CAPTAIN S. R. HELLER, JR., USN, IVO FIORITI, and JOHN VASTA

AN EVALUATION OF HY-80 STEEL AS A STRUCTURAL MATERIAL FOR SUBMARINES

PART II

Editor's Note: Part I of this paper was published in the February 1965 issue of THE JOURNAL. *Biography of the author will be found on page 29 of that issue.*

FABRICATION

THE DISCUSSION of pre-fabrication exploration in Part I was concerned with difficulties which were forecast on the basis of past experience with welding new materials and on the metallurgical structure of the material itself. Also covered was "near-laboratory" experience in preparing specimens for evaluation of material-electrode combinations and qualification of welding processes. It is time now to turn from theory and laboratory to actual shipyard experience.

Early Experience

For several years after the end of World War II, the Bureau of Ships was engaged in a research program for the development of a high yield strength steel which program has been mentioned earlier. One of the several materials under investigation, that previously referred to as *low-carbon Special Treatment Steel,* stood out above all others as the possessor of the best combination of all desirable properties. This "low-carbon STS" was used by the Norfolk Naval Shipyard in the fabrication of several medium-sized ship-type structures for testing by the Shipyard's Underwater Explosion Research Division. The results of this testing were extremely encouraging. At about the same time, the University of California, under contract with the Ship Structure Committee as part of its research program for solution of the brittle-fracture problem, used it in tests of the highly restrained welds associated with hatch corner reinforcements. In these torturous tests, the low-carbon STS showed ductile behavior at failure and much greater energy absorption at fracture than the other quenched and tempered steels tested. Thus, the steel had performed excellently in small-size laboratory specimens and in large-size shipyard specimens; fabrication under these conditions had presented no great problems. Now was the time to work it into a ship.

At the outbreak of the Korean Incident two significant ships were in the preliminary design stage in the Bureau of Ships. One of these became the experimental submarine USS *Albacore* (AGSS569); the other, the lead ship of a new class of aircraft carriers, USS *Forrestal* (CVA59). Both were to have low-carbon STS used in important structural features.

Low-carbon STS was specified for the pressure hull plating of *Albacore* but with framing of HTS. At first glance this combination may appear strange. Actually it was a continuation of earlier practice in surface ship protection systems which practice had been evolved because of the non-availability of shapes rolled or extruded of STS. The plating was purchased by the Navy Purchasing Office, Washington under Contract N600s-S-11751 of 22 February 1951 to the chemical composition shown in Table VII. In addition, yield strength was specified to be between 80,000 and 95,000 psi at 0.2 per cent offset with a minimum elongation of 20 per cent in a 2-inch gage length. Furthermore, Charpy Keyhole impact energy, for thicknesses between ½ inch to 1¼ inches inclusive, was required to be 40 foot-pounds at −40°F. Similar Charpy impact energies of 25 foot-pounds for plates thinner than ½ inch and of 40 foot-pounds for plates thicker than 1¼ inches were expected but not required.

Portsmouth Naval Shipyard fabricated the *Albacore* hull during 1951-1952 using electrodes conforming to Military Specification MIL-E-986, Grade 260, of 1 November 1949 for all butt welds in the hull plating and the semi-automatic metal inert gas (MIG) welding process with AirCo A650 wire for the attachment of the HTS frames. At this time the specification for the Grade 260 electrodes required a minimum Charpy Keyhole impact energy of 23 foot-pounds at 0°F and a minimum yield strength of 110,000 psi for the weld metal in the *as-deposited* condition. There were no specific requirements for chemical composition or for inspection tests for acceptance. Moisture content of the electrode coatings was, however, required not to exceed 0.2 per cent.

