REVISTA SOLDAGEM & INSPEÇÃO

ISSN 1980-6973 (Online) | ISSN 0104-9224 (Print)

ORIGINAL PAPER

# Evaluation of High Strength Cast Steel Welded Joints Suitable to Mooring Components

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**How to cite:** Jorge JCF, Santos Filho AMF, Diniz JLC, Souza LFG, Mendes MC. Evaluation of high strength cast steel welded joints suitable to mooring components. Soldagem & Inspeção. 2022;27:e2720. https://doi.org/10.1590/0104-9224/SI27.20

**Abstract:** This work investigates the performance of high strength cast steel welded joints to confirm their feasibility for application in mooring components. Three welded joints, with ultimate tensile strength in the range of 700 to 900 MPa, were obtained by the shielded metal arc welding process, the most applied in repair operation. After welding, a post welding heat treatment was performed to relieve the residual stresses. The results obtained in tension, impact Charpy-V, and hardness tests, at different positions of the heat affected zone were compared with equivalent welded joints performed with rolled steels currently applied in mooring chain links. These results showed that cast steels can obtain results equivalent to the rolled steels. Furthermore, the composition of cast steels for more stringent requirements (UTS > 860 MPa) is adjusted with higher nickel contents, while rolled and forged steels show increased C, Cr, and Mo contents. As a consequence, a refined microstructure with excellent impact toughness was obtained. Thus, these steels present a high potential to be used in this application contributing to reduce manufacturing costs.

**Key-words:** Cast steel; Welded joint; Mechanical properties; Mooring components.

## 1. Introduction

In the last decades, oil and natural gas are being more actively produced throughout the world to meet the increasing energy demand. Energy sources at sea and under the seabed have captured engineering society's attention [1]. As a consequence, a great number of offshore structures are being built, leading to exploration and development in deep water [2-4]. Moored floating units offer an attractive solution for oil and gas discovery in a big range of water depths [2]. Currently, more than 300 floating units are operating worldwide [5].

The safe continuous operation of these offshore units is directly dependent on the integrity of their mooring systems that keep them in position during service. They are submitted to several loads as well as continuous exposure to a corrosive environment. The mooring systems consist of long lengths of steel chain links, wire or polyester ropes, and other accessories [6,7] designed for an operational life of about 20 years, and periodic inspections (5 years) are mandatory for monitoring the structural integrity of these components because they are an important point of failure of mooring lines [8]. Thus, the components of mooring lines have fundamental importance, concerning the selection and maintenance of the materials used [9]. High strength low alloy steels are usually used because of the weight of mooring lines for exploration into deep water [10]

To achieve high strength, these steels are usually quenched and tempered [10-13] to provide a microstructure containing bainite and martensite in contrast to ferritic and pearlitic microstructure obtained in the conventional steel presenting a yield strength of 460MPa or less [14]. Based on this scenario, steels presenting lower carbon and lower carbon equivalent contents are more appropriate to attain the stringent requirements of the International Association of Classification Societies (IACS) [15] for mooring components (**Table 1**). As the chemical composition is not specified [15], the same steel can be quenched and tempered at different temperatures to obtain different grades [2,16].

Received: 15 Apr., 2022. Accepted: 11 Aug., 2022.
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**Table 1.** Mechanical properties required for mooring components according to the IACS W22 specification [15].

| Grade | YS (MPa) | UTS (MPa) | El (%) | RA (%) | $E_{cv}$ at -20 °C (J) |
|---|---|---|---|---|---|
| R3 | 410 | 690 | 17 | 50 | 40 |
| R3S | 490 | 770 | 15 | 50 | 45 |
| R4 | 580 | 860 | 12 | 50<br>(35*) | 50 |
| R4S | 700 | 960 | 12 | 50 | 56 |
| R5 | 760 | 1000 | 12 | 50 | 58 |

Where: YS = Yield Strength; UTS = Ultimate Tensile Strength; El = Elongation; RA = Reduction of Area; Ecv = Charpy-V test result. (*) Requirement for cast steels.

While rolled material is usual for manufacturing the mooring chain links, forged materials are preferentially recommended for connecting accessories. However, sometimes the use of forgings can be a challenge due to the complex geometry of the components [17], as shown in Figure 1.

Fabrication of mooring chains using rolled bars involves for each of the links, several manufacturing steps including hot bending of the link's bar, welding and heat treatment [18]. The same complex route is due to the manufacturing of forged connecting links, such as shackles [16]. For these components, the process involves multi-step forming at high temperature, to transform a cylindrical rod into the overall curved shape of a shackle, followed by heat treatment performed also in several steps (annealing, quenching, and tempering). To simplify the manufacturing cycle, cast steel parts can become an interesting alternative because a reduction in the production cost of the order of 30% can be reached [13], encouraging researchers to focus on cast steels [19,20]. Although information regarding carbon content and heat treatment procedures remain still limited for selecting casting steels that are suitable for offshore structures, these steels are extensively used in the naval and offshore industry [13,21-24] in the manufacturing of industrial parts earlier produced by expensive manufacturing processes, such as extrusion or forging and other complex thermo-mechanical processes [13].


(a) Hall stockless cast anchors for ships (b) Shank and schackle for high holding power steel plate anchor (c) Tip and padeye for torpedo anchor

(d) Socket for wire rope (e) Mooring chain link (f) Mooring shackle

**Figure 1.** Some components applied in mooring lines manufactured in cast steels.

When comparing high strength cast steels applied in mooring components manufactured by different routes (Table 2), the advantages of cast steels can be noted, because these steels present lower carbon and carbon equivalent contents in comparison to the forged steel widely used in the offshore industry, such as DIN 34CrNiMo6 [17], AISI 4130 [25,33] and AISI 8630 [26]. While chromium is the main contributing factor increasing the mechanical strength in rolled steels, higher nickel contents are the preference in cast steels. It is well known the refining effect of nickel on the microstructure.

**Table 2.** Characteristics of high strength steels used in mooring components manufactured by different routes [11,17,25-32].

| Steel | Type | Component | UTS (MPa) | C | Mn | Cr | Ni | Mo | Ceq* |
|---|---|---|---|---|---|---|---|---|---|
| A | Cast steel | Mooring schackle [27] | 704 | 0.24 | 1.37 | 0.45 | 0.69 | 0.32 | 0.63 |
| B | Cast Steel | Padeye for torpedo [17] | 791 | 0.25 | 1.17 | 0.58 | 0.59 | 0.35 | 0.67 |
| C | Cast Steel | Mooring schackle [28] | 880 | 0.21 | 0.80 | 0.55 | 2.78 | 0.31 | 0.70 |
| E | Rolled Steel | Chain link [29] | 716 | 0.31 | 1.60 | 0.04 | 0.01 | 0.07 | 0.59 |
| G | Rolled Steel | Chain link [30] | 891 | 0.22 | 1.12 | 1.07 | 0.70 | 0.22 | 0.70 |
| H | Rolled Steel | Chain link [31] | 884 | 0.23 | 1.50 | 1.00 | 0.60 | 0.40 | 0.80 |
| J | Rolled Steel | Chain link [11] | 1,000 | 0.23 | 0.59 | 1.91 | 0.91 | 0.44 | 0.86 |
| K | Forged Steel | Connector [25] | 730 | 0.27 | 0.53 | 0.93 | 0.19 | 0.21 | 0.60 |
| L | Forged Steel | Connector [26] | 800 | 0.32 | 0.90 | 0.97 | 0.86 | 0.41 | 0.82 |
| M | Forged Steel | Schackle [32] | 950 | 0.30 | 0.85 | 0.90 | 0.81 | 0.38 | 0.76 |

*Ceq = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15.

Considering that most of these components have a weight of the order of tons and the presence of fabrication defects can compromise the supply and/or operation, it is important to develop repair procedures to avoid the premature scrapping of the component. It must be emphasized that castings usually show several manufacturing defects, such as shrinkage, sand inclusions, and voids, which associated with heterogeneous chemical composition, can cause changes on the mechanical properties. Besides, there are more complex situations involving not only the replacement of wrought or forged by cast material but requiring the welding of cast steels as a step of the manufacturing process, such as the welding of padeyes of torpedo anchors [17]. As a consequence, some works [17,24,27,28,34] have studied cast steel welded joints for offshore and naval industries, aiming to show that welding of cast pieces does not present a risk to the reliability of the structural work of the equipment. However, evidences of mechanical properties and qualified procedures are still limited.

Based on the above, this work shows some comparative results with steels used in the offshore industry manufactured by different routes and discusses the behavior of the high strength cast steel welded joints suitable for the application of mooring components.

## 2. Evolution of Cast Steel Welded Joints Used in Mooring Components

The need for cost reduction and technological improvement motivated the attention of marine component and structure manufacturers regarding the need to develop manufacturing and repair procedures supported by consistent technical-scientific foundations. Particularly, the repair of cast steels is still controversial due to the limited requirements to qualify for this operation. The ASTM A488 Standard [35] which covers the qualification of procedures for steel castings seems to be a version of the ASME IX Code [36] for cast steels. At the same time, the IACS W28 Specification [37] is dedicated to weldable steels for hull construction and marine structures. The execution of a post welding heat treatment (PWHT) at a temperature of not less than 550 °C to stress relief is the unique mandatory requirement. Thus, when a mooring component needs to be repaired by welding, alternative procedures are usually agreed with the Classification Societies on a case-by-case basis as a consequence of the lack of specific requirements. It can lead to endless technical discussion and sometimes to unnecessary scrapping of the component.

