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An analysis of the study of mechanical properties and microstructural relationship of HSLA steels used in ship hulls

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AN ANALYSIS OF THE STUDY OF MECHANICAL PROPERTIES AND MICROSTRUCTURAL RELATIONSHIP OF HSLA STEELS USED IN SHIP HULLS

By

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

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ABSTRACT

Title of Dissertation: **An Analysis of the Study of Mechanical Properties and Microstructural Relationship of HSLA Steels used in Ship Hulls**

Degree: **Master of Science**

This dissertation is the study of mechanical properties and microstructures of **H**igh-**S**trength **L**ow-**A**lloy steels primarily used in military ship construction. Their improved properties compared to mild steels and higher strengths allow a reduction in plate thickness, stiffener size and results in a ship of lighter weight with greater load carrying capacity. First, the background information and a literature review on metallurgical and mechanical behaviours, the importance of the impact tests, effects of alloying elements in **HSLA** steels and some special topics of interest on the steels are given. Second, the interpretation of the experimental results such as chemical analysis, tensile and impact tests, corrosion testing, metallographic investigations and hardness tests of the materials used are presented. Although a significant part of the uncertainty in impact tests, and fatigue tests depends on the actual loading, the ambient temperature, and other factors, the attention to these tests were limited. Third, the structural integrity, the failure analysis and fatigue properties of hull materials are analysed. Moreover, preventive measures such as the strengthening mechanism in **HSLA** steels, corrosion prevention, and weld fatigue improvement techniques are discussed. Goal-Based New Ship Construction Standards and the requirements of internationally recognized classification societies regarding hull materials are investigated. In addition, differences of opinion about economic issues and the materials selection process are considered. Finally, the development of materials characterization and recommendations for further research and standards of shipbuilding materials are summarised and discussed.

KEYWORDS: **HSLA**, **Materials**, **Impact**, **Fatigue**, **Corrosion**, **Standards**.

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LIST OF ABBREVIATIONS

- log (P_f)	Optimum Target Reliability Level [Target Safety Level]
% EL	Percent Elongation
% RA	Percent Reduction in Area
ΔB	Economic Benefit per Ship due to reduced costs
ΔC	Additional Cost per Ship of the risk control measure
ABS	American Bureau of Shipping
ALARP	As Low As Reasonably Practicable – Principle
ASM	American Society of Metals
ASTM	American Society for Testing and Materials
BCC	Body Centred Cubic
BV	Bureau VERITAS
Class NK	Nippon Kaiji Kyokai
CSR	Common Structural Rules
DNV	Det Norske VERITAS
FCC	Face Centred Cubic
FSA	Formal Safety Assessment
GBS	Goal-based Standards [Goal-based New Ship Construction Standards]
GL	Germanischer Lloyd
HAZ	Heat–Affected–Zone [Volume of material adjacent to a weld]
HRC	Rockwell–C Hardness Number
HSLA	High–Strength Low–Alloy [e.g. **HSLA**-65, **HSLA**-80, **HSLA**-100]
HSS	High Strength Steel [e.g. Grade AH32, DH32, EH32, AH36, DH36]
HY	Higher Yield Strength [Extra High Strength Steels, e.g. HY-80, HY-100]
IACS	International Association of Classification Societies
IMO	International Maritime Organization

JIS	Japanese Industrial Standards
LR	Lloyd’s Register of Shipping
MS	Mild Steel [Ordinary Strength Hull Steels, e.g. Grade A, B, D, E, DS, CS]
MSC	Maritime Safety Committee
NB	Net Benefit
P_f	Probability of Failure
RMS	Royal Mail Ship
SAW	Submerged Arc Welding [a welding method]
S-N Curve	Curve for Fatigue Failure [**S**tress versus **N**umber of cycles to failure]
SOLAS	Safety of Life at Sea
SSC	Ship Structure Committee
TIG	Tungsten Inert Gas [a welding method]
TS	Tensile Strength
VLCC	Very Large Crude Carriers
wt %	Weight Percent
YS	Yield Strength
YTU	Yangon Technological University [in Myanmar]
α phase	Ferrite phase in the **Fe–Fe_3C** phase diagram
γ phase	Austenite phase in the **Fe–Fe_3C** phase diagram

1 INTRODUCTION

The purpose of this chapter is to review the historical background of different types of steel used in ship constructions and their successive development and failures. In addition, a variety of materials being used in shipbuilding nowadays, predominantly MS (mild steels), HY or HSS (high tensile or higher strength) steels, and newly introduced HSLA (high-strength low-alloy) steels will be presented. Besides, some vessel disasters such as RMS Titanic (1912), New Carissa (1999), and MSC Napoli (2007) will be discussed in brief.

1.1 Ordinary Mild Steels vs. Royal Mail Ship Titanic

In the late 19th century, steels became the principal shipbuilding materials mostly ordinary mild steels containing 0.15 to 0.25% carbon and with reasonably high manganese content. The means of transportation at that time for travelers and correspondences around the world was by passenger steamships which were built with mild steels. The well-known vessel “Royal Mail Ship Titanic” was built using the best mild steel plate obtainable in the period of 1909 to 1911 (Felkins, 1998). *RMS Titanic* struck a large iceberg during its maiden voyage in April 1912 and sank, causing the death of 1500 passengers and crews. It was found that the steel experienced a high ductile-to-brittle transition temperature, i.e., the steel was brittle at low ambient temperatures. Besides, the brittle condition was attributable to high sulphur content; the effects of these ductile-to-brittle transition temperatures will be discussed in the succeeding Chapters in detail. As soon as the bow section of the vessel struck the iceberg, it took on water and submerged, as shown in Figure 1.1, by lifting the stern above the water line (see also Kemp, 2005, pp.586-587).

Figure 1.1 RMS TITANIC wreck illustration.

Source: Felkins, 1998.

The suspended stern section created a maximum bending moment amidships which caused the vessel to tear separately, beginning at or near the top deck where the bending stresses were tensile (in a hogging condition, the deck of the vessel is placed in tension, and the bottom structure in compression). In addition, it has also been found that the wrought iron rivets contained an elevated amount of incorporated slag in the construction of *Titanic*, and that the orientation of the slag within the rivets may hold a clarification for how the ship accumulated damage during its encounter with the iceberg (Htay Aung, 2004, p. 2).

Furthermore, sulphur has been attributed to both chemical and microstructural factors. The chemical compositions of major alloying elements of the hull steel that proved by various investigators were 0.20-0.21% C, 0.065-0.069% S, 0.01-0.045% P, and 0.47-0.52% Mn. The sulphur and phosphorus level measured in the ship's hull steel was higher than that acceptable in modern steels. Both of these elements can decrease the fracture toughness of the steel, but have been seen to have little effect on the transition temperature. The steel was also found to be low in Mn. As a result, this can lead to sulphur embrittlement if there is insufficient Mn to tie up all the sulphur in MnS particles. To be more comprehensive, a literature review on metallurgical and mechanical behaviours, the importance of the impact tests, effects of alloying elements in hull steels and some special topics of interest, i.e. effects of corrosion and welding on hull steels, are also analysed in this paper.

1.2 High Tensile Steels vs. New Carissa and MS*C Napoli*

In the early part of 20^{th} century, high tensile steels become available for ship construction in the manganese-silicon alloy compositions to substitute mild steels. These steels were first used on warships just prior to World War I and their primary use was to provide backing for armour belts where high impact loads were expected. In the past two decades, the use of high tensile steels has led to these becoming a major cause of fatigue failure. The majority of high tensile steel ships have experienced an increase in the rate of fatigue cracking especially the Class III or nuisance cracking of internal structural members; this is discussed in Chapters two and four. Reduction of high tensile steel scantlings based upon the increased strength capacity was allowed by the classification societies, under the condition that calculations were performed to insure that buckling failure modes do not happen (Ship Structure Committee-374, 1994, p. 1-1). Det Norske VERITAS (DNV) warned that the use of high tensile steel may lead to decreased fatigue life unless measures were taken to improve stress-concentration factors locally.

Figure 1.2 Bulk Carrier NEW CARISSA.

Source: http://www.shipstructure.org/newcar.shtml

One of the case studies conducted under the provision of SSC is "Complete Hull Failure in a Stranded Bulk Carrier *NEW CARISSA*" that broke into two parts in February 1999, as shown in Figure 1.2. The ship was built with high tensile steel in 1989. The structural failure of the ship was the result of a combination of sea floor scouring effects, bottom pounding, and transverse bending from waves. The eventual break-up of the vessel into two parts can be viewed as a direct result of a combination of these effects. (Retrieved from the World Wide Web: http://www.shipstructure.org/newcar.shtml)

There have been many examples in the marine industry of premature fatigue failures of high tensile steel structures. A recent one is "*MSC NAPOLI*" which was also constructed using high tensile steel in 1992. As shown in Figure 1.3, the ship grounded in January 2007 on the Cornish coast near a World Heritage Site and caused a threat of hazardous chemicals escaping from containers which were flung into the water as heavy gales hit the broken ship. The causes of the Napoli's structural failure already at this time have still to be ascertained.

Figure 1.3 Grounded MSC **NAPOLI.**

Source: http://news.bbc.co.uk/2/hi/uk_news/england/devon/6336979.stm

For that reason, the interpretation of the conducted experimental results such as chemical analysis, tensile tests, impact tests, corrosion testing, metallographic investigations and hardness tests of the materials used are discussed in Chapter three. Also the failure analysis of hull materials is introduced and the fatigue properties of hull steels and their structural integrity discussed in Chapter four.

1.3 High-Strength Low-Alloy Steels vs. New Air Craft Carrier

The focus of this research is the study of mechanical properties and microstructures of **H**igh-**S**trength, **L**ow-**A**lloy (**HSLA**) steels primarily used in military ship construction. In the early 1980's, steelmakers were producing grades of **HSLA** steel plate with improved weldability, low temperature toughness, high strengths, and weight reduction because of its high strength-to-weight ratio (Czyryca, 2003). **HSLA** steel is a low carbon, copper precipitation strengthened steel and has been used in surface ship structural applications since 1984, after an evaluation of properties, welding, and structural performance.

In addition, a substantial reduction in hull fabrication costs and higher productivity was achieved through the substitution of **HSLA** for high tensile steel, with the significant factor in cost savings being the reduction or elimination of preheating for welding. Their higher strength allows a reduction in plate thickness, stiffener size and results in a ship of lighter weight with greater load carrying capacity. Service-life weight and stability allowances are key performance parameters for the new aircraft carrier designs (Kemp, 2005, pp.7-8). (Figure 1.4).

Figure 1.4 New Aircraft Carrier Design.
Source: Czyryca, 2003, p. 65.

Many times, one of the materials problems is to select the right material from the many thousands that are available. There are a lot of criteria on which the final decision is normally based. First of all, a material must be characterized for the properties required in service conditions. On only rare occasions a material possesses the maximum or ideal combination of properties. Therefore, it may be necessary to trade off one characteristic for another. The classic example involves strength and ductility; normally, a material having a high strength will have only a limited ductility in the case of high tensile steels. In such cases a reasonable compromise between two or more properties may be necessary.

In the second place, any deterioration of material properties that may occur during service operation, for instance significant reductions in the strength may result from exposure to ambient temperatures or corrosive environments. Moreover, the major considerations in the choice of the shipbuilding structural steel for the construction of ships are strength and ductility, fracture toughness and fatigue life, corrosion resistance, ease of use in fabrication and construction, weldability, and cost. In addition to these factors, it is necessary to study the rules and regulations pertaining to hull materials from the internationally recognized classification societies such as American Bureau of Shipping (ABS), Det Norske VERITAS (DNV), and Nippon Kaiji Kyokai (ClassNK).

Finally, probably the overriding consideration is that of economics; what will the finished product cost? A material may be found that has the ideal set of properties but is prohibitively expensive. Here again, some compromise is inevitable. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired product (Htay Aung, 2004, p. 3). Therefore, the essential technical and safety criteria are discussed in this paper. Furthermore, IMO safety assessments such as Goal-Based New Ship Construction Standards are analysed. Also consequences of the regulatory standards and economic issues are considered. Finally, the findings and recommendations for further research are summarized and the future standards of shipbuilding materials considered.

2 THEORETICAL BACKGROUND OF HULL STEELS

The aim of this chapter is to investigate the chemical, metallurgical, and mechanical behaviours of the steels used in ship constructions. Moreover, the role of alloying elements in HSLA steels is discussed. Furthermore, the relationship between the microstructures, properties, and fabrication process of materials used in the ship construction are studied. In addition, the significance of impact tests, the effects of welding and corrosion of hull steel are analysed.

2.1 Metallurgical and mechanical behaviours of hull steels

Historically, it was generally accepted that steel for structural purposes has been a low-carbon, plain carbon steel with about 0.2% C. Later, the production of high tensile steels was stipulated and more thoroughly in shipbuilding. However, in recent years a strong demand has been created for structural steels with higher strengths, greater toughness, more ductility, and better welding characteristics than possessed by the plain-carbon structural steels and the high tensile steels. Serious complications have been encountered in the construction of large ships, oil and gas transmission lines, and offshore oil drilling platforms with the use of plain-carbon steels and high tensile steels. This has led to the development of a class of steels known as *High-Strength Low-Alloy* steels or **HSLA** steels, ASM Metal Handbook vol. 1, 1978, pp. 403-420, (see Appendices A & B).

HSLA steels have the combined properties of both plain carbon structural steels and high tensile steels but with a lighter weight (because of their high strength-to-weight ratio) and higher load carrying capacity. A further incentive for the development of **HSLA** steels comes from the automotive manufacturing industry where there is a need to reduce the weight of automobiles and make them more fuel efficient. This can be partially accomplished by reducing the thickness of the steel sheets and plates. However, a reduction in thickness also requires an increase in strength. These requirements meet in **HSLA** steels (Htay Aung, 2004).

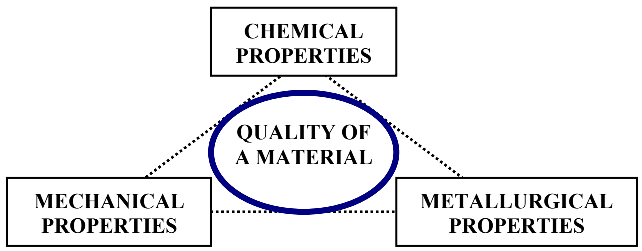


Figure 2.1 Relationships between properties of a material.

Source: ©Htay Aung, 2007.

According to Figure 2.1, the quality of a material depends on its chemical properties such as compositions of alloying elements, metallurgical properties such as heat treatment, microstructures and fracture toughness, and mechanical properties such as ductility, strength and processing techniques. Therefore, the following sub-sections discuss these properties.

2.1.1 Structure-Properties relationship in plain carbon steels

It is important to know that the mechanical behaviour of iron-carbon alloys rely on their microstructures such as fine and coarse pearlite, spheroidite, bainite, martensite, and austenite. According to the **Fe–Fe$_3$C** phase diagram (Appendix C), steels that are processed under equilibrium or near-equilibrium conditions can form (i) pure ferrite at very low carbon levels generally under 0.005% C, (ii) ferrite plus cementite particles at slightly higher carbon levels between 0.005 - 0.022% C, (iii) ferrite plus pearlite mixtures between 0.022 - 0.76% C, (iv) pure pearlite at 0.76% C, and (v) mixtures of pearlite plus cementite networks between 0.76 - 2.14% C. Normally, the compositions of carbon percentage in shipbuilding steel plates are between 0.10 - 0.30%C.

Any excess carbon, above 0.005% C, will form an iron carbide compound called **cementite** (Fe_3C). Cementite can exist as a particle, as a component of lamellar pearlite, or as a proeutectoid network on prior austenite grain boundaries in hypereutectoid steel. Cementite is much harder but more brittle than ferrite.Thus, carbon in the form of cementite has a further influence on the strength of steel. The layer thickness of each of the ferrite and cementite phases in the microstructure also influences the mechanical behaviour of the material. The higher percentage of carbon in steels produces the greater amount of cementite that leads to increase the hardness and strength and drop off the ductility and toughness of the steels (Callister, 2000).

Additionally, in most steels the microstructure consists of both ferrite (α) and cementite (Fe_3C) phases. According to the iron–iron carbide phase diagram (Appendix C), upon cooling to room temperature, an alloy within this composition range must pass through at least a portion of the γ phase field; distinctive microstructures are subsequently produced.

The microstructure for the eutectoid steel (0.76%C) that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases (α and Fe_3C) that forms simultaneously during the transformation. In this case, the relative layer thickness is approximately 8 to 1. This microstructure is called **pearlite** because it has the appearance of mother of pearl when viewed under the microscope at low magnifications. The thick light layers are the ferrite phase, and the cementite phase appears as thin lamellae most of which appears dark (Smallman, 1999, pp. 274-300).

Many cementite layers are so thin that adjacent phase boundaries are indistinguishable, which layers appear dark at this magnification (Appendix C). Mechanically, pearlite has properties intermediate between the soft, ductile ferrite and the hard, brittle cementite. Fine pearlite is harder and stronger than coarse pearlite. The reasons for this behaviour relate to phenomena that occur at the α - Fe_3C phase boundaries. There is a large degree of adherence between the two phases across a boundary. Therefore, the strong and rigid cementite phase severely restricts deformation of the softer ferrite phase in the regions adjacent to the boundary; thus the cementite may be said to reinforce the ferrite.

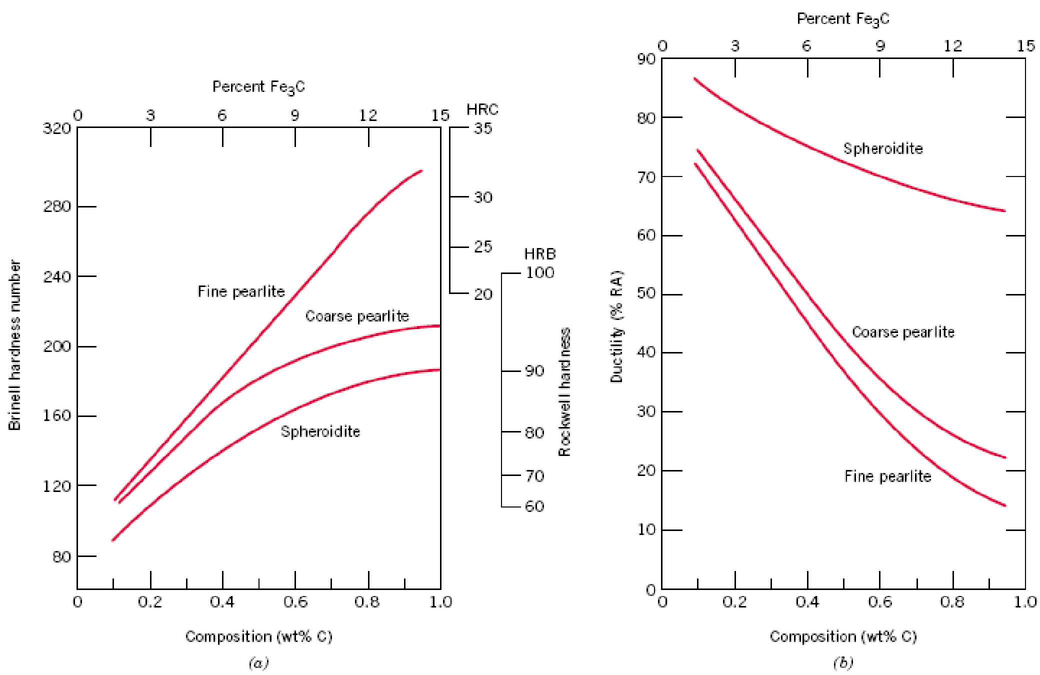


Figure 2.2 Mechanical Properties vs. Metallurgical Properties of Plain Carbon Steels.

Source: Callister, 2000.

a) Brinell and Rockwell hardness as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures.

b) Ductility (%RA) as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures.

For fine pearlite there are more boundaries through which a dislocation must pass during plastic deformation. Thus, the greater reinforcement and restriction of dislocation motion in fine pearlite accounts for its greater hardness and strength. Coarse pearlite is more ductile than fine pearlite, as illustrated in Figure 2.2 (b), which plots percent area reduction versus carbon concentration for both microstructure types (Callister, 2000). This behaviour results from the greater restriction to plastic deformation of the fine pearlite.

Spheroidite is a mixture of particles of cementite (Fe_3C) in an α ferrite matrix. Alloys containing pearlitic microstructures have greater strength and hardness than do those with spheroidite. There is less boundary area per unit volume in spheroidite, and consequently plastic deformation is not nearly as constrained, which gives rise to a relatively soft and weak material. As would be expected, spheroidized steels are extremely ductile, much more than either fine or coarse pearlite as indicated in Figure 2.2. In addition, they are notably tough because any crack can encounter only a very small fraction of the brittle cementite particles as it propagates through the ductile ferrite matrix (Callister, 2000).