In Fall, 1953, Portsmouth Naval Shipyard reported the results of *Albacore* construction. No problems worthy of mention were encountered in rolling the pressure hull plating to shape. Although the initial flatness was not as good as for HTS, rolling to shape eliminated the irregularities. Using normal quality control in welding; i.e., careful conformance to specified preheat and interpass temperatures, normal back-chipping of butt welds to sound metal magnetic particle inspection of root pass and final pass, and X-ray inspection of completed butt welds, the combination of HY-80* plate and Grade 260 electrodes proved to be very weldable. Not only did Portsmouth report that there were fewer repairs of butt and seam welds required than in any of the last three submarines built at the shipyard, but that *there were no occurrences of structural cracking of welds or plate material during the entire construction.*

On 12 June 1952, HY-80 steel (formerly called low-carbon STS) was approved for use in the side protection system in *Forrestal.* Plating was purchased using Military Specification MIL-S-16216A of 13 August 1952 to the chemical composition shown in Table VIII. It will be noted that the chemical composition limits in Table VIII are essentially the *same* as in Table VII except that the standard tolerances of the American Iron and Steel Institute for check analysis have been added. The mechanical properties specified were also the same as for the low-carbon STS in *Albacore.*

As for *Albacore,* electrodes conforming to Military Specification MIL-E-986, Grade 260, of 1 November 1949 were used for all butt welds in HY-80 plating. Attachments to plating, including stiffeners, were welded with electrodes conforming to Military Specification MIL-E-16715, type MIL-31015(16); this is the electrode commonly called "25/20" and formerly identified as Grade IV of Navy Specification 46E4 of 15 October 1944.

Although Newport News Shipbuilding and Drydock Company, the builders of *Forrestal,* did not submit a formal report on fabrication and weldability of HY-80, information available within the Bureau of Ships and from the Supervisor of Shipbuilding indicates that there were no problems encountered. It has been specifically noted that the plates procured for *Forrestal* were well within flatness tolerances.

The next use of HY-80—and the last prior to widespread adoption for submarine construction—was for the plating and framing of the missile hangars in USS *Growler* (SSG577) being built at Portsmouth Naval Shipyard. *Growler* had been started as an attack submarine and was converted during construction to a guided missile submarine. HY-80 steel was used in this ship for weight-saving. Plating was purchased using Military Specification MIL-S-16216B of 20 May 1953 which required the chemical composition shown in Table VIII.

All welding—butts and attachments—was accomplished using electrodes conforming to Military Specification MIL-E-18038, type MIL-10015(16), of 9 July 1954. Chemical composition, minimum Charpy Keyhole impact energy of 23 foot-pounds at 0°F, and a minimum yield strength of 90,000 psi were specified for the weld metal in the *as-deposited* condition. Moisture content of the electrode coatings was required not to exceed 0.2 per cent. The specification, however, did not require lot inspections or weld tests for verification of the specification requirements.

---

* The name "HY-80" was given to low-carbon STS on 15 August 1951 when Military Specification MIL-S-16216 was issued.

TABLE VII

Chemical Composition (Per Cent) for Pressure Hull Plating of USS ALBACORE (AGSS569)

Thickness (Inches)	C (Max.)	Mn	P (Max.)	S (Max.)	Si	Ni	Cr	Mo
Up to 1¼	0.20	0.15-0.35	0.035	0.040	0.15-0.35	2.00-2.50	0.90-1.40	0.15-0.25
Over 1¼	0.20	0.15-0.35	0.035	0.040	0.15-0.35	2.75-3.25	1.35-1.84	0.40-0.60

TABLE VIII

Chemical Composition (Per Cent) for HY-80 Steel Used in USS FORRESTALL (CVA59)

Thickness (Inches)	C (Max.)	Mn	P (Max.)	S (Max.)	Si	Ni	Cr	Mo
Up to 1¼	0.22	0.10-0.40	0.04	0.045	0.12-0.38	1.93-2.57	0.84-1.46	0.13-0.27
Over 1¼	0.23	0.10-0.40	0.04	0.045	0.12-0.38	2.68-3.32	1.29-1.91	0.37-0.63

Normal quality control was used; no cracking problem was noted. The only incidence of cracking observed was in the connection of the light hangar plating to the heavy reinforcement rings where the difference in thickness was in the ratio of 3:1. When adequate preheat and quality control were applied to this connection of plates of greatly different thicknesses, cracking disappeared.

Based on the impressive characteristics of HY-80 steel as revealed by extensive tests and the encouraging results of pilot usage in the field, the U. S. Navy approved HY-80 as the basic structural material for future submarine construction. USS *Skipjack* (SS(N)585), the contract design of which was completed on 11 June 1956, became the first *combatant* submarine with structure subjected to submergence pressure specified at the outset to be of HY-80 steel.

