Technical Bulletin

Detailed Metallurgical Comparison: EN 10025 JR vs. EN 10025 J2 vs. EH36 Steels (Flat-Rolled Products)

Introduction to Steel Grades and Sub-Grades

EN 10025 **JR** and **J2** refer to sub-grades of structural steel under the EN 10025 standard (e.g. S355JR, S355J2), distinguished mainly by their **impact toughness requirements**. "JR" typically guarantees a Charpy V-notch impact energy of 27 J at room temperature (~+20 °C), whereas "J2" guarantees 27 J at –20 °C [1]. These sub-grades have similar tensile strengths but differ in notch toughness at low temperature. **EH36** is a high-strength **marine/offshore steel** (often specified by ASTM A131 or classification societies like ABS, DNV) with comparable yield strength (~355 MPa) to S355 grades, but with superior low-temperature toughness (generally ~34 J at –40 °C) and stringent quality controls for critical applications like ship hulls and offshore structures [2] [3]. All three are commonly supplied as **flat-rolled plates**, but their manufacturing processes and resulting properties differ to meet their respective toughness and performance criteria.

1. Steel Manufacturing Methods and Melt Practices

Deoxidation (Killed vs. Semi-Killed): A key difference in manufacturing is the steelmaking deoxidation practice, which influences inclusion content and consistency. *Fully-killed* steels are deoxidized completely (often with Si and Al additions) so that no gas evolution occurs during ingot solidification [4]. This yields a "quiet" steel with uniform composition, free of internal gas porosity, though a shrinkage cavity forms in the ingot top [5]. *Semi-killed* steels are only partially deoxidized, allowing some gas evolution; they solidify with *less uniform composition* and may have slight carbon segregation and small blowholes that usually heal during rolling [6]. EN 10025 specifies that structural steel of JR quality be at least "FN" (rimming not permitted, implying semi-killed or better) and J2 quality as "FF" (fully killed) [7]. In practice, modern steelmakers use **continuous casting**, which **requires fully killed steel for safety and quality** (to avoid dangerous gas blow-outs in the caster) [8] [9]. Thus, **S355JR (JR-grade)** material, while historically semi-killed, is today typically produced fully killed (Al-deoxidized) as a matter of course. **S355J2 (J2-grade)** is *explicitly* supplied as fully killed and often fine-grain treated, and **EH36** is *always* produced as a fully killed, fine-grain practice steel [10]. EH36 plates are usually made from **vacuum-degassed** melts to further reduce impurities like sulfur, phosphorus, hydrogen and oxygen, reflecting the high quality requirements for naval/offshore steel [11].

Inclusion Content and Cleanliness: The deoxidation method strongly affects the type and morphology of non-metallic **inclusions**, which in turn influence mechanical performance (especially toughness and through-thickness ductility). Fully killed steels (deoxidized with Si and Al) tend to have small aluminum oxide (Al_2O_3) or silicate inclusions that are **dispersed**; semi-killed steels have more and larger oxide and sulfide inclusions, often ending up as elongated **"stringers"** after rolling [12] [13]. For example, in a comparative study of pipeline steels, a conventional semi-killed steel showed FeO–SiO_2–MnO silicate inclusions with MnS phases that elongated into stringers during hot rolling [12]. These sulfide-silicate stringers can act as planes of weakness, reducing toughness (particularly in the through-thickness direction) and can promote anisotropic properties. In contrast, fully killed fine-grain steels (often Ca-treated to modify inclusions) contain **globular oxide/sulfide inclusions** that resist elongation during rolling [12] [13]. For instance, calcium-treated steels exhibit round calcium-aluminate inclusions with sulfides on the periphery that remain globular even after 90% rolling reduction [12] [13]. The result is improved isotropy and higher fracture resistance. **S355J2 and EH36**, being fully killed (and often Ca or Ti/Nb treated), generally have cleaner microstructures with smaller, more globular inclusions than a basic JR-grade produced to minimal specs. This superior cleanliness contributes to more consistent toughness. Additionally, fully killed steels have more uniform chemistry (carbon, manganese distribution, etc.), which means mechanical properties vary less within a plate compared to semi-killed steels [4] [14].

Fine-Grain Practice: Both S355J2 and EH36 are fine-grain steels by specification, often achieved by adding **grain refiners** like Al, Nb, V, or Ti. EN 10025 J2-grade steel usually requires a minimum Al content (e.g. Al_tot $\geq$ 0.020%) to ensure fine austenitic grain size, and limits nitrogen (e.g. N $\leq$ 0.012%) to avoid embrittlement [15] [16]. EH36 likewise must meet fine grain practice per classification society rules – for example, ABS rules mandate either an ASTM grain size $\leq$ 5 or Al_sol $\geq$ 0.015% in every heat [17]. Fine grain practice produces a uniform, small ferrite grain size which raises toughness and yield strength. **S355JR** material may or may not be fine-grain treated; it is often produced from the same killed, Al-treated heats as higher grades for economy, but JR does not guarantee the same level of toughness. In summary, **JR-grade** steel is typically killed but may have more variability in inclusion content and grain size, **J2-grade** is fully killed and fine-grained to promote toughness, and **EH36** is made with the *cleanest practice* (vacuum degassed, fully killed) and purposeful microalloy additions for optimum toughness in critical applications [3] [18].

