e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
Volume 4 | Number 4 | December 2026 |

Yield Strength And Fracture Toughness Of High-Strength Steels For Deep-Sea Submarine Pressure Hulls: A Systematic Review

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Abstract

The pressure hull of a deep-sea submarine requires steel that is strong and also tough at low temperature. This article aims to synthesise the relationship between yield strength and fracture toughness of high-strength steels for deep-sea submarine pressure hulls. A qualitative narrative synthesis based on document analysis was applied to two selected sources: a review of the strengthening and toughening mechanisms of HSLA, Co–Ni secondary hardening and maraging steels, and an experimental study of HY-80 steel from the hull of a Kobben-class submarine after about 55 years of operation. Key figures were extracted from both sources and recalculated where possible. The results show that high strength mainly originates from high-density dislocations, nanoprecipitates and intermetallic compounds, whereas toughness is improved by martensite refinement, metastable austenite, coherent precipitates with low lattice misfit and inclusion control. The aged HY-80 steel had an average yield point of 605.6 MPa, about 9.7% above the catalogue value of 552 MPa, and a true ultimate strength of 782 MPa that rose to 1140 MPa at a strain rate of 2159 s^{-1}. Johnson–Cook and failure parameters ($d = 0.414$; $\varepsilon f = 0.1289$) are available for finite element simulation, but the values of n and B and the mean of C should be re-verified. It is concluded that the proposed synergy of low-misfit precipitates and reversed austenite in a high-density dislocation martensitic matrix is promising, but the toughness of the aged hull steel has not been measured directly, so impact and K1C testing are still required.

Keywords: High-strength Steel, Submarine pressure hull, Yield strength, Fracture toughness, Johnson–Cook

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e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

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1. Introduction

Deep-sea submarines, submersibles and unmanned underwater vehicles operate under high hydrostatic pressure, low temperature, seawater corrosion and complex dynamic loads, so the structural integrity of the pressure hull governs both safety and the achievable diving depth (Wang et al., 2025). The yield strength of the hull material is a direct design variable. According to data compiled by Wang et al. (2025) from Meng et al. (2014), a hull steel with a yield strength of 310 MPa corresponds to a diving depth of about 200 m, whereas 1000 MPa and 1300 MPa correspond to about 600 m and 900 m, respectively. Titanium alloys offer high specific strength and corrosion resistance, but their high cost limits wide use in hulls (Wang et al., 2024b), so high-strength steels remain the mainstream hull material because they combine strength, toughness, weldability, corrosion resistance and cost-effectiveness (Wang et al., 2025).

Hull steels have developed from the high tensile strength steels with a yield strength of 345 MPa introduced in the USA after World War II, through high-strength low-alloy (HSLA) steels such as HY-80, HY-100, HY-130 and HSLA-100, to Co–Ni secondary hardening steels (HY-180, AF1410, AerMet100, Ferrium M54) and maraging steels (Wang et al., 2025). Raising strength alone is not sufficient. Wang et al. (2025) point out that an 18Ni maraging steel can reach a yield strength of 2.2 GPa but absorbs only 9–20 J in impact testing (Zhou et al., 2025), far below the safety threshold required for pressure hulls, because the risk of brittle failure increases under high pressure, low-temperature shock and high stress gradients. Yield strength and fracture toughness must therefore be considered together (Li et al., 2023).

Strength and toughness data for newly designed alloys are normally obtained on laboratory heats, whereas hull steel that has served for decades is rarely tested. Szturomski and Kiciński (2021) addressed this by testing HY-80 plate taken from the hull of the Kobben-class submarine ORP Jastrząb (built in 1966) after about 55 years of operation and by deriving a Johnson–Cook constitutive model and failure parameters for finite element method (FEM) simulation. The two sources are complementary: one explains how strength and toughness are created in hull steels, the other measures what a classical hull steel retains after long service and how it behaves under dynamic loading.