Bainites are generally stronger and harder than pearlitic ones because they have a finer structure (i.e., smaller Fe_3C particles in the ferrite matrix); yet they exhibit a desirable combination of strength and ductility (Cahn, 1996, pp.1570-1577).

Martensite is the hardest and strongest of the various microstructures that are produced for a given steel alloy. In addition, martensite is the most brittle so that ductility could be neglected. Its hardness is dependent on the carbon content, up to about 0.6%. In contrast to pearlitic steels, strength and hardness of martensite are not thought to be related to microstructure (Cahn, 1996, pp.1570-1577).

Austenite is slightly denser than martensite, and therefore, during the phase transformation upon quenching, there is a net volume increase. Consequently, relatively large pieces that are rapidly quenched may crack as a result of internal stresses; this becomes a problem especially when the carbon content is greater than about 0.5% (Smallman, 1999, pp. 274-300).

2.1.2 Structure-Properties relationship in HSLA steels

Yield and tensile strengths increase along with the cross-sectional area decreases with increasing carbon content because of the increase in pearlite content, as presented in Figure 2.3. The divergence of the yield and ultimate strength curves with increasing carbon content indicates that pearlite increases the work hardening rate. In addition to the mechanical properties that characterize the strength and ductility of **HSLA** steels, toughness or the energy absorbed during fracture is not only in that steels but also of considerable engineering importance. Ferritic steels are unique in that they show a transition from ductile to brittle fracture when broken at successively lower temperatures. The ductile fracture typical of higher temperatures proceeds by the growth of microvoids around carbides and/or inclusion particles, a fracture process that requires large amounts of shear or plastic deformation and, therefore, absorbs considerable energy.

In contrast, Figure 2.3 shows that increasing carbon content lowers the impact energy, and that, therefore, increasing amounts of pearlite adversely affect the ductile fracture toughness. In addition, the transition temperature marking the transition between ductile and brittle fracture is also adversely affected by the increasing carbon content. At any given carbon content level, the mechanical properties and toughness of steel may be significantly affected not only by the pearlite content but also by the ferrite grain size and chemical composition (Figure 2.2 and Appendix C). The refinement of ferritic grain size in **HSLA** steels, discussed in Chapter four, increases both strength and toughness. Good heat treatment practice is therefore directed to producing as fine a ferrite grain size as possible for critical applications of **HSLA** steels.

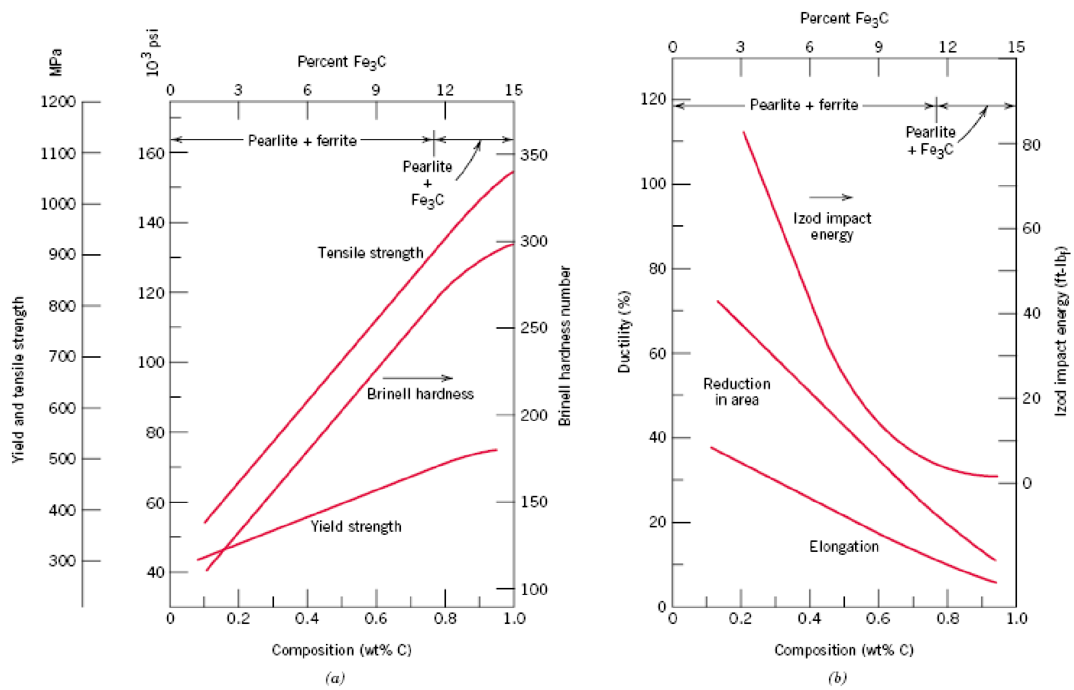


Figure 2.3 Structure-Properties Relationships of Plain Carbon Steels.

Source: Callister, 2000.

a) **Yield strength, tensile strength, and Brinell hardness versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite.**
b) **Ductility (%EL and %RA) and Izod impact energy versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite.**

Alloying, low finishing temperatures for hot rolling, and low austenitizing temperatures for normalizing are all techniques used to keep the grain size small. Grain size control is achieved by microalloying with small amounts of vanadium or niobium that produce very fine carbides. The carbides limit austenite recrystallization and/or grain growth during hot rolling at low finishing temperatures and as a result the ferrite that forms from that austenite on cooling is remarkably fine (Murakami, 2002).

The effects of the various microstructural and composition parameters on the mechanical properties of steels with ferrite-pearlite microstructures have been statistically analyzed by multiple linear regression analysis. The manganese and silicon replace iron on the BCC lattice of ferrite, and are said to dissolve substitutionally. The effect of manganese and silicon is to increase both yield and tensile strength by solid solution strengthening of the ferrite that is explained more in the following section.

2.2 Effects of alloying elements in HSLA steels

In the presence of alloying elements, the practical maximum carbon content at which **HSLA** steels can be used in the as-rolled condition is approximately 0.20%. Higher levels of carbon tend to form martensite or bainite in the microstructure of as-rolled steels, although some of the higher strength low alloy steels have carbon contents that approach 0.30%. General effects of the various alloying and residual elements commonly found in **HSLA** steels are summarized below (from ASM Metal Handbook vol. 1, 1978, pp. 403-420 and Smallman, 1999, pp. 274-300). Each particular alloying element has an influence on the structure and properties of the steel.

2.2.1 Five major alloying elements that affect HSLA Steels

Carbon noticeably increases the amount of pearlite in the microstructure and is one of the more effective and economical strengthening elements. It is an interstitial element that occupies sites between the larger iron atoms in the BCC and FCC lattices. Carbon also has a negative effect on properties, as seen in Figure 2.3 (b). For example, the percent reduction in area decreases with increasing carbon. Additionally, toughness and ductility of pearlitic steels are reduced by increases in carbon content. The ductile-to-brittle transition temperature is raised as the carbon content is increased. In order to avoid embrittlement of the *heat-affected-zone,* **HAZ,** adjacent to a weld, the carbon content should be kept below certain maximum values when the steel is to be fabricated by metal-arc welding (Figure 2.5). Increasing amounts of carbon, together with the presence of certain alloying elements, promote the formation of martensite in the heat-affected-zone. The higher the carbon content, the harder will be any martensite that forms. Low-Hydrogen electrodes and/or weld preheat may be required when welding **HSLA** steels, whereas neither would be used when welding a plain carbon steel of equal carbon content.

Manganese is the principal strengthening element in high strength structural steels when it is present in amounts over 1 %. It functions mainly as a solid solution strengthener in ferrite, a1though in hardenable steels; manganese causes a marked increase in hardenability. It has several roles as an alloying element. One of the functions is to assure that all residual sulphur is combined to form manganese sulphide (MnS). Without manganese the sulphur would combine with iron and form iron sulphide (FeS), which is a brittle compound that lowers toughness and ductility and causes a phenomenon called hot shortness. Hot shortness is a condition where a compound (such as FeS) or insoluble element (such as copper) in steel has a low melting point and thus forms an unacceptable cracklike surface condition during hot rolling. Manganese is a substitutional element and can replace iron atoms in the BCC or FCC lattice. Each 0.1% Mn added to iron will increase the yield strength by about 3 MPa. It also lowers the eutectoid transformation temperature and lowers the eutectoid carbon content. A small beneficial effect on atmospheric corrosion resistance is attributed to manganese.

Phosphorus, a tramp or residual element, is an effective solid solution strengthener in ferrite but causes a decrease in ductility and thus is carefully restricted to levels generally below 0.02%. However, like carbon, phosphorus is an interstitial element that can substantially strengthen iron. For this reason, phosphorus is added to a special class of steels called rephosphorized steels for strength. It was formerly considered to cause embrittlement when present in amounts over about 0.10%. On the other hand, this embrittling effect is influenced by the carbon content and is not so pronounced in steels with carbon contents less than about 0.15%. The atmospheric corrosion resistance of steel is increased appreciably by the addition of phosphorus, and when small amounts of copper are present in the steel, the effect of phosphorus is greatly enhanced. When both phosphorus and copper are present, there is a greater beneficial effect on corrosion resistance than the sum of the effects of the individual elements.

Sulphur, a tramp or residual element, is very detrimental to the transverse strength and impact resistance of steel and is usually restricted to below about 0.02%. However, it affects the longitudinal properties only slightly. It also impairs surface quality and weldability. Sulphur normally appears as *manganese sulphide stringers;* one of the functions of manganese is to combine with sulphur and prevent the formation of a low-melting iron/iron sulphide eutectic. These sulphide stringers enhance the machinability of steel; sulphur is deliberately added to some steels solely for the improvement in machinability that results.

Silicon is added to many carbon and low-alloy steels as a deoxidizer, i.e., it removes dissolved oxygen from molten steel during the steel-refining process. Due to the formation of oxide inclusions, oxygen is an undesirable element in steel which can degrade ductility, toughness, and fatigue resistance. Silicon increases hardenability and has a strengthening effect on low alloy structural steels. It has a moderate effect on strengthening steel; however, it is usually not added for strengthening. Each 0.1% Si increases the yield strength of steel by about 8 MPa. In larger amounts, it increases resistance to scaling at elevated temperatures.

2.2.2 Other alloying elements that affect HSLA Steels

Copper is considered a tramp or residual element in most steels and is restricted to levels below 0.04%. However, approximately 0.20% copper was used to provide resistance to atmospheric corrosion long before it was considered a strengthening agent. Its effect on resistance to corrosion is enhanced when phosphorus is present in amounts greater than about 0.05%. Copper increases the strength of both low- and medium-carbon steels by virtue of ferrite strengthening accompanied by only slight decreases in ductility. In amounts over about 0.60%, copper induces precipitation hardening of the ferrite. Copper can be retained in solid solution even at the slow rate of cooling obtained when large sections are normalized, but is precipitated out when the steel is reheated to about 510 to 605°C (950 to 1125°F). At about 1 % copper, the yield strength is increased about 68 to 135 MPa regardless of the effects of other alloying elements. Copper in amounts up to 0.75% is considered to have only minor adverse effects on notch toughness or weldability. Steels containing about 0.50% copper can exhibit hot shortness with the result that cracks and a rough surface may develop during hot working. One problem with copper in steel is that it cannot be oxidized and removed during steel refining.

Aluminium is widely used as a deoxidizer, removing undesirable oxygen from molten steel, and for control of grain size. When added to steel in specified and controlled amounts, it produces a fine austenitic grain size. Of all the alloying elements, aluminium is the most effective in controlling grain growth.

Boron has no effect on the strength of hot rolled steel but can considerably improve the hardenability of quenched and tempered grades. Its full effect on hardenability is obtained only in fully deoxidized (aluminium-killed) steels. A small amount of boron, e.g., 0.003%, is sufficient to provide ample hardenability in low-alloy steel. However, boron is a strong nitride former and can only achieve its hardenability capability if in elemental form.

Calcium is sometimes used to deoxidize steels. In **HSLA** steels, it helps to control the shape of non-metallic inclusions, thereby improving toughness. Steels deoxidized with calcium generally have better machinability than steels deoxidized with silicon or aluminium. Thus, steels properly treated with calcium do not have the characteristics associated with MnS stringers, i.e. property directionality or anisotropy.

Chromium has a positive effect on hardenability and is an important alloying element in many low-alloy steels. It is often added along with copper to obtain improved atmospheric corrosion resistance, but it also strengthens copper and vanadium-containing steels. In addition to hardenability and solid solution effects, chromium forms several important chromium carbides that are necessary for wear resistance in many steels.

Molybdenum is a potent hardenability element and is found in many low alloy steels. It is an effective strengthener and, in quenched and tempered grades, increases hardenability and decreases susceptibility to temper embrittlement. Molybdenum, like chromium, forms several types of carbides that are important for wear-resistant applications. In addition, it effectively enhances elevated temperature properties, i.e. the creep strength. Creep is an undesirable process that allows steel to slowly elongate under load and eventually the component will fail.

Nickel is added in amounts up to about 1 % in several **HSLA** steels and in amounts up to 5% for high-strength heat treated alloy grades. It is a substitutional element the iron lattice, has a small effect on increasing yield strength. It is an austenite stabilizer and also a vital element in austenitic stainless steels. It moderately increases strength by solution hardening of the ferrite. It will be presented in Chapter four. In **HSLA** steels, it enhances atmospheric corrosion resistance, and when present in combination with copper and/or phosphorus, increases the sea water corrosion resistance of steels. Nickel is often added to copper-bearing steels to minimize hot shortness. Nickel does not form carbide and remains in solid solution.

Niobium (Columbium) is also important in **HSLA** steels for its precipitation strengthening through the formation of niobium carbonitrides. Some microalloyed steels employ both vanadium and niobium. The addition of 0.02% niobium can increase the yield strength of medium-carbon steel by 70 to 103 MPa. This increased strength may be accompanied by a considerable impairment of notch toughness unless special rolling practices are used. The most common of the special controlled rolling practices are low finishing temperatures for final reduction passes and accelerated cooling after rolling is completed. Hot rolled niobium-treated **HSLA** steels are generally produced only in light gauges that can be processed economically by controlled rolling.

Nitrogen in amount up to abut 0.02% has been used to economically obtain strengths typical of **HSLA** steels. For carbon and carbon-manganese steels, such a practice is limited to light gauge products because the increase in strength is accompanied by a drop in notch toughness. In addition, nitrogen dissolves interstitially and it is a very potent strengthener of **HSLA** steels, however it significantly promotes brittle cleavage fracture. Nitrogen additions to high-strength steels containing vanadium have become commercially important because such additions enhance precipitation hardening. Precipitation hardening may be accompanied by a drop in notch toughness, but this often can be overcome by using lower carbon content.

Titanium is important in **HSLA** steels because of the formation of titanium nitride (TiN) precipitates. Titanium nitrides pin grain boundary movement in austenite and thus provide grain refinement. The effects of titanium are similar to those of vanadium and niobium, but it is only useful in fully killed (aluminium deoxidized) steels because of its strong deoxidizing effects. Titanium is a strong deoxidizer but is usually not used solely for that purpose. Another role of titanium is in steels containing boron where a titanium addition extracts nitrogen from liquid steel so that boron, a strong nitride former, remains in elemental form to enhance hardenability.

Vanadium strengthens **HSLA** steels by both precipitation hardening the ferrite and refining the ferrite grain size which will be explained in Chapter four. Although vanadium is a potent hardenability element, its most useful role is in the formation of vanadium nitride and vanadium carbide. The formation of vanadium carbide is important for wear resistance. The precipitation of vanadium carbide and vanadium nitride in ferrite can develop a significant increase in strength, which depends not only on the rolling process used but also on the base composition. Grain size refinement depends on thermal processing (hot rolling) variables as well as vanadium content. In amounts up to 0.10 to 0.12%, vanadium provides increased strength without impairing weldability. Vanadium bearing **HSLA** steels are well suited for welding applications where notch toughness is an important consideration.

Zirconium, expensive and rarely added to steel, can also be added to killed **HSLA** steels to obtain improvements in inclusion characteristics, particularly sulphide inclusions where changes in inclusion shape improve ductility in transverse bending.

Rare earth elements, principally *cerium, lanthanum* and *praseodymium,* play several important roles in **HSLA** steels for sulphide shape control, i.e. the sulphides become rounded instead of stringers. Above and beyond, they can minimize lamellar tearing in welded structures by improving *through-thickness* properties that are critical in constrained weldments. Sulphide inclusions, which are plastic at rolling temperatures and thus elongate and flatten during rolling, adversely affect ductility in the short transverse *(through-thickness)* direction. The chief role of rare earth additives is to produce rare earth sulphide and oxysulphide inclusions, which have negligible plasticity at even the highest rolling temperatures.

2.3 Importance of the impact tests

2.3.1 Significance of the impact tests

Brittle fractures in engineering structures have been a subject of considerable concern ever since it became the practice to weld ships and other large structures. The hull of a welded ship is really one continuous piece of steel. A crack that starts in such a structure can pass completely around the girth of the ship, causing it to break in two, and a number of failures of this nature have occurred as mentioned in Chapter one. Similarly, a welded gas pipeline is also a large continuous piece of steel, and brittle fractures have been known to travel in them with high velocities for distances as long as half a mile.

Brittle fractures in ships have received the most extensive attention. In general, these show that cracks start at some notch or stress raiser. These may be due to faulty design or to accidents of construction, such as arc strikes: points where a welder started his arc, leaving behind a notch in the steel. It has further been observed that brittle failures have almost universally occurred at low ambient temperatures. Finally, the hull has to be in a state of stress, which may be caused by heavy seas. Ship failures that occurred while the ship lay at a dock, however, have been recorded. In the latter case, thermal expansion due to the sun hitting the deck early in the morning can account for the stresses required to propagate fracture. The importance of the impact test lies in the fact that it reproduces the ductile-brittle transformation of steel in about the same temperature range as it is actually observed in engineering structures.

2.3.2 Ductile-to-Brittle transition temperature

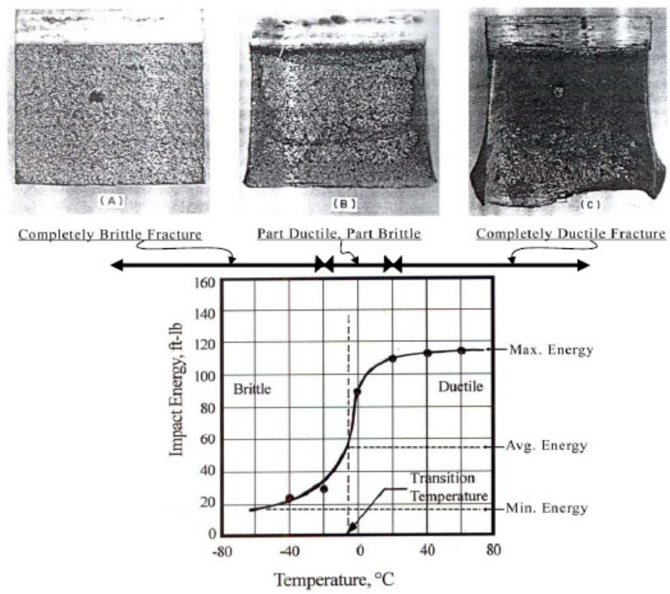


Figure 2.4 A technique of defining the transition temperature.

Source: Htay Aung, 2004, p. 40.

There is no single temperature at which average shipbuilding steel suddenly becomes brittle; the transition occurs more or less over a range of temperatures. It is common practice to speak of the transition temperature of **HSLA** steel, but this needs to be carefully defined, as there are a number of different ways of expressing it. One technique of defining the transition temperature uses the *average energy criterion*, as illustrated in Figure 2.4. The ductile-to-brittle transition is related to the temperature dependence of the measured impact energy absorption.

The impact testing techniques were established so as to ascertain the fracture characteristics of materials. It was realized that the results of laboratory tensile tests could not be extrapolated to predict fracture behaviour. For example, under some circumstances normally ductile metals fracture abruptly and with very little plastic deformation. One of the primary functions of a series of Izod impact tests is to determine whether or not a hull structural material experiences a ductile-to-brittle transition with decreasing temperature and, if so, the range of temperatures over which it occurs. The detailed discussions regarding the impact tests are explained in Chapter three.

2.4 Effects of corrosion and welding on HSLA steels

2.4.1 A fabrication technique used in shipbuilding – welding

Welding may be considered as a major fabrication technique used in shipbuilding. In welding, two or more metal parts are joined to form a single piece when one-part fabrication is expensive or inconvenient. According to Callister, 2000, the joining bond is metallurgical (involving some diffusion) rather than just mechanical, as with riveting and bolting. During arc and gas welding, the workpieces to be joined and the filler material (i.e., welding rod) are heated to a sufficiently high temperature to cause both to melt; upon solidification, the filler material forms a fusion joint between the workpieces.