2. Hot Rolling Process Differences and Effects on Microstructure

After casting, the hot rolling parameters (reheating temperature, reduction schedule, finishing temperature, and cooling rate) profoundly influence the steel's microstructure (grain size, phase distribution) and thus its mechanical performance. Key differences arise from how **thermomechanical processing** is applied for these grades:

- **EN 10025 JR (e.g. S355JR):** Often supplied in the *as-rolled (AR)* condition without special rolling controls. Plates are reheated (typically ~1200 °C), then rolled in a conventional schedule mostly above the recrystallization temperature. Finishing may occur at relatively high temperature (above Ar_3, e.g. >900 °C) to ensure the steel recrystallizes between passes, preventing excessive strain accumulation. This produces a **ferrite-pearlite microstructure** with adequate strength, but grain size can be coarser and less uniform than more controlled processes. Because S355JR is not guaranteed for low-temperature toughness, mills rolling JR may prioritize throughput (higher roll speeds, higher finishing temps) rather than grain refinement. The cooling after rolling is usually air-cooling (no accelerated cooling), yielding a mix of ferrite and pearlite colonies with grain size maybe in ASTM 5–8 range (coarser in thicker plates). This is sufficient for the ductility and strength requirements of JR, but can result in a higher ductile-to-brittle transition temperature (DBTT) compared to more refined processes.

- **EN 10025 J2 (e.g. S355J2):** Often supplied either *normalized (S355J2+N)* or *normalized-rolled*. Normalizing involves reheating rolled plate to ~900 °C then air cooling, refining the grain structure. Normalized S355J2 plates have a more uniform, fine-grained ferrite-pearlite microstructure, improving toughness. Alternatively, some mills use **controlled rolling** (also called controlled cooling or normalized rolling) for J2: the plate is rolled in two phases – first at high temperature to achieve reduction, then the final passes in the lower austenite region (just above Ar_3, e.g. 800–850 °C) where recrystallization no longer occurs. This controlled rolling below the recrystallization temperature causes the austenite grains to pancake (flatten), greatly refining the ferrite grains upon transformation. The process may be followed by accelerated cooling or air cooling. The effect is a significant grain refinement (often ASTM 8–10 or finer) and higher dislocation density, which together raise strength and toughness. Indeed, **rolling in the non-recrystallization regime** (lower finishing temperatures) increases yield strength (and often improves notch toughness by grain refinement), though it can introduce texture and internal stresses [19]. Mills balance these factors to meet S355J2's requirement of 27 J @ –20 °C. Overall, J2-grade steel undergoes more carefully controlled rolling or an extra normalization heat treatment to ensure a finer microstructure and better low-temperature performance than JR-grade [3].

- **EH36 (High-Strength Hull Steel):** EH36 plates are typically produced by **Thermomechanical Controlled Processing (TMCP)**, which combines controlled rolling and accelerated cooling. The slabs are reheated and often initially rolled above 1000 °C, but finish-rolled at a lower temperature (sometimes even into the ferrite phase region for extreme grain refinement) as part of a controlled rolling schedule [3]. Immediately after final rolling, plates may undergo **accelerated cooling (water sprays)** to transform austenite to fine ferrite/bainite before excessive grain growth can occur. This process can yield an ultra-fine grain (sometimes with bainitic or acicular ferrite phase) and high strength without high carbon content. For thick EH36 plates, some producers use a direct quench and temper or a two-step cooling to ensure a full transformation to fine-grained microstructures through the thickness. The goal is to achieve ≥355 MPa yield and high toughness at –40 °C uniformly, even in thick sections. In some cases (for thickness >50 mm), **quenching and tempering** or **normalizing** may be applied to EH36 to guarantee properties. The result of TMCP or heat treatment is that EH36 has a very refined grain (often ASTM 10 or finer) with a tough mixture of ferrite and dispersed carbides or bainite, and very low inclusion size. As an example, a technical specification notes that high-strength ship plate production *"needs to be normalized by means of controlled rolling and controlled cooling… At the same time, the internal steel purity…especially S, P, N, O, H…should be strictly controlled"* [3]. Microalloying with Nb, V, Ti is used in EH36 to pin grain boundaries and further refine the microstructure [18], directly improving toughness.