The objective of this article is to synthesise these two sources in order to (i) compare the strengthening and toughening mechanisms of the three hull steel classes, (ii) summarise the static and dynamic properties of aged HY-80 hull steel, and (iii) identify what is still missing for a reliable link between yield strength and fracture toughness in deep-sea submarine pressure hulls.

2. Research Methods

This study is a qualitative, literature-based synthesis that follows the logic of a systematic review (an explicit review question, eligibility criteria, structured data extraction and transparent synthesis) but is limited to two purposively selected sources. The review question was: how do the strengthening and toughening mechanisms of high-strength hull steels relate to the yield strength, toughness and dynamic behaviour that can be demonstrated for hull steel in service?

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A source was eligible if it (i) was a peer-reviewed article in an indexed journal, (ii) concerned high-strength steel for submarine or deep-sea pressure hulls, (iii) reported yield strength, tensile strength, toughness or failure data, or the mechanisms controlling them, and (iv) was available in full text. Two sources met these criteria and were included: the review of Wang et al. (2025) in the Journal of Materials Science and the experimental study of Szturomski and Kiciński (2021) in Materials. Because the selection is purposive and limited to two sources, no database search or PRISMA flow diagram was produced; this is acknowledged as a limitation. Additional studies cited in the text to support individual statements were taken from the reference lists of the two included sources and were not subjected to data extraction.

For each source the following items were extracted: bibliographic data; type of evidence; steel class and composition; yield strength (R_e), ultimate strength (R_m), toughness indicators (Charpy impact energy, fracture toughness K_{1C}) and ductility; strengthening and toughening mechanisms; and, for the experimental study, test method, strain rate and constitutive and failure parameters. Derived quantities (percentage differences, means and parameter back-calculations) were recalculated by the authors of this article from the published data and equations, and are marked as recalculated. Discrepancies between recalculated and published values are reported in the Discussion and were not silently corrected. The evidence was synthesised narratively by theme.

3. Results and Discussion

a. Result

Table 1 summarises the two sources. They differ in type of evidence and are complementary: Wang et al. (2025) give a broad, mechanism-oriented synthesis of 211 references on three hull steel classes, including toughness data, whereas Szturomski and Kiciński (2021) give primary tensile and failure data for a single steel (HY-80) taken from a hull in service, without toughness testing.

Table 1. Characteristics of the included sources

Characteristic	Wang et al. (2025)	Szturomski and Kiciński (2021)
Evidence type	Narrative review (211 references)	Experimental study with constitutive modelling
Journal	Journal of Materials Science, 60: 15387–15420	Materials, 14(15): 4213
Materials	HSLA, Co–Ni secondary hardening and maraging steels	HY-80 plate from the hull of ORP Jastrząb (built 1966), about 55 years in service
Methods	Analysis of composition, heat treatment and microstructure reported in the literature	Quasi-static tension (MTS machine, 4 specimens, 10^{-4} s^{-1}); rotary-hammer tension (4 specimens, 535–2159 s^{-1})
Main output	Strengthening and toughening mechanisms; proposed concept of low-misfit co-precipitation with reversed austenite	R_e, R_m, E; Johnson–Cook parameters; failure parameters for stress triaxiality $\eta = 0.33$
Toughness data	Yes (impact energy and K_{1C} compiled from the literature)	No impact or fracture-toughness test; ductility and failure strain only

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Figure 1 shows the relationship between hull yield strength and diving depth given by Wang et al. (2025) from Meng et al. (2014): about 200 m at 310 MPa, 350–400 m at 550–690 MPa, 450–500 m at 785–900 MPa, 600 m at 1000 MPa and 900 m at 1300 MPa. Three steel classes serve this range (Table 2). HSLA steels combine moderate carbon (0.05–0.2 wt%) with Ni, Cr, Mo and microalloying elements; Co–Ni secondary hardening steels contain about 10 wt% Ni and 7–14 wt% Co; maraging steels are ultra-low-carbon Fe–Ni martensites strengthened by intermetallic precipitates.