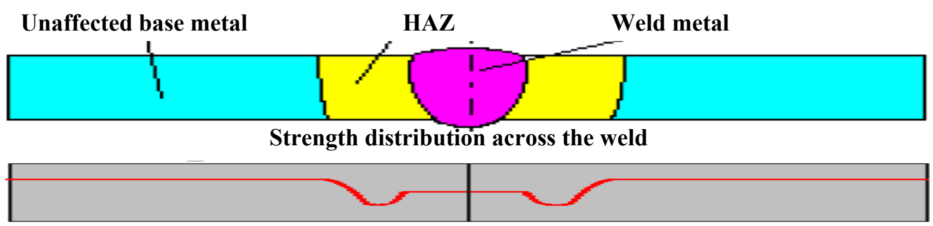


Figure 2.5 The zones in the vicinity of a typical fusion weld and strength distribution.
Source: Adapted from Ashby and Jones, 2002, p. 156.

Thus, there is a region adjacent to the weld which may have experienced microstructural and property alterations; this region is termed the *heat -affected-zone* that was already explained in the previous section. Potential alterations include as illustrated in Figure 2.5:

1. If the workpiece material was formerly cold worked, this heat-affected zone may have experienced recrystallization and grain growth, and thus, a diminishment of strength, hardness, and toughness, as represented schematically in Figure 2.5.
2. Upon cooling, residual stresses may form in these regions weakening the joint and thus failure starts from that area, the red profile in Figure 2.5.
3. This zone, particularly in steels, may have been heated to temperatures sufficiently high so as to form austenite. Upon cooling to room temperature, the microstructural products that are formed depend on the cooling rate and alloy composition. For plain carbon steels with low hardenabilities, normally pearlite and a proeutectoid phase will be present. For alloy steels, however, one microstructural product may be martensite, which is ordinarily undesirable because it is so brittle.

Most ship failures occur from weld joints as mentioned, particularly at the HAZ. Therefore the properties of the unaffected base metals and the metals at HAZ are examined in Chapter three whereas the fatigue strength of welded joints and weld fatigue improvement techniques in hull structures are analysed in Chapter four.

2.4.2 Service conditions – design against corrosion

There is a natural tendency for nearly all metals to react with their environment. The result of this reaction is the creation of a corrosion product which is generally a substance of very similar chemical composition to the original mineral, from which the metal was extracted. The variables in the corrosion environment, which include fluid velocity, temperature, and composition, can have a decided influence on the corrosion properties of the materials that are in contact with it. In most instances, increasing fluid velocity enhances the rate of corrosion due to erosive effects. The rates of most chemical reactions rise with increasing temperature; this also holds for the great majority of corrosion situations. Increasing the concentration of the corrosive species (e.g., H+ ions in acids) in many situations produces a more rapid rate of corrosion. However, for materials capable of passivation, raising the corrosive content may result in an active-to-passive transition, with a considerable reduction in corrosion (Fontana, 1986).

	Platinum
	Gold
	Graphite
	Titanium
	Silver
	316 Stainless steel (passive)
	304 Stainless steel (passive)
↑	Inconel (80Ni–13Cr–7Fe) (passive)
	Nickel (passive)
	Monel (70Ni–30Cu)
Increasingly inert (cathodic)	Copper–nickel alloys
	Bronzes (Cu–Sn alloys)
	Copper
	Brasses (Cu–Zn alloys)
	Inconel (active)
	Nickel (active)
	Tin
	Lead
Increasingly active (anodic)	316 Stainless steel (active)
	304 Stainless steel (active)
	Cast iron
↓	Iron and steel
	Aluminum alloys
	Cadmium
	Commercially pure aluminum
	Zinc
	Magnesium and magnesium alloys

Figure 2.6 Galvanic series of metals and alloys in sea water.

Source: Fontana, 1986.

Cold working, or plastically deforming ductile metals, is used to increase their strength; however, a cold-worked metal is more susceptible to corrosion than the same material in an annealed state. For example, deformation processes are used to shape the head and point of a nail; consequently, these positions are anodic with respect to the shank region. Another example is when a ship hull is fabricated, there is also a tendency to gain stresses with result that of course corrosion might happen. Thus, differential cold working on a structure should be a consideration if a corrosive environment may be encountered during service condition (Htay Aung, 2004).

A typical galvanic series in sea water is shown in Figure 2.6. The positions of the metals in this galvanic series apply only in a sea water environment; and where metals are grouped together they have no strong tendency to form couples with each other. Some metals appear twice because they are capable of having both a passive and an active state. A metal is said to be passive when the surface is exposed to an electrolyte solution and a reaction is expected but the metal shows no sign of corrosion (Fontana, 1986).

It is generally agreed that passivation results from the formation of a current barrier on the metal surface, usually in the form of an oxide film. This thin protective film forms, and a change in the overall potential of the metal occurs, when a critical current density is exceeded at the anodes of the local corrosion cells on the metal surface.

The more common bimetallic corrosion cell problems in ship hulls are formed by the mild steel hull with the bronze or nickel alloy propeller. Also above the waterline problems exist with the attachment of bronze and aluminium alloy fittings. Where aluminium superstructures are introduced, the attachment to the steel hull and the fitting of steel equipment to the superstructure requires special attention. Corrosion testing techniques, rates of corrosion of various shipbuilding hull structural steel plates, and preventive measures are presented in Chapters three and four that follow (see also Appendix D).

3 INTERPRETATION OF THE EXPERIMENTAL RESULTS

The aspiration of this chapter is to interpret the experimental results such as chemical analysis, tensile tests, impact tests, corrosion testing, metallographic investigations and hardness tests of the materials used. Various hull steels from different sources have been used to obtain better results while conducting these experiments. Above and beyond, each of the experimental results will be briefly discussed.

3.1 Background

According to Figure 2.1, it is essential to identify that the quality of a material depends on the relationship between the chemical, mechanical and metallurgical properties of that material. The hull plates which were not necessarily certified Grade A plates but offered by stockists as suitable alternatives, were examined. These plates originated from a number of steel suppliers and had widely differing chemistries. The test certificates did not always reflect the actual chemistries or mechanical properties. Some of the plates exhibited strength levels which were outside the limits for Grade A to facilitate a comparison with the properties of **HSLA** hull steel plates (see Appendices A & B). The experimental techniques used, the results obtained and the discussions in this paper are taken and adopted, due to the time and the research facilities, from the *M.E. Thesis* which was conducted by the author in 2003 - 2004 at two local shipyards, two local steel mills and YTU (Htay Aung, 2004).

However, some of the diagrams and technical details from the *M.E. Thesis* will be skipped while carrying out the present paper. Thus, the experimental methods were carefully designed to produce data as precise as possible at that time. One of the reasons is to analyse the importance of chemical, metallurgical and mechanical properties of hull materials from the point of view of IMO safety assessments such as Goal-Based New Ship Construction Standards, which are discussed in Chapter five. The first experiment was the chemical analysis in which the chemical compositions of the various hull structural shipbuilding steel plates were determined. Next to the chemical analysis would be the mechanical testing such as tensile tests, impact tests, and hardness tests. The mechanical properties of hull structural materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions. This necessarily involves an understanding of the relationships between the microstructures (i.e., internal features) of hull structural materials and their mechanical properties. To fulfil these requirements, corrosion testing and metallographic investigations of these hull steels were also observed and discussed.

3.2 Chemical analysis

3.2.1 Experimental procedures

Chemical analyses of steels are usually performed by wet chemical methods (such as that of ASTM E350) or spectrochemical methods (such as those of ASTM E281 and E282). The wet analysis was used to determine the compositions of various structural steels intended to conduct the entire project. First, the samples were machined, to obtain chips, in accordance with ASTM E59. Then each constituent was determined by wet chemical methods mentioned above. The results were recorded as shown in Table 3.1.

3.2.2 Results and discussion

According to the Table 3.1 (Htay Aung, 2004), it was observed that the sample 1-A to 4-

B contained reasonable carbon content (0.16-0.18%). Maximum manganese content was observed in sample 3 (1.00%) and the rest samples had only reasonable levels (i.e., 0.61-0.99% Mn). The amount of phosphorus in sample 1 was very low, 0.009% whereas that of sample 4 was reasonably high, about 0.023%. Moreover, it was found that the sulphur contents in samples 3 and 4 were between 0.009 – 0.013%, while it was 0.018 – 0.020% in samples 1 and 2. Both sulphur and phosphorus can decrease the fracture toughness of steel, but have been seen to have little effect on the transition temperature, which is discussed later.

Table 3.1 Experimental results of the compositions of the steel plates.

Sample	Thickness (mm)	Chemical Composition (%)							Origin of the plate
		C	Si	Mn	P	S	Cr	Ni	
1-A	10	0.17	0.23	0.69	0.009	0.018	-	-	**ENGLAND**
1-B	10	0.18	0.19	0.64	0.009	0.020	-	-	
2-A	12	0.18	0.33	0.99	0.010	0.020	0.10	-	**CHINA**
2-B	12	0.18	0.33	0.97	0.010	0.020	0.10	-	
3-A	12	0.16	0.19	1.00	0.022	0.011	0.20	0.29	**JAPAN**
3-B	12	0.16	0.187	1.00	0.021	0.010	0.19	0.28	
4-A	12.6	0.18	0.23	0.68	0.023	0.013	0.04	0.01	**UKRAINE**
4-B	12.6	0.18	0.23	0.61	0.022	0.009	0.03	0.01	

Notes: A – denotes for the base metal cut from *Heat-Unaffected-Zone*.

B – denotes for the base metal cut from *Heat-Affected-Zone*.

Source: Htay Aung, 2004, p. 29.

The chemical compositions of the Titanic hull steel were established by various investigators as mentioned in Chapter one. It was deduced that the sulphur and phosphorus level measured in the Titanic hull steel was higher than that of acceptable levels. The role of alloying elements in **HSLA** steels was discussed in Section 2.2.

Chemical analysis determines the percentage compositions of the various elements that make up the structure of an alloy as well as any other impurities present in those alloys. These analyses permit the use of chemically characterized alloyed parts to be qualified for use in very critical applications.

3.3 Tensile tests

3.3.1 Experimental procedures

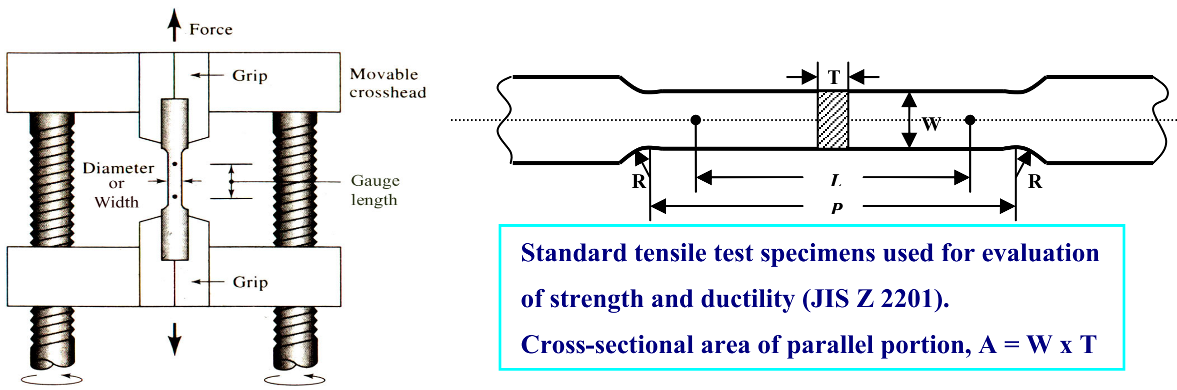


Figure 3.1 Tensile test machine and specimen specifications.

Width **W(mm)**	Gauge length **L (mm)**	Parallel length **P (mm)**	Radius of fillet **R (mm)**	Thickness **T (mm)**
T min.	4√A	1.2 L approx.	15 min.	Thickness of material

Source: Askeland, 2004, p. 149 & JIS Handbook, 2000.

The purpose of this test is to determine the strength of a steel plate in tension. The behaviour of the steel plate during the test is also used as a guide to its ductility. The test was carried out in a testing machine on a specimen previously made in accordance with JIS Z2201 as shown in Figure 3.1 that represents the schematic diagram of the tensile testing machine (left) and a plate or flat specimen (right). The data obtained were recorded, calculated and then tabulated as described in Table-3.2.

3.3.2 Results and discussion

Table 3.2 Experimental results of the strength of the steel plates.

Specimen	Thickness (mm)	YS MPa (ksi)	TS MPa (ksi)	% EL in 50 mm (2 in.)
1-A	10	315 (45.7)	519 (75.3)	22
1-B	10	319 (46.2)	512 (74.3)	21
2-A	12	307 (44.6)	531 (77.0)	21
2-B	12	312 (45.3)	527 (76.4)	19
3-A	12	327 (47.5)	576 (83.6)	21
3-B	12	329 (47.8)	578 (83.9)	23
4-A	12.6	303(44.3)	459 (66.7)	25
4-B	12.6	302 (43.9)	464 (67.3)	25

Source: Htay Aung, 2004, p. 32.

According to the Table 3.2 (Htay Aung, 2004), tensile properties of specimens 1, 2, and 3 meet the properties required for the **HSLA** hull structural steels, however specimens 4 is suitable for ordinary strength hull steel, as described in Appendix B. The relationships between the microstructure and the mechanical properties of the shipbuilding steel plates were already explained in Section 2.1.

The tensile test, if properly conducted and interpreted, is an informative and versatile test, providing information on both the strength and ductility properties of materials. In addition to the direct application of some of the tensile properties in design, practical experience built up around the tensile test makes it useful in specifying materials for particular applications as well as in the control of the uniformity of material supplied for those applications.

3.4 Impact tests

3.4.1 Experimental procedures

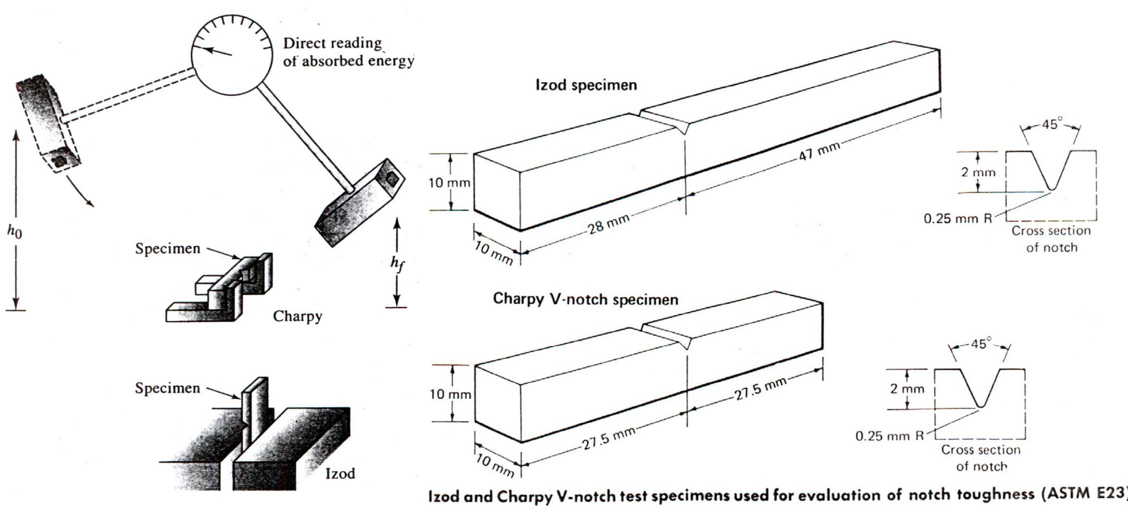


Figure 3.2 Impact test machine and specimen specifications.

Source: ASM Handbook, Vol. 1, 1978, p. 689.

Grade A steel is the most common grade of ship plate used in the construction of merchant ships. However the impact energy and fracture toughness data are not generally available for this grade, mainly because it is not generally required to meet the toughness specification. There are many ships now in use which are beyond their original design life and consequently may contain an increasing number and size of defects which may initiate a catastrophic fracture. In these circumstances the base toughness of steel plate is an important consideration and raises concerns about the safety of sea going vessels. The toughness of the plate used in the fabrication of such vessels is one of the principal areas of concern. The impact test was carried out on a specially prepared specimen in the form of a notched bar. The specimens used in the experiment were 10 mm squares with three notches milled at right angles in accordance with ASTM E23 (Figure 3.2).

The Izod impact testing machine consists essentially of a pendulum which is suspended above and swings across a vice or rest which carries the specimen. A schematic diagram of the impact testing machine can be seen in Figure 3.2 (Left). During the test, the specimen was struck by the pendulum, starting at an elevation h_0, swung through its arc. The specimen was broken and the pendulum reached a lower final elevation h_f. If the initial and final elevations of the pendulum were known, then the difference in potential energy, impact energy, could be calculated. However, the value of the impact energy could be automatically measured by the testing machine. The results of a series of Izod impact tests performed at various temperatures are presented in Table 3.3. These results are also illustrated graphically in Figure 3.3 (See also Figure 2.4).

3.4.2 Results and discussion

While impact tests have proven to be very useful and able to demonstrate the existence of the ductile-to-brittle fracture transition in steel, the results obtained from them are essentially the energy to fracture and the morphology of the fracture, which do not readily lend them to predict structural design problems. At the time when Titanic sunk, there was no theory regarding determination of the ductile-to-brittle transition temperatures from the impact test. Nowadays, it is felt that a much better way of obtaining engineering parameters, such as those giving the relationships between an applied stress and the probable size of an inherent flaw in an available material, is through fracture mechanics.

According to the Table 3.3 and as revealed in Figure 3.3 (Htay Aung, 2004), ductile-to-brittle transition temperatures for specimens 3-A and 3-B were – 3°C, thus suitable for low temperature service conditions while specimens 4-A and 4-B were not, because these specimens had a transition temperature of about 10°C. Specimens 1-A and 1-B had reasonable ductile-to-brittle transition temperatures between – 1.5°C to – 2°C while specimens 2-A and 2-B had moderate impact energy and less ductile compared with those of the specimens 1 and 3.

Table 3.3 Experimental results of the impact properties of the steel plates.

Specimen	Impact Energy, kg-m (J)					Approx. TT
	- 40°C	-20°C	0°C	20°C	40°C	
1-A	3.3 (32.373)	3.5 (34.335)	12.4 (121.644)	16.2 (158.922)	17.0 (166.77)	**- 2 °C**
1-B	3.3 (32.37)	3.5 (34.335)	12.5 (122.625)	16.5 (117.2)	17.0 (166.77)	**- 1.5 °C**
2-A	3.1 (30.411)	3.4 (24.1)	13.9 (136.359)	17.2 (122.1)	18.4 (180.504)	**8 °C**
2-B	3.0 (29.43)	3.3 (32.37)	13.9 (136.359)	17.1 (121.4)	18.5 (181.485)	**8 °C**
3-A	3.2 (31.392)	3.4 (33.354)	12.4 (121.644)	16.2 (158.922)	16.5 (161.865)	**- 3 °C**
3-B	3.2 (31.392)	3.4 (33.354)	12.4 (121.644)	16.1 (114.3)	16.6 (162.846)	**- 3 °C**
4-A	3.9 (27.7)	4.1 (40.221)	13.1 (128.511)	17.0 (166.77)	18.5 (181.485)	**10 °C**
4-B	3.8 (27.0)	4.1 (40.221)	13.0 (127.53)	17.0 (166.77)	18.4 (180.504)	**10 °C**

Note: Approx. TT means Approximate Transition Temperature.

Source: Htay Aung, 2004, p. 35.

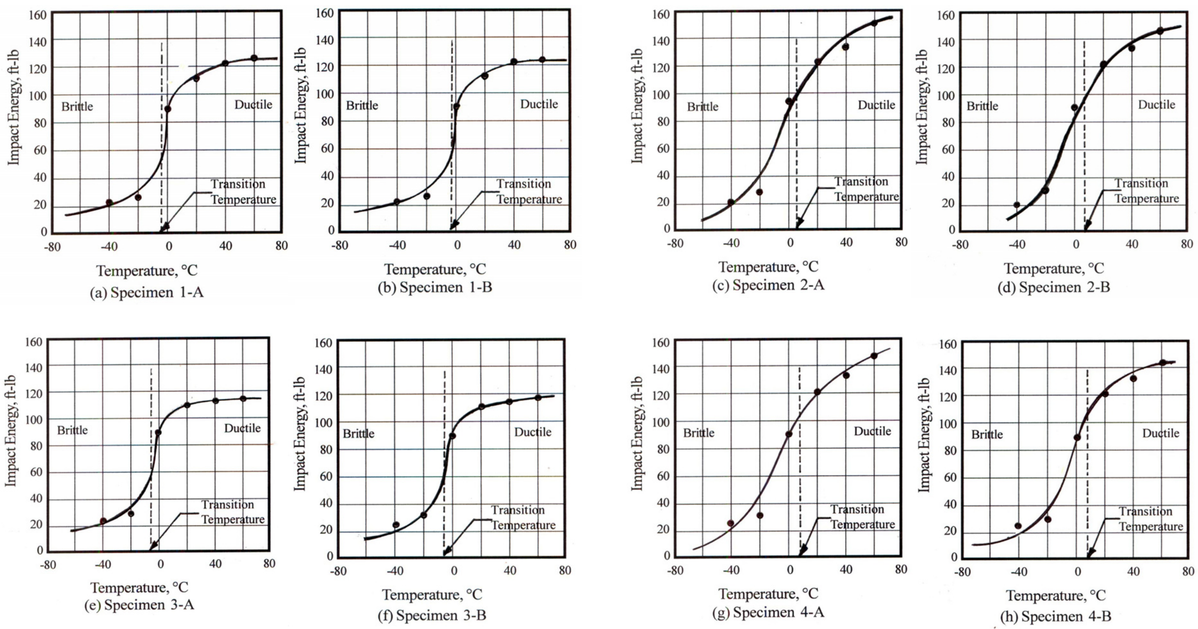


Figure 3.3 Ductile-to-brittle transition temperature curves for the specimens.

