MATHEMATICAL MODEL OF SHIPBUILDING STEEL AND METHOD OF ITS USE WHEN DESIGNING SHIP HULL

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ABSTRACT

The consideration is given to the mathematical modelling of a shipbuilding steel, meant to make ship designing systems. The mathematical interpretation of the mechanical, technological and operational characteristics of the ship is given. There is also an example of model while sea-river going ships designing.

INTRODUCTION

In an overall system of ship designing it is preferable to treat hull material - construction steel - in an autonomous mathematical model (MMM) that contains a complex of mathematical relations, equalities and inequalities, adequately reflecting physical, technological, performance and economic aspects of the design task as well properties of the materials used. A steel model can be effectively used in a design system for sea-river going ships (SRS) as their hulls are usually built of a number of steel grades. Consequently, it is possible to supplement the traditional task of general ship designing with a mathematical model to optimise material distribution procedures and realise additional economic benefits.

If such a methodology is used to analyse a SRS as a unit of a flotilla of one type of ship operated on one route than the structure of the model can be somewhat simplified while still remaining suitable for investigation of the influence of the parameters of selected steels on the general operational characteristics of the flotilla.

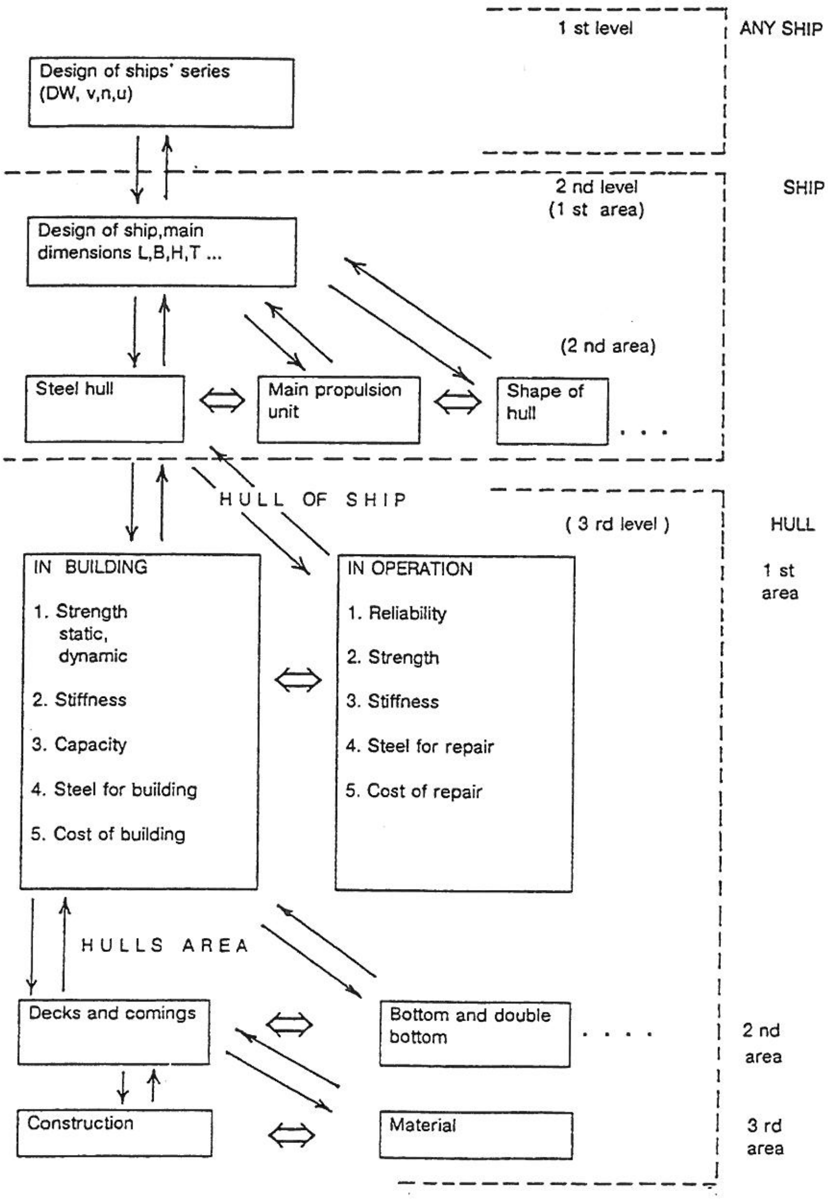

Fig. 1. The structure of the ship's mathematical model.