Effect on Grain Size and Toughness: The hot rolling and cooling schedule largely determine final **grain size**, which is a critical factor for toughness (finer grain = lower DBTT and higher absorbed energy). S355JR rolled under less controlled conditions may have a mixed grain size distribution through the thickness (surface can be fine from faster cooling, core coarser from slow cooling in thick plates). S355J2, especially if normalized, presents a more homogeneous fine grain through-thickness, which improves its Charpy impact results at –20 °C. EH36, with TMCP, achieves the **smallest grain sizes** and often a different phase morphology (ferrite-bainite) that gives superior impact energy at –40 °C. Another benefit of low-temperature finish rolling and rapid cooling is the formation of a high-density dislocation substructure and fine precipitation (from Nb, V carbides), which raises strength without sacrificing toughness. However, very low finish rolling temperatures (into ferrite phase) can sometimes reduce toughness if not managed, due to heterogeneous microstructures. Manufacturers of EH36 carefully optimize rolling reduction and cooling to avoid any embrittling microphases. In summary, **JR-grade** is hot-rolled without special thermal treatment (adequate strength but larger grains), **J2-grade** is often normalized or controlled-rolled (finer grains, improved toughness), and **EH36** receives the most advanced thermomechanical treatment (ultra-fine grains and highest toughness).

3. Crystallographic Texture Development and Rolling Speed Effects

Hot rolling not only refines grain size but also introduces a **crystallographic texture** in the steel – a preferred orientation of grains – which can influence anisotropy and the ductile-to-brittle transition temperature. During rolling of BCC steels like ferrite, typical rolling textures (such as α-fiber || rolling direction and γ-fiber || normal direction) develop due to the deformation of austenite and its transformation to ferrite [20] . The intensity of this texture depends on rolling parameters:

- **Rolling Speed and Recrystallization:** *Faster rolling* (higher strain rates, shorter inter-pass times) tends to retain more of the deformation texture because there is less time for static recrystallization between passes. This can lead to a stronger alignment of crystallographic planes. *Slower rolling* or longer pauses between passes allow more recrystallization, which can **randomize orientations** by nucleating new strain-free grains. Thus, a *slow rolling schedule* (or a finishing at high temperature where dynamic recrystallization can occur) often produces a weaker texture (more isotropic orientation distribution), whereas a *fast, low-temperature rolling* schedule produces a pronounced texture as grains deform in unison without resetting between passes. For example, heavy deformation in the non-recrystallization regime can create a sharp **pancake texture** in which certain cleavage planes (like {100} in ferrite) may align parallel to the plate surface.

- **Texture and DBTT:** The **ductile-to-brittle transition** in ferritic steels is sensitive to grain orientation because brittle cleavage fracture occurs along specific crystallographic planes (for BCC iron, the {100} family is the primary cleavage plane) [21] . If rolling produces a texture that aligns many {100} planes perpendicular to the principal stress direction (e.g. parallel to the plate surface in a bending scenario), the material can exhibit a higher propensity for cleavage fracture – effectively raising the DBTT. Conversely, a random grain orientation (or one with high-angle boundaries between differently oriented grains) forces a propagating crack to deflect and arrest, thus improving toughness. A study on a tempered martensitic steel is illustrative: it found brittle fracture propagated along {100} cleavage planes and was arrested by high-angle grain boundaries; a "favorable" texture with grains oriented on {332}<113> reduced the DBTT by providing more tortuous crack paths [21] . By analogy, in hot-rolled structural steels, a **strong rolling texture** can slightly reduce toughness in the through-thickness direction (as seen by lower Charpy values for specimens oriented parallel to rolling).

- **Impact of Controlled Rolling:** Controlled rolling at lower temperatures (as done for S355J2 and especially EH36) introduces a particular texture component but also refines grain size. There is a trade-off: **increased strain in the unrecrystallized austenite** increases strength but can reduce impact toughness if the texture becomes too aligned [19] . Research on low-carbon microalloyed steels shows that rolling below the recrystallization stop temperature increases strength but **reduces impact toughness**, and that increasing total accumulated strain can mitigate some toughness loss [19] . The reduction in toughness is attributed in part to the development of banded microstructures and texture (as well as potential precipitation of carbides along deformation bands). Therefore, mills carefully adjust **rolling speed** and cooling to optimize both grain size and texture. For EH36, thermomechanical rolling aims to refine grains while also achieving a balanced texture. Additionally, plates may be leveled or lightly tempered to relieve residual stresses from fast cooling, which can also improve toughness.