The excessive concern about the behavior of cast steel welded joints promoting unacceptable higher manufacturing costs, probably associated with the limited knowledge on the subject, motivated the development of systematic research to understand the consequences of welding on the properties of cast steels repaired by welding.

Initial research [38,39] produced welded joints simulating a repair using an ASTM A 27 Grade 60 30 cast steel (0.2C,0.84Mn,0.44Si), widely applied in Hall Stockless anchors for ships (Figure 1a) was started in 1992. Various conditions were incorporated to produce more conservative results, as follows:

a) joint geometry was designed to simulate a major repair (Figure 2). A weld repair is considered major when the depth of the groove prepared for welding exceeds 25% of the thickness of 25mm, whichever is smaller. All other weld repairs are considered minor [15];

b) the shielded metal arc welding process (SMAW) was used because it is the preferred process for repair operations;

c) A semi-V groove was applied to remove Charpy-V impact test specimens with the notch integrally at the heat affected zone (HAZ), although this test is not required for cast steels used in ordinary anchors [40,41].

d) the base metal was obtained in the as-cast condition and after a heat treatment at 900 °C.

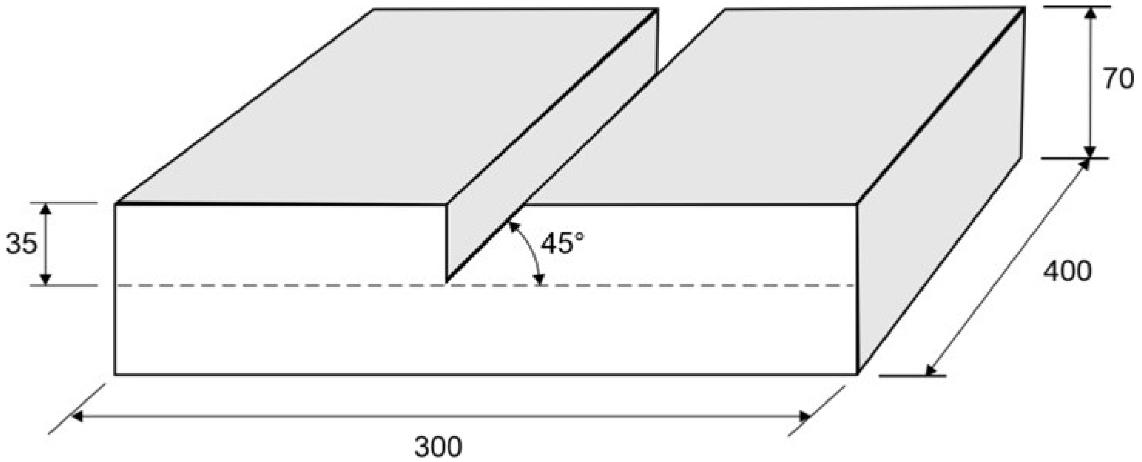

**Figure 2.** Schematic view of the joint geometry. Dimensions in millimeters.

Table 3 shows that welded joints using base metal previously submitted to a heat treatment provide acceptable results. On the contrary, very poor results are observed when the base metal is in the as-cast condition. However, it is important to emphasize that it is not an issue because the material is always heat treated before the drop and proof load tests, the mandatory qualification tests. Cast anchors are submitted to drop tests, where each part of the anchor is raised to a height of 4 meters and dropped onto a steel slab without fracturing (Figure 3). After the drop test, hammering tests are carried out to check the soundness of the component. After approval on the drop test, the anchor is assembled (shank, fluke, and schackle) and a proof load test is executed to check the strength and fitness for service [15].

All these results reveal that the welding did not cause deleterious effects on the properties and they confirm the feasibility of the repair operation. Also, it is noted that the results obtained at the HAZ are always superior to the base metal. From these findings, it can be inferred that, besides the application in ordinary anchors (Figure 1a), this cast steel can be also proposed to other mooring components, such as shanks of high holding power anchors (Figure 1b) or tips of the torpedo (Figure 1c), where the welding is applied in the manufacturing process. These promising results motivated the study of cast steels with higher strength [27,28,34].

**Table 3.** Mechanical properties of the ASTM A27 Grade 60 30 cast steel welded joint [38].

| Condition (*) | UTS (MPa) | Bending | Ecv (joules) | |
|---|---|---|---|---|
| | | | HAZ | Base metal |
| As cast | 482 | Rejected | 22 | 7 |
| Normalized | 519 | Approved | 70 | 33 |
| Normalized + PWHT | 479 | Approved | 53 | 32 |
| Minimum | 415 | | 27 | 27 |

Where: UTS = Ultimate Tensile Strength; Ecv = Absorbed energy at 25 °C. (*) Condition of the base metal previous to welding.

**Figure 3.** Drop test of a cast anchor.

Jorge et al. [27] developed an alternative procedure without PWHT for the execution of a minor repair in ASTM A 148 Gr. 80 50 cast steel used in anchor shackles. The welding procedure performed by the SMAW process incorporated a hammering after each welding pass to relieve the residual stresses and the temper bead technique was also applied to promote a tempering of the microstructure. After repair, the schackle was submitted to a proof load test (Figure 4). The proof load is specified to be about 70% of the minimum breaking load (MBL) of the chain links, depending on the material grade and the link's size. Moreover, the proof load test can induce beneficial effects of compressive residual stresses at zones where high-stress ranges can cause cracking [42,43].

**Figure 4.** Proof load test of a mooring schackle.

The results showed that acceptable mechanical properties allowed the qualification of the welding procedure and the repaired schackle was considered approved after the proof load test. Moreover, it was verified a reduction of about 50% in manufacturing costs of cast shackles for steel plate anchors by avoiding the scrapping of the schackles.

For major repairs, some requirements are mandatory, including the execution of a PWHT [15]. Regardless of the execution of a final proof load test, welding procedures need to be adjusted so as not only to promote material with good mechanical and metallurgical characteristics but also to efficiently reduce residual stresses.

In this respect, Table 4 shows the results obtained by Mosciaro and Jorge [34] when welding a high strength cast steel applied in mooring sockets (Figure 1d), where it is noted that acceptable mechanical properties are obtained in the as welded condition. However, it is worth noting that the microstructure existing at the last welding pass, containing untempered martensite in the as welded condition (Figure 5), can contribute to the propagation of existing cracks. Also, the measurements performed by the hole-drilling strain-gage method according to the ASTM E 837 standard [44] showed that PWHT is an effective way to reduce the residual stresses. Thus, the PWHT is crucial to the safe major repair of high strength cast steels.

**Table 4.** Effect of PWHT on the mechanical properties and residual stresses of high strength cast steel welded joints [34].

| Condition | UTS (MPa) | Ecv at 0 °C (joules) | | | Residual Stress (MPa) | |
|---|---|---|---|---|---|---|
| Position | Transversal | WM | HAZ | BM | Longitudinal | Transversal |
| As welded | 740 | 139 | 75 | 86 | 463 | 39 |
| PWHT | 721 | 159 | 85 | 81 | -10 | -37 |

UTS = Ultimate Tensile Strength; WM = Weld Metal; HAZ = Heat Affected Zone; BM = Base Metal.

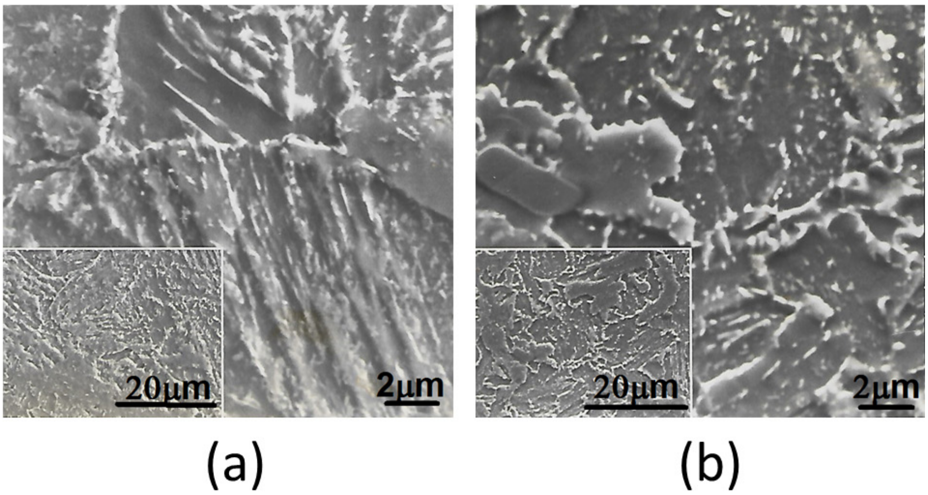


**Figure 5.** Microstructure of the HAZ after etching with nital 2% (SEM). (a) As welded; (b) PWHT.

The same conclusion was emitted by Santos et al. [17] for the welding of an ASTM A 148 Gr. 105 85 high strength cast steel (Basic composition: 0.25C, 1.17Mn, 0.43Si, 0.58Cr, 0.59Ni, 0.35Mo) applied in padeye for torpedo anchors (Figure 1c). Even executing the temper bead technique and obtaining acceptable mechanical properties (Table 5), the microstructure of the HAZ close to the top surface composed of a mixture of bainite and martensite was not appropriate (Figure 6). Consequently, the PWHT was also recommended for this project.