Source: Htay Aung, 2004, pp. 37-39.

Systematic investigations into the failures of various types of shipbuilding steel structures have firmly established notch toughness as an important parameter for selecting the right material to be used if subjected to impulsive loading at low temperatures. Perhaps the most thorough such investigation, was that of the brittle fractures encountered in welded transport ships during and immediately following World War II. There were several factors that contributed to the brittle fractures that occurred in ships: the fractures originated at a stress raiser, such a design feature or fabrication defect as described in bulk carrier New Carissa (Figure 1.2); the fractures occurred at low ambient temperatures, as explained in the Titanic. The fractures were characteristically brittle in appearance, even though the failed plates possessed adequate ductility in room temperature tensile tests as discussed in Section 2.3. The investigation revealed that the notch toughness was substantially lower at failure temperatures and below that at room temperatures. On the other hand, a material possesses higher the transition temperatures that create more brittle area material itself. Therefore the selection and designing of hull structural steels with sufficient notch toughness at anticipated service temperatures very is important factors.

3.5 Corrosion testing

3.5.1 Experimental procedures

Specimens with thickness of 25mm square blocks were employed in the laboratory corrosion tests. Standard surface conditions were desirable and necessary in order to facilitate comparison with the results of others. These were done by polishing with No. 120 abrasive paper. After surface preparation, the specimens should be carefully measured to permit the calculation of the surface area. After measuring, the specimen was degreased by washing in a suitable solvent such as acetone, dried and weighed to the nearest 0.1 mg. Then the specimens were exposed to the corrosion environments immediately (Fontana, 1986). The corrosion environments used were fresh water, sea water, aeration at sea water, and oxidizing agent addition to sea water. After 180 days (for specimens 1-A to 2-B) and 120 days (for specimens 3-A to 4-B), the specimens were weighed again and then the corrosion rates were calculated. The data obtained were recorded and then tabulated as described in Table 3.4.

3.5.2 Results and discussion

Corrosion rates (results of a series of corrosion testing) obtained from small specimens must be interpreted with some caution because of discrepancies that may exist with regard to actual equipment materials and the actual process environments and conditions. Experience, good judgment, and knowledge of what one intends to accomplish are helpful. The economical or acceptable corrosion rate depends on many factors including the cost for the finished product. It is well known that a material showing 50 mpy may be economically accepted or a complete absence of corrosion may be the only choice.

Table 3.4 Experimental results of the corrosion rates of the steel plates.

Specimen	IT (days)	Corrosion Rates (avg.), mdd (mpy)				Applicable Environments
		F	S	A	O	
1-A	180	30.33 (5.60)	45.66 (8.43)	57.47 (10.61)	318.55 (58.81)	**F, S, A**
1-B	180	32.01 (5.91)	45.77 (8.45)	56.98 (10.52)	306.75 (56.63)	**F, S, A**
2-A	180	39.70 (7.33)	80.22 (14.81)	139.05 (25.67)	470.27 (86.82)	**F, S**
2-B	180	40.68 (7.51)	80.92 (14.94)	139.21 (25.70)	476.88 (88.04)	**F, S**
3-A	120	23.24 (4.29)	37.48 (6.92)	53.68 (9.91)	221.54 (40.90)	**F, S, A**
3-B	120	23.35 (4.31)	37.65 (6.95)	53.79 (9.93)	221.65 (40.92)	**F, S, A**
4-A	120	43.39 (8.01)	100.86 (18.62)	227.72 (42.04)	506.62 (93.53)	**F, S**
4-B	120	45.23 (8.35)	102.54 (18.93)	233.78 (43.16)	520.38 (96.07)	**F, S**

Notes: **F = Fresh water (pH = 7)** **mdd = mg/dm²/day**
S = Sea water (pH > 7 or pH = 8) **mpy = mils per year** $\} \; mdd \times \frac{1.44}{sp.gr.} = mpy$
O = Oxidizing agent addition to sea water **1 mpy = 0.0254 mm/yr**
A = Aeration at sea water **IT = Immersion Time (days)**

Source: Htay Aung, 2004, p. 43.

According to the Table 3.4 (Htay Aung, 2004), the corrosion rates of specimens 1 and 3 can be accepted for all environments, except oxidizing condition in the sea water. Specimens 2 and 4 can be suitable for fresh and sea water in the absent of other strong oxidizing reagents. Corrosion prevention is an essential consideration in the selection of hull structural steel plates for a given structural application. Corrosion can reduce the load-carrying capacity of a component either by generally reducing its size or by pitting, which not only reduces the effective cross section in the pitted region, but also introduces stress raisers that may initiate cracks. Obviously, any measure that reduces or eliminates corrosion will extend the life of a component and increase its reliability.

Over-all economics, environmental conditions, degree of protection needed for the projected life of the part, consequences of unexpected service failure, and importance of appearance are the chief factors that determine not only whether a hull structural steel part needs to be protected against corrosion, but the most effective and economic method of achieving that protection as well (Roberge, 2000). Guide to corrosion prevention for structural carbon steels in various environments is summarized and mentioned in Appendix B (see also Section 4.3.2).

3.6 Metallographic investigations and hardness tests

3.6.1 Experimental procedures – metallographic investigations

Metallographic investigation is one of the most useful tools in materials' characterization. Microstructures obtained are invaluable to the metallurgical engineer in solving heavy problems in several areas. Metallographic study is also an important tool in analyzing as to why a part failed in its service conditions. First, specimens were cut from the respective structural steels, conducted throughout the entire project. After the specimens were cut off, they were prepared by grinding, rough polishing, and finish polishing.

Afterwards, metallographic polishing papers of grades, 2, 1, 0, 00, 000, and 0000 were used to obtain a mirror-like finish. The surface was then exposed to etching with 2% nital for observation under the optical microscope and a photomicrograph of the specimen was taken. A standard nital solution must contain 1 to 5 ml HNO_3 and 100 ml C_2H_5OH (95%) or CH_3OH (95%). Light from the optical microscope was reflected (scattered) from the specimen surface, depending on how the surface was etched. The results of the metallographic investigations are illustrated in Figure 3.5 together with HRC values.

3.6.2 Experimental procedures – hardness tests

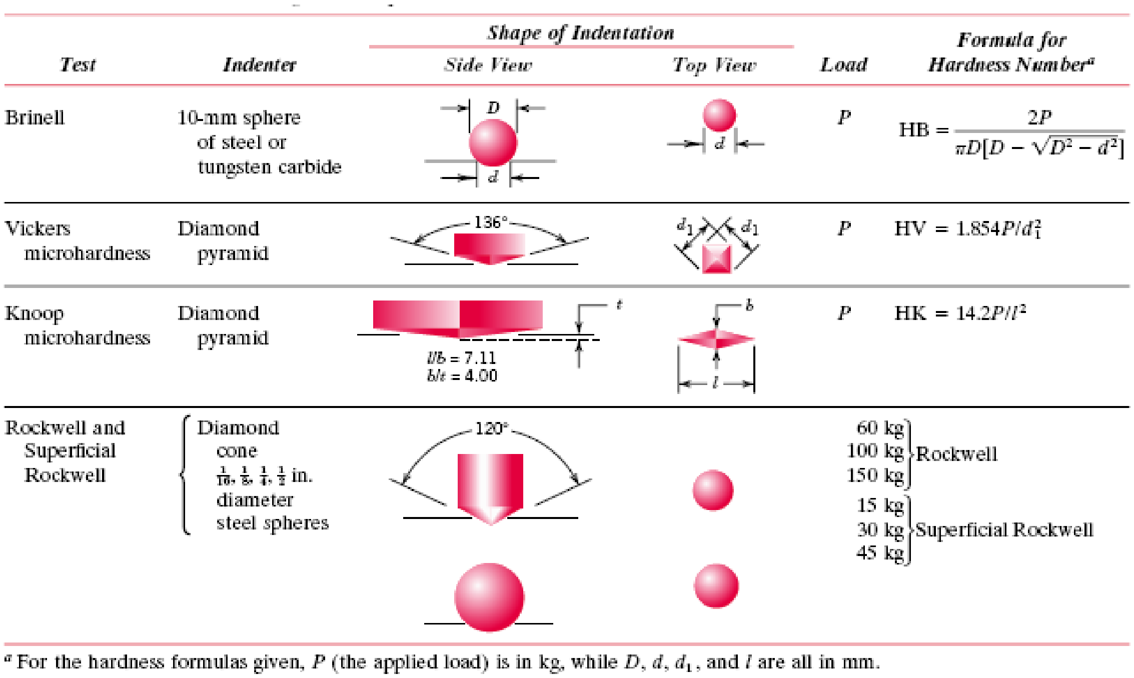


Figure 3.4 Hardness testing techniques.
Source: Callister, 2000.

Another mechanical property that may be important to consider is hardness, which is a measure of a material's resistance to localized plastic deformation. Hardness tests are performed more frequently than any other mechanical test for several reasons. They are simple and inexpensive---ordinarily no special specimen needs to be prepared, and the testing apparatus is relatively inexpensive. The test is non-destructive---the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.

The different types of hardness testing techniques with their characteristic indenter geometries are illustrated in Figure 3.4. Empirical hardness numbers are calculated from appropriate formulae using indentation geometry measurements. However, Rockwell hardness testing technique is used to conduct the hardness numbers measurement for the shipbuilding hull structural steel plates. The specimens used in the test were the output of metallographic study, as explained early. A hardness number was determined by the difference in depth of penetration resulting from the application of an initial minor load (10 kg) followed by a larger major load (150 kg); the test accuracy was enhanced by utilization of a minor load. The test on a specimen was repeated three times to obtain precise data. The conducted test results were mentioned with their respective photomicrographs in Figure 3.5.

3.6.3 Results and discussion

First of all, the microstructures of the structural steels together with the results of hardness tests were illustrated in Figure 3.5 that contain ferrite (white areas), pearlite (dark ones), and elongated inclusions (mostly MnS). Ferrite is structureless and appears similar at all magnifications, but it requires a high magnification to see the almost pearlitic structure because the narrow plates cannot be distinguished under low magnifications and the whole pearlite grain appears dark. Pearlite is stronger than pure iron (ferrite) and is readily machinable, but is not so ductile.

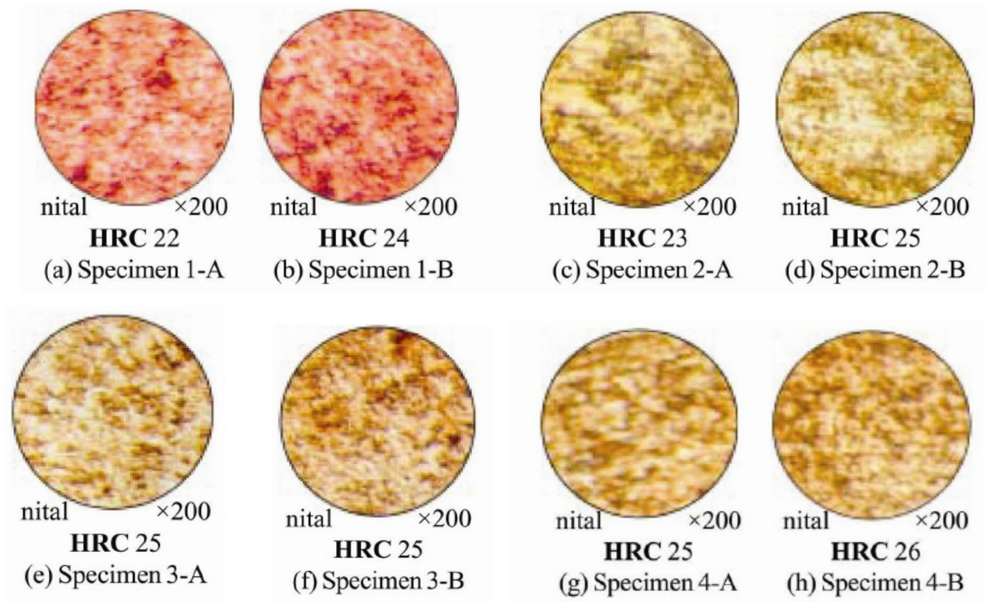


Figure 3.5 Photomicrographs and hardness values of the hull steels.
(The experimental results)

Notes: **White area – Ferrite**
Dark area – Pearlite
Dove-grey elongated inclusions – MnS
HRC – Rockwell-C hardness number
All specimens were as hot-rolled conditions as horizontal in position.

Source: Htay Aung, 2004, p. 45.

However, sulphur is present in hull steels as iron sulphide (FeS is pale yellowish in colour and forms a network in grain boundaries) or manganese sulphide (MnS is dove grey in colour and forms globules in the as-cast conditions). FeS being soft and weak, it causes red shortness, or brittleness, at hot rolling temperatures while MnS globules are elongated into threadlike forms during rolling. Sulphur in this form does not greatly affect the strength of steel and aids machinability. Thus, Mn levels should be reasonably high in all hull structural steel plates to reduce the formation of FeS.

On the other hand, oxides do not become very plastic at the usual hot-working temperatures and consequently do not appear as continuous ribbons under the microscope. They do, however, frequently become distributed in groups, the groups as a whole becoming elongated in the direction of rolling; but the individual particles, more or less angular in form, are not greatly elongated by working. The oxides of iron and manganese appear as spots from light to dark grey in colour.

Finally, aluminium also forms oxides in hull steels; these are usually finely divided and appear as dotted stringers or elongated clouds in the rolling directions. These oxides tend to come out during polishing and leave small pits appearing black under the microscope. The actual alumina particles are lighter in colour. Silica tends to form round, glassy inclusions which are more or less transparent. The oxides of Fe and Mn, being basic, react with the silica to form silicates of those metals. These silicates are grey to black in colour. They are plastic at hot-working temperatures and become elongated into continuous threads. Besides, phosphorus in hull steels forms a chemical compound, iron phosphide, Fe_3P, which goes into the solution in the iron, ferrite, and cannot be seen on photomicrographs.

The hardness test is also of primary concern in selecting shipbuilding structural steel plates. It is a simple alternative to the tensile test that provides an indication of alloy strength, i.e., wear resistance. The extent of the metallurgical changes and the crack susceptibility in the HAZ resulting from the welding thermal cycle will mainly depend on the degree of hardness induced. The hardness values of all specimens studied can be accepted as the hardness values for the hull structural steels grades (Htay Aung, 2004).

4 STRUCTURAL INTEGRITY OF HULL STEELS

The objective of this chapter is to briefly consider the structural integrity of hull steels such as longitudinal and transverse hull strengths. In addition, the failure analysis and fatigue properties of hull materials are introduced. Furthermore, preventive measures such as the strengthening mechanism in HSLA steels and corrosion prevention is discussed.

4.1 Structural strength of ships

Ship structures, while in service, are expected to be subject to strength deterioration such as mechanical damage (e.g., bending and shear stresses), fatigue cracking, and/or welding and corrosion failures which can give rise to important issues in terms of safety, the environment and financial expenditures. It has been recognized that such strength related deterioration is almost always involved in the catastrophic failures of ship structures including total losses.

Htay Aung (2004) stated that the steel plates used in shipbuilding, when in service, are subjected to forces or loads. The mechanical behaviour of a steel plate reflects the relationship between its response and deformation to an applied load or force. Factors to be considered include the nature of the applied load and its duration, as well as the environmental conditions. In addition, service temperature may be an important factor. As mentioned in Chapter one the bulk carrier NEW CARISSA was built with high strength carbon steels that are very sensitive to high temperatures while in service. Sustained elevated temperatures can quickly anneal the steel by removing strengtheners from the matrix of the material that leads to the loss of the strength of the hull plates.

Furthermore, quenching (rapid cooling) of hot steel is known to cause embrittlement, which encourages the reduction of the structural fracture resistance so that the ship broke-up into two pieces (see also section 1.2 and Figure 1.2).

Generally, a ship can be assumed as a beam so that in terms of longitudinal hull strengths, it is important to know how a ship will experience stresses during service conditions such as sagging or hogging. In the case of RMS Titanic, which was built with ordinary mild steels, for example, the huge imbalance stresses caused severe bending of the hull in the amidships section, and during its sinking the forward expansion joint opened up sufficiently to break the two parts so that the hull broke into three pieces (see also section 1.1 and Figure 1.1).

Figure 4.1 Large cracks in the ship's stern of MSC **NAPOLI.**

Source: http://news.bbc.co.uk/2/hi/uk_news/england/devon/6336979.stm

Comstock (1986, p. 194) stated that transverse loads that initiate transverse stresses tend to alter the contour of a ship’s cross section. These transverse stresses may appear from the hydrostatic loadings, structural weights of ship and cargoes, reactions of local weights and due to the movement of cargoes, entering green seas, and/or impact of stormy seas. It is essential to resist such stresses to prevent a ship from damages. Therefore, transverse strengths are also as important as the longitudinal strengths as in the case of MSC NAPOLI which is shown in Figure 4.1. When grounding the ship lost the transverse strengths, which caused longitudinal strength failures of the ship's hull (see also section 1.2 and Figure 1.3).

Jönsson (2007) explains that transverse members that are supporting the longitudinal members to get longitudinal hull strengths especially in the longitudinal bending of the ship tend to deform. If there are no sufficient transverse members, a ship can easily deform by local stresses, pressures from the bottom, rolling, unsymmetrical straining or torsional stress. Stresses are hence indirectly set up in the transverse structures for the strength of the ships. Transverse failures, therefore, can affect the longitudinal hull strengths and could be able to cause buckling. Buckling is typically considered in design in terms of strength along with the critical buckling stress which is a function of the properties of the material such as yield strength and modulus of elasticity.

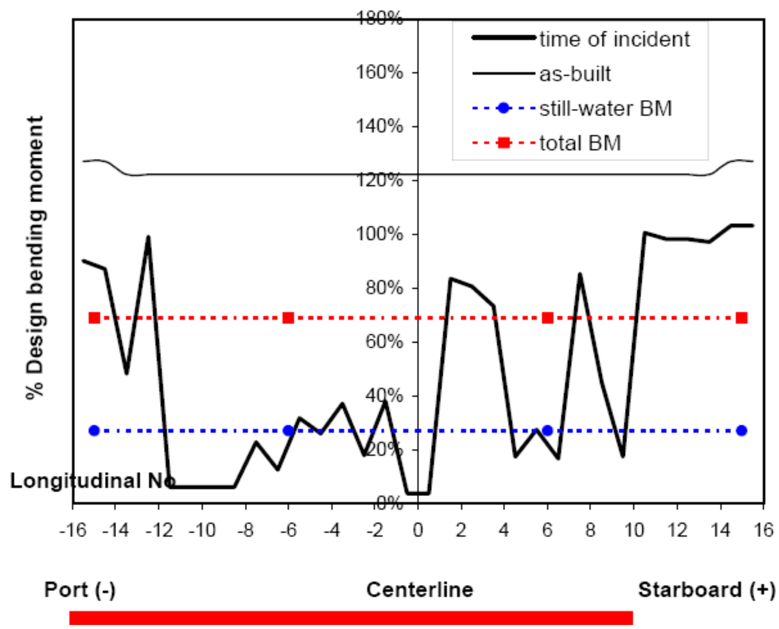


Figure 4.2 Critical buckling strength of deck plating of MV CASTOR.

Source: ABS Technical Report, 2001, p. 22.

Note: Extent of crack - from side shell at the portside to the 10th longitudinal starboard

Figure 4.2 illustrates the bending moment (obtained by multiplying the critical buckling stress with the hull girder section modulus at deck) corresponding to the critical buckling strength of deck plating at the time of MV CASTOR (partly built with high tensile steels in 1977 and the accident that occurred in 2000) incident and as built. These graphs take account of the effects of both the reduced hull girder strength and the reduced buckling strength of individual plate panels due to corrosion wastage and loss of under deck supporting structures (ABS Technical Report, 2001, pp. 19-25).

