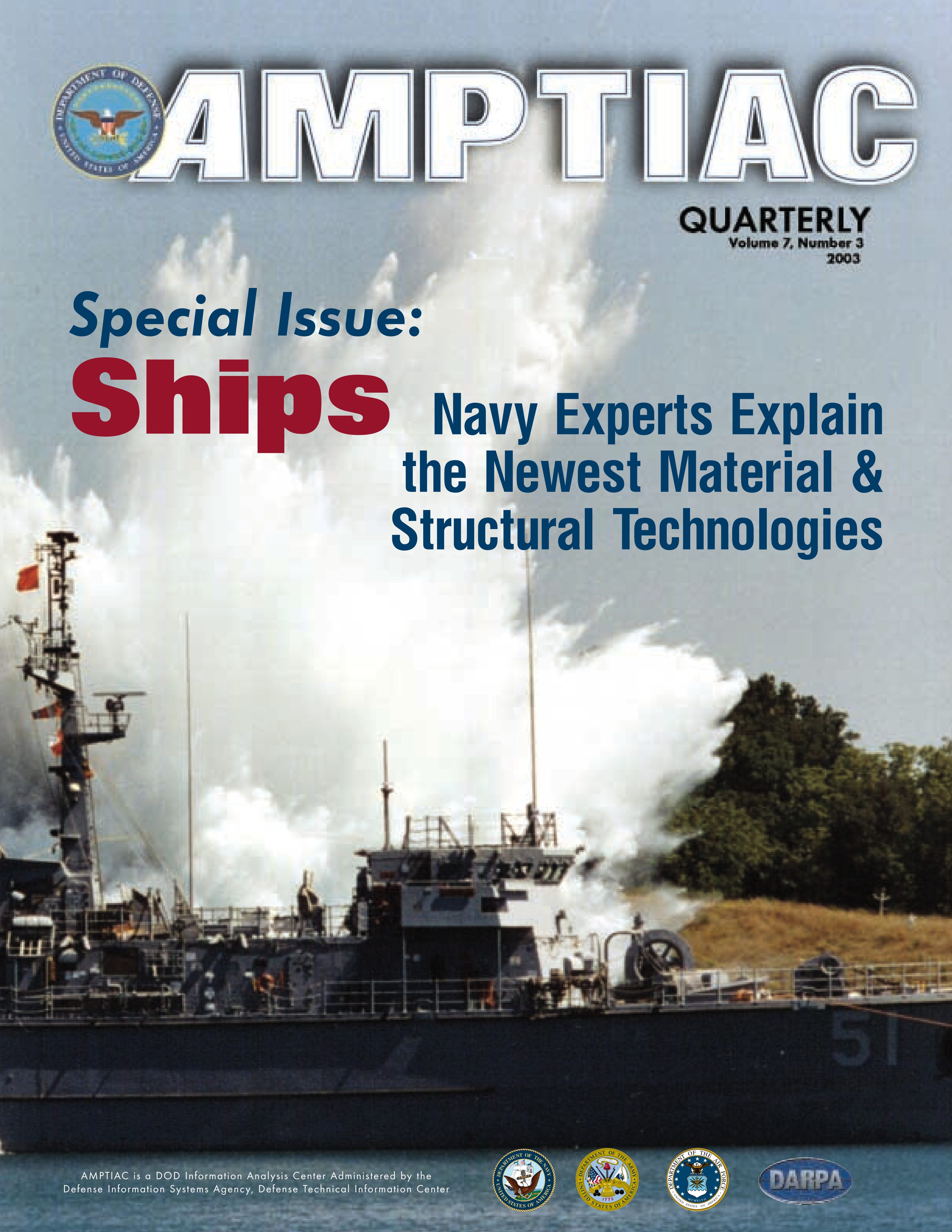

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Special Issue:
Ships

Navy Experts Explain the Newest Material & Structural Technologies

AMPTIAC is a DOD Information Analysis Center Administered by the Defense Information Systems Agency, Defense Technical Information Center

Editorial: There's More to AMPTIAC than the *Quarterly*

The issue you hold in your hands has been 14 months in the making. It began with a simple idea: turn the spotlight on the age-old art of building ships. We wanted to show the exciting new technologies that are offering novel materials for ship construction, changing the way ships are built, and indeed creating one of the most fundamental shifts in Navy combatants since steel replaced wood.

This simple mission turned out to be much more complex. The project underwent a number of different iterations, but finally settled in and came together. It has been a labor of love for yours truly, for I really do believe that even though airplanes and tanks often grab the spotlight, Navy ships are still the most challenging structural and materials engineering systems fielded in today's military. Nothing has the complexity, impact, size, and sheer force of a fighting vessel, nor can many things capture the imagination in quite the same way.

So here it is, finally, and I am thankful that it is done. Not just because it is off my desk and I can get on to the next project, but we are proud because AMPTIAC has compiled something that probably has not existed before: an overview of the newest technologies being incorporated into structures and materials for use aboard Navy combatants. And the people providing the perspective are the experts at the Office of Naval Research, NSWC-Carderock, and the Naval Research Lab. You won't find this level of detail, variety, and expert content focused on this subject anywhere else.

