sqrt{\text{in.}}$ was required. Therefore, based upon $\Delta K_{f_1} < 0.6(\sigma_{YS_1}/\sigma_{YS_2})K_{Q_2}$ valid tests could not be performed at temperatures below -75 F. At -75 F and higher, the crack length criterion could not be met $(2.5(K_Q/\sigma_{YS})^2 > a, B)$.

Fatigue crack growth rate measurements show that ESR A533B is superior to EF quality steels of comparable strengths. The fatigue resistance in bending fatigue is approximately 2-3 times better than air melted electric furnace A533B. This also tends to verify the crack growth rate data.

Creep rupture tests were similar to those of air melted A533B. This is expected since electroslag remelting does not appreciably affect those factors which govern creep resistance and rupture strength.

Although the major portion of this investigation has been concentrated on plate material, experience has shown that a high quality plate will usually result in a high quality weld. Preliminary welding tests on this material have indicated this to be the trend. The initial data have shown improvements in weldability and provide confidence that more extensive welding studies will confirm the results thus far obtained.

Table 5 — Fracture Toughness Data for Electroslag Remelted A533B

| Temp, F | YS, ksi | $K_f$ ksi$\sqrt{\text{in.}}$ | $K_Q$, ksi$\sqrt{\text{in.}}$ | $.6\left(\frac{\sigma_{YS\ 1}}{\sigma_{YS\ 2}}\right)K_Q$ ksi$\sqrt{\text{in.}}$ | $2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2$, in. | B, in. | Reason for invalidity[a] |
|---|---|---|---|---|---|---|---|
| -300 | 100 | 30.9 | 45.5 | 18.1 | .518 | 1.999 | 1. |
| -100 | 79.0 | 36.0 | 85.2 | 42.8 | 2.910 | 2.000 | 2. |
| | | 30.3 | 50.8 | 25.4 | 1.04 | 1.984 | 1. |
| -75 | 74.9 | 36.5 | 91.8 | 48.7 | 3.75 | 1.974 | 2. |
| | | 31.3 | 75.1 | 39.8 | 2.51 | 1.998 | 2. |
| | | 28.9 | 83.5 | 44.3 | 3.10 | 1.994 | 2. |
| -50 | 72.1 | 29.8 | 71.4 | 39.3 | 2.45 | 1.980 | 2. |

(a) 1. $K_f > 0.6(\sigma_{YS_1}/\sigma_{YS_2})K_Q$
2. $B < 2.5(K_Q/\sigma_{YS})^2$

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