Production Experience with Submarines

Construction of *Skipjack* was begun with use of MIL-260 and MIL-10015(16) electrodes permitted for welding HY-80 steel just as had been permitted in the construction of *Albacore* and *Growler*. The general construction practices—fit-up, welding controls, inspection, and the like—employed were essentially the same as had been used successfully for the earlier nuclear submarines—*Nautilus, Seawolf,* and *Skate*—which had HTS hulls of about the same scantlings. No appreciable welding problems were encountered. Indeed, the earlier experience with *Albacore, Growler,* and *Forrestal* was being repeated. Construction continued apace.

In the spring of 1958, MIL-11018 electrodes, whose superiority in notch toughness over earlier electrodes had been demonstrated, was authorized for use in submarines subsequent to *Skipjack* after existing stock was exhausted. At about the same time, although in a *totally unrelated* manner, extensive cracking was discovered in the HY-80 structure of *another* submarine. Consequently, reinspection of *Skipjack's* structure was initiated. Because of the advanced state of outfitting and the consequent difficulty and prohibitive expense involved in making a *complete* reinspection, *Skipjack* was subjected to a limited reexamination. Very few defects were discovered and those were minor. *Skipjack* was considered structurally sound. Nevertheless, inquiry into the difficulties encountered on the *other* submarine was begun.

During the early stages of this inquiry, cracks were found in the connections of frame webs to shell. When this problem was probed further, it was discovered that cracking persisted in the repair welds. In a few cases as many as six cycles of welding and inspection were required before successful repair was achieved. Furthermore, welds previously inspected and found satisfactory were, on reinspection as much as three weeks later, found to have severe cracks. Sleuthing pointed to reheating to make a weld in the vicinity as the culprit. Still later, boundaries of "hard" tanks were reexamined and found to have cracks although previous inspections, some as much as four months earlier, had resulted in acceptance. These defects were attributed to high restraint. All the forecastable difficulties were belatedly appearing.

The inquiry was broadened to include *all* submarine building yards and the cognizant Supervisors of Shipbuilding. As might have been expected, each "expert" interviewed espoused a different factor as contributing to the problem and each proposed a different remedy. The consensus was, however, that compliance with BUSHIPS Notice 9110 of 2 July 1958 would be a big step toward eliminating the problem. The guidance contained in this BUSHIPS Notice 9110 included controls for

a. Preparation, storage, and issue of electrodes
b. Preheat and interpass temperature

c. Heat input
d. Welding sequence

In addition, from all the contributing factors cited and the remedies proposed during the inquiry came the realization of the need for

1. Protection from the weather
2. Avoiding highly restrained construction
3. Standardization of inspection procedures and records
4. Better training and qualification of welders and inspectors.

In summary, all concerned with submarine construction became convinced of the *necessity for close control* of the entire fabrication process.

Satisfied that the indoctrination afforded by the promulgation of the aforementioned BUSHIPS Notice 9110 and the lessons of the broad inquiry into fabrication practices were significant steps toward the solution of the cracking problem but not a panacea, the Bureau of Ships continued its efforts. The total fabrication process was attacked on a broad front. As described in earlier sections of this paper, base material specifications were improved and made more definitive, and electrode development was intensified. Non-destructive inspection techniques were improved and standardized; inspectors were carefully trained in their conduct and interpretation. Extruded and rolled shapes, castings, and forgings of HY-80 steel were produced, qualified, and authorized for use. Construction details were redesigned to avoid high restraint and stress concentrations. Finally, all these improvements were combined with the required controls into a single document, NAVSHIPS 250-637-3 of November 1960, which became the gospel for fabrication, welding, and inspection of HY-80 steel in submarine construction. Later revisions to this publication have removed ambiguity, closed loopholes, improved clarity, and incorporated results of research and development.

The effectiveness of this concerted effort is graphically presented in Figure 10 where the decline in the incidence of weld defects is related to time. The significant events—issue of BUSHIPS Notice 9110 in July 1958, the inquiry into construction practices in 1958-9, and the publication of NAVSHIPS 250-637-3 in November 1960—have been indicated in Figure 10. The most encouraging finding shown in Figure 10 is that the incidence of weld defects at *every* submarine building yard declined and this continued even when heavier scantlings were incorporated in later classes. The most annoying finding shown in Figure 10 is that a structure entirely free from flaws has not yet been achieved. Clearly this was never really expected although it was devoutly to be desired. Certainly the very low incidence of weld flaws at the present time is ample evidence that submarine construction can be and is "under control." Equally obvious is that careful attention to details, vigorous inspection, and constant vigilance are required. The seriousness of the few defects that defy detection must be determined. It is with this facet—the resistance to fracture in the presence of a flaw—that the next section is concerned.