That all being said, there is one critical feature of this publication that needs some attention: the DOD center behind it. Some of you out there have been reading this publication for seven years now. You undoubtedly remember about two years ago when we shifted over to our current layout format and full color reproduction. You also have probably noticed that we are publishing these large special issues fairly often. It is all a part of our mission to bring you the most in-depth, focused, and technologically exciting coverage of Defense materials and processing advances available anywhere.

But the side effect of the more noticeable and attention-grabbing Quarterly, is that AMPTIAC itself has lost some attention. The reality is that the center has grown with numerous projects, focused reports, and database efforts over the past few years, but there are many out there that may read this publication and not even know that the center exists.

We want to put more emphasis on the other efforts AMPTIAC is involved in, and let our customers and potential customers know that we are here for you. We help with questions, assist in materials selection, and provide consultation on a variety of materials and processing-related issues. We have more than 210,000 DOD technical reports in our library and direct access to hundreds of thousands more throughout DOD, DOE, NASA, and other US Government agencies. We have dozens of focused reports tailored to specific technology areas and many more compiling vast amounts of data into handbook-style resources.

The basic message here is to take note of this magazine, read it, and enjoy. But if you think AMPTIAC is just the Quarterly, Think Again.

Wade Babcock
Editor-in-Chief

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Inquiries about AMPTIAC capabilities, products and services may be addressed to

David H. Rose
Director, AMPTIAC
315-339-7023
EMAIL: amptiac@alionscience.com
URL: http://amptiac.alionscience.com

We welcome your input! To submit your related articles, photos, notices, or ideas for future issues, please contact:

AMPTIAC
ATTN: WADE G. BABCOCK
201 Mill Street
Rome, New York 13440

PHONE: 315.339.7008
FAX: 315.339.7107
EMAIL: amptiac_news@alionscience.com

Meeting the Challenge of Higher Strength, Lighter Warships

Ernest J. Czyryca, David P. Kihl, and Robert DeNale
Survivability, Structures, and Materials Directorate
Carderock Division, Naval Surface Warfare Center
West Bethesda, MD

INTRODUCTION

Modern warships, surface combatants and submarines, require high strength steel plate in increasing portions of the hull structure for weight reduction, better stability, increased payload, increased mobility, and survivability. Nearly 50% of the total Department of Defense requirement for alloy and armor steel plate is used in naval shipbuilding. In service, naval ship structures are subjected to a complex spectrum of loads and environments, and the structural steels and welding materials used in hull fabrication must demonstrate high fracture toughness for these extreme conditions. The routine dynamic loads in service include wave loading, sea slap, slamming, vibration, thermal excursions in both tropical and arctic seas, cargo buoyancy, aircraft/helo landing, and weapons reactions. The structural integrity of the hull must be assured for continuous sea-keeping in these severe environments, as well as in response to the effects of hostile weapons. The fracture safety of Navy ships is addressed through the use of structural steels and welding materials for hull fabrication that demonstrate high fracture toughness and flaw tolerance for these extreme service conditions [1]. Thus, the key requirements for naval shipbuilding steels are not only strength, weldability, and toughness at low temperature under shock events (Figure 1), but are also driven by economics, in order to keep an affordable ship acquisition cost.

Figure 1. Naval Shipbuilding Steels Require High Strength, Weldability, and Toughness at Low Temperature Under Shock Loading.

The Groundwork: HSLA-80 & HSLA-100 Steels

In the early 1980's, steelmakers were producing grades of High-Strength, Low Alloy (HSLA) steel plate with improved weldability, low temperature toughness, and yield strengths of 60,000 to 80,000 psi. The Navy initiated a project to develop and certify HSLA steels that were weldable with reduced or no preheat, high strength, high toughness, and high quality weldments equivalent in performance to the High Yield (HY)-series steels (HY-80 and HY-100). The focus was weight reduction in CG 47- and DDG 51-class warships with an affordable hull fabrication cost.

The project demonstrated that a modified ASTM A 710, Grade A steel plate could meet the minimum yield strength requirement of 80,000 psi, have a high Charpy V-notch impact energy at low temperatures, and possess excellent weldability using the processes and practices for HY-80 without preheat. HSLA-80 steel, then, is an optimized version of ASTM A 710 steel and was certified for use in ship construction in 1984 after an extensive evaluation of plate properties, welding, and fabrication characteristics, including the construction and destructive test of structural models [2,3]. Cost savings from $2,000 to $3,000 per ton of fabricated structure have been estimated for using HSLA-80 in place of HY-80, where reduced material, labor, energy, and inspection costs are combined. Through 2001, approximately 40,000 tons of HSLA-80 have been used in US Navy combatant ship construction. (See Figure 2.)