**Table 5.** Mechanical properties of the ASTM A 148 Gr. 105 85 cast steel welded joint [17].

| Condition | UTS (MPa) | Ecv at the HAZ (joules) | $HV_{0.5}$ at the top surface |
|---|---|---|---|
| As welded | 812 | 41 | 477 |
| Temper Bead | - | 54 | 476 |
| PWHT | 791 | 55 | 340 |
| Minimum required | 725 | 34 | |

Where: UTS = Ultimate Tensile Strength; Ecv = Absorbed energy at -30 °C.

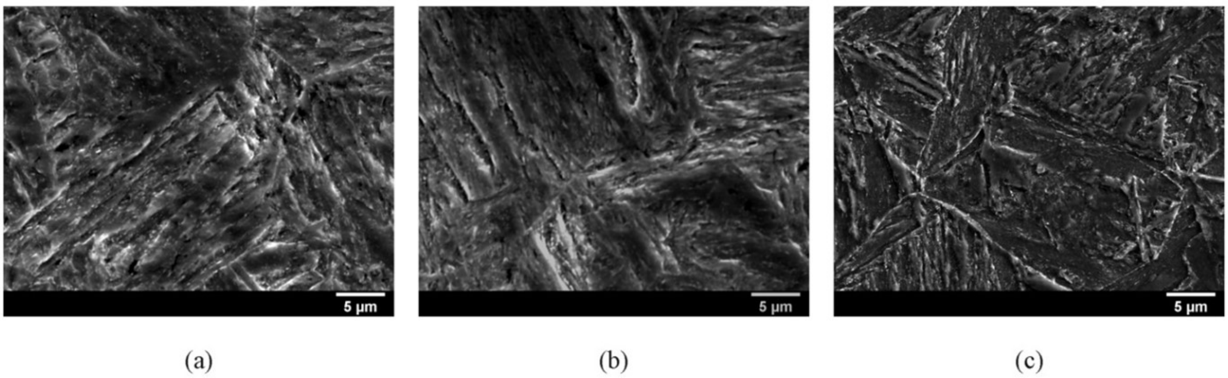


**Figure 6.** Microstructural evolution of the HAZ at the top surface after etching with nital 2% (SEM). (a) As welded; (b) Temper Bead; (c) PWHT.

Finally, Sumam et al. [28] studied a cast steel with superior mechanical strength used in mooring shackles (Figure 1f). For this application, a different chemical composition (Basic composition: 0.21C, 0.80Mn, 0.30Si, 0.55Cr, 2.78Ni, 0.31Mo) with a higher nickel content necessary to comply with the stringent requirements, high ultimate tensile strength associated with high impact toughness, for grade R4 of the IACS W22 [15], as shown in Table 1.

Table 6 shows the mechanical properties of the welded joint, where it is noted the lower hardness values compared to the previous steel (Table 6). This behavior is due to the lower carbon and higher nickel contents, both contributing factors to the formation of refined tempered martensite (Figure 7).

**Table 6.** Mechanical properties of the R4 quality cast steel welded joint [28].

| Condition | UTS (MPa) | Ecv at the HAZ (joules) | $HV_{0.5}$ at the top surface |
|---|---|---|---|
| As welded | 883 | 88 | 314 |
| PWHT | 892 | 94 | 281 |
| Minimum required | 860 | 50 | - |

Where: UTS = Ultimate Tensile Strength; Ecv = Absorbed energy at -20 °C.

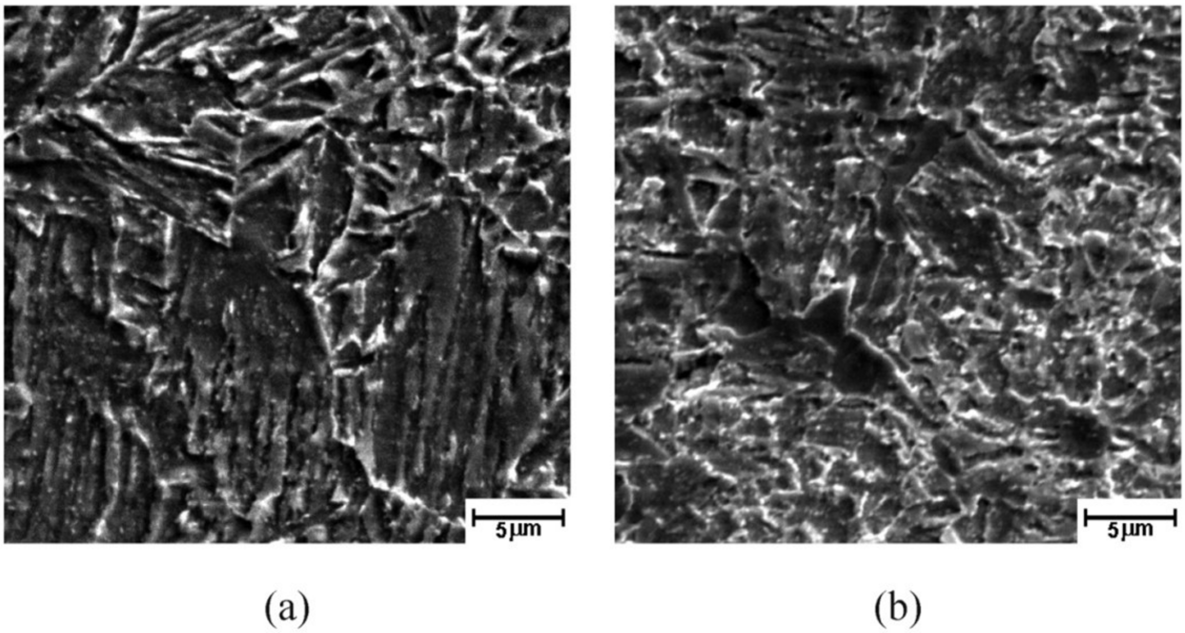


**Figure 7.** Microstructural aspect of the HAZ at the top surface after etching with nital 2% (SEM). (a) As welded ; (b) PWHT.

## 3. Case Studies

The promising results shown before induced a positive scenario for welding high strength cast steels. Thus, three high strength cast steels welded joints were studied and compared with rolled steels currently used in mooring components. All studies were conducted by the SMAW process, the most recommended welding process to repair operations.

The main goals are:

a) To confirm the feasibility of high strength cast steel welded joints for application in mooring components;

b) To show that an equivalent welding procedure can be obtained due to the lower carbon and carbon equivalent contents compared to quenched and tempered rolled steels widely applied in mooring components;

c) To provide a more conservative analysis because the Charpy-V notch is positioned integrally at the HAZ, as shown schematically in Figure 8. From this figure, it is observed that the current standards [32,35,43] are unable to evaluate the HAZ. Although these standards [32,35,43] show requirements at the fusion line, it is important to remember that the fusion line means that 50% of the notch is in weld metal [35,43]. As the HAZ is usually narrow (~3 mm), only a small part of the notch is effectively positioned at the HAZ.

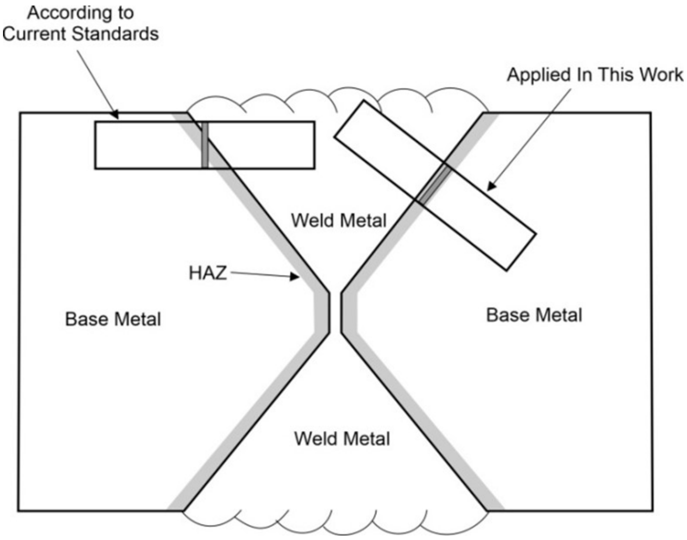


**Figure 8.** Detail of the Charpy-V test specimens.

### 3.1. Materials

Table 7 shows the characteristics of the high strength cast steels studied in this work, where different ultimate tensile strengths are observed. A description of each material is presented below:

a) **Case 1** - **Welding of round bars and pins for high holding power anchors**

An ASTM A 148 Gr. 80 50 high strength cast steel was used to produce a slab with dimensions 200x200x50 mm. The material was previously normalized, quenched, and tempered at 640 ºC.