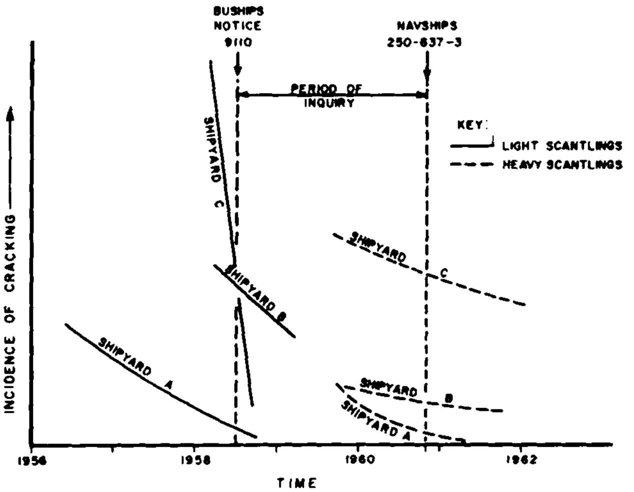


Figure 10. Incidence of Weld Defects Discovered During Submarine Construction.

RESISTANCE TO FRACTURE

Despite vigorous inspection during construction, there are always a few defects that defy detection. Submarines, however, are subject to cyclic loading because of depth excursions and may be subject to dynamic loading by enemy attack. The effect of these varying loads in the presence of these defects must now be explored.

Low-Cycle Fatigue

Since the fatigue performance of highly stressed details constructed of HY-80 steel was imperfectly understood, the Bureau of Ships undertook a comprehensive test program to obtain the needed data. Extensive experimental data have now been obtained from a variety of laboratory-type specimens, both plain and welded, as well as from testing nearly full-scale submarine structures incorporating structural details considered prone to develop early fatigue cracks. By building such large complex structures, it has been possible to represent the important variables associated with fabrication of welded HY-80 submarine pressure hulls under typical shipyard practice. Thus, size effects, welding procedure, restraint, residual stress, and such other elusive factors as random distribution of defects and flaws were contained in the large structures.

Just as for any other structural material subjected to repetitive loading, HY-80 steel will first develop a fatigue crack at a point of geometrical discontinuity where the stress intensity is highest. This fatigue crack will then characteristically grow with each loading cycle, and the rate of crack growth follows a consistent pattern. Because of its high notch

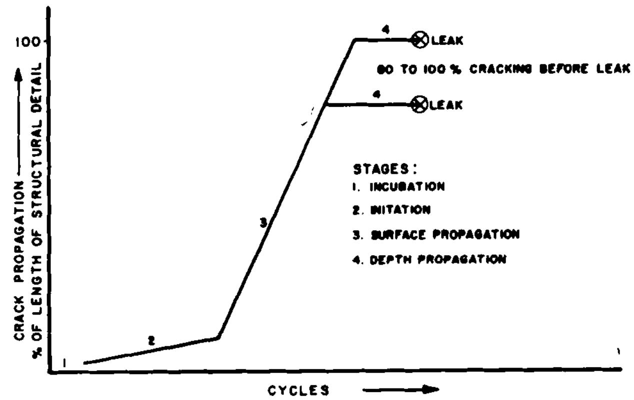


Figure 11. Schematic Representation of Fatigue Crack Growth.

toughness, HY-80 steel does not permit rapidly propagating brittle or low energy shear type fracture. Contrary to the behavior of some high strength steels currently being investigated for pressure vessel application, HY-80 steel, in the presence of fatigue cracks, has never exhibited any catastrophic failure tendencies.

The typical fatigue crack growth pattern for a highly stressed structural detail in the nearly full-scale HY-80 submarine test structures [15] is shown schematically in Figure 11. The pattern is composed of four stages:

1. *Incubation*—the crack is microscopic and defies detection.
2. *Initiation*—the crack is macroscopic and can be detected, but growth rate is very slow.
3. *Surface Propagation*—the crack grows in length at a faster rate.
4. *Depth Propagation*—after the crack has primarily propogated on the surface, it progresses through the plate to failure (a leak).