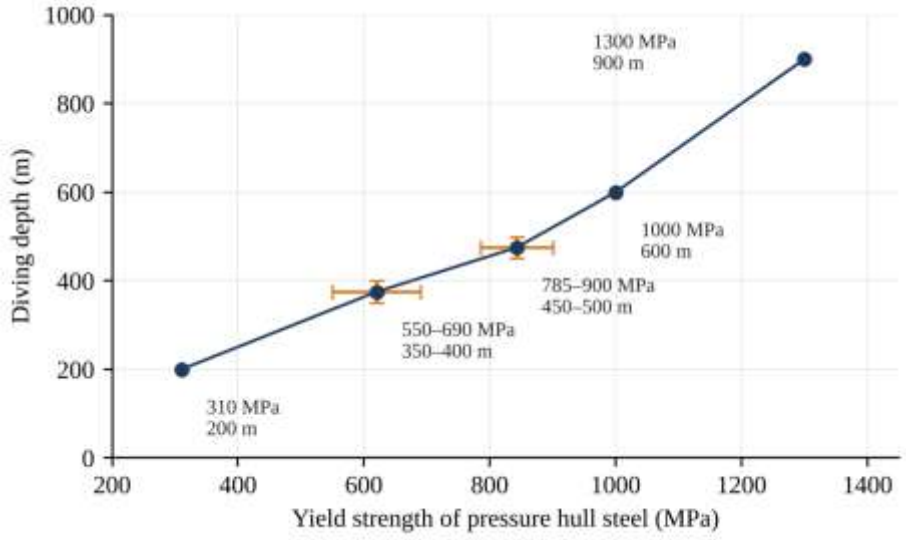

Figure 1. Hull yield strength and diving depth (data from Meng et al., 2014, as compiled by Wang et al., 2025).

Table 2. Comparison of the three hull steel classes (compiled from Wang et al., 2025)

Class	Typical alloying	Main strengthening	Main toughening routes	Reported performance
HSLA (HY-80/100/130, HSLA-100, NS-90, Q2N)	C 0.05–0.2 wt%; Ni 3.3–5.0; Cr, Mo, V, Cu, Nb microalloying	Dislocations in martensite; MC and M_2C carbides; Cu-rich precipitates	Grain refinement; high-angle boundaries; Cu-rich and carbide co-precipitation; reversed austenite; Ce modification of inclusions	Cu-bearing grades: yield ≈ 1 GPa with 185 J at −40 °C and 65 J at −84 °C; 1056 MPa with 204 J at −40 °C and 74 J at −85 °C (direct quenching)
Co–Ni secondary hardening (HY-180, AF1410, AerMet100, Ferrium M54)	Ni ≈ 10; Co 7–14; Cr, Mo; C 0.10–0.30; Ti, V, W in Ferrium M54	Nanoscale M_2C (and MC) carbides; > 60% of yield strength in Ferrium M54	Ni ≈ 10 wt%; film-like austenite; low C for weldability; La/Ce inclusion control	HY-180 > 1200 MPa; AerMet100 yield ≈ 1750–1800 MPa with K_{1C} = 135 MPa $m^{1/2}$

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Class	Typical alloying	Main strengthening	Main toughening routes	Reported performance
Maraging (18Ni series, Custom 465)	Ni ≈ 18 (10 in Custom 465); Co 8.5–9; Mo; Ti; C ≤ 0.03	Ni_3Ti, Ni_3Mo, NiAl and Laves precipitates in Fe–Ni martensite	Limited in conventional grades; coherent low-misfit Ni(Al,Fe) precipitates; Co-free designs	18Ni(350) yield up to 2400 MPa with marked toughness loss; 2.2 GPa grade: 9–20 J; low-misfit Ni(Al,Fe) steel ≈ 2.0–2.2 GPa with ≈ 8% elongation

In all three classes high strength is built on a martensitic matrix with a high dislocation density, reinforced by nanoscale precipitates. The contribution of precipitates to the yield strength is described by (Wang et al., 2025):

$$\Delta\sigma_p \approx G \cdot b \cdot f^{0.5} / d \quad (1)$$

where $\Delta\sigma_p$ is the yield-strength increment due to precipitates, G the shear modulus, b the Burgers vector, f the volume fraction and d the diameter of the second-phase particles. Smaller and more numerous particles therefore give larger strengthening.