This cast steel is intended to manufacture round bars and pins used to connect different parts (shank, fluke, and schackle) of high holding power anchors (Figure 1b).

As consumable for welding, covered electrodes of the class AWS E 7018-1 of 3.25 mm diameter were used.

b) Case 2 – Welding of chain links for application in Grade R3 mooring chain.

A high strength cast steel, Grade R3 according to the IACS W22 [15], was used to produce a 105 mm-diameter mooring chain (Figure 1e). The material was previously normalized, quenched, and tempered at 600 ºC. As consumable for welding, covered electrodes of the class AWS E 11018M of 4.0 mm diameter were used.

c) Case 3 – Welding of chain links for application in Grade R4 mooring components.

A high strength cast steel, Grade R4 according to the IACS W22 [15], was used to produce schackles for a 120 mm-diameter mooring chain (Figure 1f). A 148 mm-diameter round bar was used in the experiment. The material was previously normalized, quenched, and tempered at 640 °C.

As consumable for welding, covered electrodes of the class AWS E 12018M of 4.0 mm diameter were used.

**Table 7.** Chemical composition and ultimate tensile strength of the cast steels studied.

| Case | Steel | UTS (MPa) | Chemical composition (Wt, %) | | | | | | Ceq |
|---|---|---|---|---|---|---|---|---|---|
| | | | C | Mn | Si | Cr | Ni | Mo | |
| 1 | A | 655 | 0.24 | 1.37 | 0.38 | 0.40 | 0.47 | 0.18 | 0.63 |
| 2 | B | 720 | 0.23 | 1.50 | 0.31 | 0.37 | 0.67 | 0.29 | 0.67 |
| 3 | C | 945 | 0.19 | 0.78 | 0.39 | 0.64 | 2.58 | 0.33 | 0.69 |

Where: UTS = Ultimate Tensile Strength; Ceq = Carbon equivalent = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15.

For comparison, some rolled steels widely applied in the same mooring components cited above were selected.

Table 8 shows the characteristics of the high strength rolled steels and the following comments are due:

a) **Case 1** - As the anchor's parts can use materials produced by different routes attaining 540 MPa, a rolled steel (R1) removed from steel plates was used;

b) **Case 2** – A rolled steel (R2) widely applied in mooring chain links was used and;

c) **Case 3** - Two rolled steels (R3 and R4) used in mooring chain links obtained from different suppliers were used.

**Table 8.** Chemical composition and ultimate tensile strength of the rolled steels applied in mooring components.

| Case | Rolled steel | UTS (MPa) | Chemical composition (Wt, %) | | | | | | Ceq |
|---|---|---|---|---|---|---|---|---|---|
| | | | C | Mn | Si | Cr | Ni | Mo | |
| 1 | R1 | 543 | 0.15 | 1.39 | 0.23 | 0.45 | 0.01 | 0.031 | 0.48 |
| 2 | R2 | 723 | 0.34 | 1.84 | 0.29 | 0.16 | 0.02 | 0.02 | 0.69 |
| 3 | R3 | 939 | 0.26 | 1.10 | 0.28 | 1.17 | 0.63 | 0.25 | 0.79 |
| 3 | R4 | 942 | 0.22 | 1.47 | 0.30 | 1.06 | 0.63 | 0.23 | 0.78 |

### 3.2. Welding

Welded joints were obtained by the SMAW process, in the flat position. The joints were prepared with an X-joint type groove (Figure 8). A groove angle of 60 degrees was machined.

Different parameters were used for each case due to the specific characteristics of the steels, as follows:

a) **Case 1** - Preheat temperature of 150 °C, nominal heat input of 2.0 kJ/mm, PWHT at 580 °C for 2 hours;

b) **Case 2** - Preheat temperature of 200 °C, nominal heat input of 1.4 kJ/mm, PWHT at 580 °C for 2 hours;

c) **Case 3** - Preheat temperature of 200 °C, nominal heat input of 1.6 kJ/mm, PWHT at 600 °C for 2 hours;

### 3.3. Mechanical tests and metallographic examination

Test specimens were removed transversally to the weld beads to tension, bending and impact Charpy-V tests to evaluate the compliance with the requirements. The tension and bending tests were carried out at room temperature (25 °C). Charpy-V impact tests at -20 °C for cases 1 and 3 and, 0 °C for case 2, were also performed on standard test pieces (10x10x55mm). The notch was positioned in the thickness section at positions corresponding to 1mm (1FL), 3mm (3FL), and 5mm (5FL) parallel to the fusion line (Figure 8).

Macro and micrographic examinations were also performed. The microstructure was observed by optical microscopy (OM) in the same regions where the Charpy-V notch was positioned. The samples were prepared using the conventional procedure of grinding and polishing, and 2% nital was used as the etchant.

### 3.4. Results and analysis

#### 3.4.1. Tension and bending tests

Table 9 shows the results of tension and bending tests, where it is noted that all results are acceptable. Figure 9 confirms the absence of defects after bending tests (Figure 9).

**Table 9.** Results of tension and bending tests.

| Test / Case | Tension test / YS (MPa) | UTS (MPa) | Bend Test | Impact Charpy-V tests / Absorbed energy (joules) | | |
|---|---|---|---|---|---|---|
| | | | | 1FL | 3FL | 5FL |
| 1 | 547+/-2 | 633+/-1 | Approved | 68+/2 | 63+/-3 | 60+/-2 |
| Required | 355 | 540 | Defects<3.2mm | | 40 joules at -20 °C | |
| 2 | 622+/-3 | 755+/-4 | Approved | 92+/-10 | 91+/-11 | 100+/-4 |
| Required | 410 | 690 | Defects<3.2mm | | 50 joules at 0 °C | |
| 3 | 828+/-2 | 913+/-1 | Approved | 86+/-1 | 90+/-7 | 88+/-3 |
| Required | 580 | 860 | Defects<3.2mm | | 36 joules at -20 °C | |

Where: YS = Yield Strength; UTS = Ultimate Tensile Strength.

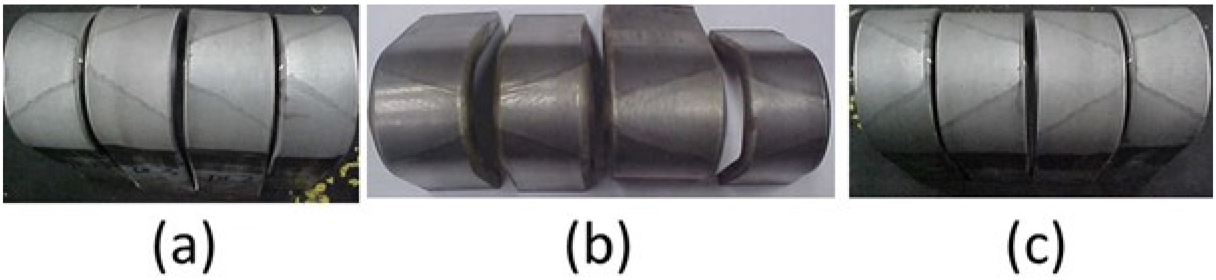

**Figure 9.** Test specimens after bending tests. (a) Case 1 – Steel A; (b) Case 2 – Steel B; (c) Case 3 – Steel C.

### 3.4.2. Impact toughness and microstructure

Figure 10 shows the macrographs of the welded joints. It is noted the absence of welding defects and a narrow HAZ (~3mm). Thus, it can be inferred that the position of the Charpy-V notch corresponds integrally to the HAZ for 1FL and base metal for 5FL. As the weld bead contour and HAZ profiles are not linear, the Charpy-V notch at 3FL can be composed of intercritical and subcritical regions of the HAZ and even base metal. As a consequence, a higher scatter band can be expected for the results obtained at this position, depending on the position where the notch is positioned. Moreover, a higher level of heterogeneity along with the thickness due to segregation usually observed in cast steels is another contributing factor to different results obtained in the same region. However, the results show that quenched and tempered high strength cast steel can provide more homogeneous results than those observed in cast steels [24,45,46].

The relationship between microstructure and impact toughness is discussed separately for each case due to its complexity.

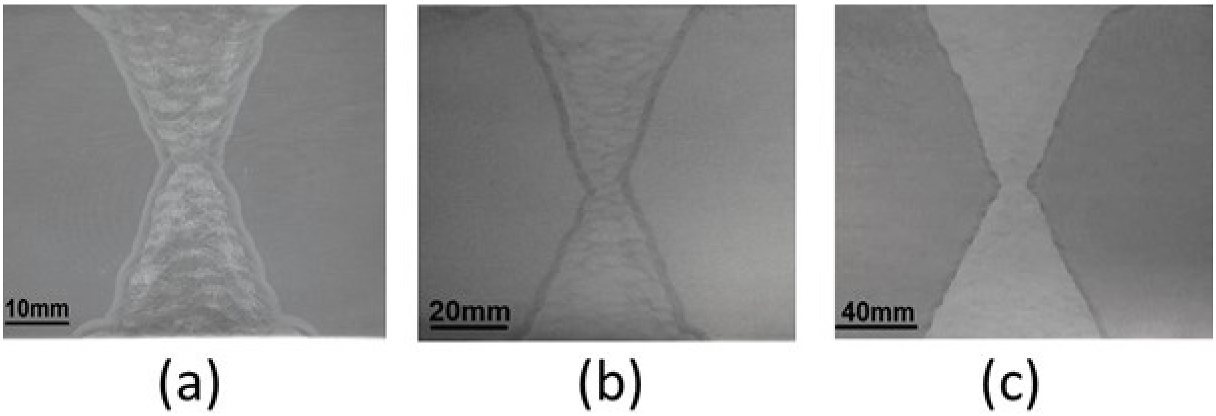


**Figure 10.** Macrographs of the welded joints after etching with nital 2%. (a) Case 1 – Steel A; (b) Case 2 – Steel B; (c) Case 3 – Steel C.