Following the HSLA-80 project, an alloy development and qualification project commenced resulting in approval of HSLA-100 steel as a replacement for HY-100 to further reduce fabrication costs. HSLA-100 is also a very low carbon, copper-precipitation-strengthened steel, with higher alloy content than HSLA-80 [4]. The new steel was developed to match the strength and toughness of HY-100, and be weldable using the same consumables and processes of HY-100, without its preheat requirements. The program for the development of HSLA-100 consisted of three phases: (1) alloy design, where the composition of the steel was formulated through a progressive optimization using laboratory-scale heats; (2) trial plate production at a steel plate mill to an interim specification; and (3) plate production for the certification program in thickness from .25 inch to 3.75 inches.

HSLA-100 steel plate and weldment certification included the characterization of mechanical, physical, and fracture properties; evaluation of weldability and welding process limits for structures of high restraint (those prone to large amounts of residual stress); studies of fatigue properties and effects of marine environments; and the fabrication and evaluation of large-scale structural models to validate the laboratory-developed welding process parameters [5]. Based on the properties and weldability demonstrated in the evaluation, HSLA-100 steel was certified for use in surface ship structures and ballistic protection, and was selected to replace HY-100 for fabrication cost reductions in the construction of USS *John C. Stennis* (CVN 74). Estimated cost savings for fabricated structure in CVN 74 construction ranged from $500 to $3,000 per long-ton (2240 pounds), depending on complexity of the structure [6]. Through 2001, approximately 30,000 tons of HSLA-100 steel plate were used in Navy surface combatant construction - primarily in aircraft carriers. Figure 3 shows the cumulative tonnage of HSLA-80 and HSLA-100 steels used in ship construction after certification.

Figure 2. **HSLA-80 Steel Plate is Used in Navy Surface Combatant Construction, Including Cruisers, Destroyers, and Aircraft Carriers.**

HSLA-65 STEEL

The high strength steel (HSS) plate used in Navy surface combatant structures includes HSS (ABS DH/EH-36) of 50 ksi (345 MPa) yield strength, HY-80 or HSLA-80 of 80 ksi (550 MPa) yield strength, and HY-100 or HSLA-100 of 100 ksi (690 MPa) yield strength. Although heavier gage plate is required in some structures, most ship structure, including the hull shell plating, uses plate in the 6 to 30 mm (.25 inch to 1.25 inches) thickness range. No high-strength steel plate grade for yield strengths between HSS (50 ksi minimum) and HY/HSLA-80 (80 ksi minimum) was certified for surface combatant structures, nor have design criteria been developed. Except for ship protection plating (armor), the use of higher strength steel in a ship structure is usually a means to reduce weight and is a cost versus benefit decision. Thinner plate and less weld metal are required for HY/HSLA-80 structure compared to HSS (DH/EH-36). However, buckling limits, requiring additional stiffening, may prevent optimum use of HSLA/HY-80 for weight reduction. Additionally, plate cost per ton for HSLA and HY steels are more than double that of HSS and fabrication costs are significantly higher also.

It was evident in the HSLA-80 steel project that a 65 ksi yield strength steel, based on the "true" HSLA steels developed for pipeline and offshore applications, could meet the requirements for shipbuilding plate with improved strength, toughness, and weldability. These HSLA steels use low carbon and microalloying in conjunction with thermo-mechanical processing techniques instead of expensive alloy additions and heat treatment. (Compare this to the HY/HSLA-80 steels which rely on high amounts of alloy elements (Ni, Cr, Mo, Cu) and off-line heat-treating (quenching and tempering) to obtain their properties.)

The Naval Sea Systems Command recommended continuation of the steel development program for an HSLA-65 grade. This was due to design studies (destroyer-type hull) which showed that the utility of 80 ksi yield strength steel was limited (due to buckling limits), and a 65 ksi yield strength steel could achieve similar weight savings. Fabrication costs could be reduced for most surface ship hull structures by using a 65 ksi yield strength steel whose material and fabrication costs were similar to HSS, and simultaneously provide a weight savings. Candidate steels for the HSLA-65 grade were controlled-rolled, micro-alloyed, inclusion shape controlled, low C-Mn steels, similar to line-pipe grade API 5LX 65.

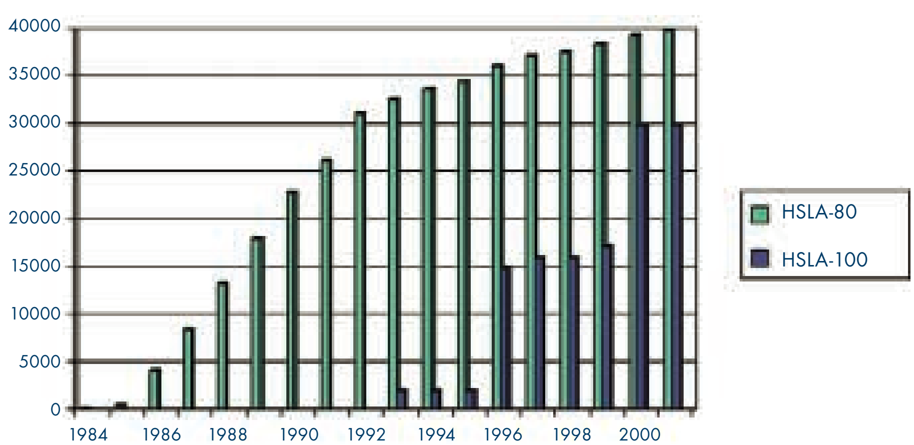

Figure 3. **Cumulative Tonnage of HSLA-80 and HSLA-100 Steels Used in Ship Construction.**