In HSLA steels, microalloying with Nb (Wu et al., 2015), V (Baker, 2009) and Ti (Wang et al., 2022) produces fine MC and M_2C carbides, such as TiC and Mo_2C, that pin dislocations. Cu-rich particles are increasingly used as well: 1 wt% Cu in solution adds less than 50 MPa, whereas 1 wt% Cu precipitated as Cu-rich particles adds about 150–200 MPa (Wang et al., 2025).

In Co–Ni secondary hardening steels, nanoscale M_2C carbides dominate (Wang et al., 2025). In Ferrium M54, precipitation strengthening contributes more than 60% of the yield strength (Wang et al., 2024a), and the MC and M_2C precipitation can be tuned to balance strength and fracture toughness (Mondiere et al., 2018); HY-180 exceeds 1200 MPa through $(Cr,Mo)_2C$ (Wang et al., 2025).

In maraging steels, solution strengthening contributes only about 200 MPa, whereas aging at 400–600 °C precipitates Ni_3Ti, Ni_3Mo and NiAl phases (Niu et al., 2019; Wang et al., 2021). NiAl alone contributed about 700 MPa to the yield strength of one ultrahigh-strength maraging steel (Sun et al., 2018), and maraging-type steels strengthened by several types of nanoscale precipitates reach tensile strengths of 1.8–2.0 GPa with 8–10% total elongation (Niu et al., 2019; Sun et al., 2018).

Four toughening routes are reported (Wang et al., 2025). First, grain refinement: finer prior austenite grains give finer martensite packets and blocks that promote a more uniform stress distribution and reduce crack propagation paths (Wang et al., 2008), but at the nanoscale grains cannot store dislocations and toughness deteriorates. Second, metastable austenite, either retained or reversed (Kuzmina et al., 2015): film-like austenite at lath boundaries acts as a soft phase that blunts cracks and absorbs energy through transformation-induced plasticity (Lacroix et al., 2008). Third, low-misfit coherent precipitates, which reduce stress concentration at particle–matrix interfaces and thereby suppress crack initiation, in contrast with semi-coherent or incoherent Ni_3Ti and Ni_3Mo (Floreen, 1968). Fourth, inclusion control: non-metallic inclusions are

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inevitable by-products of steelmaking, and rare-earth modification of MnS and Al_2O_3 inclusions with Ce (Han et al., 2024) or La (Garrison and Maloney, 2005), together with vacuum melting routes such as VIM + VAR, reduces their harm. Table 3 lists the strength–toughness combinations that the review reports for selected steels.

Table 3. Selected strength–toughness combinations reported in Wang et al. (2025)

Steel / route	Strength	Toughness indicator	Key mechanism	Original study
Cu-bearing HSLA, Ti microalloyed (0.04C–5Ni)	Yield ≈ 1 GPa	185 J at −40 °C; 65 J at −84 °C	Co-precipitation of Cu-rich particles with MC and M_2C carbides	Kan et al. (2022a)
Cu-bearing HSLA, direct quenching and tempering	Yield 1056 MPa	204 J at −40 °C; 74 J at −85 °C	High dislocation density; Cu-rich particle coarsening suppressed	Kan et al. (2022b)
Ni-alloyed steel with QLIT treatment	Not reported in the review	−196 °C impact energy 27 J → 84 J	Thin-film reversed austenite enriched in Ni, Mn and Cr	Zhou et al. (2022)
AerMet100 (Co–Ni secondary hardening)	Yield up to 1750 MPa	K_{1C} = 135 MPa $m^{1/2}$	Nanoscale M_2C; Ni ≈ 10 wt%; stabilised austenite	Wang et al. (2025)
Low-misfit Ni(Al,Fe) steel	Yield ≈ 2.0–2.2 GPa	Elongation ≈ 8%; impact energy not reported in the review	Coherent B2 precipitates, 2.7 nm, > 10^{24} m^{-3}	Jiang et al. (2017)
18Ni maraging steel (conventional)	Yield up to 2.2 GPa	Impact energy 9–20 J	Semi-coherent or incoherent Ni_3Ti, Ni_3Mo	Wang et al. (2025)
Laminated martensite–austenite steel	≈ 2 GPa	Excellent fracture toughness (no value given in the review)	Grain-boundary delamination; Mn segregation	Liu et al. (2020)