#### 3.4.2.1. Case 1 - Welding of round bars and pins for high holding power anchors

Figure 11 shows that the cast steel was able to achieve adequate impact toughness, with equivalent results compared to rolled steel, even being higher alloyed steel with superior mechanical strength (Tables 7 and 8). Also, this result is higher than the minimum required (40 joules). Furthermore, it is important to emphasize that welding does not promote deleterious effects on the impact toughness because the results obtained at the HAZ (FL1) are slightly higher than those observed in the base metal (Table 9 and Figure 11). It can be explained by the presence of refined tempered martensite at the HAZ, while upper bainite predominates in base metal (Figure 12).

Although the rolled steel machined from steel plates is cheaper, they are not a complete solution to round bars with a larger diameter due to the limited availability of thickness of steel plates. Thus, cast steel is an interesting option for these parts because it attains the requirements at an acceptable cost for all diameters necessary.

Based on the above, it can be concluded that the ASTM A 148 Gr. 80 50 cast steel studied in this work is weldable by the SMAW process, with adequate mechanical properties. It presents equivalent impact toughness compared to rolled steel, even having a higher level of alloying elements. The results also showed that cast steel is a more costlier-effective choice to round bars, pins, and schackles for high holding power anchors. This steel can also be proposed for other mooring components.

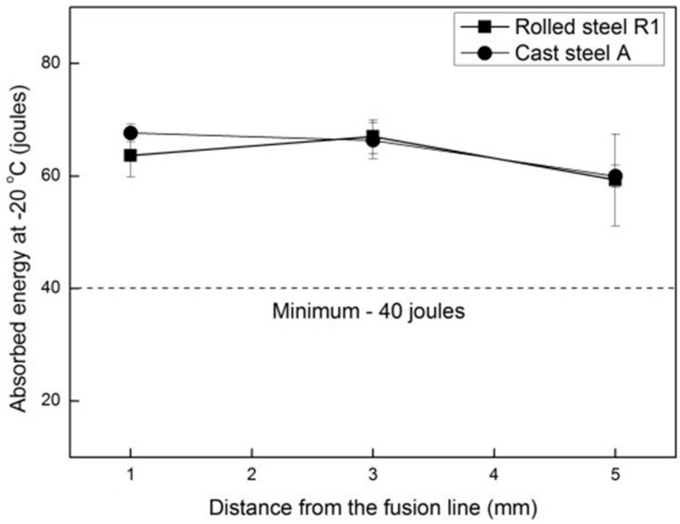


**Figure 11.** Impact toughness of the welded joints obtained with cast steel A and rolled steel R1.

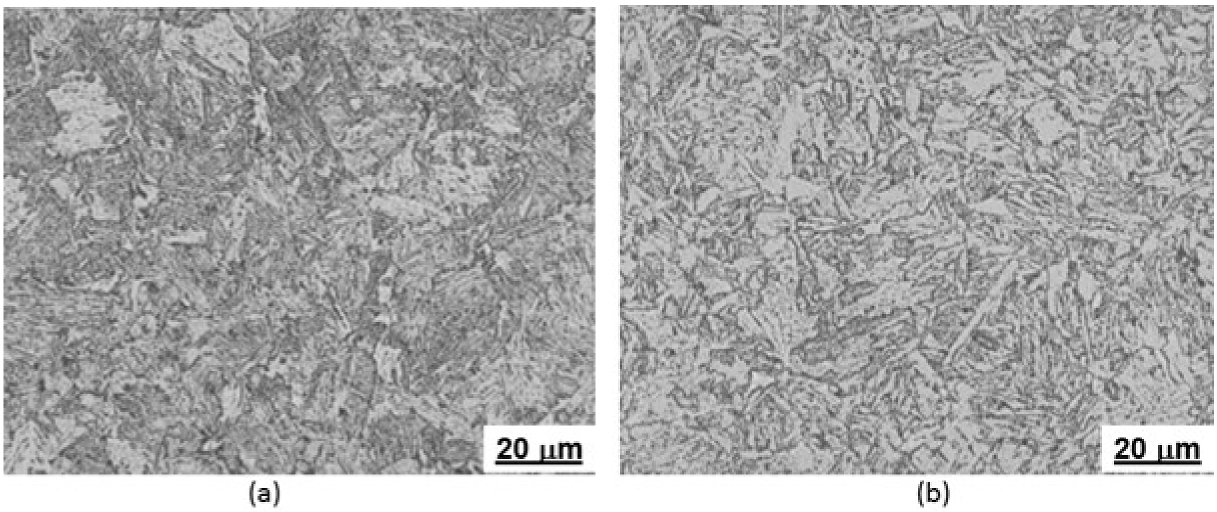


**Figure 12.** Microstructure of the regions of the cast steel welded joint (case 1) after etching with nital 2% (OM). (a) Coarse grain region of the HAZ; (b) Base metal.

### 3.4.2.2. Case 2 – Welding of chain links for application in Grade R3 mooring chain

Figure 13 shows the results achieved the impact toughness required (50 joules) for approval of welding procedures by the Classification Societies [47]. It is noted that the cast steel can obtain impact toughness higher than the rolled steel with the same strength level. Besides the lower carbon and carbon equivalent contents presented by the cast steel, it is worth noting the higher nickel content, while rolled steel depends on the C and Mn contents to improve the mechanical strength. As well known, the nickel exerts a decisive effect on the refinement of the microstructure [48-51]. The higher nickel content also favors the presence of martensite. As a consequence, the predominance of tempered martensite is observed also for base metal (Figure 14).

Based on the above, it can be concluded that the quenched and tempered Grade R3 cast steel studied in this work, welded by the SMAW process, provides adequate mechanical properties after PWHT. Also, cast steels present slightly superior impact toughness compared to quenched and tempered rolled steel having the same level of strength.

This steel can be an alternative to replace damaged mooring chain links and contribute to avoiding the scrapping of chain segments. Of course, this steel can also be proposed for other mooring components.

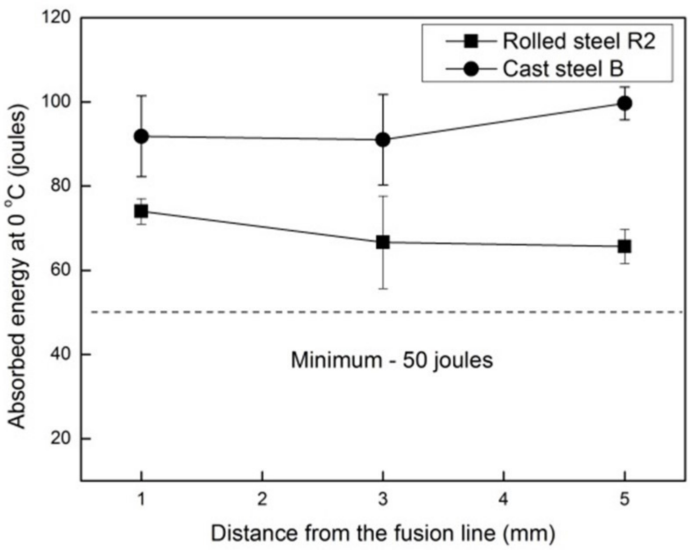


**Figure 13.** Impact toughness of the welded joints obtained with cast steel B and rolled steel R2.

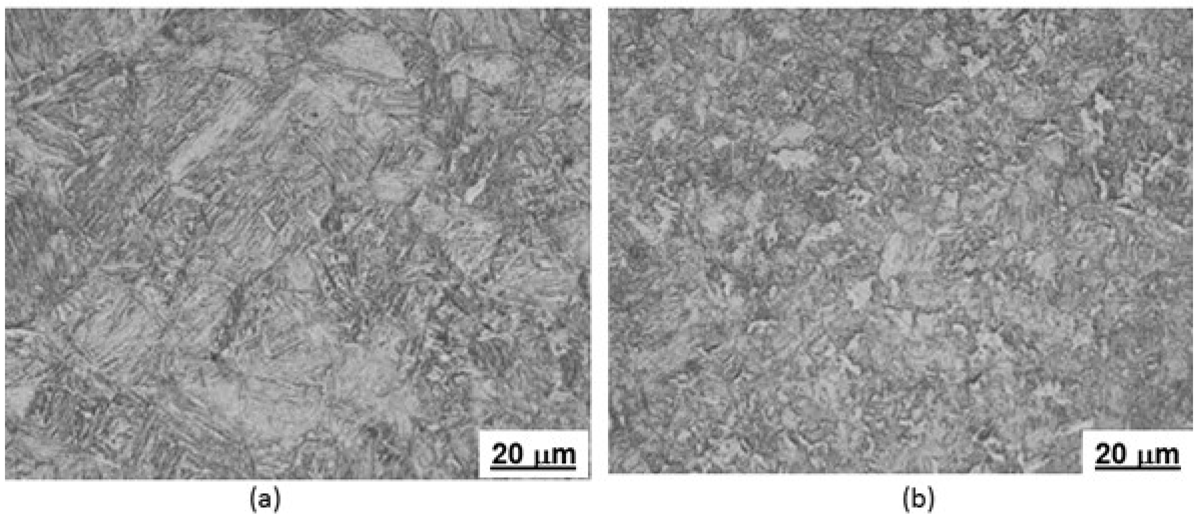


**Figure 14.** Microstructure of the regions of the cast steel welded joint (case 2) after etching with nital 2% (OM). (a) Coarse grain region of the HAZ; (b) Base metal.