Service-life weight and stability allowances are key performance parameters for the new aircraft carrier designs, with 50-year service life and a hull-form similar to the CVN 68-class, as seen in Figure 4. Weight reduction under such constraints is difficult and expensive, and it is an absolute surety that improved capabilities and threat growth over the ship's life will continually increase its weight. Any measures that enable increased weight margins in aircraft carrier construction must therefore be considered.

The replacement of HSS with higher strength HSLA-65 will result in the use of thinner plates and thus structur-

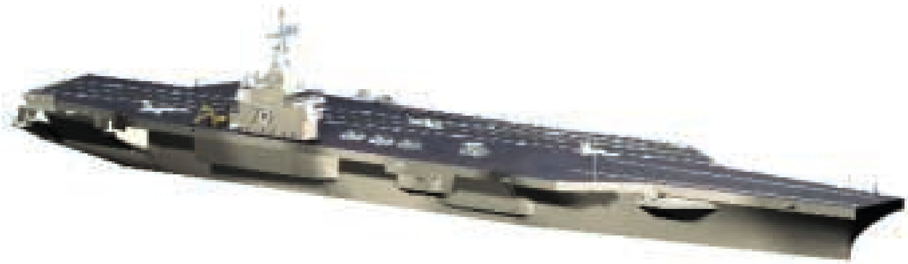

Figure 4. **HSLA-65 Steel Plate Will Enable Weight Reduction in New Aircraft Carrier Design.**

al weight reduction estimated to be on the order of 1,500 long-tons per ship – the largest weight reduction measure available to the design. The cost of HSLA-65 steel plate is approximately equivalent to that of HSS, and HSLA-65 welding processes, procedures, and consumables are the same as for HSS. The smaller volume of weld metal for thinner plate will also reduce total fabrication costs. Thus, the HSLA-65 system can be a cost-effective weight saver.

HSLA-65 Development & Welding Optimization

HSLA-65 steel development gained momentum in the early 1990's when Northrop-Grumman Newport News Shipbuilding (NNS) sought the implementation of a cost-effective, industrial specification (ASTM), HSLA-65 structural grade for aircraft carrier primary structures. NNS estimated significant weight savings if the steel was used in the construction of CVN 76 and CVN 77. CVN 69-class vessels had progressively increased in weight, decreasing lifetime growth margin. An interim standard specification for a "clean," low-carbon steel was proposed by NNS and reviewed through an ASTM subcommittee, with Naval Surface Warfare Center (NSWC), the American Bureau of Shipping, and steel manufacturers among the membership. In 1995, ASTM A 945, *Standard Specification for High-Strength Low-Alloy Structural Steel Plate with Low Carbon and Restricted Sulfur for Improved Weldability, Formability, and Toughness*, was issued in the annual standards. Between 1994 and 2000, several major projects studying steel and welding were concurrently conducted on HSLA-65, which provided mechanical, physical, and fracture properties; evaluation of weldability and welding process limits; studies of fatigue properties and effects of marine environments; and the fabrication characteristics. Some of these programs are summarized as follows:

- The NNS Aircraft Carrier Research Project conducted initial characterization of HSLA-65 production plate and review of CVN 77 critical and non-critical structures for potential HSS replacement.
- Office of Naval Research (ONR) Seaborne Materials projects evaluated commercially produced ASTM A 945, Grade 65 (HSLA-65) steel plate strength, toughness, fatigue, and weldability, where weldments are fabricated using HSS-type welding. The welding development for HSLA-65 investigated HSS-class welding consumables to determine performance requirements, identify consumables of improved toughness for HSLA-65 welding, and characterize HSLA-65 heat-affected zone toughness under high heat input welding.
- ONR Manufacturing Technology projects characterized HSLA-65 welding with commercially available consumables for gas metal arc welding (GMAW), submerged arc welding (SAW), shielded metal arc welding (SMAW), and flux cored arc welding (FCAW) using typical shipyard welding procedures The effects of shipyard HSS fabrication practices (flame straightening, hot / cold forming, post-weld thermal stress relief) on HSLA-65 steel and weldments were also examined. The project focused on optimization of HSLA-65 welding consumables and procedures, weld joint performance analysis, and verification of HSLA-65 weld joint performance under the extremes of service performance.