The Ship Structure Committee-374 (1994, pp. 31-32) mentioned that suitable consideration for buckling is necessary to facilitate the structural strength of the ship. To develop the full compressive and bending strengths of longitudinal or shell plating, the local buckling strength of the flanges and web must exceed the applied compressive loads. Although ship accidents typically cause great concern to the public, maintenance to avoid and repair of the failures is also very costly and intricate. It is therefore of great importance to build up advanced technologies which know how to tolerate for proper management and control of such strength related failures. The following sub-sequence sections will analyse and discuss the structural integrity of hull steels involving the failure analysis and fatigue properties of hull materials, and some preventive measures.

4.2 Failure analysis in hull structures

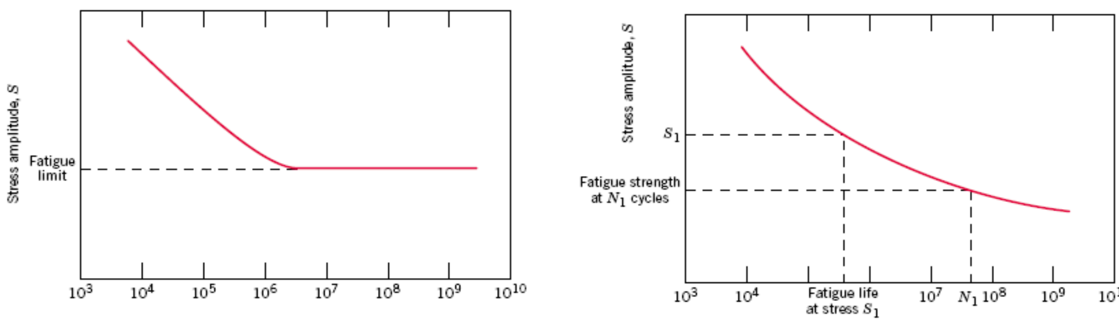
It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously. Comstock (1986, pp. 251-253) disclosed that in service condition, all ships' hulls are experienced by the cyclic loads that lead to the fatigue failures. Application time may be for only a fraction of a second, or it may extend over a period of many years. It is necessary to know the characteristics of the steel plates and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur. Therefore, the structural engineers are responsible for the design calculations while the metallurgists take part in the materials characterizations.

The role of structural engineers is to determine stresses and stress distributions within members that are subject to well-defined loads. This may be accomplished by experimental testing techniques and/or by theoretical and mathematical stress analyses. Materials and metallurgical engineers, on the other hand, are concerned with producing and fabricating materials to meet the service requirements as predicted by these stress analyses. If the structural engineers and the metallurgists cooperate, it will lead to the achievement of the international requirements and minimise vessel disasters globally, and hence could facilitate the reduction of the financial expenditures such as cost of building, running, and maintenance of ships.

4.2.1 A hidden enemy of ship structures - fatigue

Failure, at relatively low stress levels, of structures that are subjected to fluctuating and cyclic stresses is termed as fatigue (Callister, 2000, p. 832). Fatigue is also the progressive, localised, and permanent structural damage that occurs when a material is subjected to cyclic or fluctuating stresses and strains. Buckling (see also section 4.1) is caused by the bending and compressive stresses of the structures while fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress, and plastic strain.

The ASM metals handbook volume 11 (2002, p. 102) states that unless any one of the above three is present, fatigue cracks will not initiate and propagate. The cyclic stress and strain starts the crack; the tensile stress produces crack growth (propagation). Although compressive stress will not cause fatigue cracks to propagate, compression loads may do so. The handbook also explains that the process of fatigue consists of three stages: 1) initial fatigue damage leading to crack nucleation and crack initiation, 2) progressive cyclic growth of a crack or crack propagation, and 3) sudden fracture of the remaining cross section. Ashby (2002, pp. 146-154) clarified that an important feature is that the load is not large enough to cause immediate failure but instead failure occurs after the damage accumulated has reached a critical level.



Cycles to failure, *N* (logarithmic scale) **Cycles to failure, *N* (logarithmic scale)**

(a) a material that displays a fatigue limit **(b) a material that does not display a fatigue**

Figure 4.3 Typical S-N curves for Fatigue Failures.

Source: Callister, 2000.

Fatigue strength and fatigue limit are the two key features in the fatigue phenomenon. The fatigue strength of a structural component is commonly represented in terms of the S-N curve which plots the magnitude of a cyclical stress or stress amplitude (S) against the cycles to fatigue failure (N) to determine the fatigue limits as illustrated in Figure 4.3. In this figure, some materials display the fatigue limit (Figure 4.3, a) while others do not (Figure 4.3, b). Additionally, in low-cycle fatigue ($\leq 10^4$ cycles to fractures), or if the material has an appreciable work-hardening rate, the stresses may also be above the static yield strength whereas in high-cycle fatigue situations ($\geq 10^4$ cycles to fractures), materials performance is commonly characterised by an S-N curve (Ashby, 2002, p. 146). By and large, fatigue failure will occur at a lower number of cycles than the fatigue limit.

Murakami (2002, p. 3) concluded that the S-N curve would be expected to decrease steadily and continuously from a high stress level to a low stress level up to numbers of cycles larger than 10^7 when a fatigue limit is determined from the condition for crack initiation.

The SSC – 436 (2005, p. 1) mentioned that even though the S-N curves used in most fatigue limit predictions, in practice, these data do not necessarily represent shipbuilding industries. It should be possible to improve the prediction accuracy of fatigue analyses in the real shipbuilding processes. The SSC – 400 (1997, p. 4) explains that ship structures experience cyclic stress variations caused by the hydrostatic loadings, seaway motions, structural weights of ship and changes in cargo distributions, dynamic effects such as hull girder whipping, machinery and hull vibration.

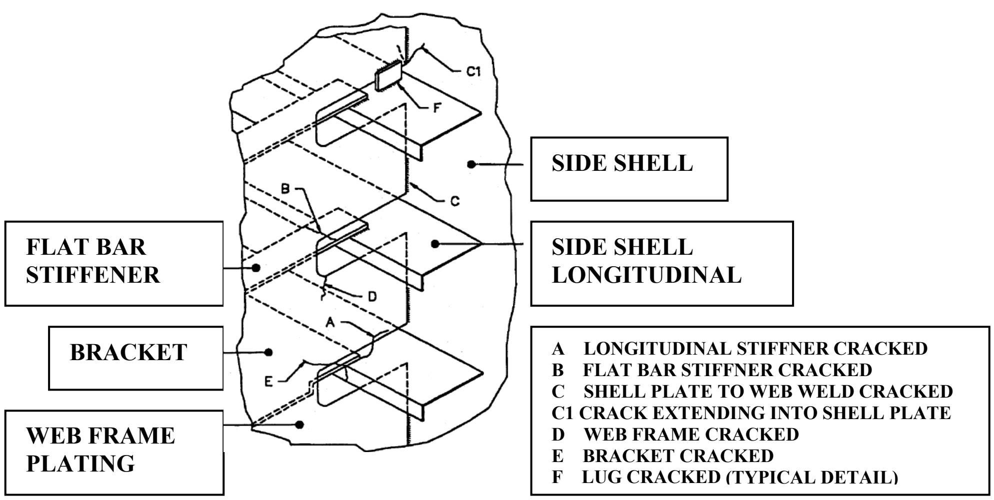


Figure 4.4 Example of Fatigue Cracking in Ship Structural Details.

Source: SSC – 400, 1997, p. 4.

Moreover, these cyclic stresses can cause fatigue cracking in the structural members and details of the ship if they are inadequately designed, the materials from which the ship was constructed is improperly used or poorly maintained. Figures 4.4 summarises the typical examples of fatigue cracking problems in ship structural details. The various ship types are to a greater or lesser extent sensitive to fatigue cracks. However, larger ships are more sensitive than smaller ones. Serious incidents of cracks involving primary or secondary structures can pose a direct threat to the safety and operational capability of a ship. Comstock (1986, pp. 251-253) revealed that steel has a specific fatigue limit and hypothetically can be subjected to an unlimited number of stress cycles without failing as long as this limit is not exceeded.

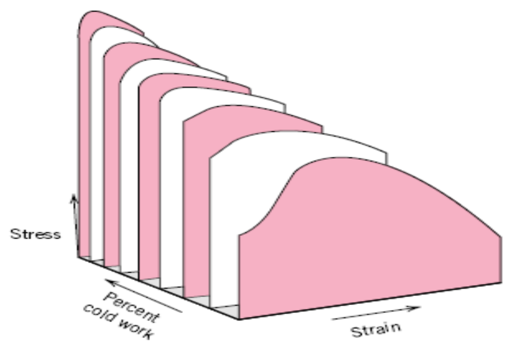


Figure 4.5 Effect of cold work on the stress–strain behaviour for a low carbon steel.
Source: ASM Handbook, Vol. 1, 1978, p. 221.

Furthermore, the fatigue limit of various structural steels is approximately proportional to the ultimate tensile strength of the material and not to the yield point. Normally, the high tensile steels have a higher fatigue limit than ordinary mild steels. As illustrated in Figure 4.5, a low carbon steel can be strengthen by strain hardening or cold working without changing any chemical compositions. Consequently, the steel achieves the required strengths with the same Young's modulus of elasticity; however, it loses ductility, becomes stiffer, and attains internal stresses due to the effect of cold working. Fatigue problems are more likely to occur in ships fabricated from high tensile steel than low carbon steel unless there are some changes in ship design. Therefore, fatigue may become an important consideration for higher yield (or tensile) strength steels than ordinary mild steels.

It is generally accepted that the factors affecting fatigue failures are:

1. Strain-rate [Fatigue cracks initiate and propagate in regions where the strain is most severe];

2. Stress concentrations and structural defects such as scratches, and gouges [because most engineering materials contain defects and thus regions of stress concentration- that intensify strain, most fatigue cracks initiate and grow from structural defects];
3. Direction of the applied stress both in fabrication and service conditions; improper heat treatment and fabrication processes such as welding in shipbuilding processes [Under the action of cyclic loading, a plastic zone develops at the defect tip. This becomes an initiation site for a fatigue crack. The crack propagates under the applied stress through the material until complete fracture results];
4. Compositions and types of materials such as ordinary mild steels, high tensile steels, or **HSLA** from which a ship or a structure is fabricated;
5. Grain size such as coarse or fine grain size [On the microscopic scale, the most important feature of the fatigue process is nucleation of one or more cracks under the influence of reversed stresses that exceed the flow stress, followed by development of cracks at persistent slip bands or at grain boundaries]; and
6. Environmental situations such as corrosive medium, operating temperatures and/or exposure time.

Statistics show that fatigue becomes a more important factor, like other mechanical properties as interpreted in Chapter three, because ships built with high tensile steels experience a lot of marine failures which have occurred during the last three decades. Caridis (2001, pp. 46-48) noted that 44 vessels together with 300 lives were lost throughout the period 1990-92. These failures are due to the lack of structural integrity of the ships. He also points out some important factors that according to the research by Lloyd's Register of Shipping on accident causes show that the average age of ships lost was 19 years, with several of them exceeding 25 years of age.

According to INTERCARGO (2006), during the 10-year period 1996-2005, 96 bulk carriers over 10,000 dwt have been identified as lost (or on average 9.6 ships per year), 372 crew members have lost their lives (or on average 37 deaths per year), 21.11 years was the average age of the bulk carriers lost, and 4.0 million dwt has been lost (or on average 402,514 dwt per year). Their statistics show that structural failures, collisions, flooding, groundings and cargo loading-unloading are major causes of bulk carrier casualties. It is also clarified that apart from the structural failures, groundings and collisions have had a great impact on bulk carrier casualties. The structural failures often involved cracks in the side shell plating, which in general propagated towards the forward section. In the cases in which the crack propagated from areas of high local stress concentrations, this occurred in the presence of extensive corrosion.

4.2.2 Fatigue in service condition – corrosion fatigue

A common cause of the premature failure of structural components is corrosion fatigue cracking. Generally, details of ship structural failures are not published often, probably for commercial or legal reasons (Caridis, 2001, p. 46). From the published information however it is clear that fatigue, principally when it takes place in a corrosive environment, continues to play an important role in ship losses. The effects of corrosion fatigue are an important consideration in the structural integrity of hull steels. The ASM metals handbook volume 11 (2002, p. 252) states that corrosion fatigue is associated with the alternating or fluctuating stresses that occur in a corrosive environment and cause accelerated crack initiation and propagation at a location where neither the environment nor the stress acting alone would be sufficient to produce a crack.

Moreover, corrosion fatigue depends strongly on the interactions among loading, metallurgical, and environmental parameters. An aggressive environment usually has a deleterious effect of fatigue life, producing failure in fewer stress cycles than would be required in a more inert environment. Additionally, fatigue cracking is identified by the presence of several small cracks adjacent to the fracture and of compacted corrosion product on the fracture surface in a corrosive environment that normally introduces stress raisers on the surface. The rough surface that results is detrimental to the fatigue properties of the structural components. An important feature of corrosion fatigue is that the stress range required to cause fracture diminishes progressively as the time and number of stress cycles increase. It is, therefore, impractical and uneconomical to attempt solely to design against corrosion fatigue (ASM metals handbook volume 11).

4.2.3 Fatigue strength of welded joints

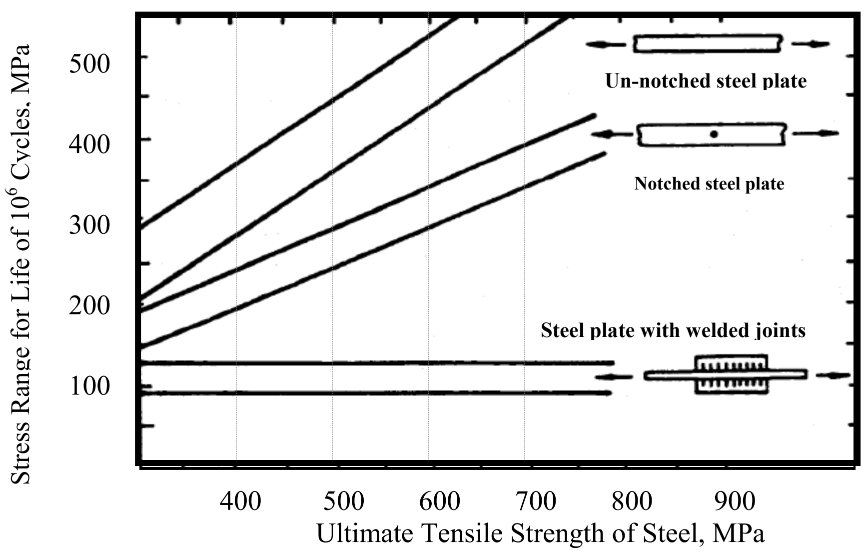


Figure 4.6 Effect of Tensile Strength on Fatigue Strength of Steel.
Source: Adapted from SSC – 400, 1997, p. 7.

The SSC – 400 (1997, pp. 6-7) explains that the fatigue strength of un-notched steel plate and notched plate increases with tensile strength, while the fatigue strength of welded joints is independent of the tensile strength. This can be seen in Figure 4.6 which compares the fatigue strength of steel plate at 10^6 cycles as a function of the ultimate tensile strength of the steels. The use of high tensile and **HSLA** steels in the construction of ships can potentially lead to a significant reduction in the weight of the structure compared with ordinary mild steels, and hence in the subsequent building and operating costs. This reduction is achieved through generally lighter scantlings and higher permissible design stresses, but results in correspondingly higher operational fatigue stresses particularly in those ships made with high tensile steels. The low fatigue strength of welded joints is therefore normally a limiting factor in the design of more efficient ship structures using high tensile steels (see also Chapter one and the previous sections of this Chapter). The SSC – 400 (1997, p. 8) also describes that there are several substantial mechanisms that contribute to the reduction in fatigue strength in welded joints. The main mechanisms include the presence of initial crack-like defects, stress concentration at the weld toe, and residual tensile stresses.

The SSC – 436 (2005, p. 6) classifies that the fatigue strength of welded joints is reduced by three main classes of imperfection as follows:

1) Planar Flaws (or Surface Weld Discontinuities)
    i) cracks and lack of fusion or penetration
    ii) undercut, root undercut, concavity and overlap (on some occasions, undercut and root undercut in welds are treated as shape imperfections).
2) Non-Planar Flaws (or Embedded Weld Discontinuities)
    i) cavities
    ii) solid inclusions, e.g. porosity and slag (on some occasions cavities and solid inclusions are treated as planar flaws).
3) Geometrical / Shape Imperfections
    i) axial and/or angular misalignment
    ii) imperfect weld profile
    iii) undercut and root undercut (if it gives rise to stress concentration effects).

4.3 Preventive measures

4.3.1 The strengthening mechanisms in HSLA Steels

Although an alloy having high strengths, some ductility, and toughness; ordinarily, ductility is sacrificed when it is strengthened. Since hardness and strength (both yield and tensile) are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation. In contrast, the more unconstrained the dislocation motion is, the greater the facility with which a metal may deform is, and the softer and weaker it becomes.

In general, strengths in carbon steels can be attained by the strain hardening (as discussed in section 4.2.1), by the addition of certain alloying elements, or by heat treating the steel. The required strength in **HSLA** steels is developed by the combined effects of (a) fine grain size developed during controlled hot rolling and (b) precipitation strengthening due to the presence of vanadium, niobium and titanium in the composition. The present discussion is confined to strengthening mechanisms for **HSLA** steels by grain size reduction.

The most important method used to increase the strength of **HSLA** steels involves a refinement of the grain size. A fine-grain material is harder and stronger than coarse grain material, since the former has a greater total grain boundary area to impede dislocation motion. A large portion of the greater strength of **HSLA** steels is due to the smaller ferritic grain sizes in them. A major factor in reducing the ferritic grain size is the addition of a small amount of a strong carbide-forming element or elements such as vanadium, niobium and titanium to the **HSLA** steels (see also section 2.2). The ASM metals handbook volume 1 (1978, p. 418) states that in order to achieve good transverse properties, rare earth elements may be added in addition to niobium- or vanadium-containing steels to control the shape of sulphide inclusions. For **HSLA** compositions containing titanium, rare earth additions are not required; titanium itself has the desired effect on the shape of sulphide inclusions.

Hosford (1993) explains that the most important of these elements is niobium, which can have a significant effect on the property of the steel even in an amount smaller than 0.05 percent. The development of a microstructure with a 5μm grain size is complicated; it involves a controlled rolling procedure with a number of hot rolling stages lying within different temperature ranges. However, a significant factor in this sequence is a final hot rolling stage at a temperature (828°C) where recrystallization of the austenite does not occur, so that the austenite grains are in a deformed or worked state when the austenite transforms to ferrite (see Chapter two and Appendix A). Because the austenite grains are flattened during the rolling deformation, the total austenitic grain boundary area is increased, resulting in an increased number of the ferrite nucleation sites. This, in turn, causes an additional decrease in the ferrite grain size.

Htay Aung (2004, pp. 51-52) mentions that while refinement of the grain size is probably the most important mechanism used to increase the strength of **HSLA** steels, it is not the only one. One beneficial effect of grain refinement is revealed by a reduction in the ductile-to-brittle transition temperature (see section 3.4). Improvement in strength is also obtained by precipitation hardening. The microalloying elements can further produce other precipitates in the ferrite. These are finer than those that appear in the austenite and form largely as a result of interphase precipitation at ferrite-austenite boundaries during the transformation of austenite to ferrite. However, these hardening precipitates may promote nucleate inside the ferrite grains as well.

4.3.2 Corrosion prevention in hull structures

The corrosion properties of steels are considerably reduced by the combined effects of the heat of the welding processes during ship fabrication and the service conditions in corrosive environments. The metal adjacent to the weld may heat above the recrystallization and grain growth temperatures when a cold worked metal (see Figure 4.5) is joined by using the welding process. Certain alloying elements such as chromium could be lost at HAZ (see Figure 2.5) that leads to severe failures at weld joints. It is also possible that the galvanic action takes place due to the connection between the base metal and weld metal (as discussed in section 2.4). Thus, corrosion prevention in hull structures is of prime concern.

Roberge (2000, pp. 360-361) summarised that there are basically five methods of corrosion control: 1) change to a more suitable material, 2) modifications to the environment, 3) use of protective coatings, 4) the application of cathodic or anodic protection, and 5) design modifications to the system or component. The ASM metals handbook volume 1 (1978) states that corrosion prevention is an essential consideration in selection of hull structural steel plates for a given structural application. Corrosion can reduce the load-carrying capacity of a component either by generally reducing its size or by pitting, which not only reduces the effective cross section in the pitted region, but also introduces stress raisers that may initiate cracks. Obviously, any measure that reduces or eliminates corrosion will extend the life of a component and increase its reliability.