Szturomski and Kiciński (2021) machined four quasi-static tensile specimens (8 mm diameter, EN ISO 6892-1) from plate removed while ORP Jastrząb was adapted as a training simulator; tests ran at a strain rate of 10^{-4} s^{-1}. Table 4 gives the results. The average Young's modulus is 211.2 GPa, the yield point R_e is 605.6 MPa and the ultimate strength R_m is 782.0 MPa at an ultimate strain of 0.1007. Scatter between specimens is small (R_e 601.7–610.5 MPa; R_m 777.5–784.1 MPa). The measured yield point is about 9.7% above the catalogue value of 552 MPa (80 ksi) (recalculated). The values in Table 4 are true values; the corresponding engineering ultimate strength is about 710 MPa (recalculated as 782.0/(1 + 0.1007)).

Table 4. Tensile properties of HY-80 hull steel after about 55 years of service (10^{-4} s^{-1})

Specimen	E (GPa)	R_e (MPa)	R_m (MPa)	ε_m (–)	A = $\sigma_{pl=0}$ (MPa)
HY 80_1	208.6	605.9	783.9	0.1028	563.9
HY 80_2	210.8	610.5	777.5	0.0958	576.0
HY 80_3	214.6	604.4	784.1	0.0996	561.2
HY 80_4	210.7	601.7	782.6	0.1045	536.0
Average	**211.2**	**605.6**	**782.0**	**0.1007**	**559.3**

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Source: Szturomski and Kiciński (2021, Table 2). R_m and ε_m are true ultimate strength and the corresponding strain.

Four dynamic tests were performed on a rotary hammer at 10, 20, 30 and 40 m/s, giving strain rates of 535, 1033, 1552 and 2159 s^{-1} (strain rate = hammer speed/measuring length). The strength used for calibration rose from 782 MPa (quasi-static) to 1047, 1115, 1130 and 1140 MPa, an increase of 46% at the highest rate (recalculated). The authors adopted the Johnson–Cook model:

$$\sigma_{pl} = (A + B\varepsilon_{pl}^{n})[1 + C\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)][1 - ((\theta - \theta_0)/(\theta_{melt} - \theta_0))^{m}] \quad (2)$$

where $A = \sigma_{pl=0}$, B and n are hardening parameters, C is the strain-rate coefficient, $\dot{\varepsilon}_0 = 10^{-4}\ s^{-1}$, θ is temperature and m the thermal-softening exponent. The coefficient C is obtained from the rate-dependent strength as:

$$C = [R_{m,true}(\dot{\varepsilon}) / R_{m,true}(\dot{\varepsilon}_0) - 1] / \ln(\dot{\varepsilon}/\dot{\varepsilon}_0) \quad (3)$$

From the averages in Table 4 the authors obtained A = 559 MPa, B = 518 MPa and n = 0.379; from the dynamic tests (Table 5) they obtained C = 0.0268. The temperature term was taken from the literature (Holmquist, 1987, cited in Szturomski and Kiciński, 2021): $\theta_0 = 293.15$ K, melting temperature 1733–1793 K and m = 0.75–1.15. Figure 2 compares the rate term with the measurements.