Domestic steel plate mills delivered plate from 0.25 to 1.25 inch thick to ASTM A 945, Grade 65 for these projects. All plate production methods (controlled rolled, quenched and tempered, and thermo-mechanical controlled processing with accelerated cooling) covered by ASTM A 945 were represented in the evaluations. The conclusions of the ONR and NNS projects on HSLA-65 steel and welding are summarized in Table 1.

HSLA-65 SYSTEM CERTIFICATION

The testing and analyses performed for HSLA-65 steel plate and weldments using HSS welding processes, procedures, and consumables have shown that the material system has the properties and characteristics to meet the performance requirements for combatant ship structure. The material properties and characteristics developed in these evaluations paralleled those conducted for HSLA-80 and HSLA-100 and were sufficient to support certification of the HSLA-65 steel system for Navy ship non-primary structure. However, structural fatigue, plate buckling, lateral pressure, local instability, stub column, & grillage tests were required to validate design criteria and take full advantage of the higher strength of the HSLA-65 system for application in primary structure. (Grillage structure commonly refers to plate with attached longitudinal and transverse stiffeners.)

Certifying HSLA-65 for Structures

The testing and evaluation of HSLA-65 steel structural properties and stability focused on six areas of HSLA-65 structural behavior: (1) welded structure compressive properties, (2) local stability of stiffener elements, (3) plate buckling, (4) lateral deformation of plates, (5) fatigue strength, and (6) grillage strength. Lack of data in these areas currently prevents the efficient use of HSLA-65 in surface combatant primary structures.

Figure 5. **Photograph of Satisfactory 1.25 Inch Thick HSLA-65 SMAW Explosion Crack-starter Test after Third Shot.**

Figure 6. **Photograph of Satisfactory 1.25 Inch Thick HSLA-65 FCAW Explosion Bulge Test after Sixth Shot.**

Because of the critical need for weight reduction in new aircraft carriers, a project for complete structural evaluation to certify HSLA-65 steel for use in primary hull structure of surface combatant ships was conducted and completed in 2002. The effort focused on extreme conditions of anticipated use to provide a database and confidence for general structural use certification. This would also minimize the risk in ship design with a new, 65 ksi yield strength grade. Design criteria for HSLA-65 plate buckling, lateral pressure capacity, structural fatigue, stability of structural members, and grillage performance, validated by structural testing were necessary for certification and the HSLA-65 system design for primary structure. Once certified for surface combatant structure, HSLA-65 has high potential benefit to the Navy beyond aircraft carrier applications. Future application for DD(X), LPD 17 & LHA(R) Classes can be anticipated.

An additional weight savings will be derived by replacing inefficient HSS rolled shapes with HSLA-65 built-up (welded) shapes. HSS rolled shapes are not produced to shipbuilding sizes and are typically oversize, whereas HSLA-65 built-up shapes can be designed and fabricated to meet strength requirements and thus save weight. In addition, fabrication and installation costs will be reduced by decreasing the large tolerance variations rolled shapes present which lead to fit problems in assembling parts cut from the rolled shapes. Design criteria for HSLA-65 steel built-up tees (two flat plates welded in a "T"-shaped cross section) are required to proportion the sizes such that local buckling of flange and web elements is prevented. In the certification process, specific structural element tests were conducted representing extreme conditions for built-up shapes (stub columns and local instabilities) to provide a database and support design criteria for welded HSLA-65 steel shapes.

Table 1. **Major Findings of the ONR and NNS HSLA-65 Projects.**

- All plates from domestic steel mills met the composition, tensile, and impact requirements of ASTM A 945, Grade 65, and all met or exceeded a minimum impact toughness of 70 ft-lb at –40 °F (transverse) set as a performance requirement for Navy surface combatant structures;
- All plates used compositions and processing based on steels for other commercial applications, (not exclusive to military type plate) such as HY/HSLA-80 or HY/HSLA-100 steel plate;
- Ship fabrication practices, such as cold forming, flame straightening, and post-weld stress relief, are limited by the same temperature restrictions that apply to HSS (DH36) for the same practices;
- Most 70-series welding consumables have specified minimum yield strength less than HSLA-65 (under-matched yield strength welds). In practice, however, most provided weld metal yield strength and tensile strength sufficient to result in ultimate failure in the HSLA-65 base plate;
- The weldability of HSLA-65 is equal to or better than HSS;
- Several classes of 70-series welding consumables (depending on plate composition and welding procedure) showed excellent Charpy V-notch impact toughness (exceeding 25 ft-lb at –40 °F, set as a performance requirement for Navy surface combatant structures);
- HSLA-65 welded structural element tests for fracture toughness showed ductile behavior, high flaw tolerance, and significant margin against brittle fracture at –20 °F service temperature (welds with toughness exceeding 20 ft-lb at –40 °F);
- The high-cycle fatigue properties of HSLA-65 butt welds and cruciform joints (whose cross section resembles a Latin cross; see also Figure 9) were within the bands of scatter for results for HSS and HY-80 as-welded joints;
- HSLA-65 plate welded with 70-series consumables exceeded the reduction in thickness in explosion bulge tests required for HY-80 weldments, and performed well in crack-starter explosion bulge tests (See Figures 5 & 6).