Htay Aung (2004, p. 47) observes that over-all economics, environmental conditions, degree of protection needed for the projected life of the structural components, and consequences of unexpected service failures are the chief factors from the point of maintenance. These factors determine not only whether a hull structural steel part needs to be protected against corrosion, but the most effective and economic method of achieving that protection as well. The guide to corrosion prevention for structural carbon steels in various environments is summarised in Appendix D.

4.3.3 Weld fatigue improvement techniques

The SSC – 400 (1997, p. 15) reveals that the relatively low fatigue strength of welded joints is because of imperfections at the weld joints such as: 1) Planar Flaws (or Surface Weld Discontinuities), 2) Non-Planar Flaws (or Embedded Weld Discontinuities), and 3) Geometrical / Shape Imperfections. By reducing or eliminating these defects, the fatigue strength of welded joints in ship structures can be increased. This can be accomplished by using some improvement techniques such as improvements in the design of welded details, improvements in the welding and fabrication procedures, and weld fatigue improvement techniques. It have to also be noted that in many cases, better detail design, fabrication and/or weld fatigue improvement techniques can result in improved application and adherence of protective coatings at welds, thereby not only improving fatigue performance, but also corrosion protection.

The SSC – 400 (1997, pp. 18-20) expresses that the fatigue strength of welded joints is achieved by removal of pre-existing crack-like defects at the weld toe, reduction of the notch stress concentration factor by improving the shape of the weld, and/or removal of detrimental tensile residual stresses and/or introduction of favourable compressive residual stresses in the weld toe region. However, it is not feasible to modify the joint geometry or imperfections of welded detail in the existing welded joints to increase their fatigue strengths. A summary of the classification scheme of some weld improvement techniques is mentioned in Appendix E. For more detailed information refer to SSC documents SSC – 357, 366, 379, 383, 390, 396, 397, 401, and 402.

5 GOAL-BASED NEW SHIP CONSTRUCTION STANDARDS AND FINANCIAL CONSIDERATIONS

The rationale of this chapter is to study the correlation between the technical, legal and economical aspects regarding hull materials. It includes an analysis of the newly introduced IMO safety assessments, Goal-based New Ship Construction Standards and the Standards of internationally recognized classification societies. Moreover, some of the financial and economic issues such as cost-benefit analysis in the materials selection process are considered.

5.1 Goal-based New Ship Construction Standards

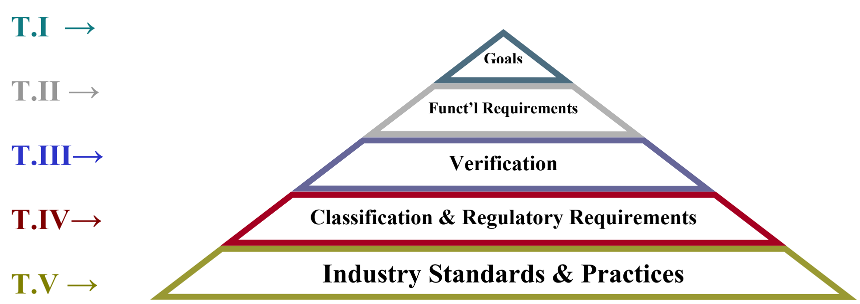


Figure 5.1 Goal-based New Ship Construction Standards

Source: ©Htay Aung, 2007.

The notion of "Goal-based New Ship Construction Standards" was introduced at IMO at the 89th session of the Council in November 2002 through a proposal by the Bahamas and Greece, suggesting that IMO should play a larger role in determining the standards to which new ships are built, traditionally the responsibility of classification societies and shipyards. The Maritime Safety Committee agreed in principle on a five-tier system as illustrated in Figure 5.1, a proposal by the Bahamas, Greece and IACS at MSC 78.

The Committee also agreed that the first three tiers constitute the **GBS** to be developed by IMO, whereas Tiers IV and V contain provisions developed/to be developed by classification societies, other recognized organizations and industry organizations (Hoppe, 2005, pp. 172-173).

5.1.1 Safe and environmentally friendly

Tier I is a set of goals to be met in order to build and operate safe and environmentally friendly ships. MSC 81/6/6 (IMO, 2006 March 7) paragraph 11 states that the current version of the **GBS** at IMO (MSC 80/WP.8), focusing on hull structures, refers to issues like “design life” and “fatigue life” for ships. It is also mentioned that these issues are not yet clearly associated with safety of life at sea and protection of the marine environment. For example, as many parameters are uncertain or unknown at the design stage, it is obvious that a clear interpretation of the term “design life” would refer to a time period where the failure probabilities were below some targets. The terms “safety margin” and “safety factors” also have clear probabilistic interpretations (see also document MSC 80/INF.6).

Moreover, MSC 81/6/14 (IMO, 2006 March 21) expresses that the term “safe” means that specified, acceptable safety levels are met, regarding the risk to persons, to the ship and to the environment. The widely used principle for determining criteria for acceptable risks is the ALARP (As Low As Reasonably Practicable) principle, which dictates that risks should be managed to be “As Low As Reasonably Practicable”. Both risk levels and the cost associated with mitigating the risks are considered, and all risk reduction measures should be implemented, as long as the cost of implementing them is within acceptable limits. The document also indicates that IMO/flag States may set target safety levels related to the protection of life at sea and the environment based on analysis of historic data and political requirements. MSC 82/5/5 (IMO, 2006 September 25) also specifies that ships have to be safe and environmentally friendly, implying that risks associated with ship operations have to be tolerable and ALARP. In addition, both safety factors and safety margins are directly concerned with the materials properties, which are already analysed and interpreted in Chapters two and three. It is also correctly stated that the safety margins account for uncertainties in design parameters.

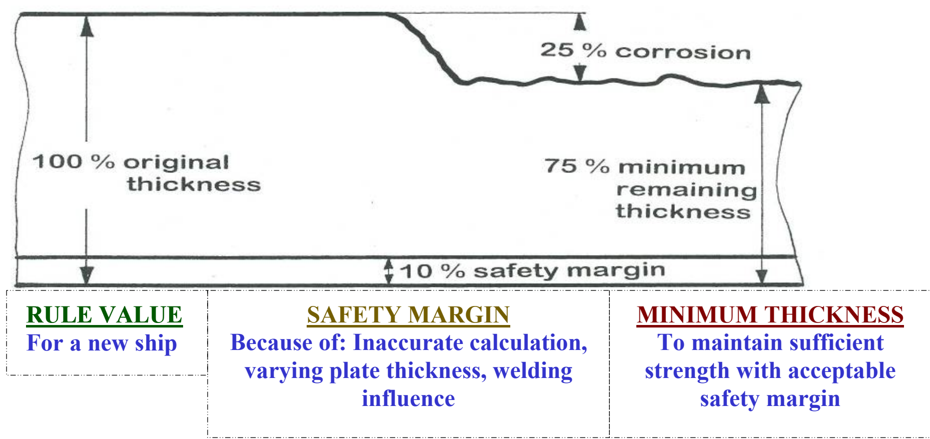


Figure 5.2 Minimum necessary plate thickness.

Source: Jönsson, 2007.

Figure 5.2 (Jönsson, 2007) demonstrates the rule value, the safety margin, the minimum necessary plate thickness during certain period of time for the ship hull. It is, therefore, necessary to have a safety margin in all kinds of steel design in order to allow for several unknown factors such as defects in the material, faults in workmanship, impact loadings, excessive loading, corrosion or deterioration, wear and tear, stress discontinuities, certain assumptions in basic theory and stress analysis.

The term "fatigue life" also has a clear probabilistic interpretation (about 2.5% probability of cracking during "fatigue life"), MSC 80/INF.6. Therefore, the goals to be formulated in Tier I would contain the target safety levels for human safety and environmental safety.

5.1.2 Functional requirements

Functional requirements or Tier II is a set of requirements relevant to the functions of the ship structures to be complied with in order to meet the above-mentioned goals on Tier I, which have been structured to form three groups: design, construction and in-service considerations. Environmentally friendly recycling is considered as well. To meet these requirements, ships are to be designed, constructed and equipped with suitable safety margins to withstand, at net scantlings, in the intact condition, the environmental conditions anticipated during the ship's design life and the appropriate loading conditions, to allow overall close-up inspections or condition measurements for all structural elements (see also Chapter four). For example, the ultimate hull girder capacity and ultimate strength of plates and stiffeners are prime requirements for the structural strength of any type of hull structural steels and thus it is necessary to take into account ultimate strength calculations. It is obvious, that the loss of a function, or a malfunction, affects the safety of the ship. The functional requirements are extremely important for the structural integrity of the ship, as discussed in Chapter four, such as deformation and yielding, buckling, fatigue, welding and corrosion.

As the coating system is important in corrosion protection for any type of ship, it has to be applied and maintained in accordance with manufactures' specifications (see also Appendix D). As shown in Figure 5.2, a corrosion addition has to be included in the net scantling and has to be sufficient for the specified design life. In Tier II of **GBS**, the specified design life is not to be less than 25 years. Ships are to be designed in accordance with North Atlantic environmental conditions and relevant long-term sea state scatter diagrams. Thus, in order to reach the goals with the safety levels defined in Tier I, for each of the functions a target failure probability has to be defined. The setting of these values will have to consider the proportionality between the function failure and its consequences regarding safety, MSC 81/6/14 (IMO, 2006 March 21).

The MSC 82^{nd} session agreed to include ergonomic principles as functional requirements in Tier II. IMO/flag States may set the target failure probabilities based on an analysis of existing ships and Formal Safety Assessment (FSA). Therefore, in order to achieve the target safety levels from Tier 1, the target failure probabilities are required to be set. For more detailed information refer to IMO documents MSC 80/WP.8, MSC 80/6, MSC 80/6/8, MSC 80/6/9, MSC 81/6/INF.6, MSC 81/6/2, MSC 81/6/6, MSC 81/6/WP.7, MSC 81/6/14, MSC 82/5/5, MSC 82/5/11, and IMO Res.A971(24).

5.1.3 Verification

Verification of compliance criteria or Tier III provides the necessary instruments for demonstrating that the detailed requirements in Tier IV comply with Tier I and Tier II. Although there is general agreement among the IMO membership countries that a credible, transparent and auditable verification system is necessary, so far the issue of how exactly to verify compliance with the functional requirements has not been discussed in any detail and is one of the tasks of the MSC and its working group for the future (Hoppe, 2005, p. 178).

Hoppe (2005, p. 179) also mentions that verification, in general, should consist of four steps: 1) verification that prescriptive rules by classification societies are in accordance with the **GBS**; 2) verification that the design of individual ships meets classification societies' rules; 3) verification that the construction of ships meets classification societies' rules; and 4) verification that the ship throughout its life meets applicable rules. The detailed verification framework that is prescribed in Annex 3 of MSC 81/6/WP.7 (IMO, 2006 May 17) is shown in Appendix F.

5.1.4 Classification and regulatory requirements

Technical procedures and guidelines, classification rules and industry standards or Tier IV are the detailed requirements developed by IMO, national Administrations and/or classification societies and applied by national Administrations and/or classification societies acting as Recognized Organizations in the design and construction of a ship in order to meet the Tier I and Tier II requirements.

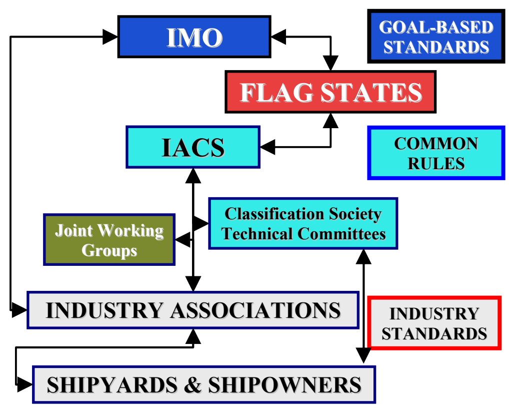


Figure 5.3 Regulatory Process

Source: IACS (2004, May 12)

Figure 5.3 (IACS, 2004 May 12) illustrates the regulatory process, in which the IMO and Flag States are at the top of the regulatory process, by defining the required **GBS** for ship building and by verifying their implementation through IACS common rules and Industry standards. IACS has to keep a dialogue with both the IMO and the Industry on the on-going common rule developments through the establishment of joint working groups and through the Technical Committees of each Member. The Industry has to co-operate with both **GBS** and common rules, and to implement its own standards. However, the industry standards have to be implemented in accordance with both IMO **GBS** and IACS common rules. The following sub-sequence sections discuss the subject of the IMO requirements, IACS requirements and industry standards and practices.

5.1.4.1 IMO requirements

IMO is currently working on the development of **GBS** for ship construction and equipment. In essence, this means that IMO would state what has to be achieved, in terms of, for example, ship design life, safety margins, corrosion targets and the dynamic loads that ships have to be able to withstand. However, it would not be involved in the details of precisely how this has to be done, as discussed in the previous sections. There is no legislation to control or guide these matters so the introduction of a mechanism to ensure harmonised, internationally agreed standards, under the umbrella of IMO will be a positive step in the right direction.

In order to press this idea forward, MSC 80/WP.8 (IMO, 2005 May 18) decided the basic IMO **GBS** principles which are mentioned in the Annex 1 as: broad, over-arching safety, environmental and/or security standards that ships are required to meet during their lifecycle; the required level to be achieved by the requirements applied by class societies and other recognized organizations, Administrations and IMO; clear, demonstrable, verifiable, long standing, implementable and achievable, irrespective of ship design and technology; and specific enough in order not to be open to differing interpretations.

There is no intention that IMO would take over the detailed work of the classification societies, but rather that IMO would state what has to be achieved, leaving classification societies, ship designers and naval architects, marine engineers and ship builders the freedom to decide on how best to employ their professional skills to meet the required standards. However, the key factor is that the standards would be internationally agreed, transparent and capable of being monitored by national Administrations (IMO, 2007 July).

5.1.4.2 IACS requirements

The minimum required yield strength, for instance, for ordinary hull structural steels identified by IACS have to be 235 MPa, see Appendix B. Likewise, other standards are also defined by IACS in order to meet actual design requirements. In terms of incorporation of **GBS** in IMO instruments, however, there is a general agreement that Tier I should be prepared in the form of amendments to SOLAS Chapter II-1, whereas Tiers II and III could be included in a separate Code or a Resolution, to be made mandatory under the SOLAS.

In order to implement **GBS** for new ship construction of bulk carriers and oil tankers, it was agreed that carrying out a pilot project using the IACS Common Structural Rules (CSR) would be advantageous to help uncover issues that had not been discussed and resolved previously and also to determine what, if any, changes were needed. This pilot project has to be completed before amending SOLAS (IMO, 2007 July). The objective of the pilot project is to conduct a trial application of Tier III for oil tankers and bulk carriers with the intention of validating the Tier III verification framework, identifying the shortcomings and making proposals for improvement.

The MSC noted that the Group agreed on a revised version of the Ship Construction File (SCF) and that the SCF, as a result of **GBS**, could become an independent mandatory requirement under SOLAS Chapter II-1 and not part of the classification rules. However, most of the content in the file would emerge from the application of classification rules.
A correspondence group on **GBS** for oil tankers and bulk carriers was established, to monitor the pilot project and disseminate information on its progress and to develop draft SOLAS amendments for the incorporation of **GBS** for oil tankers and bulk carriers in SOLAS Chapter II-1.

5.1.5 Industry standards and practices

Codes of practice and safety and quality systems for shipbuilding, ship operation, maintenance, training, manning, etc. or Tier V includes industry standards and practices that are applied during the design and construction of a ship. It was agreed that Tiers IV and V would be developed by classification societies, other recognized organizations and industry organizations. MSC 81/6/WP.7 (IMO, 2006 May 17) discusses the safety level approach with the view to identifying those things that needed to be done in order to develop **GBS** using this approach, with the understanding that these items would form the basis for a long-range work plan. MSC noted that there may be a need to consider the level of safety for the ship holistically, and to develop **GBS** for the design and construction of new ships, as identified in the High-level action plan of the Organization (IMO, 2006 January 23, Res.A.971 (24)).

MSC 81 also approved the following list of items that needed to be considered in order to develop **GBS** using the safety level approach: development of a risk model; development of **GBS** guidelines; determination of the current safety level; examination and reconsideration the five-tier system and to modify Tier I and Tier II; consideration of the relationship between overall failure of the ship and the contribution of individual failure modes; and the development of a long-range work plan. Moreover MSC has worked, on the basis of a prescriptive approach for **GBS** at its 82^{nd} session, for provisions for hull construction for bulk carriers and oil tankers and of a safety level approach for all other ship types. The work plan also includes an item to explore the linkage between FSA and **GBS** and an item on how **GBS** could be incorporated in the appropriate IMO instruments. A report will be submitted by the groups at MSC 83 in October 2007, in which the report of the pilot project with the IACS CSR will also be considered.

5.2 Financial considerations on HSLA steels

5.2.1 Materials selection process

Materials selection means balancing between adequately good engineering properties and different business-related factors, (Håkansson, 2002). One of the problems in the process is to select the right materials from the many thousands that are available. There are a lot of criteria on which the final decision is normally based. In such cases a reasonable compromise between two or more properties may be necessary.

The major considerations in the choice of the structural steel for ship construction are strength and ductility, fracture toughness and fatigue life, corrosion resistance, ease of use in fabrication and construction, weldability, stock holding and manufacturing cost for the finished product (the ship) as illustrated in Figure 5.4. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired product.

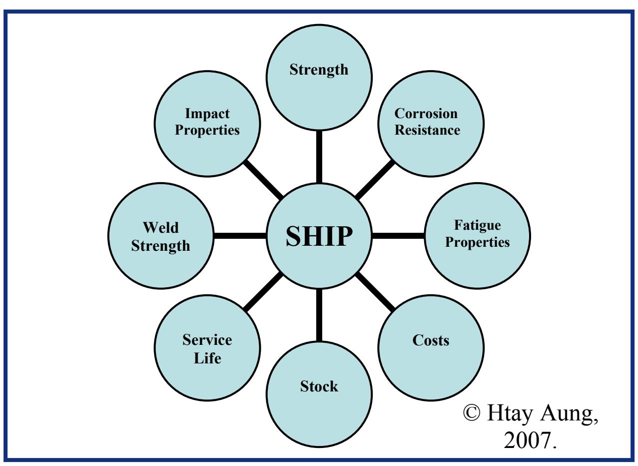


Figure 5.4 Materials Selection.

A material must be characterized by the properties required in service conditions. On only rare occasions does a material possess the maximum or ideal set of properties. The classic example involves strength and ductility; normally, high strength materials will have only limited ductility in the case of high tensile steels. It may, therefore, be necessary to substitute one characteristic for another. **HSLA** steels, however, have the combined properties of weldability as mild steels and higher strength like high tensile steels and thus **HSLA** steels are the proper choice for new ship construction. Håkansson (2002) demonstrates that a useful rule of thumb for the estimation of possible thickness reduction when using steel with increased strength (see Appendix G for detail explanation) is:

$$t_2/t_1 = \sqrt{(YS_1 / YS_2)}$$

Where; t = thickness
YS = Yield Strength
Index 1 = the reference steel
Index 2 = the high strength steel

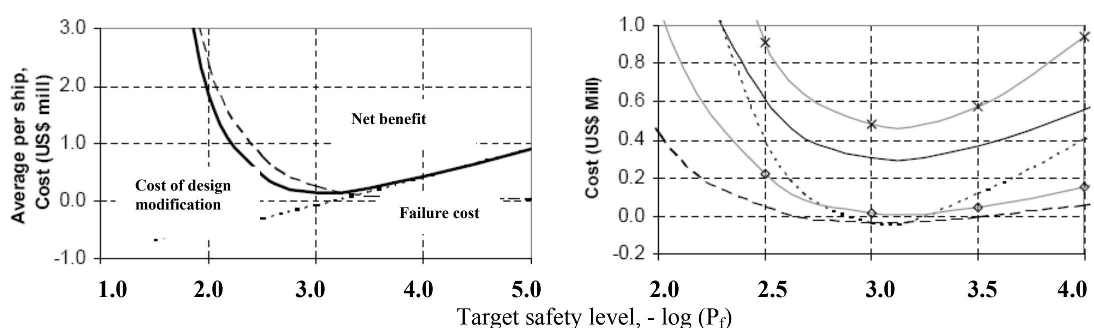
Designing with higher strength steel is not complicated, but deflection, buckling, loading condition and fatigue in weldments have to be considered as discussed in the previous sections. In addition, any deterioration of material properties that may occur during service operation, for instance, significant reductions in the strength, may result from exposure to the ambient temperatures or the corrosive environments. Finally, probably the overriding consideration is that of economics; what will the finished product (ship) cost? A material may be found that has the ideal set of properties but is prohibitively expensive. Here again, some compromise is inevitable.