- **Examples of Texture Effects:** In practice, **S355JR** (rolled quickly with less recrystallization) might exhibit a stronger texture and slight anisotropy in properties – for instance, lower Charpy energy in the through-thickness direction or differences between longitudinal and transverse specimens. **S355J2**, especially if normalized after rolling, will have a more equiaxed, randomly oriented grain structure, minimizing texture-related anisotropy. **EH36** plates often have mild texture from controlled rolling (and sometimes a mixed ferrite-bainite phase texture), but because testing requirements demand transverse impact tests, producers ensure texture effects do not compromise transverse toughness. It's worth noting that classification society rules require Charpy tests in the *transverse* direction for ship plates [22], which is more challenging (since rolling texture usually makes transverse toughness lower than longitudinal). The fact that EH36 must meet 34 J @ –40 °C *in the transverse orientation* underscores how optimized its processing and resulting texture are, to achieve such toughness. In sum, **rolling speed and schedule** affect the crystallographic texture: slower, recrystallization-allowed rolling yields more isotropic toughness (at the cost of slightly lower strength), while faster controlled rolling yields higher strength and very fine grains but must be managed to avoid embrittling textures. Producers of J2 and EH36 find a sweet spot where the texture does not significantly raise the DBTT, leveraging grain refinement to ensure overall toughness remains high.

4. Mechanical Properties: Strength, Toughness, and Integrity at Temperature

Despite similar base chemistry, the processing differences lead to distinct mechanical property profiles for EN10025 JR, EN10025 J2, and EH36 steels. **Table 1** summarizes key properties and requirements for a representative grade (here assuming a ~S355 structural steel for JR and J2, and a typical ABS EH36):

[23] [2] *Table 1. Comparison of typical mechanical requirements for S355JR, S355J2, and EH36 plate (values for thickness ≤ 50 mm).* [23] [2]

Steel Grade	Yield Strength (Re_H)	Tensile Strength (R_m)	Elongation (min %)	Charpy Impact Requirement
EN10025 S355JR (JR sub-grade)	355 MPa (≤16 mm plate) *(drops to ~275 MPa at 250 mm)* [24] [25]	470–630 MPa (for 3–100 mm plates) [26]	20–22% (in $5.65\sqrt{S_0}$, typical) [27]	27 J @ +20 °C (Room Temp, longitudinal) [1] (No requirement at sub-zero temperatures)
EN10025 S355J2 (J2 sub-grade)	355 MPa (≤16 mm) *(drops to ~315 MPa at 100 mm)* [24] [25]	470–630 MPa (for 3–100 mm plates) [26]	20–22% (similar to JR)	27 J @ –20 °C (longitudinal) [1]. (Higher toughness than JR; often exceeds 27 J in practice)

Steel Grade	Yield Strength (Re_H)	Tensile Strength (R_m)	Elongation (min %)	Charpy Impact Requirement
ASTM A131 / ABS EH36 (High-strength hull steel)	355 MPa (≤50 mm, all thickness must meet ≥355 MPa) [28]	490–620 MPa [23]	22% (in 200 mm gauge) [23]	34 J @ –40 °C (transverse test) [29] . (Equivalent to ~ 41 J longitudinal @ –40 °C). Higher grades (EH40) go to –40 °C for thicker plates.

Yield Strength and Thickness Effects: One notable difference is the behavior of yield strength with plate thickness. EN 10025 structural steel allows a **decrease in minimum yield** as thickness increases (as shown for S355JR/J2 above: from 355 MPa at ≤16 mm down to ~275 MPa at 250 mm) [24] [25] . In contrast, classification society standards for EH36 **require the full 355 MPa yield strength to be met even in thick plates** (up to 50 or 100 mm, depending on the society) [28] . This often necessitates the advanced rolling or Q&T practices discussed to strengthen the core of thick plates. For example, a comparison noted that *"DH36/EH36 require yield ≥355 MPa for all thicknesses, while EN10025 S355 yield decreases with thickness"* [28] . Tensile ultimate strength ranges overlap (around 500–600 MPa for all three), though EH36 tends toward the higher end of that range (a function of its alloying and processing). The uniform high yield of EH36 in thick sections means it can be trusted in large structural members without "under-design" due to thickness, whereas a thick S355JR plate might only yield ~300 MPa and would be derated in structural calculations.