The principal structure of the model on the basis of this system principle is illustrated on Fig. 1 and contains elements of the external design task, but only in that its part which is related to the hull material: for example, consideration is given to the specific consumption of materials in a flotilla of one type of ships, the probability of brittle failures, corrosion, wear, etc. In such a case the best system decomposition procedures is to be determined by the requirements of setting up relations with a considerable influence of the complex shipbuilding steel properties.

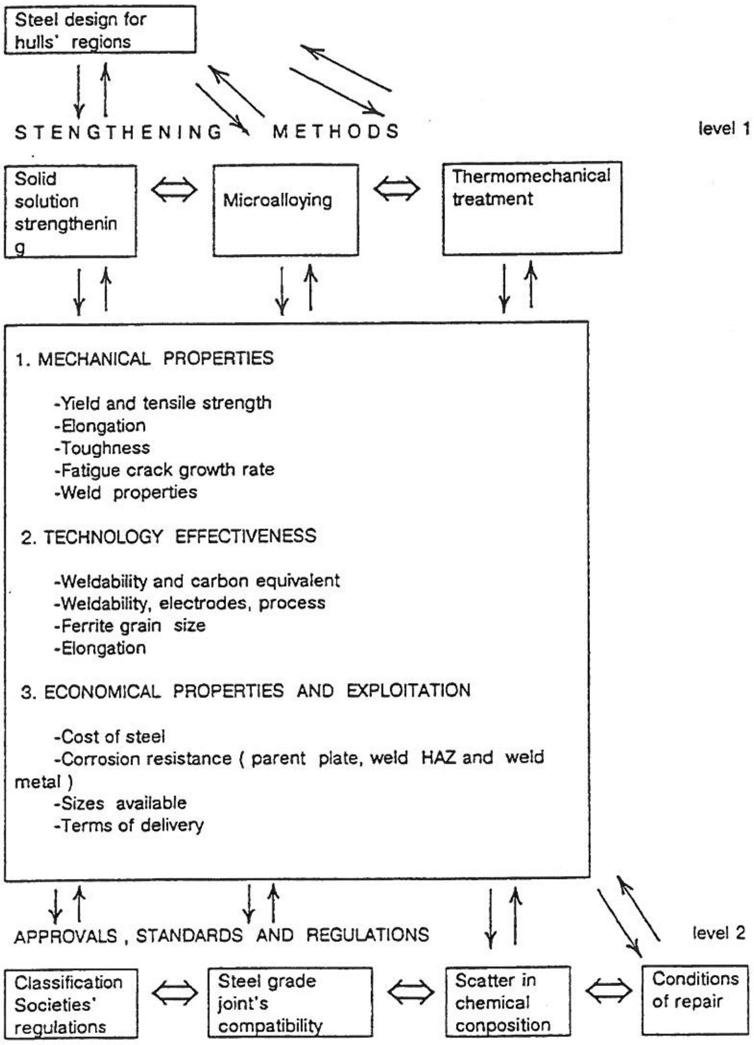

Fig. 2. The structure of the mathematical model for shipbuilding steel.

Hence its follows that the end of structural elements of each system shall be oriented to the estimation of influence of material properties of a corresponding hull zone. The system in Fig. 1 allows a search for optimal decision for multicriterion model setting with the use of Pareto region. When a sufficiently powerful means of calculation is available the search can be carried out on the basis of a single criterion scheme.

MATHEMATICAL MODEL OF STEEL

Let the vector **x** - vector, the components of which are ship characteristics and dimensions, chemical composition and some other structural parameters of the ship hull steel, and $\mathbf{x} \in \{X\}$ - form the area of task solution, than material properties form a set $\mathbf{y} \in \{Y\}$, where also found steel yield point, tensile strength, values of fracture toughness, plasticity, weld ability, weld joint and basic metal corrosion speed, steel price, etc. We can assume that displacement, propeller power and weight load components also form dependable variables.