Figure 7. **Left, Welded HSLA-65 Steel I-beam Test Series After Compression Tests for Local Instability and Right, Instrumented I-beam Under Test.**

Structural Property Column Tests The stability of structural members under compressive loads is typically quantified by linear-elastic formulae which are only valid for stresses within the initial linear elastic range of the stress-strain curve. Ship structures are typically designed against buckling above the proportional limit at stresses near the yield strength. (The proportional limit defines the point at which stress is no longer linearly proportional to strain.) To predict inelastic buckling, the proportional limit and yield stress are used to correct the linear-elastic buckling formulas and account for inelastic effects.

A series of compression tests was conducted on very short sections of built-up HSLA-65 I-beams. The flanges and web of the I-beam were proportioned to preclude local buckling, and the overall length of the specimen was short enough to preclude column buckling. With the presence of longitudinal fillet welds to introduce realistic residual stresses and fabrication-induced, out-of-plane deformations, the HSLA-65 I-beams were instrumented to measure deformation and then loaded to failure after significant plasticity had occurred. The recorded load-deflection curves show the point of deviation from initial linearity: the structural proportional limit. The results were used to correct elastic buckling formulations for inelastic behavior. Compared to data from similar tests of HSS and HSLA-80 I-beams, appropriate factors of safety were determined for HSLA-65 working stress for structural design.

Local Instability Tests The built-up tee-stiffeners of ship steel structure need flange and web elements of proper width-to-thickness (b/t) proportions to avoid local buckling under compressive loads (i.e. to prevent buckling of flange and web elements of the stiffeners.) Neglecting this mode of failure can lead to more serious, global-buckling failures, since the load carrying capacity of individual members is reduced. Column tests were conducted on lengths of built-up HSLA-65 I-beam sections, short enough to preclude column buckling, but long enough to eliminate low aspect ratio effects, where plate buckling modes dominate. Flange and web dimensions were designed to have the same stability to achieve a lower-bound strength; i.e., the flange did not stabilize the web and the web did not stabilize the flange. End caps were welded at each end to provide good load transition into the beam.

The columns were instrumented with strain and displacement gages to ensure even load distribution, as well as define the onset of buckling and post buckling behavior. (See Figure 7.) Four slenderness ratios (width-to-thickness ratios) were tested, similar to tests performed for HSS and HSLA-80 steels. The HSLA-65 tests showed structural behavior and ultimate strength as expected for steel with yield strength between HSS and HSLA-80. The analysis of HSLA-65 structural behavior provided the experimental basis to establish slenderness ratio limits for the design of HSLA-65 plating stiffeners.

Plate Buckling Tests Ship structure is composed almost entirely of orthogonally stiffened plating. Both the plating and stiffeners must be designed to sustain working loads. Plate panels in the ship are welded around their periphery to stiffeners or adjacent panels. The welding introduces residual stresses, which can adversely affect the strength of the panel. Plate buckling is generally characterized by a plate slenderness parameter, which is a function of the width-to-thickness ratio, yield strength, and elastic modulus. For design purposes, the edges of the plate panel are assumed simply supported, and under increasing uniform compressive edge load, the plate will first buckle and then develop post-buckling strength until ultimate collapse occurs.

HSLA-65 plate panels with welded edges were fabricated with different widths and loaded in axial compression such that buckling behavior over a wide range of slenderness was evaluated. The panels were instrumented with strain gages and displacement transducers to determine the inception of buckling and track the post-buckling behavior of each panel. The results for HSLA-65 plate panel tests compared favorably with the curves used for design against plate buckling and ultimate strength in naval ships.

Lateral Pressure Tests Most plate panels of ship hull structure are subjected to and designed for sustained lateral pressure loadings of various magnitudes associated with draft, ballast, fuel, and flooding conditions. In addition, certain structural members

Figure 8. **Welded HSLA-65 Steel Plate Lateral Pressure Test, Showing Stiffeners in Cylinder Interior (Top), Exterior View of Test Plate Prior to Test (Middle), and Instrumented Plate After Rupture in Test (Bottom).**