Of particular importance is that the structure has experienced extensive surface cracking (almost completely along the detail) prior to through cracking—and yet NO catastrophic fracture propagation has ensued. Indeed, through cracking (a leak) is of very short length.

Dynamic Loading

The foregoing has been concerned with propagation of cracks solely by cyclic loading. Also of concern is the performance of these fatigue-induced cracks under dynamic loads. To determine these characteristics a series of explosion bulge tests was conducted on flat plate specimens, each of which was 1½ inches thick and contained a central butt weld [16]. The specimens were loaded in bending to an approximate stress of 50,000 psi, with the number of cycles ranging up to 100,000—well beyond the expected number of depth excursions an actual submarine would experience. The specimens loaded up to 50,000 cycles had no discernible cracks (incubation stage); the specimens loaded up to 75,000 cycles had short cracks at the toe of the weld (initiation stage); the specimens loaded to 100,000 cycles had longer cracks at the toe of the weld (surface propagation stage). The overall effect of fatigue cracking is a decrease in the number of *succeeding* explosive shots that may be applied before the cumulative damage (length and depth of crack) causes failure. Nevertheless, once a crack developed, whether caused by fatigue or prior explosive loading, there was no discernible difference in resistance to explosion. In other words, the material is not sensitive to the cause of the crack, only to the existence of a crack.

A summary of test results [16] is given in Table IX. It is significant to note the depth of bulge and reduction in thickness *concurrent* with the progressive growth of the initial fatigue cracks under successive explosive loadings. This performance is a good example of the excellent toughness of HY-80 steel. Of even greater significance is that, for Specimen 5, *three* explosive shots were required to extend the several initial fatigue cracks, ⅛ inch long, to 12 inches and *even then* there was NO catastrophic fracture propagation.

Although much was learned from the explosion bulge tests with the welded flat plate specimens, the behavior of more complex structures was desired. Accordingly, a test program was devised to determine the performance of typical stiffened cylinders subjected to underwater explosion. Relatively large-

TABLE IX

Summary of Explosion Bulge Tests of Butt-Welded Plates Loaded Cyclically

Specimen No.	No. of Cycles	No. of Shots	Bulge Depth (in.)	Reduction in Thickness (%)	Crack Length (in.)	
					Initial	Final
1	0	7	4.75	16.0	0	2
2	12,500	5	5.9	17.6	0	½-1
3	25,000	4	5.3	15.3	0	4
4	50,000	5	6.6	24.0	0	plate separated
5	75,000	3	6.0	10.3	many ⅛	12
6	100,000	3	5.4	14.4	many up to 5	plate separated

NOTE: Specimen No. 1 was 2 inches thick; all others were 1½ inches thick.

scale models were constructed to assure realistic structures typical of shipbuilding practice. Three models were built:

Model 1—of HTS to represent a post World War II design

Model 2—of HY-80 steel with the *same strength* (same operating depth) as Model 1

Model 3—of HY-80 steel with the *same weight* (greater operating depth) as Model 1

Such a series would show not only individual performance of the models, but also *comparative* performance of the two materials.

All three models were loaded dynamically by detonating explosive charges placed alongside the models underwater at distances such that the test structures would be subjected to shock waves similar to those which an actual submarine might experience from enemy attack. Since the models had external "T"-frames welded to the shell, the most critically loaded details were the welds attaching these frames to the shell.

The performance of the two HY-80 models was most revealing. The first shot against Model 2 (same strength as Model 1) initiated several small cracks at the toes of the welds connecting the frames to the shell and some permanent deformation inward. The second shot of the same intensity caused a very slight propagation of these cracks into the shell plating and the permanent deformation inward to increase substantially. Thus, the structure had successfully withstood two explosion attacks of high intensity and was still watertight. Cracks had propagated only very slightly even in the presence of severe deformation. Indeed, the performance was very similar to the cyclically-loaded flat plate specimens which were subjected to explosion bulge tests described earlier. Similar tests but of greater severity were conducted against Model 3 with essentially identical results; very slight propagation of cracks into the shell plating and slightly further around the girth; substantial increase in permanent deformation inward.