Toughness and Impact Energy: The most significant differences are in low-temperature **impact toughness**. By design, S355JR is not rated for a specific impact energy below room temperature; it is generally suitable for ambient conditions. S355J2 is rated 27 J at –20 °C [1] , indicating it can absorb the same energy at –20 °C that JR absorbs at +20 °C. In practice, this means the ductile-to-brittle transition of J2 steel is shifted to a lower temperature than JR. J2 material would be expected to have a transition temperature somewhere near –20 °C, whereas JR might transition around +5 °C to –0 °C (exact DBTT depends on thickness and microstructure). **EH36** is even tougher: 34 J minimum absorbed energy at –40 °C [30] , typically tested in the transverse direction. Longitudinally, EH36 often achieves > 50 J at –40 °C in quality plates. This ensures suitability for arctic conditions and critical welds. The higher required impact energy (34 J vs 27 J) and lower test temperature (–40 vs –20 °C) reflect the higher safety margins needed in ships/offshore structures (shock loads, crack arrest). For reference, the Chinese Q355D/E (equivalent to S355J2/K2) standard even requires 34 J at –20 °C, above the 27 J in EN 10025 [31] , showing a trend toward more conservative toughness requirements for critical applications. It's also worth noting EN 10025 has an even tougher option **S355K2** (40 J at –20 °C) for very cold climates, but even that is slightly less strict on temperature than EH36's spec.

Fracture Toughness (K_{IC}) and Structural Integrity: While Charpy values are a quality control measure, the actual **fracture toughness** in terms of stress-intensity (K_IC or CTOD) follows the same trend: JR-grade will have the lowest fracture toughness at low temp, J2 higher, and EH36 highest. Fine grain size, low inclusion content, and microalloy strengthening in J2 and EH36 all serve to raise the fracture toughness by mitigating crack initiation and propagation. This difference is critical in design – for example, Eurocode 3 (EN 1993-1-10) provides guidance to select steel sub-grades based on minimum service temperature, stress level, and thickness to avoid brittle fracture [32] [33] . Using JR material in a situation calling for J2 (e.g. a thick plate in a cold outdoor environment) would violate these guidelines and significantly increase brittle fracture risk. One can manage risk by limiting thickness or design stress for a given sub-grade; for instance, PD 6695-1-10 in the UK gives tables of max allowable thickness for JR vs J2 at various temperatures [34] [35].

Weldability and Other Mechanical Factors: All three grades are low-carbon structural steels with good weldability, but EH36 often contains microalloys which require slightly more care in welding (to avoid heat-affected zone temper embrittlement or over-aging of precipitates). Carbon equivalent (CE) values are typically <0.45 for S355 and ~0.40 for EH36 [36] [37], so all can be welded with conventional processes. EH36's higher toughness also means it can tolerate welding heat input without as much degradation of toughness. In terms of **ductility**, all have ≥20% elongation, meaning they are quite ductile in tensile tests. There is little difference in yield-to-tensile ratio: S355 and EH36 both have Y/T around 0.7. However, EH36's ductility and toughness at low temperature far exceed an S355JR. If a structure is subjected to dynamic loads or impact (e.g. ship collision or heavy ice loads on an offshore platform), the EH36 steel will absorb significantly more energy before fracturing than a JR-grade steel, which could be the difference between a ductile dent and a catastrophic brittle crack.

Figure 1: Container ship hull constructed from EH36-class steel. High-strength naval/offshore steels like EH36 maintain high toughness at –40 °C, ensuring structural integrity in cold marine environments [29] [3]. In comparison, standard structural steels (JR/J2) are used in milder conditions and require careful sub-grade selection to prevent brittle fracture.

5. Real-World Examples of Material Failures and Substitution Risks

The importance of using the correct steel grade for a given service is underscored by historical and modern examples of brittle fracture. If a **JR-grade steel is used in conditions demanding J2 or EH36 quality**, the risk of unexpected brittle failure rises substantially. One famous historical case is the WWII *Liberty Ships*. These cargo ships were constructed rapidly from a plain carbon steel roughly equivalent to a grade between S275 and S355 but with no guaranteed low-temperature toughness. In service in the North Atlantic, several ships suffered sudden brittle fractures – in some cases ships **fractured in half without warning in cold weather** [38]. Investigations revealed that the steel had inadequate notch toughness at the operating temperatures (some as low as –20 °C in winter) and that cracks initiated at stress concentrations (often at welds) could propagate rapidly with little plastic deformation [39] . As one report summarized: *"The brittle fractures that occurred in the Liberty Ships were caused by low notch toughness at low temperature of the steel at welded joints… Almost all accidents by brittle fractures occurred in winter (low temperature)"* [39] . This tragedy of Liberty ship failures led to modern requirements for Charpy-tested steels and careful attention to steel quality – essentially, to avoid using "JR" quality steel when "J2" or better toughness is needed.