Table 5. Dynamic tensile results and strain-rate coefficient C

Specimen	Strain rate (s^{-1})	Raw dynamic strength (MPa)	R_m used for C (MPa)	C	JC rate term (MPa)*	Deviation (%)*
HY 80_d1_v10	535	1265.28	1047	0.021873	1107	+5.7
HY 80_d2_v20	1033	1528.10	1115	0.026366	1120	+0.5
HY 80_d3_v30	1552	1554.92	1130	0.026877	1129	−0.1
HY 80_d4_v40	2159	1556.62	1140	0.027108	1136	−0.4

*Source: Szturomski and Kiciński (2021, Tables 1 and 3). *Recalculated by the authors of this article as $782 \times (1 + 0.0268\ \ln(\text{strain rate}/10^{-4}))$; deviation = (model − test)/test.*

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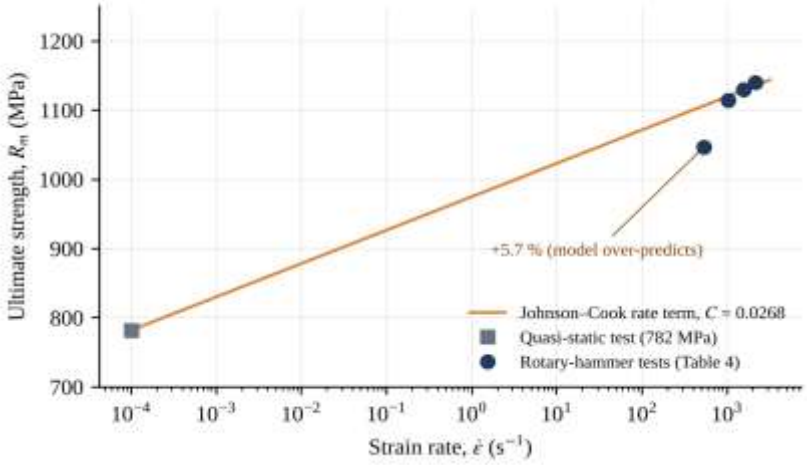

Figure 2. Strain-rate dependence of the ultimate strength of aged HY-80 steel (test data from Szturomski and Kiciński, 2021; model line recalculated).

For failure, the authors used the stress-triaxiality indicator $\eta = p/\sigma_{HMH}$, which equals 0.33 in uniaxial tension. From the true stress–strain curve they derived a damage variable $d = 1 - \sigma/\bar{\sigma} = 1 - 489.9/836.0 = 0.414$ at sample fracture, a failure strain $\varepsilon_{failure} = 0.2280 - 0.0991 = 0.1289$ and a degraded stiffness $E' = (1 - d)E \approx 124$ GPa. Damage evolves linearly with plastic displacement, $d = u_{pl}/u_{failure}$ with $u_{failure} = \varepsilon_{failure} \cdot L$, where L is the characteristic element length. These failure parameters are valid for $\eta = 0.33$ only; the amount of material did not allow tests at other triaxialities.

Wang et al. (2025) conclude that the three steel classes rely on similar mechanisms: a high-density dislocation martensitic matrix, nanoscale precipitates, intermetallic compounds and Cu-rich particles for strength, and martensite refinement, tuned austenite stability and low-misfit nanoparticles for toughness. On this basis they propose the synergistic co-precipitation of low-misfit nanoprecipitates and reversed austenite within a high-density dislocation martensitic matrix. Figure 3 summarises how the steel classes, mechanisms and hull performance indicators relate to this concept.