The relation between the variables:

$$F:\{X\} \to \{Y\} \tag{1}$$

contains the transfer function F - a mathematical model reflecting the process of creation and operation of SRS ships. Using the common definition of a quality function and not developing it in detail we can assume [2]:

$$G:\{X\} \quad \{Y\} \to \{V\} \tag{2}$$

where $\{V\}$ is a set of estimates of ship conditions - specific quantity of metal, overall cost, profitability, i.e.:

$$g(x)=g[x,F(x)] \tag{3}$$

The region of admissible solutions in the set up task is found by the following relations:

$$\left\{x^{fl}\right\} \leq \{x\}, \text{where } \left\{x^{fl}\right\} \in \begin{vmatrix} L_1 < L < L_2 \\ B_1 < B < B_2 \\ T_1 < T < T_2 \\ \dots \\ v_1 < v < v_2 \\ n_1 < n < n_2 \end{vmatrix} \tag{4}$$

for the main dimensions, speed, number of ships in flotilla, etc. as well:

$$\left\{x^{f2}\right\} \in \left| \begin{array}{c} C_1 < C < C_2 \\ Mn_1 < Mn < Mn_2 \\ Si_1 < Si < Si_2 \\ Cu_1 < Cu < Cu_2 \\ \ldots \\ Ni_1 < Ni < Ni_2 \\ F_1 < F < F_2 \end{array} \right| \qquad (5)$$

for chemical elements and some parameters of the material ($F = d^{-0.5}$, where d is the steel grain size) having an effect on the mechanical properties.

MECHANICAL PROPERTIES OF STEEL

Functional limitations are divided in to those related to a flotilla, ship hull zone and material and depend on the actual conditions of a ship building and operation. For example, building conditions impose limitations on the hull weight at launching, and when developing hull construction it is necessary to take into account numerous requirements of the Register of Shipping, i.e.: minimal thickness, moment of inertia of equivalent girder members, etc. For hull materials the Register rules specify carbon equivalent, bounds of crack resistance, etc. In accordance with the generally accepted notations the steel model (MMM) is defined by the transfer function F from a relation:

$$F: \{X\} \rightarrow \{Y\} \qquad (6)$$

$$x \in \left| \begin{array}{c} C \\ Si \\ Mn \\ Cu \\ Cr \\ Ni \\ N \\ F\ldots \end{array} \right|, \; y \in \left| \begin{array}{c} R_e \\ R_m \\ T_{cr} \\ Cev \\ E \\ c(F) \end{array} \right| \qquad (7)$$

For admissible solutions of dependent and independent variables:

$$\left\{x^{fl}\right\} \in \left| \begin{array}{c} 0{,}08 < \mathrm{C} < 0{,}16 \\ 0{,}2 < \mathrm{Si} < 1{,}0 \\ 0{,}3 < \mathrm{Mn} < 1{,}6 \\ 0{,}03 < \mathrm{Cu} < 0{,}8 \\ 0{,}1 < \mathrm{Cr} < 2{,}0 \\ 0{,}1 < \mathrm{Ni} < 2{,}0 \\ 0{,}005 < \mathrm{N} < 0{,}01 \\ 3{,}0 < \mathrm{F} < 15{,}0 \end{array} \right| , \left\{y^{fl}\right\} \in \left| \begin{array}{c} 240 < \mathrm{R_e} < 400\,\mathrm{Mpa} \\ 340 < \mathrm{R_m} < 620\,\mathrm{Mpa} \\ 27 < \mathrm{T_{c1}} < 34\,\mathrm{J} \\ 0{,}4 < \mathrm{Cev} < 0{,}47\,\% \\ -60 < \mathrm{dE} < 32{,}6\,\mathrm{mV} \\ 300 < \mathrm{c(F)} < 600\,\$\mathrm{USD} \end{array} \right| \qquad (8)$$

where R_e = yield strength,
R_m = ultimate tensile strength and
T_{c1} = ductile/brittle transition temperature of the steel plates according the Register Rules,
Cev = carbon equivalent and
dE = electrochemical corrosion potential of the steel,
c(F) = steel price.

The main correlation of the transfer function reflects the mechanical properties of the steel with chemical composition and microstructure in accordance with the Hall-Petch equation [3]:

$$R_e = R_i + K_y\left[d^{-0,5}\right] \qquad (9)$$

and Petch's correlation:

$$\beta\ Tc = \ln\beta - \ln c - \ln\left[d^{-0,5}\right] \qquad (10)$$

where R_i = friction stress for movement of dislocations inside grains,
d = polygonal ferrite grain diameter,
Tc = ductile/brittle transition temperature and
K_y, β and c = constants for each type of steel.