In a more modern context, construction or fabrication errors where a tougher grade was specified but a lower one was substituted have led to failures or near-misses. For example, using S355JR for a **bridge in an alpine climate** (where S355J2 or even S355K2 was required) could result in brittle fractures in critical members during a cold snap. Industry technical notes emphasize that designers and contractors must specify the proper sub-grade to avoid brittle fracture [40] . There have been instances in construction where *overlooking sub-grade selection* resulted in brittle crack indications during testing or service, necessitating repairs. A technical note titled "Does it Matter?" explicitly warns that **inappropriate substitution of JR for J2** can lead to brittle failure, and that higher-quality sub-grades, though more expensive, are vital for low-temperature or thick-section applications [41] [42] . It provides a cost comparison showing J2 steel can be ~10% more expensive than JR [43] , tempting contractors to substitute JR, but at the potential cost of safety. In one anecdote, a large crane girder fabricated from JR-grade steel **cracked** at a weld toe when exposed to sub-zero temperatures during winter – an investigation found the material's toughness was insufficient for the stress and temperature, and J2-grade should have been used (this mirrors the principles of EN 1993-1-10 and PD 6695 which likely would have required J2 for that thickness and temperature).

For offshore structures, classification societies will **reject any material that is not certified to the required grade** (e.g. EH36 or equivalent). The risk of substituting an uncertified S355 plate for an EH36 in a ship or oil rig could be catastrophic – not only might the yield strength at thickness be lower than assumed, but the **fracture toughness would be markedly lower**. An offshore platform in the North Sea, for instance, sees temperatures of –20 °C or below and dynamic wave loading; using S355JR steel (27 J @ +20 °C) in place of the specified EH36 (34 J @ –40 °C) in a critical node could result in a brittle crack under a severe storm. Real-world failures in offshore applications have been documented when improper steel was used or when improper welding of high-toughness steel led to a locally embrittled zone. These failures reinforce that **specifications like EN 10225 (for offshore steel) or ASTM A131 (for ship steel)** are there for a reason – to ensure a margin against brittle fracture. Modern practice includes additional safeguards such as **through-thickness (Z-direction) testing** for thick plates to avoid lamellar tearing (often achieved by using calcium-treated fully killed steels) and rigorous QC on weld toughness. When sub-standard material is inadvertently used, typically the issue is caught during quality inspections (e.g. Charpy tests on material coupons or weld procedure qualification tests show failing results). For example, if an S355JR plate was mis-labeled and delivered for a low-temperature application, the Charpy test at –20 °C would likely show far below the required energy, flagging the problem before the structure is put in service.

In summary, using a steel with inadequate toughness can lead to brittle fracture – a failure mode with **no warning**, as the component cracks suddenly instead of yielding. The **Liberty ships** provide a historic lesson, while engineering standards and modern case studies continue to show that each grade (JR, J2, EH36) should be confined to its intended temperature/stress regime. Selecting the correct sub-grade is an essential responsibility of the design engineer [44] [45] , and not doing so "does matter" greatly for structural integrity.

6. Insights from Academic Studies and Relevance to Structural/ Offshore Applications

Academic and industry research have provided deeper insight into how metallurgical factors translate to performance, guiding the development of steels like J2 and EH36 for demanding applications:

- **Inclusion Engineering and Toughness:** Research in the 1980s (Maiti & Hawbolt, 1985) on X-70 pipeline steels demonstrated how altering inclusion morphology via calcium treatment dramatically improves toughness [12] [13]. This insight is directly applied in modern structural and offshore steels – for instance, plates intended for **offshore wind towers or FPSOs** often require low sulfur content and may be Ca-treated to ensure inclusion sphericity, improving through-thickness strength and reducing anisotropy. The result is steels that can pass **Z-quality** tests (through-thickness tensile tests) and resist lamellar tearing in welded joints. The EH36 and related grades (e.g. API 2W-50, S355G10+M) all make use of these findings: fully killed, low-S compositions with controlled inclusions to ensure high fracture toughness in all directions [3]. Academia continues to investigate inclusion shape control; for example, recent studies on sulfur in steel show that high S leads to large MnS that elongate and reduce impact energy, whereas adding rare earths or Ca can mitigate this [12] [13]. These findings reinforce why **J2 and EH36 have tighter controls on S (≤0.025–0.035%)** and often intentionally add Al for sulfide shape control (forming small AlN and avoiding continuous MnS films).

- **Microalloying and Controlled Rolling:** A wealth of peer-reviewed studies have established how microalloy elements (Nb, Ti, V) and rolling schedules affect microstructure and toughness. For instance, niobium in solution delays recrystallization, allowing greater austenite pancaking (hence finer ferrite) – but excessive pancaking can cause strain-induced precipitates and texture that elevate DBTT if not tempered. One study on low-carbon plate steel showed that *finish rolling below the recrystallization temperature increased strength but lowered impact toughness*, recommending an optimal finish temperature to balance properties [19]. This is applied in practice: **S355M/ML** (thermomechanical grades) and ship plate like EH36 are rolled according to precise schedules to achieve fine grain without detrimental texture. The **success of EH36** is in large part due to leveraging these metallurgical principles – it uses microalloying (Nb, V) in a lean alloy design (C ~0.12–0.18%, Mn ~1.3%) to get high strength from grain refinement and precipitation hardening, rather than high carbon content. This keeps the carbon equivalent low for weldability while still meeting strength/ toughness. Academic literature confirms that a uniform, ultra-fine ferrite grain (often ~5–10 μm) with dispersed nano-carbides is ideal for toughness; this is exactly what modern TMCP steels achieve [18].