### 3.4.2.3. Case 3 – Welding of chain links for application in Grade R4 mooring components

Figure 15 shows that the results achieved the minimum required for approval of welding procedures by the Classification Societies [15].

As observed in the previous studies, the cast steel showed adequate properties, with impact toughness equivalent to the rolled steel with the same strength level. Besides the lower carbon and carbon equivalent contents presented by the cast steel, it is worth noting the higher nickel content, while rolled steels used a balance of carbon, manganese, and chromium to improve the mechanical strength. Thus a refined martensitic microstructure and high impact toughness are expected [48-53].

Besides, the refined and homogeneous microstructure (Figure 16) is responsible for similar Charpy-V values for all distances from the fusion line studied (Figure 15).

Based on the above, it can be concluded that the quenched and tempered Grade R4 cast steel welded by the SMAW process can provide adequate mechanical properties after PWHT. Also, cast steel present more homogeneous and equivalent impact toughness compared to rolled steel having the same level of strength. Thus, this steel can be an alternative to repair damaged mooring components and contribute to avoiding the scrapping of high weight components. As commented in the previous case, this steel can also be proposed for other mooring components.

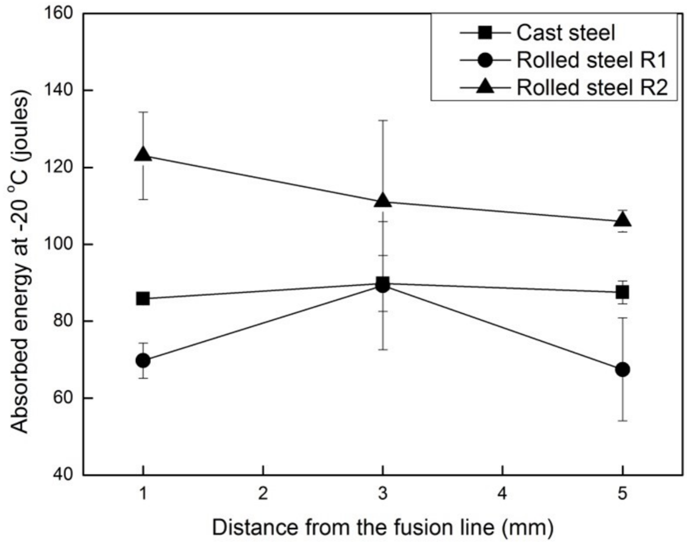


**Figure 15.** Impact toughness of the welded joints obtained with cast steel C and rolled steels R3 and R4.

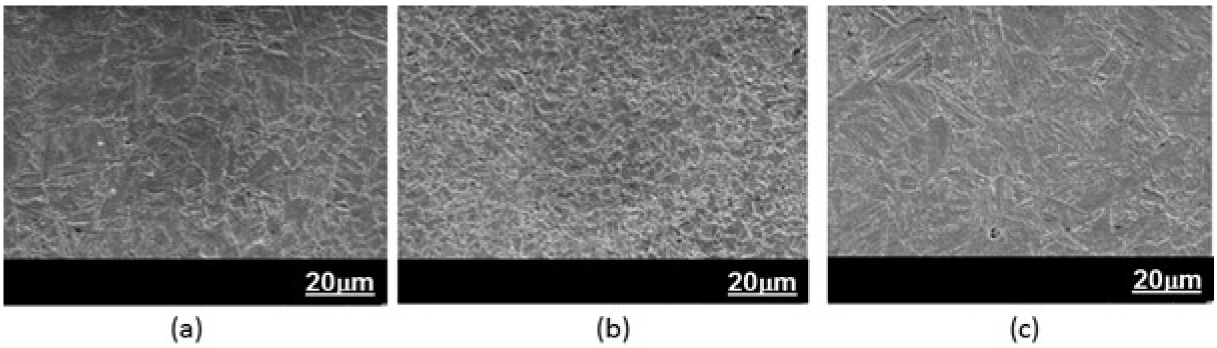


**Figure 16.** SEM images of the microstructure of the regions of the cast steel welded joint of case 3 after etching with nital 2%. (a) Coarse grain region of the HAZ; (b) Fine grain region of the HAZ; (c) Base metal.

## 4. Relevant Aspects

The evolution of cast steels has been supported by the development of compositions where the carbon content is kept low and alloying elements are added to achieve high strength associated with high impact toughness. While the increase in strength is obtained by balancing the elements carbon, manganese, and chromium in forged and rolled steels, the element nickel has been the great differential to improve the performance of cast steels. As a consequence, high strength cast steels having mechanical strength higher than around 900 MPa with good weldability were developed, thus minimizing operational problems and avoiding scraping of a high volume of the defective material. These steels are adequate to Grade R4 of the IACS W22 [15].

According to Kah et al. [54], the welding of quenched and tempered steels is usually limited by the risk of cold cracking and the HAZ softening phenomena. The lower carbon and carbon equivalent contents permit the adoption of lower preheat temperatures to avoid cold cracking, while the HAZ softening is usually associated with microstructural changes such as the coalescence of the carbides at the subcritical region and/or the formation of upper, granular, or coalesced bainite and polygonal ferrite at the intercritical region of the HAZ are more sensitive in steels containing higher carbon contents [55]. In addition, nickel also exerts an important effect on hardenability [51,52].

Although some authors consider that the addition of nickel is expensive [10,11] and propose the adoption of cheaper elements such as silicon to increase the hardenability, they state that future work is still required to confirm the precise effect of the ferritizing alloying elements because they can cause deleterious influence on the properties due to the formation of undesirable microstructural constituents such as granular bainite [56-58].

The fundamental effect of nickel as the important contributing factor to the improvement of the mechanical properties in high strength steels is seen in Figure 17. From this figure, it is clear the higher impact toughness for higher Ni contents is due to the microstructural refinement, reversing the expected drop of this property for superior strengths. Also, a “more tough martensite” is obtained when low carbon and high nickel contents are added (Figure 18).

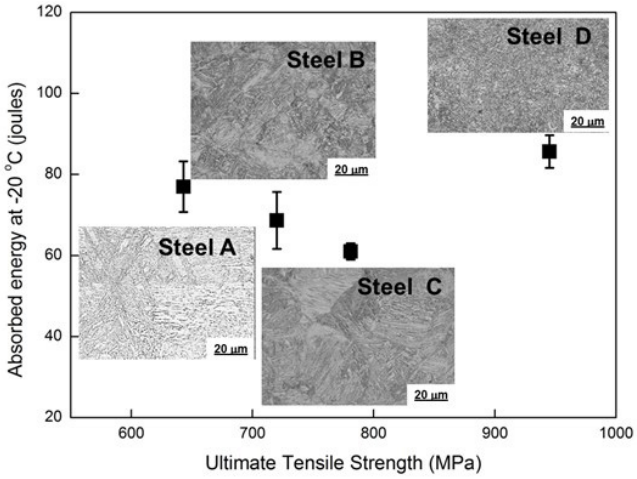


**Figure 17.** Evolution of the microstructure and impact toughness of the HAZ of cast steel welded joints with increasing ultimate tensile strength. The Charpy-V notch was positioned at 1mm from the fusion line for welded joints. Steel A: 0.24C, 1.37Mn, 0.40Cr, 0.47Ni, 0.18Mo, Ceq-0.63; Steel B: 0.23C, 1.50Mn, 0.37Cr, 0.67Ni, 0.29Mo, Ceq-0.67; Steel C: 0.25C, 1.17Mn, 0.58Cr, 0.59Ni, 0.35Mo, Ceq-0.67; Steel D: 0.19C, 0.78Mn, 0.64Cr, 2.58Ni, 0.33Mo, Ceq-0.69.