5.2.2 Cost-benefit analysis

The option of target safety level may be more rationally selected based on cost benefit or cost effectiveness analysis and these are more consistent with the FSA approach. The following example, extracted from MSC 81/6/INF.6 (2006, February 7) submitted by IACS to IMO, demonstrates the cost benefit analysis on the hull structure [due to hull girder collapse which is the most critical failure mode for loss of tanker in sagging in severe weather conditions] together with the cost of the initial design as a function of safety level of the five selected test vessels, Figure 5.5 (a). The figure shows the average result for the test vessels, with equal weight on each case and represents the result of the cost benefit analysis in terms of net benefit, NB, simply defined by:

$$NB = \Delta B - \Delta C$$

Where; ΔB = the economic benefit per ship due to reduced costs associated with failure from the implementation of the risk control measure
ΔC = the additional cost per ship because of the risk control measure (deck strengthening providing a certain reduction in failure probability)



(a) Average result for all vessels **(b) Average results for individual vessel**

Test Vessels				
Vessel Type	**Lpp (m)**	**Breadth (m)**	**Depth (m)**	**Line styles in diagram (b)**
Suezmax	**263**	**48**	**22.4**	——————
Product/Chemical Carrier	**174.5**	**27.4**	**17.6**	— — — — —
VLCC 1	**320**	**58**	**31**	- · - · - · -
VLCC 2	**316**	**60**	**29.7**	——×——
Aframax	**234**	**42**	**21**	——◇——

Figure 5.5 Cost-Benefit Analysis.
Source: MSC 81/6/INF.6 (2006)

The present value related to damage has been accumulated over the lifetime for various target safety levels. The minimum point of the sum of the two curves in Figure 5.5 (a) provides the cost optimum target reliability level; i.e. - log (P_f) = 3.25 (P_f = 5.6 x 10^{-4}). Results are also calculated for the individual ships, as illustrated in Figure 5.5 (b). The cost optimum target level shows little variation between the cases. This indicates that the different vessels have a relatively constant ratio between the extra costs related to safety enhancement compared with the costs associated with failure. It also shows that the impact of safety level on costs is more significant increasing with ship size; i.e. steeper curves for larger vessels. The absolute value of the cost at minimum levels depends on the probability of failure of the initial design (Ma, 2007).

However, the annual probability of failure in principle increases with ship age. If steel renewal is carried out, this may again reduce the probability. In the cost benefit assessment it is considered too optimistic to apply the failure probability corresponding to gross scantlings throughout the entire lifetime. In contrast, it is considered too pessimistic to use the failure probability corresponding to net scantling (i.e. corrosion addition) since this is the minimum state before steel renewal (the target reliability level) is required.

5.2.3 Cost-benefit analysis of HSLA steels

There are several reasons that the calculated annual probability of failure could be higher than in reality in the previous section. One is because the assumptions for the calculation are the North Atlantic environmental conditions; however, ships generally avoid the most severe weather by weather routing. Another reason is that normally the steel strength is significantly higher than the requirement. Therefore, it could be over-protective and costs extra to estimations the optimum safety level.

The question is simply how much money should be invested into the initial design compared with the chance of failure and its associated costs. Which type of steel or steels (MS, **HY**, and **HSLA**) will be the winning alternative for the ship hull structural materials? It is easier said than done because it depends on the purpose of applications, whether it is a tanker, bulk carrier, cruise or war ship. It also depends on the initial new building, operating and maintenance costs. In the case of optimizing the design, the costs related to strengthening of the design can be associated with the fact that the marginal additional cost related to steelwork is likely to be less than the overall unit cost, since the structure is to be welded anyway. Some designs may need steel renewal during their lifetime, whereas other designs may be above the criterion throughout their entire lifetime, saving both materials costs and welding costs.

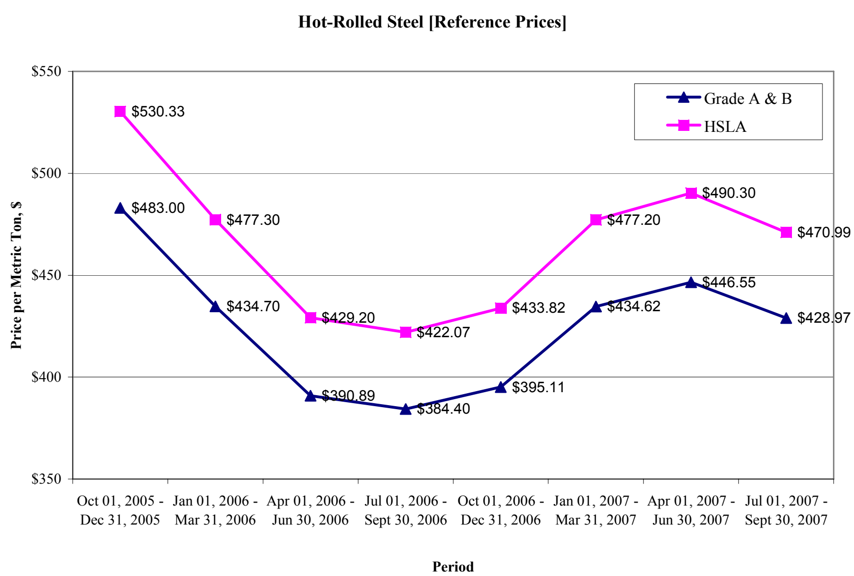


Figure 5.6 Comparison of prices between Ordinary Mild steels & HSLA steels.

Source: United States Department of Commerce (2007)

Additionally, the unit price of steel, a unit price for steelwork, and salvage costs have to be considered when making decisions to build a new ship, because these costs significantly vary depending on the region concerned. Figure 5.6 (United States Department of Commerce, 2007) reveals the price per metric ton for ordinary mild steels and **HSLA** steels during the period of October 2005 to September 2007. From the given information, it could be possible to predict the price of high tensile steels, which will be in between the mild steels and **HSLA** steels and it could be more close to the price of **HSLA** steels. Even though the steel price fluctuates in certain intervals, the curve trends are almost parallel, which means that the different between unit price for the steels is constant (i.e., $ 41.62 in average) for every period.

Normally **HSLA** steels have more advantageous qualities, such as high strength-to-weight ratio (high specific strengths, i.e. strong but light weight), weldability, and ease of fabrication than the MS and **HY** steels; it could be possible to reduce the unit price for steelwork and salvage costs because these are dependent on the weight of steels used. Therefore, it is likely to reduce the initial new building costs (see Appendix G for further explanation). As discussed in Chapter four, **HSLA** steels are strengthened by the fine grain practice and the addition of some alloying elements such as copper and niobium that support the surface smoothness and corrosion resistance of the steels, which is much better than MS and **HY** steels. Furthermore, every 25 μm increase in the average hull roughness results in a power increase of 2 – 3 %, or a ship speed reduction of about 1 % (Nakazawa, 2007). Due to the light weight, high payload (high load carrying capacity), good corrosion resistance and surface smoothness of **HSLA** steels, the ships built with **HSLA** steels have higher transport efficiency and thus are more fuel saving than MS and **HY** steels. Consequently, it is expected to reduce the operating costs and lower the maintenance costs. Therefore, the selection of the optimum steels for ship construction is critical in terms of safety, performance, and economic considerations.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The focus of this research is the study of mechanical properties and microstructures of **HSLA** steels, primarily used in military ship construction. The dissertation has been conducted pursuant of the following objectives: to analyse the importance of properties of hull materials; to recommend the safety of the ship and its structural integrity; to study the rules and regulations such as Goal-Based New Ship Construction Standards; to emphasis the materials selection processes and economics issues; to examine the future standards of shipbuilding materials and to contribute with some knowledge and skills, that is gained from the research to the global maritime industry. This concluding Chapter observes and evaluates in accordance with the above objectives, and draw conclusions from the entire attempt.

Chemical analysis, primary important property of materials, determines the percentage compositions of the various elements that make up the structure of an alloy as well as any other impurities present in those alloys. In the presence of alloying elements the practical maximum carbon content, at which **HSLA** steels can be used in the as-rolled condition, is roughly 0.20%. The carbon content for shipbuilding steels is normally less than 0.30 wt % (Appendix C). Increasing carbon content lowers the impact energy that tends to form martensite or bainite in the microstructure, and therefore, adversely affect the ductile fracture toughness. Thus, the carbon content is reduced to 0.07 wt % in the contemporary **HSLA** steels (see Table 3.1 and Appendix A). However, the amounts of manganese and silicon are normally greater in both **MS** and **HY** steels to compensate the required strength, because the effect of Mn and Si is able to increase both yield and tensile strength by solid solution strengthening of the ferrite in **HSLA** steels. In addition to chemical analysis, one of the most useful tools in materials' characterization is the metallographic investigations which are very useful for the metallurgical and structural engineers in identifying and solving heavy problems in several areas (see Section 3.6). Therefore, these analyses permit the use of the alloyed parts to be qualified for use in very critical applications.

The tensile test, if properly conducted and interpreted, is an informative and versatile test, providing information on both the strength and ductility properties of materials (see Table 3.2 and Appendix B). Due to the higher strength of **HSLA** steels, strength-to-weight ratios of the steels are considerably superior to MS and **HY** steels. Higher strength of **HSLA** steels allows a reduction in plate thickness, stiffener size and results in a ship of lighter weight with greater load carrying capacity; as a result, it could be able to reduce the initial shipbuilding materials costs and operation costs as well (see Section 5.2 and Appendix G). In addition, the tensile properties are useful in designs such as computations of service loads, safety factors and safety margin, and for that reason the tensile test makes it useful in specifying materials for particular applications as well as in the control of the uniformity of material supplied for those applications. Another mechanical property that might be important to consider is hardness value or wear resistance of the materials, which is also of primary concern in selecting shipbuilding structural steel plates (see Section 3.6).

At the time when Titanic sunk, there was no theory regarding determination of the ductile-to-brittle transition temperatures. It was also realized that the results of laboratory tensile tests could not be extrapolated to predict fracture behaviour. For instance, under some circumstances normally ductile metals fracture abruptly and with very little plastic deformation. The impact tests have proven to be very useful and able to demonstrate the existence of the ductile-to-brittle fracture transition in steel, the results obtained from them are essentially the energy to fracture and the morphology of the fracture. The accomplished impact test results of shipbuilding steels were mentioned in Table 3.3 and the trends of typical S-curves were illustrated in Figure 3.3 while the IACS requirements were expressed in the Appendix B. Systematic investigations into the failures of various types of shipbuilding steel structures have firmly established notch toughness as an important parameter for selecting the right material to be used if subjected to impulsive loading at low temperatures. Therefore, there are many benefits from the impact tests if properly conducted before a ship is built.

Another factor to be considered is to determine not only whether a hull structural steel part needs to be protected against corrosion, but also the most effective and economic method of achieving that protection. It is well known that a material showing *50 mpy* may be economically accepted or a complete absence of corrosion may be the only choice (see Section 3.5). It is possible to reduce the plate thickness in both **HY** and **HSLA** steels due to their higher strengths, however, the corrosion is the major problems in the **HY** steels rather than in **HSLA** steels because **HSLA** steels can endure corrosion due to certain alloying elements in them such as niobium and copper (see Section 2.2). The corrosion properties of steels are considerably reduced by the combined effects of the heat of the welding processes during ship fabrication and the service conditions in corrosive environments. The cost for corrosion protection is part of the maintenance cost and hence, corrosion prevention in hull structures (Appendix D) is of prime concern.

A huge amount of welding is required to construct a ship and it is importance to have the structural integrity of the vessel, careful welding processes are severely adhered to. Even small defects in weldments are able to create the initiation point for larger cracks; as a consequence fracture and failures originates from the weld joints. In addition, the majority of ship failures occur from weld joints, particularly at the HAZ; that is because certain alloying elements such as chromium could be lost at HAZ, which leads to severe failures at weld joints (see Section 2.4). It is also possible that the galvanic action takes place due to the connection between the base metal and weld metal. Therefore the properties of the unaffected base metals and the metals at HAZ have to be examined. It is feasible to modify the joint geometry or imperfections of welded details in the existing welded joints to increase their fatigue strengths; however, it is not economically practicable (see Section 4.3.3 and Appendix E).

The cyclic stresses or the hidden enemy of ship structures is fatigue. During operation, it could be able to cause cracking in the structural members and details of the ship due to fatigue. Additionally, the fatigue limits of various structural steels are approximately proportional to the ultimate tensile strength of the material and not to the yield strength (see Section 4.2). In general, **HSLA** steels and **HY** steels have a higher fatigue limit than ordinary mild steels. However, there are many fatigue problems encountering the ships built with **HY** steels, because these steels are very sensitive to cyclic stresses. The fatigue properties of the hull structural materials have to be carefully considered for the structural integrity of the ship and its longitudinal hull strength. It is, therefore, necessary to have safety standards in all kinds of steel design in order to allow for several unknown factors such as defects in the material, impact loadings, excessive loading, fatigue limits, corrosion or deterioration, wear and tear, stress discontinuities, certain assumptions in basic theory and stress analysis.

Goal-based New Ship Construction Standards is run by IMO currently in terms of ship design life, safety margins, corrosion targets and the dynamic loads that ships have to be able to withstand. However, there is no legislation to control or guide these matters so the introduction of a mechanism to ensure harmonised, internationally agreed standards, under the umbrella of IMO, will be a positive step in the right direction (see Section 5.1 and Appendix F). In order to achieve the IMO **GBS**, it is necessary to have sufficient well qualified human resources to set up rules and regulations that require designing the safety and characterization of shipbuilding materials. This may be accomplished by experimental testing techniques and/or by theoretical and mathematical stress analyses as discussed in the previous Chapters.

The role of structural engineers, who determine stresses and stress distributions within structural members that are subject to well-defined loads, is very important. Materials and metallurgical engineers, on the other hand, are concerned with producing and fabricating materials to meet the service requirements as predicted by these stress analyses. If the structural engineers and the metallurgists cooperate, it will lead to the achievement of the international requirements and minimise vessel disasters globally, and hence could facilitate the reduction of the financial expenditures such as building, running, and maintenance costs of the ships.

The selection of the optimum steels for ship construction is critical in terms of safety, performance, and economic considerations. As mentioned above, reduction of plate thickness not only can reduce the materials costs and the weight but also costs for the welding because the welding costs normally are calculated based on the total weight of the steels used in ship construction. Due to the light weight (because of high strength-to-weight ratio), good corrosion resistance and surface smoothness of **HSLA** steels, the ships built with **HSLA** steels have higher efficiency, and more fuel saving than MS and **HY** steels. Consequently, it is expected to reduce the initial building cost, the operating cost and lower the maintenance cost (see Section 5.2 and Appendix G). All in all, the total cost (the initial cost, the operating cost and the maintenance cost) for ships built with **HSLA** steels is practically not much higher than that for the ships built with either **HY** steels or **MS** steels. Therefore, it is much better to choose expensive **HSLA** steels rather than cheaper ordinary mild steels to build a new ship from the financial considerations points of view.

6.2 Recommendations

It is recommended that all material characterization processes are considered during the ship construction phase. They will impact operational features downstream because they play a major role in many aspects.

It is also suggested that the reduction of plate thickness due to higher strength of steels is achieved through generally lighter scantlings and higher permissible design stresses, but it results in correspondingly higher operational fatigue stresses and buckling in the ships. For this reason, careful attention is paid to buckling modes of overall structures and thicker plate is often essential even when its specific strength is overmatched to the service conditions.

The weldability of a hull structural steel is vital because there are noteworthy demands to reduce welding costs. However, it could be possible to produce flaws and adverse effects on the service performance of the ship in operation unless welds are done carefully. Therefore, it is proposed not only to study welding, the properties of the unaffected base metals and the metals at HAZ, but also to examine the weldability of the hull structural steels.

In several cases corrosion is considered only when damage has occurred; by this time counteractive measures may be several times the cost of original materials. Normally, coatings are used to protect the ship hull; however, they require a considerable amount of care during application and regular maintenance and hence coating is a never-ending process. Therefore, it is advised that corrosion damage can also be mitigated by cathodic protection, either by sacrificial anodes or by impressed current systems not only for the longer life of the steels but also for the reduction of overall maintenance costs.

It is also recommended that fracture toughness is one of the most important attributes of hull structures beside the strength, weldability and corrosion properties of the hull structural materials. The hull structural steels must have an adequate amount of fracture resistant under high impact loads at temperatures as low as possible, compared with operational temperature range. The combination of dynamic loading and cracks or defects in areas of stress concentration, may result in unimpeded, rapid crack propagation through the material in the transition scheme. Therefore, steels with high fracture toughness are noticeably prime choices to limit damage propagation. This allows them to withstand high intensity loading and remain ductile, sustaining damage without rupture or fracture. Alloying and processing methods are likely to produce the steels with very low transition temperatures (high values of fracture toughness); however, this can increase cost and reduce availability of the materials.

Finally, the following further investigations are necessary in order to gain a deeper understanding and the best and accurate selection of the shipbuilding materials globally;

1. accident investigations, failure modes and failure analysis of ship structures,
2. fracture mechanics, fatigue tests, bend tests and welding tests,
3. impact of new ship construction strategy and costing strategies,
4. optimising the fuel economy for upcoming ships, and
5. ship recycling processes.

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APPENDIX [A] – Required chemical compositions for hull structural steels.

Type	Grade	Chemical Composition (wt. %)									
		C	Mn	S	P	Si	Cu	Ni	Cr	Mo	V
Ordinary Mild Steels[1]	A	0.21 max	2.5 x C	0.035 max	0.035 max	0.35 max	-	-	-	-	-
	B	0.21 max	0.80-1.10	0.035 max	0.035 max	0.35 max	-	-	-	-	-
	D	0.21 max	0.60-1.35	0.035 max	0.035 max	0.10-0.35	-	-	-	-	-
	E	0.18 max	0.70-1.35	0.035 max	0.035 max	0.10-0.35	-	-	-	-	-
Higher Strength Steels[2]	AH32	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
	DH32	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
	EH32	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
	AH36	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
	DH36	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
	EH36	0.18 max	0.90-1.60	0.035 max	0.035 max	0.10-0.50	0.35 max	0.40 max	0.25 max	0.08 max	0.10 max
Extra High Strength Steels[3]	ASTM A543	0.23 max	0.10-0.40	0.04 max	0.035 max	0.20-0.35	-	2.60-3.25	1.50-2.00	0.45-0.60	0.03 max
	HY-80	0.18 max	0.10-0.40	0.025 max	0.025 max	0.15-0.35	-	2.00-3.25	1.00-1.80	0.20-0.60	-
	HY-100	0.20 max	0.10-0.40	0.025 max	0.025 max	0.15-0.35	-	2.25-3.50	1.00-1.80	0.20-0.60	-
High Strength Low Alloy Steels[4]	ASTM A710	0.07 max	0.40-1.65	0.025 max	0.025 max	0.40 max	1.00-1.30	0.70-1.50	0.60-0.90	0.15-0.25	-
	HSLA 80	0.05 max	0.75-1.85	0.025 max	0.025 max	0.05-0.35	0.20 min	1.50-5.60	0.60-0.90	0.15-0.25	0.02 min
	HSLA 100	0.08 max	0.80-2.25	0.015 max	0.015 max	0.10-0.90	0.20 min	1.50-5.60	0.60-0.90	0.15-0.25	0.02 min

Notes:

1. For all grades exclusive of Grade A shapes and bars the carbon content +1/6 of the manganese content is not to exceed 0.40%. The upper limit of manganese may be exceeded up to a maximum of 1.65% provided this condition is satisfied. A maximum carbon content of 0.23% is acceptable for Grade A plates equal to or less than 12.5 mm (0.5 in.) and all thicknesses of Grade A shapes. Grade D may be furnished semi-killed in thickness up to 35 mm (1.375 in.) provided steel above 25.0 mm (1.00 in.) in thickness is normalized. In this case the requirements relative to minimum Si & Al contents and fine grain practice do not apply.
2. The elements Cu, Ni, Cr, Mo, and V need not be reported on the mill sheet unless intentionally added. Grade AH 12.5 mm (0.50 in.) and under in thickness may have a minimum manganese content of 0.70%.
3. Extra high strength hull structural steels developed for navy ship construction; all of them are quenched & tempered steels.
4. **HSLA** steels are similar to ASTM A710 which is standard specification for low-carbon age hardening steels.

Source: Adapted from ABS Rules for Materials and Welding (2007), pp. 7-54, ASM Metal Handbook vol. 1, 1978, pp. 185, 403-420 & Storch (1995), pp. 113-115.