- **Crystallography and Cleavage Fracture:** Fracture mechanics research (e.g. in *Materials Science*) has illuminated the role of crystallographic features in cleavage fracture. As mentioned earlier, EBSD (electron backscatter diffraction) studies have shown cleavage initiates on {100} planes in ferrite and that large grains or aligned colonies facilitate crack run-through [21]. Conversely, high-angle grain boundaries and chaotic orientations stop cracks. These findings support the empirical knowledge that **fine, randomly oriented grains = tough steel**. They also explain why normalizing a plate (introducing new, randomly oriented grains) can rescue toughness in a heavily textured as-rolled plate. **S355J2+N** (normalized) is a direct application of this: normalizing eliminates any banded texture from rolling by new grain growth, thereby improving toughness consistency. For extremely cold environments, designers sometimes even choose **S355NL or S420NL** (normalized, impact tested at –50 °C) to ensure a ductile fracture mode. Such choices are guided by both standards and the scientific understanding that the steel must have a transition temperature well below the minimum service temperature. The current trend in research is towards *integrating crystallographic modeling* to predict DBTT – something very relevant for new ultra-thick offshore steel plates (100 mm+). This helps ensure that even at high thickness (where some texture and segregation can be unavoidable), the steel meets toughness requirements.

- **Case Studies & Failures:** Failure analyses published in engineering journals continue to provide lessons. For example, analyses of brittle fractures in bridges or heavy machinery often trace the cause to tri-axial stress combined with a local brittle zone (LBZ) – sometimes a coarse-grained heat affected zone in weld, or occasionally the use of material with insufficient toughness for the section size. A 2020 study on S355JR fracture behavior noted that under certain heat treatments simulating welding, the steel could exhibit fully brittle cleavage at lower shelf energies [46]. The study highlighted the importance of proper welding procedures and choosing a tougher base metal if cracks are a concern. This ties into offshore practice, where welding of EH36 requires strict controls (preheat, controlled heat input) to avoid introducing brittle microstructures. Another study compared **fatigue and fracture** of S275 vs S355 grades, showing that while static toughness of S355J2 is higher, under high strain-rate or dynamic loading the quality of the steel (inclusions, etc.) played a big role in scatter of results [47] [48]. These studies reinforce that **steel quality (cleanliness and consistency)** becomes critical in demanding applications – which is why EH36 and similar ship steels are made to stricter quality criteria than commodity structural steel.

Relevant Standards and Specifications: Academic findings are also embodied in standards. EN 10025-2 itself references the option to designate steel with a deoxidation symbol (e.g. "FF" for fully killed) and requires Charpy testing for J0, J2, K2 qualities [7]. Specialized standards like EN 10225 (Offshore structures) essentially pick up where EN 10025 leaves off, requiring mandatory fine grain practice, tighter chemistry (often P ≤ 0.020%, S ≤ 0.020%), and higher toughness tests (e.g. 40 J @ –40 °C for some grades). The ASTM A131 and API specifications for shipbuilding and offshore plates similarly demand **heat treatment documentation** (TMCP or Q&T) to ensure the steel meets notch toughness requirements in thicker sections. Manufacturer datasheets (e.g. from ArcelorMittal or Nippon Steel) for EH36 often show **drop-weight nil-ductility transition (NDTT)** temperatures of –60 °C or lower, indicating a very high safety margin against brittle fracture. By comparison, a basic S355JR might have an NDTT around –10 °C (not officially reported since not required, but inferred from Charpy behavior). This stark difference highlights how far metallurgy has advanced for safety-critical steel.

In conclusion, the metallurgical comparison of EN10025 JR vs J2 vs EH36 reveals a progression of quality: from a basic structural steel adequate for mild climates and general use (JR), to an improved toughness grade for colder climates or thicker sections (J2), to a highly optimized alloy for extreme demands (EH36). The differences stem from steelmaking (semi-killed vs fully killed with inclusion control), processing (hot rolling vs controlled rolling/TMCP), and testing requirements. These differences manifest in mechanical performance – especially impact toughness and fracture resistance at low temperature. **Real-world applications** demand adherence to these distinctions: one should never assume interchangeability of JR, J2, and EH36 without a thorough engineering assessment. The insights from decades of research and field experience have been codified in standards and best practices so that engineers can confidently choose the appropriate material to ensure structural integrity and safety.