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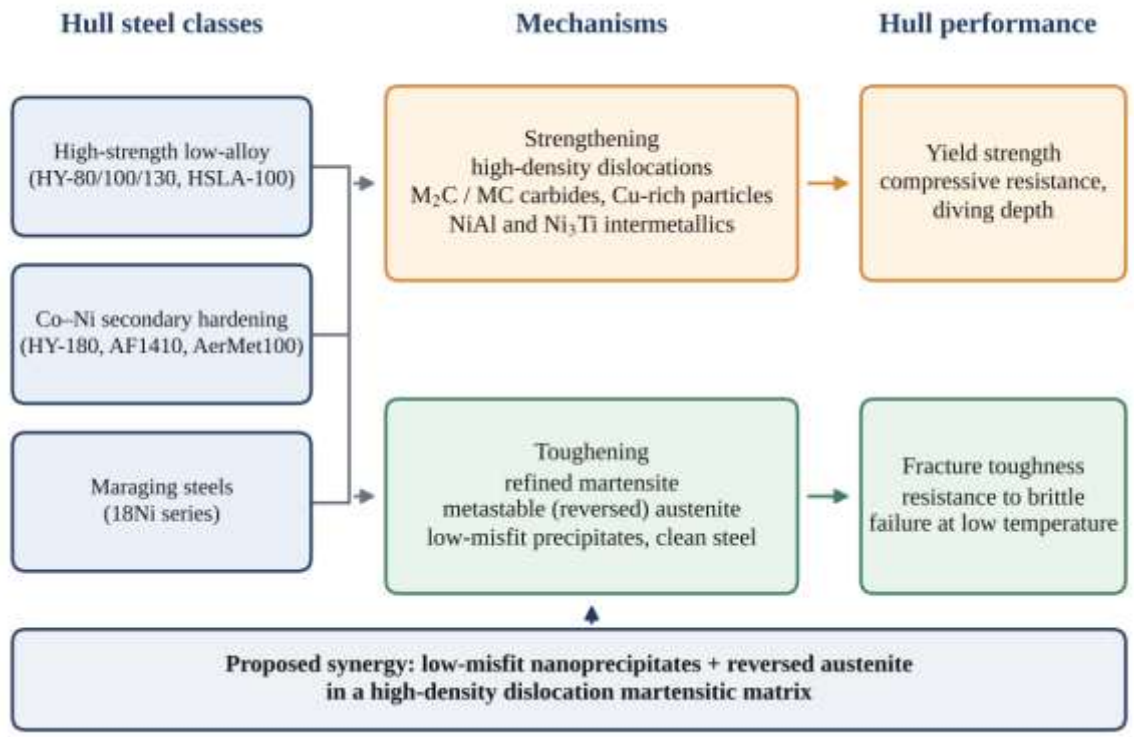

Figure 3. Framework of the synthesis: steel classes, mechanisms, hull performance and the proposed synergy concept (prepared by the authors from Wang et al., 2025).

b. Discussion

The two sources describe the same problem from opposite ends. The review shows that strength is cheap to obtain, but toughness depends on how the strength is produced. Precipitates that are semi-coherent or incoherent with the matrix, such as Ni_3Ti and Ni_3Mo in conventional maraging steels, deliver very high strength at a large cost in toughness (2.2 GPa with only 9–20 J), whereas coherent low-misfit precipitates and thin-film metastable austenite give a better balance (about 1 GPa with 185 J at −40 °C in Cu-bearing HSLA steel; 27 J to 84 J at −196 °C with reversed austenite). Equation (1) explains the strength gain from finer and denser precipitates but contains no interface term, so it cannot by itself predict toughness. This supports the argument of Wang et al. (2025) that yield strength and fracture toughness have to be designed together.

The aged HY-80 hull steel provides the in-service counterpart. A measured yield point of 605.6 MPa, about 9.7% above the 552 MPa catalogue value, indicates no loss of yield strength after about 55 years, in agreement with the conclusion of Szturomski and Kiciński (2021). The comparison is made with the catalogue value because no as-built data for the same plate are available. Interestingly, 605.6 MPa lies inside the 550–690 MPa band that Table 1 of Wang et al. (2025) associates with a diving depth of 350–400 m. This is an illustration of the strength–depth relation, not a certification: hull

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depth also depends on geometry, and Szturomski and Kiciński (2021) warn that erosive wear still reduces hull strength and may limit the maximum operational depth.