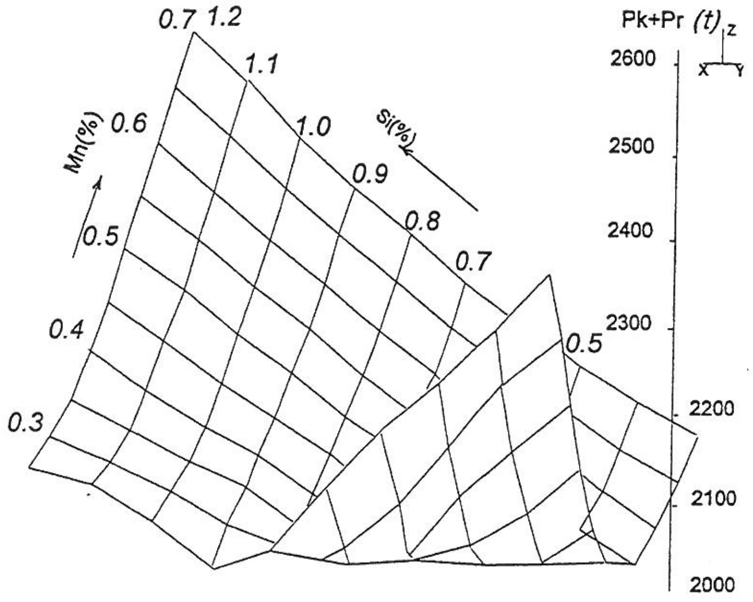

Fig.3. Influence of chemical composition of solid solution hardened D to D40 steels on specific quantity of steel required for a sea-river going dry cargo motor vessel with a DW of 5847 t (Pk -quantity for construction, Pr -quantity for repair).

For solid solution strengthened ferrite-pearlite steels the mechanical properties can be presented in the following way [3]:

$$R_e = 15{,}4\{3{,}5 + 2{,}1[Mn] + 5{,}4[Si] + 23[N] + 1{,}13[d^{-0{,}5}]\} \qquad (11)$$

$$R_m = 15{,}4\{19{,}1 + 1{,}8[Mn] + 5{,}4[Si] + 0{,}25[Pr] + 0{,}5[d^{-0{,}5}]\} \qquad (12)$$

$$Tc = -19 + 44[Si] + 700\sqrt{[N]} \qquad (13)$$

where Mn, Si, N, Pr = percentage of manganese, silicon, nitrogen and pearlite in the steel.

The level of weld joint low-temperatures toughness (Tc) shall not be less than the value specified by Register Rules for the steel category concerned. To introduce this condition in functional limitations it is best to express it by means of yield strength, chemical composition and structural characteristics of the steel [3]:

$$Tc = -\left(3{,}3 \cdot 10^{-4} R_e + 0{,}391\right) \cdot (273 + Tx) + 2{,}74\left(S \cdot 240 / R_e\right)^{0{,}5} \qquad (14)$$

$$Tc = -19{,}0 + 44{,}0Si + 100 \cdot N^{0{,}5} + 22{,}0Pr - 11{,}5d^{-0{,}5} \qquad (15)$$

$$Tc < 27{,}0 - 12{,}36R_e^{\,0{,}235} \quad \text{for grade E steel} \qquad (16)$$

$$Tc < 27{,}0 - 5{,}965 \cdot 10^{-3{,}0}\ R_e^{\,1{,}438} \quad \text{for grade D steel} \qquad (17)$$

The corrosion properties of the steel can be evaluated directly using uniform corrosion speeds of a hull plating or the difference of potentials of the weld joint and parent metal zones [4]:

$$E = \varphi\left(\Delta\ Cr_e, \Delta\ Mn_e, C_w, C_p, Q, \beta\right) \qquad (18)$$

where ΔCr_e, ΔMn_e = the differences in chromium and manganese equivalents of weld metal adjacent zones of the weld joint;

C_w, C_p = carbon equivalents of weld metal and parent plate,

Q = heat input of welding and

β = a parameter that depends on heat treatment condition.

Steel price in the mathematical model is a function of its chemical composition and mechanical properties. In comparative calculations for mild and low-alloy steels with solid solution hardening it can be approximated by the function:

$$C = \left\{4{,}34R_e^{\,0{,}6512} + 7{,}23[Cr] + 47{,}6[Ni] + 16{,}53[Cu] + 9{,}11R_e^{\,-1{,}807} \cdot K_{Ic}^{1{,}799}\right\} \cdot K_{ind},(\$) \qquad (19)$$

where K_{Ic} = the fracture toughness of steel plate. The last term takes into account heat treatment of plates with thickness' of 8-12 mm,

K_{ind} = coefficient of price index level, which is equal to 1,650-1,70 for February 1996.