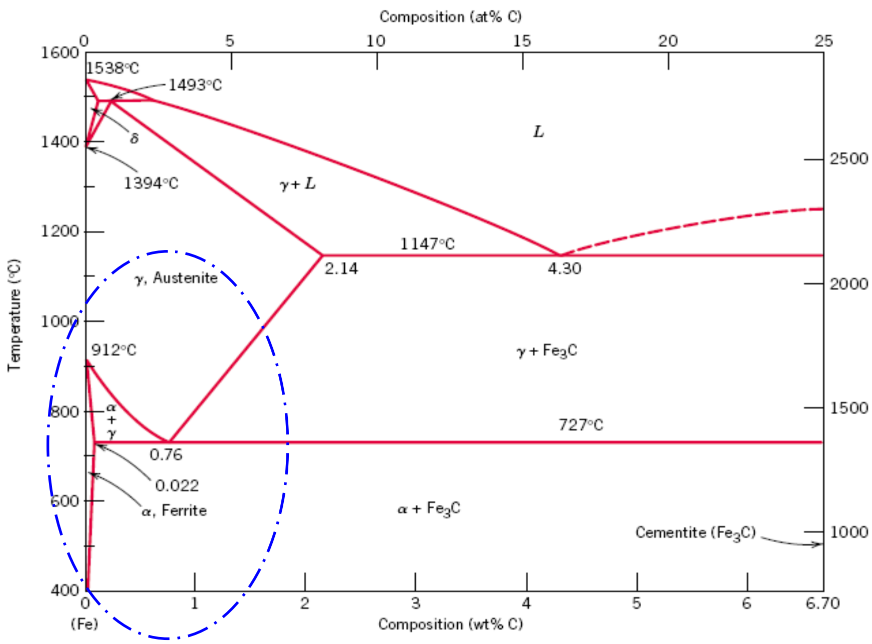
APPENDIX [B] – Required mechanical properties for hull structural steels.

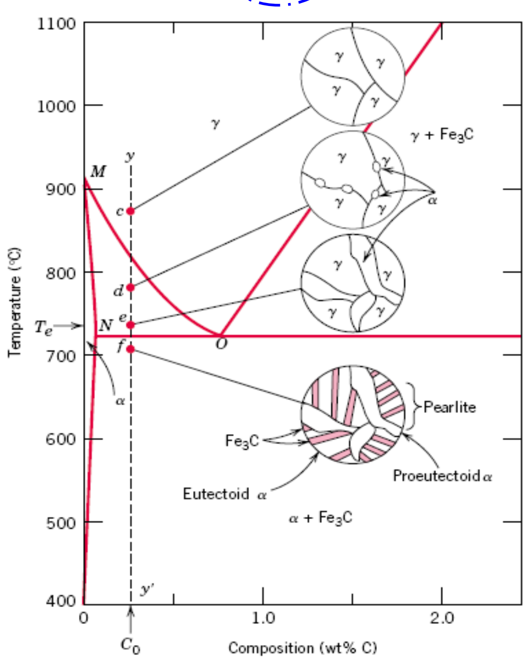
Type	Grade	Tensile Properties			Charpy V- Notch Impact Test	
		YS [MPa]	TS [MPa]	% Elong.	Test Temp. [ºC]	Average Impact Energy kg-m (J)
Ordinary Mild Steels	A	235-250	400-520	20-22	-	-
	B	235-250	400-520	20-22	0	2.8 (27.47)
	D	235-250	400-520	20-22	- 10	2.8 (27.47)
	E	235-250	400-520	20-22	- 40	2.8 (27.47)
Higher Strength Steels	AH32	315 min	465-586	18-22	-	-
	DH32	315 min	465-586	18-22	- 20	3.5 (34.34)
	EH32	315 min	465-586	18-22	- 40	3.5 (34.34)
	AH36	351 min	490-620	19-22	-	-
	DH36	351 min	490-620	19-22	- 20	3.5 (34.34)
	EH36	351 min	490-620	19-22	- 40	3.5 (34.34)
Extra High Strength Steels	ASTM A543	586 min	720-790	16-18	These grades are used for special purpose ships, for instance, navy and surface ships. However, the impact values of these steels are generally not mentioned in class rules. [The author]	
	HY-80	550 min	690-1035	18-20		
	HY-100	690 min	690-1035	16-18		
High Strength Low Alloy Steels	ASTM A710	350-620	415-690	18-20		
	HSLA 80	550 min	580-620	22-25		
	HSLA 100	690 min	720-1080	21-22		

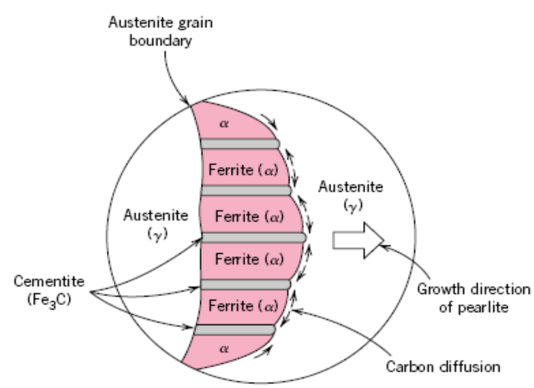
Note: The code ASTM stands for “American Society for Testing and Materials”.

Source: Adapted from ABS Rules for Materials and Welding (2007), pp. 7-54, ASM Metal Handbook vol. 1, 1978, pp. 185, 403-420 & Storch (1995), pp. 113-115.

APPENDIX [C] – The iron–iron carbide phase diagram.







Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows.

Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.30 wt%C).

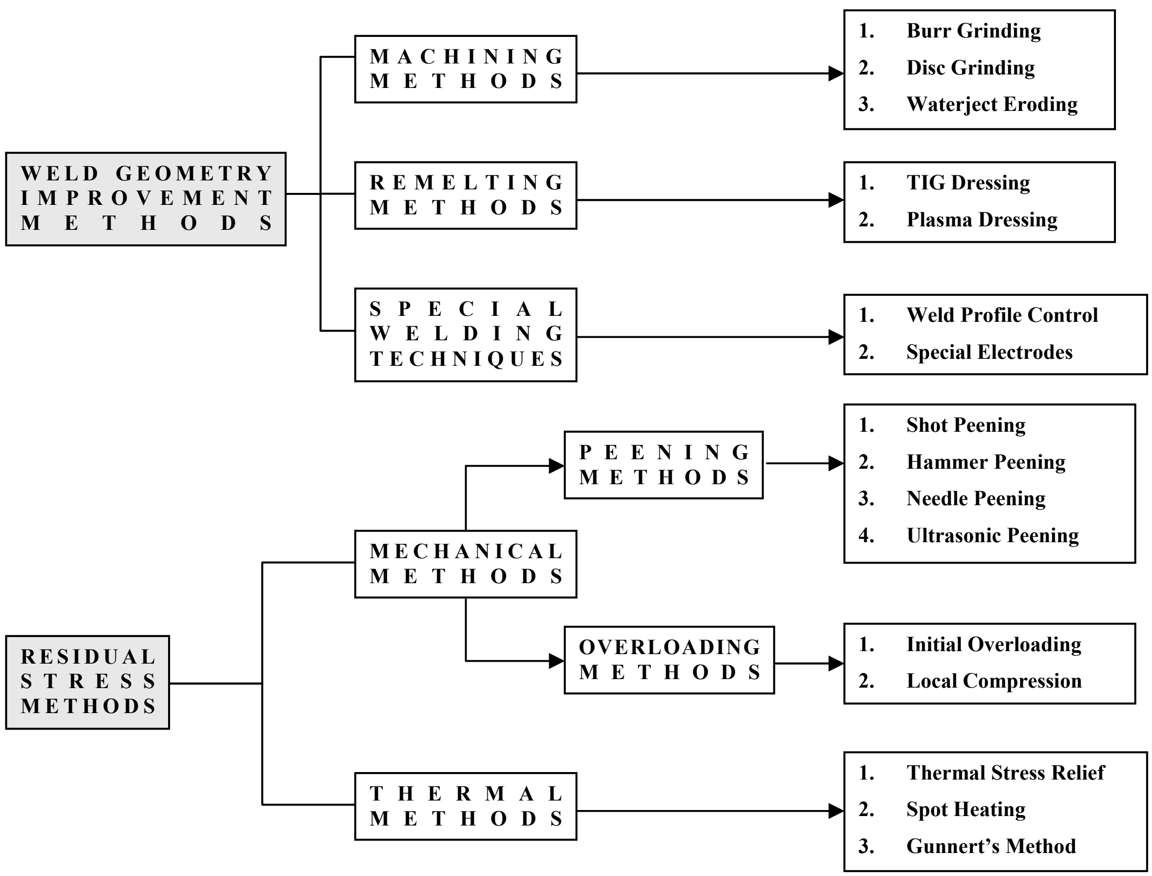
Source: Adapted from Callister, 2000.

APPENDIX [D] – Guide to corrosion prevention for carbon steels in various environments.

Preventive Method	Fresh water	Seawater	Steam system	Acids and pickling baths
Metal coatings; electroplating, galvanizing	Galvanizing used in potable water	Not recommended	Not recommended	Not recommended
Painting; chemical treatment, priming and painting	Fairly effective	Special paint systems used	Not recommended	Not recommended
Cathodic protection	Fairly effective with organic coatings	Very effective	Not recommended	Effective under special conditions
Inhibitors; liquid and vapour	Effective in some application, especially cooling waters	Fairly effective in some applications	Very effective	Very effective
Alloying addition to steel	Not effective	Only effective with much alloying	Chromium-Molybdenum steels are very effective	Only effective with much alloying
Removal of oxygen form environment	Seldom used	Very effective, especially in desalination and hot seawater	Very effective	Not recommended
Removal of more noble metals; elimination of galvanic couples	Effective	Necessary	Advisable	Not effective
Organic coatings other than paint	Fairly effective with cathodic protection	Used to advantage with cathodic protection	Not recommended	Have been used

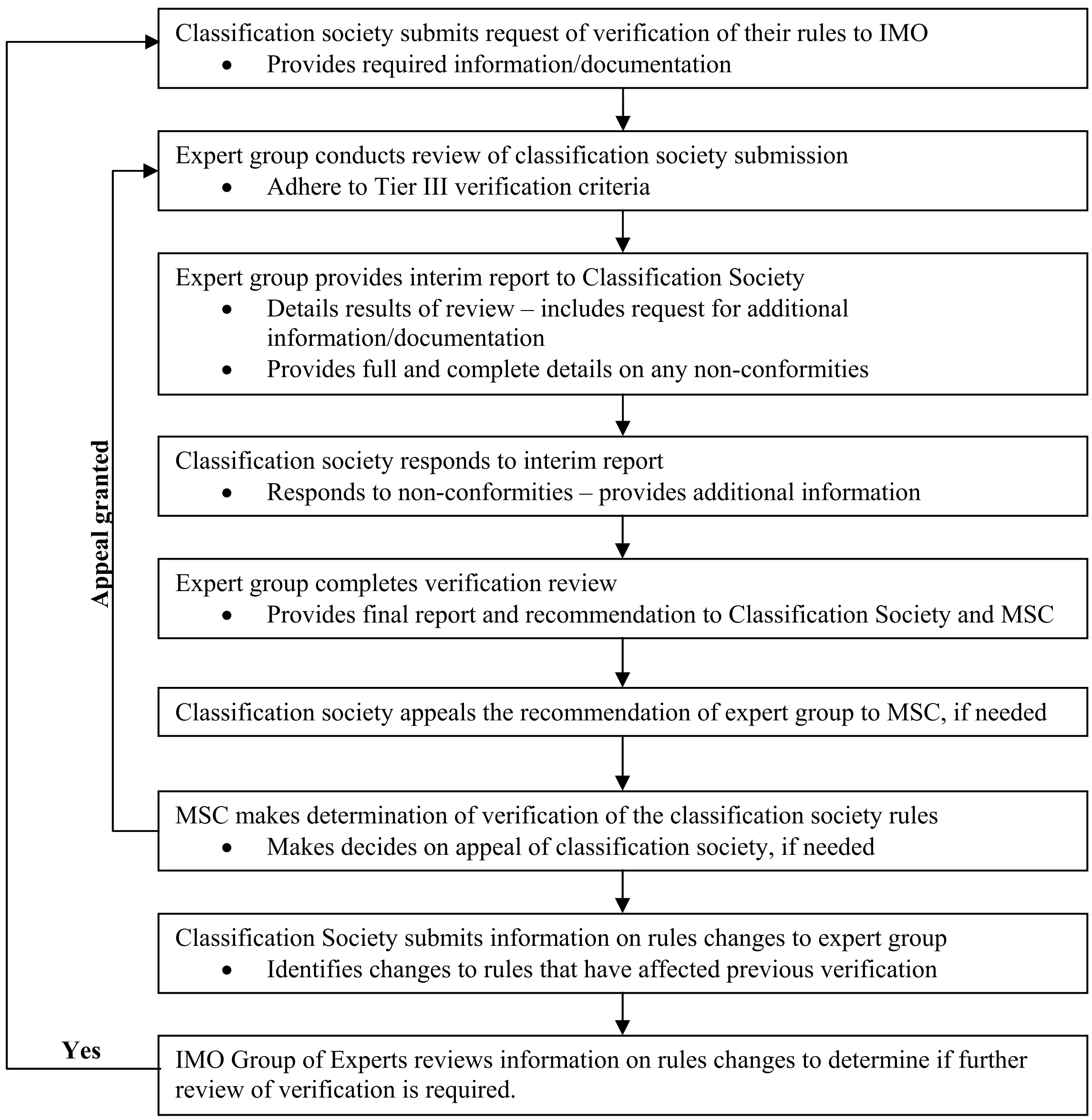
Source: Adapted from Trethewey, 1995 & ASM Metal Handbook vol. 1, 1978, pp. 713-759.

APPENDIX [E] – Classification scheme of some weld improvement techniques.



Source: Adapted from Ship Structure Committee-400 (1997, p. 22).

APPENDIX [F] – Verification Framework – Classification Society Rules.



Source: IMO – Report of the Working Group, MSC 81/6/WP.7 (2006, May 17).

APPENDIX [G] – Strength, plate thickness and welding costs of hull structural steels.

Yield Strength	690 MPa	355 MPa	235 MPa		690 MPa	355 MPa	235 MPa
Density (g/cm^3)	7.85	7.85	7.85	Groove type	X	X	X
Welding method	SAW	SAW	SAW	Groove angle	70	70	70
Electrode price (kr/kg)	135	70	50	Groove depth (mm)	8.0	7.5	10.0
Powder price (kr/kg)	61	55	55	Unbevelled edge (mm)	6.0	9.0	10.0
Efficiency (%)	98	98	98	Weld deposit area (mm^2)	125	121	197
Labour cost (kr/h)	500	500	500	Weld deposit (kg/m)	0.99	0.95	1.54
Investment cost (kr/h)	60	60	60	Weld deposit (kg/h)	3.0	5.0	5.0
Add. materials cost (kr/h)	413	357	255	Add. materials (kg/h)	3.1	5.1	5.1
Powder (kr/h)	183	275	275	Powder usage (kg/h)	3.0	5.0	5.0
Total cost (kr/h)	1156	1192	1090	Plate thickness (mm)	17.5	24.4	30.0

Steel	Thickness (m)[a]	Vol./unit area (m^3)	Density (t/m^3)[b]	Total weight (ton)	Cost ($/ton)[c]	Total cost ($)
HSLA (690 MPa)	0.0175	0.0175	7.85	0.137375	470.99	**64.70**
MS (235 MPa)	0.030	0.030	7.85	0.2355	428.97	**101.02**

Note:

1. These tables are the discussion results with the International Welding Engineer Dr. Kenneth HÅKANSSON, ThyssenKrupp Marine Systems, Kockums AB, and the author.
2. The data used in the upper table are from the unpublished software, with the permission of Dr. Kenneth HÅKANSSON.
3. In the lower table, the cost for **HSLA** steel is 64.70 US$ while that of MS is 101.02 US$, see also Sections 5.2.1 and 5.2.3. [1 g/cm^3 = 1 t/m^3; 1 US$ = 7.0 SEK in 2007]
4. Superscript, **a** in lower table is calculated by using the formula in the Section 5.2.1.
5. Superscript, **b** in lower table is from Software, Kockums AB, Malmö, Sweden.
6. Superscript, **c** in lower table is from United States Department of Commerce, 2007.

APPENDIX [H] – Glossary of Terms.

Brittle fracture: a mode of fracture characterized by rapid crack propagation. Brittle fracture surfaces of metals are usually shiny and have a granular appearance.

Cold working: plastic deformation of metals and alloys at a temperature below that at which it recrystallizes. Cold working causes a metal to be strain-hardened.

Ductile fracture: a mode of fracture characterized by slow crack propagation. Ductile fracture surfaces of metals are usually dull with a fibrous appearance.

Ductile-to-brittle transition: the transition from ductile to brittle behaviour with a decrease in temperature exhibited by BCC alloys; the temperature range over which the transition occurs is determined by Charpy and Izod impact tests.

Ductility: a measure of a material's ability to undergo appreciable plastic deformation before fracture; it may be expressed as percent elongation (**%EL**) or percent reduction in area (**%RA**) from a tensile test.

Fatigue life: the total number of stress cycles that will cause a fatigue failure at some specified stress amplitude.

Fatigue limit: for fatigue, the maximum stress amplitude level below which a material can endure an essentially infinite number of stress cycles and not fail.

Fatigue strength: the maximum stress level that a material can sustain, without failing, for some specified number of cycles.

Fracture toughness: critical value of the stress intensity factor for which crack extension occurs.

Grain boundary: the interface separating two adjoining grains having different crystallographic orientations.

Grain size: the average grain (an individual crystal in a polycrystalline metal or ceramic) diameter as determined from a random cross section.

Hot working: permanent deformation of metals and alloys above the recrystallization temperature.

Hydrogen embrittlement: the loss or reduction of ductility of a metal alloy (often steel) as a result of the diffusion of atomic hydrogen into the material.

Hypereutectoid alloy: for an alloy system displaying a eutectoid, an alloy for which the concentration of solute is greater than the eutectoid composition.

Hypoeutectoid alloy: for an alloy system displaying a eutectoid, an alloy for which the concentration of solute is less than the eutectoid composition.

Impact energy (notch toughness): a measure of the energy absorbed during the fracture of a specimen of standard dimensions and geometry when subjected to very rapid (impact) loading. Charpy and Izod impact tests are used to measure this parameter, which is important in assessing the ductile-to-brittle transition behaviour of a material.

Longitudinal direction: the lengthwise dimension; for a rod or fibre, in the direction of the long axis.

Modulus of elasticity or Young's modulus, *E*: stress divided by strain (σ/ε) in the elastic region of an engineering stress-strain diagram for a metal ($E = \sigma/\varepsilon$); also a measure of the stiffness of a material.

Precipitation hardening: hardening and strengthening of a metal alloy by extremely small and uniformly dispersed particles that precipitate from a supersaturated solid solution; sometimes also called **age hardening**.

Recrystallization temperature: for a particular alloy, the minimum temperature at which complete recrystallization will occur within approximately one hour.

Recrystallization: the process whereby a cold-worked metal is heated to a sufficiently high temperature for a long-enough time to form a new strain-free grain structure. During recrystallization the dislocation density of the metal is greatly reduced.

Safe stress: a stress used for design purposes; for ductile metals, it is the yield strength divided by a factor of safety.

Shear strain, γ: shear displacement a divided by the distance h over which the shear acts ($\gamma = a/h$).

Shear stress, τ: shear force S divided by the area A over which the shear force acts ($\tau = S/A$).

Strain hardening or cold working (strengthening): the hardening of a metal or alloy by cold working. The increase in hardness and strength of a ductile metal as it is plastically deformed below its recrystallization temperature.

Strain, ε: change in length of sample divided by the original length of sample ($\varepsilon = \Delta l / l_o$).

Strength-to-weight ratio: the strength of a material divided by its density; materials with a high strength-to-weight ratio are strong but light weight.

Stress concentration: the concentration or amplification of an applied stress at the tip of a notch or small crack.

Stress corrosion (cracking): a form of failure that results from the combined action of a tensile stress and a corrosion environment; it occurs at lower stress levels than are required when the corrosion environment is absent.

Stress raiser: a small flaw (internal or surface) or a structural discontinuity at which an applied tensile stress will be amplified and from which cracks may propagate.

Stress, σ: average uniaxial force divided by the original length of sample ($\sigma = F/A_o$)

Tensile strength, TS: the maximum stress in the engineering stress-strain diagram, in tension, that may be sustained without fracture; often termed *ultimate (tensile) strength*, **UTS**.

Toughness: a measure of the amount of energy absorbed by a material as it fractures. Toughness is indicated by the total area under the material's tensile stress–strain curve.

Transverse direction: a direction that crosses (usually perpendicularly) the longitudinal or lengthwise direction.

Weight percent (wt. %): concentration specification on the basis of weight (or mass) of a particular element relative to the total alloy weight (or mass).

Yield strength, YS: the stress at which a specific amount of strain occurs in the engineering tensile test; a strain offset of 0.002 is commonly used.

Source: Adapted from Askeland, 2004 & Roberge, 2000.