The most important gap is toughness. Wang et al. (2025) identify brittle failure under low temperature, high pressure and shock as the main risk, yet the aged-hull study measured tensile and failure strain only: no Charpy V-notch or K_{1C} test and no microstructural examination were reported. It is therefore not known whether the precipitates and austenite that govern toughness in the review have changed after service. Rate hardening is relevant to explosion and impact loading (782 MPa to 1140 MPa at 2159 s^{-1}), but deformation could not be measured during the dynamic tests, so conclusions on ductility or toughness at high strain rate cannot be drawn.

Checking the published numbers revealed several inconsistencies that should be resolved before the data are used in design or simulation. (i) The reported mean C = 0.0268 equals the mean of the three highest-rate values (0.026366, 0.026877 and 0.027108); the mean of all four values in Table 5 is 0.0256. With C = 0.0268 the model over-predicts the 535 s^{-1} result by 5.7% (Figure 2). (ii) Recalculating n and B from the published equations with the Table 4 averages gave n ≈ 0.32 and B ≈ 484 MPa, not 0.379 and 518 MPa; the difference may arise from rounding or from different input values, but it affects the hardening curve and should be verified. (iii) The raw dynamic strengths (1265–1557 MPa) are higher than the values used for C (1047–1140 MPa), and the conversion between them is not described. (iv) In the review, the yield strength of the Ni(Al,Fe) steel is given as close to 2000 MPa in one section and 2.2 GPa in another, and that of AerMet100 as 1750 MPa and 1800 MPa. Such differences warrant checking the original papers before single values are quoted.

This study has limitations. Only two sources were included and one of them is itself a secondary review, so original data were not re-examined; the purposive selection may bias the synthesis; and the aged-hull data come from one hull and one steel grade. Future work should (a) add Charpy and fracture-toughness tests and EBSD/TEM/APT characterisation to the aged HY-80 stock, (b) extend the failure model to other triaxialities, and (c) expand the review to a database-based systematic search so that strength–toughness data of hull steels can be compared on a common basis.

4. Conclusion

Synthesising the review of Wang et al. (2025) and the aged-hull study of Szturomski and Kiciński (2021) leads to the following conclusions. High strength in hull steels is built mainly on high-density dislocations, nanoprecipitates (M_2C and MC carbides, Cu-rich particles) and intermetallic compounds, whereas toughness is improved by refined martensite, metastable or reversed austenite, low-misfit coherent precipitates and inclusion control. The imbalance is clearest in conventional maraging steel (2.2 GPa with 9–20 J). HY-80 hull steel after about 55 years of service retained its yield strength: R_e = 605.6 MPa (about 9.7% above the 552 MPa catalogue value), true R_m = 782 MPa and E = 211 GPa. Strength increased to 1140 MPa at a strain rate of 2159 s^{-1}. Johnson–Cook (A = 559 MPa, B = 518 MPa, n = 0.379, C = 0.0268) and failure parameters (d = 0.414, $\varepsilon_{failure}$ = 0.1289, η = 0.33) are available for FEM simulation of collision, shelling and underwater explosion, but n, B and the mean of C should be re-verified (recalculated: n ≈ 0.32, B ≈ 484 MPa,

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e-ISSN : 2987-0836 DOI: https://doi.org/10.59585/ijhs

Publish : Association of Indonesian Teachers and Lecturers
International Journal of Health Sciences (IJHS)
Journal Homepage : https://jurnal.agdosi.com/index.php/IJHS/index
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mean C = 0.0256). The toughness of the aged hull steel was not measured. Charpy and K_{1C} tests with microstructural characterisation are recommended before the proposed synergy of low-misfit nanoprecipitates and reversed austenite in a high-density dislocation martensitic matrix is accepted as a design basis for deep-sea pressure hulls.

5. Compliance with Ethical Standards

Acknowledgements

The authors acknowledge the Physics Study Program, Republic of Indonesia Defense University, and the authors of the two studies synthesised in this article.

Disclosure of conflict of interest

The authors declare no conflict of interest.

Statement of informed consent

Not applicable. This article is a synthesis of published literature and involved no human participants or animals.

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