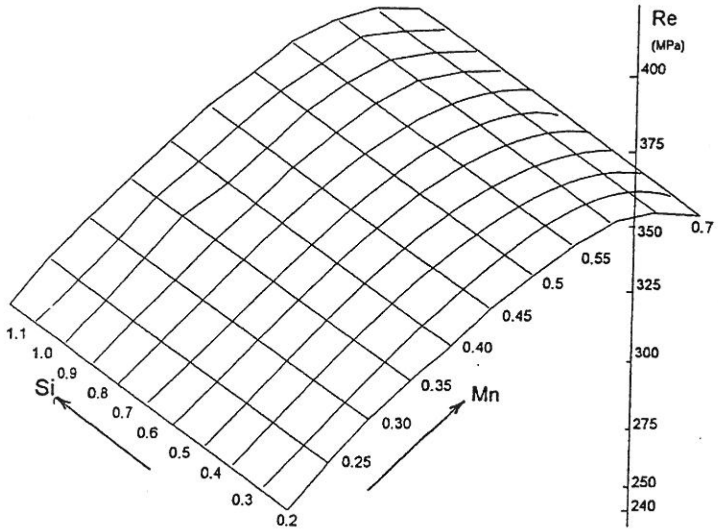

Fig.4. Influence of alloying in solid solution strengthened shipbuilding steels D to D40 on yield strength.

A mathematical model built in the above way for use in ship designing corresponds to a method widely used in machine design [1] which is also characterised by quite a large number of external and internal parameters. When working on the basis of heuristic and probabilistic-statistical approaches this method allows the optimal combination of shipbuilding steels properties to be found within the investigated range of values. It also allows the influence of material properties on a rather broad spectrum of physical and economic parameters of a ship to be estimated.

CONCLUSIONS

Undeniably, the creation and mastering of the use of each new grade of steel is a considerably complex and prolonged procedure and therefore the results obtained on the basis of the proposed scheme should be considered as approximate. At the same time establishing even theoretically an optimal set of steel properties for a specific design task allows a ship or material designer to explore the possibilities of hull performance improvement with the maximum use of shipbuilding steel properties.

Nowadays, there is a possibility for every shipyard to select from a wide range of steel grades that which is closest to the optimal variant or to order a known steel with desired changes of properties within the frame of acting limitations, chemical composition and delivery terms.

The practical use of the above approach has been realised by the design office "VYMPEL" Russia, Nyzhny Novgorod, when designing certain types of sea-river going ships. It was established that the optimal steel for hull plating (excluding the deck area) is a steel similar in chemical composition and properties to grade NV D27 S according to the rules of **Det Norske Veritas** with some improvement of corrosion properties by alloying with copper and nickel (0,2-0,35% Cu and <0,4% Ni).

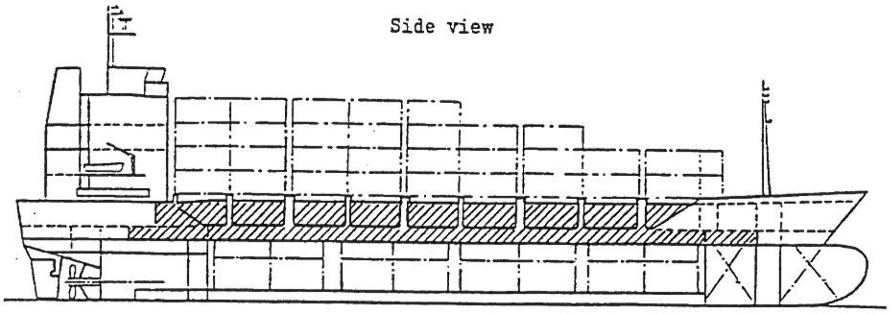

Fig.5. River-sea going trader with a cargo-carrying capacity 2400/3200 t. The head ship: "IVAN SHEPETOV" was built in 1994 for the Volga River Shipping Ltd. Shell plating was made of the specially designed optimal steel close to grade D27. It has good corrosion resistance, economic chemical composition and mechanical properties between grades D and D32.

A similar steel to grade D27 produced in Mariupol (Ukraine) according to the standard TY 14-1-4264087 (Russia) was used for the construction of a dry cargo ship "Ivan Shzhepetov" (dsn. 16510) at the Shipyard "OKA" in Navashino on the river Oka in 1994 with promising results.

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