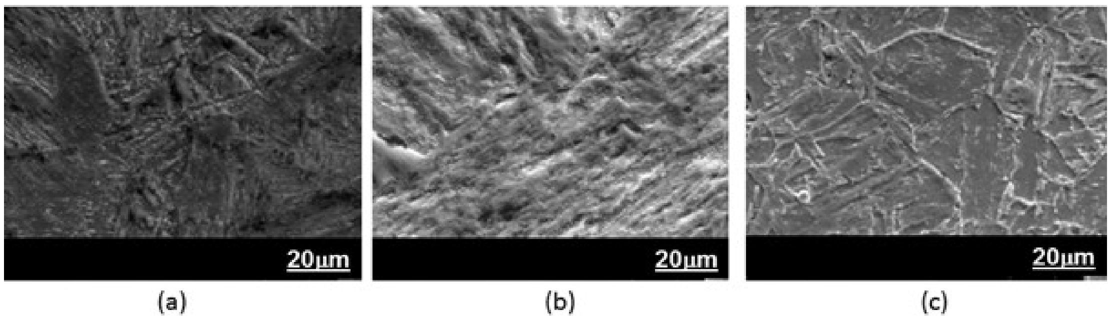


**Figure 18.** SEM images of the microstructure of the base metals studied in **Figure 15** after etching with nital 2%. (a) Steel B; (b) Steel C; (c) Steel D.

Another important matter is related to the lower chromium content of the cast steels in comparison with rolled steels used for R4 grade (Tables 1, 7 and 8). It is well known the deleterious contribution of chromium contents higher than 1% to the impact toughness of the HAZ as a consequence of the formation of granular and/or coalesced bainite mainly for higher heat inputs [57,58].

Finally, it is important to emphasize that information about the mechanical properties of welded joints is still very scarce, although studies about the development of cast steels are available. It sometimes limits the application of these steels, due to the lack of knowledge on the subject. This work contributes to confirm that arc welding of high strength cast steels can provide acceptable mechanical properties for application in mooring components, thus being an important alternative for manufacturing and repairing these accessories. High strength cast steels are a costlier-effective choice for mooring components compared to rolled and higher alloyed high-cost forged steels.

## 5. Conclusions

Based on the results obtained in the present work, the main conclusions are:

- High strength cast steel welded joints provided mechanical properties equivalent to those obtained by the quenched and tempered rolled steels;
- The procedure applied in this work is more conservative than that required by the current standards for mooring components because the Charpy-V notch was positioned parallel to the fusion line, thus allowing a more precise evaluation of the HAZ ;
- High strength cast steel welded by the shielded metal arc welding process can attain the stringent requirements for approval of welding procedures under current standards applied to mooring components, even using a more conservative procedure;
- The good performance of high strength cast steels is attributed to the addition of high nickel contents, contributing to a refined, homogeneous, and stable microstructure and;
- High strength cast steel can be considered a costlier-effective alternative to replace materials manufactured by other routes.

## Authors' contributions

JCFJ: project administration, conceptualization; methodology; writing – original draft; formal analysis; writing – review and editing. AMFSF: conceptualization; methodology; writing – review & editing. JLCD: investigation; methodology; writing – review & editing. LFGS: investigation; validation; visualization; writing – review & editing. MCM: investigation; validation; visualization; writing – review & editing.

## Acknowledgements

The authors are grateful to the following Institutions for the support to the execution of the present work: CEFET/RJ, CNPq, and FINEP.

## References

[1] Zarandi EP, Skallerud BK. Cyclic behavior and strain energy-based fatigue damage analysis of mooring chains high strength steel. Marine Structures. 2020;70:102703. http://dx.doi.org/10.1016/j.marstruc.2019.102703.

[2] Cheng X, Chen H, Liu W, Zhang Z. Influence of mooring chain steel strength on stress corrosion cracking. Applied Mechanics and Materials. 2013;404:32-39. http://dx.doi.org/10.4028/www.scientific.net/AMM.404.32.

[3] Wang HH, Li GQ, Wan XL, Wang HH, Nune KC, Li Y, et al. Microstructural characteristics and impact toughness in YS690MPa steel weld metal for offshore structures. Science and Technology of Welding and Joining. 2017;22(2):133-142. http://dx.doi.org/10.1080/13621718.2016.1204774.

[4] Zhang Y, Smedley P. Fatigue performance of high strength and large diameter mooring chain in seawater. In: Proceedings of the 38$^{th}$ International Conference on Ocean, Offshore and Arctic Engineering (OMAE2019); 2019; Glasgow, Scotland. New York: ASME; 2019. (Paper; 2019-95984). http://dx.doi.org/10.1115/OMAE2019-95984.

[5] Wang S, Zhang X, Kwan T, et al. Assessing fatigue life of corroded mooring chains through advanced analysis. In: Proceedings of the Offshore Technology Conference; 2019; Houston, Texas. Texas: OnePetro; 2019. (Paper; OTC-29449-MS. http://dx.doi.org/10.4043/29449-MS.

[6] Sagrilo LVS, Sousa JRM, Lima ECP, Porto EC, Fernandes JVV. A study on the holding capacity safety factors for torpedo anchors. Journal of Applied Mathematics. 2012;2012:102618. http://dx.doi.org/10.1155/2012/102618.

[7] Zhang Y, Zetlemoyer N, Tubby PJ. Fatigue crack growth rates of mooring chain links. In: Proceedings of the 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE2012); 2012; Rio de Janeiro, Brazil. New York: ASME; 2012. (Paper; OMAE2012-84223).

[8] Flory JF, Banfield SJ, Berryman C. Polyester mooring lines on platforms and MODUs in deep water. In: Proceedings of the Offshore Technology Conference; 2007; Houston. Texas: OnePetro; 2007. (Paper; OTC-29449-MS). http://dx.doi.org/10.4043/18768-MS.

[9] Kvitrud A. Lessons learned from the norwegian mooring lines failures 2010-2013. In: Proceedings of the 33th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2014); 2014; San Francisco, USA. New York: ASME; 2014. (Paper; OMAE2014-23095). https://doi.org/10.1115/OMAE2014-23095.

[10] Wang Z, Qi J, Liu Y. Effect of silicon content on the hardenability and mechanical properties of link-chain steel. Journal of Materials Engineering and Performance. 2019;28(3):1678-1684. http://dx.doi.org/10.1007/s11665-019-03904-8.

[11] Liu M, Guo H, Liu Z, Du C, Guo C, Zhan X, et al. Effect of tempering temperature on the microstructure and stress corrosion cracking susceptibility of ultra-high-strength mooring steel. Journal of Materials Engineering and Performance. 2021;30(6):4217-4229. http://dx.doi.org/10.1007/s11665-021-05764-7.

[12] Bolouri A, Kim T, Kang CG. Processing of low-carbon cast steels for offshore structural applications. Materials and Manufacturing Processes. 2013;28(11):1260-1267. http://dx.doi.org/10.1080/10426914.2013.792424.

[13] Blacha S, Weglowski MST, Dymek S, Kopuscianski M. Microstructural characterization and mechanical properties of electron beam welded joint of high strength steel grade S690QL. Archives of Metallurgy and Materials. 2016;61(2):1193-1200. http://dx.doi.org/10.1515/amm-2016-0198.

[14] Kitagawa Y, Kawasaki H. Recent development of high-strength and tough welding consumables for offshore structures. Kobelco Technology Review. 2013;32:1-8.

[15] International Association of Classification Societies. Offshore mooring chain, specification W22. London; 2016.

[16] Cochet J, Thuillier S, Loulou T, Decultot N, Carré P, Manach P-Y. Heat treatment of 34CrNiMo6 steel used for mooring shackles. International Journal of Advanced Manufacturing Technology. 2017;91(5-8):2329-2346. http://dx.doi.org/10.1007/s00170-016-9951-z.

[17] Santos OR Fo, Diniz JLC, Coêlho MJS, Souza LFG, Jorge JCF, Mendes MC, et al. An evaluation of the high strength cast steel welded joints for offshore industry. Soldagem e Inspeção. 2018;23(2):205-224. http://dx.doi.org/10.1590/0104-9224/si2302.08.

[18] Perez IM, Bastid P, Venugopal V. Prediction of residual stresses in mooring chains and its impact on fatigue life. In: Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2017); 2017; Trondheim-Norway. New York: ASME; 2017. (Paper; OMAE2017-61720). https://doi.org/10.1115/OMAE2017-61720.

[19] Ghosh S, Mula S, Mondal DK. Development of ultrahigh strength cast-grade microalloyed steel by simple innovative heat treatment techniques for industrial applications. Materials Science and Engineering A. 2017;700:667-680. http://dx.doi.org/10.1016/j.msea.2017.06.054.

[20] Zhao J, Lee JH, Kim YW, Jiang Z, Lee CS. Enhancing mechanical properties of a low-carbon microalloyed cast steel by controlled heat treatment. Materials Science and Engineering A. 2013;559:427-435. http://dx.doi.org/10.1016/j.msea.2012.08.122.

[21] Dhanishta S, Jadoun RS, Dixit N. Developing welding procedure to repair of casting defects for grade P91 steels by welding with matching electrode. MIT International Journal of Mechanical Engineering. 2016;6(1):28-32.

[22] Kim T, Lim S, Seok H, Kang C. Concurrent engineering solution for the design of ship and offshore bracket parts and fabrication process. International Journal of Naval Architecture and Ocean Engineering. 2013;5(3):376-391. http://dx.doi.org/10.2478/IJNAOE-2013-0140.