In comparison to the performance of the HY-80 models, that of the HTS model (Model 1) was poor. The first shot against Model 1, although of the same severity as for Model 2 (same strength) but of less severity than for Model 3 (same weight), caused several brittle fractures of considerable extent in the framing system; see Figure 12. Model 1 can, for all practical purposes, be considered to have failed on the first shot. Clearly it would be expected to withstand neither another explosive shot nor any appreciable hydrostatic load.

Comparison of HTS and HY-80

For a specific operating depth requirement, an HTS submarine hull would require thicker shell plating and more massive frames than its HY-80 counterpart because of the difference in yield strengths. Not only would the HTS structure be heavier, but it would also suffer from some significant deficiencies in material properties. Because of the greater thicknesses, a decrease in toughness would be expected and welding difficulties would increase with attendant structural degradation. The combination of greater thicknesses and more massive welds could be expected to produce a greater number of defects that go undetected, higher residual stresses, and greater restraint all of which tend toward reducing fatigue life. Moreover, thicker HTS plates and heavier rolled sections, by the very nature of the chemistry and manufacturing process of HTS, contain relatively large bands of segregation. Furthermore, even the best grade of HTS has notch toughness properties, at the temperature of interest, that are inferior to those of HY-80 of similar thickness. When these material imperfections and inferior properties have construction and fatigue cracks superimposed, all the necessary ingredients are present for a structure having high susceptibility to brittle fracture propagation.

The thoughtful analyst may properly observe: Your reasoning is impeccable and your conclusions appear sound, but have you *actual* proof? The answer, of course, has been given earlier. Figure 2 is ample evidence that the notch toughness of HTS is inferior to that of HY-80. Figures 8 and 9, the comparative explosion bulge tests of the two materials, bolster this finding. The overriding factor, however, is the comparative performance under explosive loading. The dramatic failure of the HTS model (Model 1) shown in Figure 12 is proof positive that brittle fracture propagation in HTS not only can occur, but has been demonstrated. The predicted superiority of HY-80 over HTS where resistance to fracture is concerned has been confirmed.

COMPARATIVE COSTS (HY-80 vs. HTS)

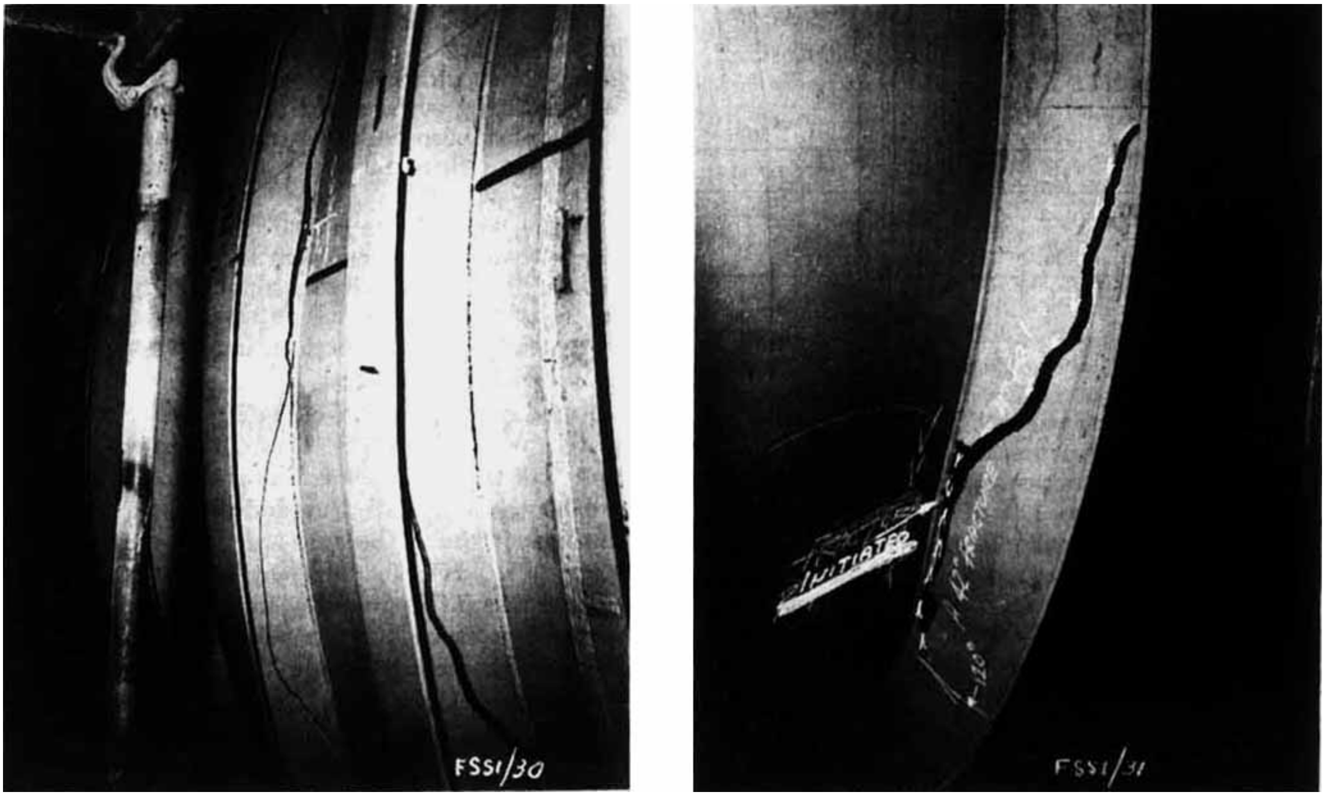
In the evaluation of any structural material, cost is a very important consideration. It not only determines the impact on the pocket book in terms of expense per unit; but it can also affect the total quantity procured. In times of essentially level annual budgets, the cost of submarine hull structure can determine the number to be built each year. The cost of a material may be appraised in two ways:

1. Material cost only
2. Total fabricated cost

Both will be explored.

Material Cost Only

Because HTS was in general use for submarine hull construction when HY-80 steel was initially developed, the comparison of the two materials is inevitable. Table X is such a comparison. Table X is based on the costs of plates 2 inches thick by 10 feet long by 8 feet wide loaded at the steel mill for shipment. As can be seen, HY-80 plate costs slightly more than twice HTS plate.



A—Overall View **B—Close-up View**

Figure 12. Underwater Explosion Test Results of HTS Structural Model.

TABLE X

Comparative Costs of HTS and HY-80 Steel Plate

Item	Cost ($/lb.) Hy-80	Cost ($/lb.) HTS
Base Price	0.1000	0.0555
Specification Price	0.1360	0.0340
Thickness Extra	0.0265	—
Width & Thickness Extra	—	0.0050
Length Extra	—	0.0005
Normalizing & Flattening	—	0.0125
Ultrasonic Inspection & Gaging	0.0120	0.0090
Cleaning (2 side)*	0.0040	—
Painting (2 side)*	0.0050	—
Pickling & Painting (2 side)*	—	0.0119
Gas Cutting Extra	—	0.0028
Ultrasonic Scanning Extra	—	0.0031
Total	0.2835	0.1343

---

* These operations have been subcontracted by the steel mills and prices tend to vary. Those given are typical.

NOTES:

1. Prices are F.O.B. at the steel mill.
2. Prices reflect the purchase of plate in quantity of a size 2" x 96" x 120".
3. Prices as of September 1964.

Total Fabricated Cost

Costs of submarine constructions vary with the shipbuilder. There are many factors that determine cost. The more significant include:

1. Type of facilities and equipment
2. Quality of personnel
3. Geographical location (weather, freight charges, wage scale)
4. Type of ownership (private or government)
5. Workload and schedule.
6. Whether or not the ship is first of a class

It is beyond the scope of this paper to analyze at length all these factors. Rather, only a gross, "ball park" comparison is necessary. The effects of the first three factors seem self-evident. The fourth factor has been studied in depth in recent times and, hence, will not be explored here further. The fifth factor involves such aspects as the number of kind of ships being built. If the ships are all of the same kind, special jigs and fixtures can become economically desirable and the same force can be used repetitively on similar jobs. On the other hand, if the workload is mixed, these economies cannot be realized. The effect of the sixth factor can be examined qualitatively also. When a submarine is first of a class, the design changes necessarily involve increased costs. This is not only true where the hull material is changed simultaneously with initiating a new class, but is also equally true for a new class using the same material. Ships subsequent to the first of a class, follow ships, are understandably cheaper since they reflect learning and experience.