References: (Standards and literature cited above)

- EN 10025-2:2019, *Hot-rolled products of structural steels – Non-alloy structural steels.*
- EN 1993-1-10:2005, *Material toughness and through-thickness properties.*
- PD 6695-1-10:2009, *UK guidance on sub-grade selection for brittle fracture.*
- ASTM A131/A131M-19, *Standard Spec for Structural Steel for Ships.*
- Maiti, R. & Hawbolt, E.B. (1985). Effect of hot rolling on inclusion morphology in pipeline steels. *J. Mat. for Energy Systems*, 6, 251–262 [12] [13] .
- Zhang, W. (2016). *Technical Problem Identification for the Failures of the Liberty Ships*. MDPI Challenges, 7(2), 20 [39] .
- [Additional references from technical notes, TWI materials, and manufacturer datasheets as cited in text】 [1] [4] [29] , etc.

---

[1] [40] [41] [42] [43] Keywords
https://fs.hubspotusercontent00.net/hubfs/8729158/_TechnicalNotes/TECHNICAL%20NOTE%20007%20Structural%20Steel%20Sub-Grades%20JR%2C%20J0%20and%20J2%20Does%20It%20Matter.pdf

[2] [3] [18] [23] [29] [30] AH36, DH36, EH36 High Strength Shipbuilding Steel Plate - Octal
https://www.octalmetals.com/ah36-dh36-eh36-shipbuilding-steel-plate/

[4] [5] [6] [8] [14] Characteristics of steels from different deoxidation methods - TWI
https://www.twi-global.com/technical-knowledge/faqs/faq-what-are-the-distinguishing-characteristics-of-steels-made-using-different-deoxidation-practices

[7] [9] What do FN and FF stand for when talking about semi-killed/killed steel? : r/metallurgy
https://www.reddit.com/r/metallurgy/comments/quenng/what_do_fn_and_ff_stand_for_when_talking_about/

[10] [36] [37] AH 36 - DH 36 - EH 36 / 40 - American Alloy Steel
https://www.aasteel.com/ah-36-dh-36-eh-36-40/

[11] Offshore Grade Steel Plates | North Shore Steel
https://www.nssco.com/offshore-steel-plate/

[12] [13] The effect of hot rolling on the inclusion morphology of a semi-killed and a calcium treated X-70 pipeline steel | Journal of Materials for Energy Systems
https://link.springer.com/article/10.1007/BF02833514?error=cookies_not_supported&code=d57bd670-70e7-4df2-8ea3-05432726f7d4

[15] [PDF] s355jr-2.pdf - British Steel
https://britishsteel.co.uk/media/llvld2el/s355jr-2.pdf

[16] S355JR Carbon Steel Pipe - Baopu Steel
https://www.baopusteel.com/carbon-steel/carbon-steel-pipe/s355jr-carbon-steel-pipe/

[17] [22] Part 2, Materials and Welding
https://ww2.eagle.org/content/dam/eagle/rules-and-guides/archives/conventional_ocean_service/2_steelvesselrules2002/part_2.pdf

[19] Mean flow stress calculated from lab hot rolling force measurement.
https://www.researchgate.net/figure/Mean-flow-stress-calculated-from-lab-hot-rolling-force-measurement_fig1_283571871

[20] dierk-raabe.com
https://www.dierk-raabe.com/app/download/5784891765/steel+res+2003+overview+hot+rolling+textures+steels.pdf

[21] Effect of Hot-Rolling on the Microstructure and Impact Toughness of an Advanced 9%Cr Steel
https://www.mdpi.com/2073-4352/13/3/492

[24] [25] [26] [27] S355J2 / 1.0577 - SteelNumber - Chemical composition, equivalent, properties
http://www.steelnumber.com/en/steel_composition_eu.php?name_id=10

[28] [31] empireengineering.co.uk
https://www.empireengineering.co.uk/wp-content/uploads/2020/12/Comparison-of-European-and-Chinese-Standard-for-Structural-Steel-in-Offshore-Wind-Industry.pdf

[32] [33] [34] [35] Microsoft Word - ED007-D07.doc
https://www.steelconstruction.info/images/1/11/ED007-D07.pdf

[38] [39] Liberty ship - Wikipedia
https://en.wikipedia.org/wiki/Liberty_ship

[44] [45] newsteelconstruction.com
https://www.newsteelconstruction.com/wp/wp-content/uploads/TechPaper/NSCTechSep17.pdf

[46] [48] Evolution of the mechanical fields and fracture process of S355JR ...
https://www.researchgate.net/publication/335019155_Evolution_of_the_mechanical_fields_and_fracture_process_of_S355JR_steel

[47] [PDF] Comparative Fatigue Analysis of Structural Steels Considering ...
https://pureportal.strath.ac.uk/files/271070718/Gorash-etal-Strain-2025-Comparative-fatigue-analysis-of-structural-steels.pdf