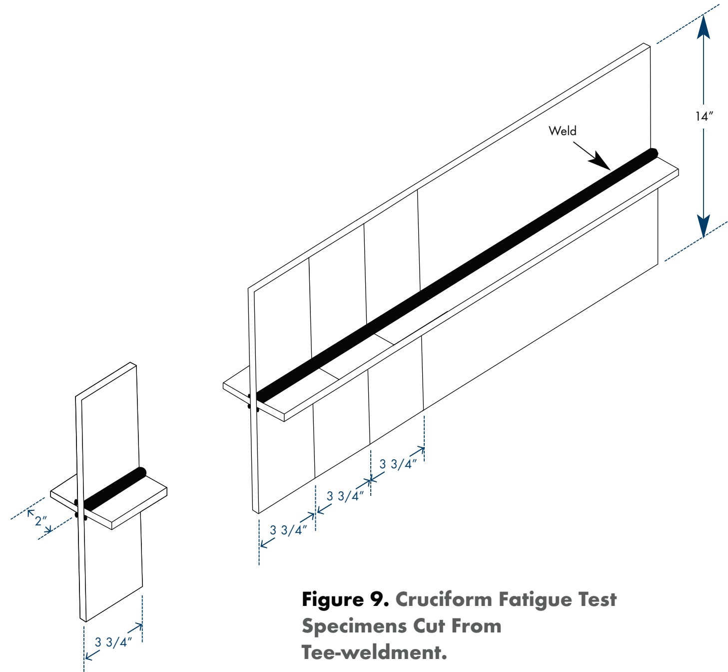

Figure 9. **Cruciform Fatigue Test Specimens Cut From Tee-weldment.**

(such as shells, tanks, and bulkheads) are designed to hold a lateral load, even though it may cause the panel to undergo some degree of permanent deformation. Design guidance has evolved which uses correction factors (known as "C-factors") to determine the maximum slenderness ratio of the panel (width-to-thickness), given the aspect ratio of the panel (length-to-width), and the hydrostatic head acting on the panel.

Tests were conducted for HSLA-65 plates to experimentally determine the elastic, inelastic, and rupture capacity, as well as to determine C-factors for the steel using the NSWC Carderock Division's pressure tank facility. A cylindrical fixture was fabricated with heavy plate internal stiffening across one end of the cylinder. The HSLA-65 test plates were welded to both the internal diameter of the cylinder and the stiffeners. With the opposite end of the cylinder capped with a heavy circular plate, the entire test assembly was placed into the pressure tank, where pressure was incrementally increased and decreased to establish the relationship between permanent deformation and applied pressure. Strain gages and displacement transducers measured the panel's response and permanent set. After sufficient data were collected to determine a C-factor for HSLA-65 plate, the pressure was increased until the ultimate holding pressure was reached. At this point, the panel failed by shearing a stiffener weld at a panel edge. Figure 8 shows views before and after lateral pressure tests. The C-factors established for HSLA-65 plate panels under lateral pressure were as expected for a steel of its yield strength.

Figure 10. **Cruciform Weld Under Fatigue Test Clamped in Hydraulic Grips.**

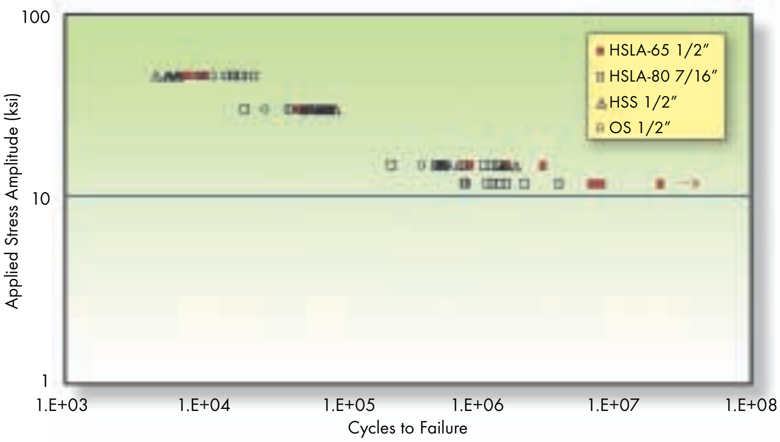

Figure 11. Results of Constant Stress Amplitude Fatigue Tests of Cruciform Weldments of Ordinary Strength (OS), HSS, HSLA-65, and HSLA-80 Steels.

Structural Detail Fatigue The use of HSLA-65 steel will result in lighter gage structure with associated higher stresses than for HSS. Fatigue strength may become a significant design consideration when the structure is subjected to cyclic stresses in service in both primary and secondary structural applications. The fatigue strength of welded structural details is determined by cycling representative weld joints at constant amplitude stress levels until failure by fatigue cracking occurs. Since the constant amplitude behavior will eventually be used to predict seaway loadings, random amplitude loadings were also applied in the HSLA-65 weld joint evaluation in order to evaluate the accuracy of the fatigue life prediction methodology. Simple tee structures were tested in order to characterize the fatigue strength of welded HSLA-65 steel.

The fatigue test joint configuration was flat plate-type with two side attachments at mid-length, with the full-penetration fillet welds of the non-load carrying side attachments oriented perpendicular to the applied axial, fully reversed load amplitude. (See Figure 9.) This configuration represents a weld detail prevalent in ship structure, and similar tests have been performed on the same type of specimen using HSS and HSLA-80 steel, which offer a basis for comparison. The fatigue tests were conducted in dedicated machines using hydraulic grips, as seen in Figure 10.