[23] Kang SS, Bolouri A, Kang C. The effect of heat treatment on the mechanical properties of a low carbon steel (0.1%) for offshore structural application. Journal of Materials Design and Applications. 2012;226(3):242-251. http://dx.doi.org/10.1177/1464420712438502.

[24] Lim S, Mun J, Kim T, Kang C. Development of low-temperature high-strength integral steel castings for offshore construction by casting process engineering. International Journal of Naval Architecture and Ocean Engineering. 2014;6(4):922-934. http://dx.doi.org/10.2478/IJNAOE-2013-0222.

[25] Salvador LSF. Efeito da composição química e tratamento térmico pós-soldagem nas propriedades de metal de solda de aços de alta resistência [dissertação]. Rio de Janeiro: Centro Federal de Educação Tecnológica Celso Suckow da Fonseca; 1997.

[26] Dai T, Lippold JC. The effect of postweld heat treatment on hydrogen-assisted cracking of 8630/Alloy 625 overlay. Welding in the World. 2018;62(3):581-599. http://dx.doi.org/10.1007/s40194-018-0578-6.

[27] Jorge JCF, Souza LFG, Santos OR Fo, Santos AMF Fo, Bott IS, Guimarães FHB. Microstructure/toughness relationship of the HAZ of an ASTM A 148 Gr. 80-50 cast steel for mooring accessories for offshore oil platforms. Soldagem e Inspeção. 2004;9(4):192-197.

[28] Sumam JA, Jorge JCF, Souza LFG, Bott IS. Effect of post welding heat treatment on a high strength cast steel for offshore application in mooring systems of oil platforms. Soldagem e Inspeção. 2004;9(4):205-212.

[29] Leal SNCC. Corrosão em elos de amarras offshore: um estudo de caso [dissertação]. Rio de Janeiro: Programa de Pós-graduação em Engenharia Metalúrgica, Pontifícia Universidade Católica do Rio de Janeiro; 2003.

[30] Pimenta JMP. Modificações nas propriedades mecânicas e na resistência à fratura do aço estrutural R4 [dissertação]. Rio de Janeiro: Programa de Pós-graduação em Engenharia Metalúrgica, Pontifícia Universidade Católica do Rio de Janeiro; 2007.

[31] Kim DC, So WJ, Kang MJ. Effect of flash butt welding parameters on weld quality of mooring chain. Arquives of Materials Science and Engineering. 2009;38(2):112-117.

[32] Chaves AP. Estudo comparativo da vida em fadiga de aços fundidos e forjados de aços de alta resistência para utilização em acessórios de linhas de ancoragem de plataformas offshore [dissertação]. Rio de Janeiro: Programa de Pós-graduação em Engenharia Mecânica e Tecnologia de Materiais, Centro Federal de Educação Tecnológica; 2010.

[33] Dornelas PHG, Farias FWC, Oliveira VHPM, Moraes DO, Zumpano PZ Jr, Payão JC Fo. Influence of welding interpass temperature on Charpy V-notch impact energy of coarse-grain heat-affected zone of AISI 4130 steel pipe. International Journal of Advanced Manufacturing Technology. 2020;108(7-8):2197-2211. http://dx.doi.org/10.1007/s00170-020-05542-0.

[34] Mosciaro HB, Jorge JCF. Evaluation of the welding procedures for offshore structures manufactured in high strength cast steels. Technology and Culture. 1997;1(1):41-45.

[35] American Society for Testing and Materials. ASTM A-488: standard practice for steel castings, welding, qualifications of procedures and personnel. West Conshohocken: ASTM International; 2012. 19 p.

[36] American Society of Mechanical Engineers. ASME boiler and pressure vessel code: qualification standard for welding, brazing, and fusing procedures; welders; brazers; and welding, brazing, and fusing operators, section IX, edition. New York: ASME; 2015.

[37] International Association of Classification Societies. W28: welding procedure qualification tests of steels for hull construction and marine structures. London; 2012. 25 p.

[38] Santos AMF Fo. Estudo sobre a zona termicamente afetada de reparos por soldagem em aço fundido de baixo teor de carbono pelo processo eletrodo revestido [thesis]. Rio de Janeiro: Universidade Federal do Rio de Janeiro; 1992.

[39] Santos AMF Fo, Guimarães AS, Jorge JCF. Uma avaliação da soldagem de aço fundido tipo C-Mn para indústria naval. In: Anais do XIX Encontro Nacional de Tecnologia da Soldagem; 1993; Águas de São Pedro, SP. São Paulo: Associação Brasileira de Soldagem; 1993. p. 273-288.

[40] International Association of Classification Societies. W8: hull and machinery steel castings. London; 2004. 6 p.

[41] International Association of Classification Societies. W29: requirements for manufacture of anchors. London; 2005. 7 p.

[42] Perez IM, Bastid P, Venugopal V. Prediction of residual stresses in mooring chains and its impact on fatigue life. In: Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2017); 2017; Trondheim-Norway. New York: ASME; 2017. (Paper; OMAE2017-61382). https://doi.org/10.1115/OMAE2017-61720.

[43] Shoup GJ, Tipton SM, Sorem JR Jr. The effect of proof loading on the fatigue behaviour of stud link chain. International Journal of Fatigue. 1992;14(1):35-40. http://dx.doi.org/10.1016/0142-1123(92)90151-2.

[44] American Society for Testing and Materials. ASTM E837-13a: standard test method for determining residual stresses by the hole-drilling strain-gage method. West Conshohocken: ASTM International; 2013.

[45] Diniz WG, Bracarense AQ, Silva GM. Avaliação das propriedades mecânicas de um aço fundido de baixo carbono, como função da sequência de processos de tratamento térmico e soldagem. In: Anais do 8º Congresso Brasileiro de Engenharia de Fabricação; 2015; Salvador, Brasil. Salvador: ABCM; 2015.

[46] Kannan K, Valencia JJ. Evaluation of high-strength steel castings possessing improved weldability. Journal of Materials Engineering and Performance. 2001;10(6):635-648. http://dx.doi.org/10.1361/105994901770344494.

[47] American Bureau of Shipping. Rules for building and classing steel vessel rules part 2, rules for materials and welding. Houston; 2013. Materials for hull construction, section 5 hull steel casting; p. 40-44.

[48] Park S, Lee K, Min K, Kim M, Lee B. Characterization of phase fractions and misorientations on tempered bainitic/martensitic Ni-Cr-Mo low alloy RPV steel with various Ni content. Metals and Materials International. 2013;19(1):49-54. http://dx.doi.org/10.1007/s12540-013-1009-2.

[49] Kim K, Lee S. Effect of Ni addition on the mechanical behavior of quenching and partitioning (Q&P) steel. Materials Science and Engineering A. 2017;698:183-190. http://dx.doi.org/10.1016/j.msea.2017.05.030.

[50] Pratomo, S.B., Oktadinata, H., Widodo, T.W. Effect of nickel additions on microstructure evolution and mechanical properties of low-alloy Cr-Mo cast steel. IOP Conference Series: Materials Science and Engineering. 2019;541:012050. http://dx.doi.org/10.1088/1757-899X/541/1/012050.

[51] Kim K, Lee M. S. Effect of Ni addition on the mechanical behavior of quenching and partitioning (Q&P) steel. Materials Science and Engineering A. 2017;698:183-190. http://dx.doi.org/10.1016/j.msea.2017.05.030.

[52] Lee BS, Kim MC, Yoon JH, Hong JH. Characterization of high strength and high toughness Ni–Mo–Cr low alloy steels for nuclear application. International Journal of Pressure Vessels and Piping. 2010;2010(87):74-80. http://dx.doi.org/10.1016/j.ijpvp.2009.11.001.

[53] Eroglu M, Aksoy M. Effect of nickel on microstructure and mechanical properties of heat affected zone of low carbon steel. Materials Science and Technology. 2002;18(1):35-40. http://dx.doi.org/10.1179/026708301125000186.

[54] Kah P, Pirinen M, Suoranta R, Martikainen J. Welding of ultra high strength steels. Advanced Materials Research. 2014;849:357-365. http://dx.doi.org/10.4028/www.scientific.net/AMR.849.357.

[55] Pirinen M, Martikainen Y, Ivanov SY, Karkhin VA. Comparative analysis of the microstructure of the heat-affected zone metal in welding of high-strength steels. Welding International. 2015;29(4):301-305.

[56] Peng K, Yang C, Fan C, Lin S. In situ observation and electron backscattered diffraction analysis of granular bainite in simulated heat affected zone of high-strength low-alloy steel. Science and Technology of Welding and Joining. 2018;23(2):158-163. http://dx.doi.org/10.1080/13621718.2017.1351777.

[57] Huang G, Wan XL, Wu KM. Effect of Cr content on microstructure and impact toughness in the simulated coarse-grained heat-affected zone of high-strength low-alloy steels. Steel Research International. 2016;87(11):1426-1434. http://dx.doi.org/10.1002/srin.201500424.

[58] Liu J, Sun J, Wei S, Lu S. Influence of chromium content on the bainite transformation nucleation mechanism and the properties of 800 MPa grade low carbon bainite weld deposited metal. Materials Science and Engineering A. 2022;840:142893. http://dx.doi.org/10.1016/j.msea.2022.142893.