An additional complication in comparing the cost of HY-80 construction with that of HTS is the

TABLE XI

Approximate Comparative Fabricated Costs of HY-80 and HTS Submarine Pressure Hulls

Ship	Total Fabricated Cost ($/lb.)	
	HY-80 (1964)	HTS (1955)
First of Class	3.50	2.00
Subsequent	2.50	1.50

difference in time. By "difference in time" is meant "what year" were the materials introduced. Significant changes in submarine design have been made since HTS was first used. With the passage of time came improved inspection methods and the demand for more stringent inspections. Also came increased costs due to inflation.

Data have been gathered from all shipyards involved in submarine construction. These have been analyzed and synthesized "ball park" approximations are presented in Table XI. The data presented in Table XI are given as costs per pound of pressure hull for nuclear submarines only; include material, labor, and overhead; and reflect HY-80 costs as of 1964 and HTS costs of 1955. The last factor may seem unfair because of inflation. Offsetting inflation in the case of HY-80 are simplification of design details and increased use of automatic welding. From Table XI it is seen that, for the first ship of a class, HY-80 construction costs about 1¾ times that of HTS whereas, for subsequent ships, HY-80 cost has dropped to about 1⅔ times that of HTS.

Cost per unit weight of material does not, however, give the total picture. Because of its higher yield strength, less HY-80 steel than HTS is required for a submarine of the same basic military characteristics: operating depth, speed, endurance, ordnance, electronics, and the like. Indeed, several comparative designs have been prepared all of which show that the pressure hull weights are essentially inversely proportional to yield strengths. Thus, for submarine hulls with the *same military characteristics*, those built of HTS will require about 70 per cent more material than those built of HY-80 steel. When this factor is considered in conjunction with the comparative costs per unit weight, the comparative costs of submarine hulls with the *same military characteristics* are about the *same*. If HY-80 steel were used, the first ship of a class would cost slightly more than for HTS whereas subsequent ships would cost slightly less.

CONCLUSIONS

From the foregoing discussion of the development of HY-80 base material and electrodes suitable for its welding, it has been clearly shown that HY-80 steel weldments do, in fact, satisfy the three primary requirements for a submarine structural material: strength-weight ratio, toughness, and resistance to fracture. The evidence validates this in the absolute sense, but is *overwhelming* when HY-80 steel is compared with its predecessor, HTS. Indeed, the substantiating evidence for the acceptability of HY-80 steel has been collected from much more extensive testing than for any previous structural material.

At the present time HY-80 steel is available in all forms—plate, rolled and extruded shapes, castings, and forgings—required for shipbuilding. To be sure this was not true at the outset when only plates were available, but American industry has successfully met the challenge.

In today's market HY-80 base material costs a bit more than twice HTS. Total fabricated cost per unit weight of HY-80 is from 65 to 75 per cent greater than for HTS. But, and this is an extremely important "but," because of the greater yield strength of HY-80, sufficient weight-saving over comparable HTS structure can be made, so that the costs of pressure hull for submarines of the same military characteristics are the same.

Although HY-80 steel is readily formed and can be satisfactorily welded in normal shipyard environment, its martensitic structure, the product of its chemical composition and heat treatment, demands careful control of the total welding process. This control and the consequence of its lack were forecast prior to the adoption of HY-80—and came to pass. The difficulties that arose because of failure to control stringently the total welding process have now been overcome and a rigorous control procedure imposed. So long as the required controls are followed, no further difficulties are anticipated.

In summary, HY-80 steel has an excellent strength-weight ratio, is tougher and more resistant to fracture than any other structural steel now available, is available in all forms required for shipbuilding, costs no more than its predecessor, HTS, for the same military characteristics, and, because of its greater yield strength, makes possible improved military characteristics. Its lone disadvantage is the rigorous control required for successful fabrication, but all complex structures, regardless of the materials used, require this.

On balance, HY-80 steel is clearly the *best* structural material now available for submarines.

REFERENCES

[15] Dunham, F. W., "Fatigue Testing of Large-Scale Models of Submarine Structural Details," SNAME New England Section, Oct., 1964.

[16] U. S. Naval Applied Science Laboratory Tech. Memo 7, Lab Proj. 9300-1, "Effects of Fatigue on the Explosion Bulge Properties of HY-80 Butt Weldments," 6 Jan. 1964.