Figure 12. Grillage Test Machine with High Load Capacity: +/- 5 Million lbs (Longitudinal), +/- 1 Million lbs (Transverse), and 25 psi Lateral Pressure.

The fatigue stress amplitude levels included tests to determine fatigue strength at long lives, which would provide data for design against fatigue over the ship's life. This would help prevent maintenance problems as the ship structure ages. The results indicated that HSLA-65 weldments are comparable in fatigue properties to HSS and HSLA-80 weldments over the life range investigated. Results of this testing are shown in Figure 11. Fatigue strength of weldments is related to the stress concentration at the toe of the weld (weld geometry) and not to the yield or tensile strength of the steel. Thus, as the strength of the steel and the design stress increases, closer attention must be given to fatigue design in order to obtain adequate structural life.

Grillage Tests As previously noted, ship structure generally consists of longitudinally and transversely stiffened plating. The preceding tests addressed the properties of local structural issues, such as the capacity of plating between stiffeners, the proportions of the flange and web elements of stiffeners, and the fatigue strength of a welded detail.

However, local structural issues like these must be understood before the larger, general structure can be designed. As the overall structure increases in size, the size, shape, and length of the members may be limited to control buckling of main load-carrying members. Due to the complicated nature of buckling mode interaction and the effects of initial deformations and residual stresses from fabrication, the ultimate load carrying capacity of a large structure is best determined experimentally. Grillage test structures, containing multiple longitudinal and transverse stiffeners, were evaluated for catastrophic modes of buckling failure and to define margins of safety for design against ultimate failure. (See Figures 12 and 13.) The grillage test structures were 8 ft wide X 24 ft long containing three bays, and fabricated by NNS. Instrumentation, out-of-plane deformation, testing, analysis and documentation were performed by NSWCCD, home to the unique grillage test facility.

Figure 13. HSLA-65 Grillage After Test in Grillage Test Machine.

HSLA-65 Steel Design Criteria / Guidance

The HSLA-65 structural testing provided experimental validation for design criteria for plate buckling, lateral pressure capacity, structural fatigue, stability of structural members, and grillage performance. The data support full implementation, unrestricted use of HSLA-65 for primary hull structure and minimum risk of unanticipated problems in construction and service. The structural tests demonstrated adequate performance of the HSLA-65 system (both bulk material and welded structure) to perform as expected under current criteria and guidance.

STEELS FOR THE FUTURE NAVY

The HSLA steel research and development projects provided the Navy with the opportunity to develop lower-cost alternatives to the HY steel systems and new high strength welding products for higher productivity. The Navy's investment in high strength steel research has had a major payoff in providing metallurgical approaches to obtaining weldable, tough, structural steels not burdened by the cost and welding limitations of the HY-series steels of the 1960's.

Advanced ultra-low carbon steel metallurgical systems and processing technology previously limited to research or foreign production are becoming domestically available for commercial production. The synergism of sophisticated hot metal treatments, microalloying, improved slab production, thermo-mechanical controlled processing, and accelerated on-line cooling, have the potential for achieving up to 150 ksi yield strength in an inherently weldable alloy steel plate.

Advanced HSLA metallurgical systems, steel plate processing technology, and advanced joining methods for high-strength steel systems will continue to be part of Navy R&D through the 21st century. The performance requirements for the ships of the "Navy-After-Next" can be expected to increase the demands on the steel systems. Improved ship protection at reduced weight is one requirement that will demand alloy steel systems extending over the 130 to 150 ksi yield strength range for design against future weapon threats.

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Ernest J. Czyryca is a research project leader in the Metals Department of the Naval Surface Warfare Center, Carderock Division. He holds degrees in Metallurgical Engineering (Drexel University), Civil Engineering (Johns Hopkins University), and Engineering Mechanics (Pennsylvania State University). In his 40-year career with the Navy, he has been involved in or managed R&D projects in naval structural metals, alloys for machinery applications, metals processing, mechanical metallurgy, welding metallurgy, fatigue of metals and structures, fatigue design, fracture properties and fracture mechanics, and failure analyses. He is author or co-author of more than 150 technical reports and papers published in professional society journals.

Dr. David P. Kihl is a structural naval architect and has been employed at the Carderock Division, NSWC since 1978. He received his BS degree in Civil Engineering from the State University of New York at Buffalo, and his MS and DSc degrees in Structural Engineering from The George Washington University. Over his 25-year career, he has authored or co-authored more than 100 technical documents, including NSWC reports, journal articles, and conference proceedings, many dealing with life prediction and failure criteria of surface ship structures. Most recently he received the American Society of Naval Engineers *Jimmie Hamilton* Award, awarded annually for the best original technical paper in Naval Engineering.

Robert DeNale is head of the Metals Department at the Naval Surface Warfare Center, Carderock Division. His areas of scientific and engineering interest include welding, nondestructive evaluation and high strength steel casting metallurgy. He has authored numerous publications and US Navy technical reports. He has been awarded 7 US patents, edited two books, and made more than 50 presentations at professional society meetings.