Characteristics of Grade R4 Steel Manufactured by Ingot Casting and Used in the Production of Offshore Mooring Chains

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The objective of this study is to characterise grade R4 steel manufactured by ingot casting that is used as the raw material for the production of offshore mooring chains. Rolled bars of grade R4 steel have been selected and metallographic analyses and micro hardness, tensile and Charpy V-notch impact tests performed. Tensile and Charpy V-notch impact tests have also been carried out on mooring links manufactured from the same grade R4 steel. Based on the results presented, the influence of the rolling reduction ratio of the bars and the influence of the ingot casting cooling and reheating process have been observed. Both factors have been found to increase product quality, particularly with respect to the central segregation and homogeneity of the rolled bars.

KEY WORDS
~ Mooring chain steel
~ R4 steel
~ Mechanical properties
~ Ingot casting
~ Charpy test

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1. INTRODUCTION

Deep-sea exploration and the use of marine resources are prevalent all over the world. Offshore platforms and floating production storage and offloading (FPSO) are an effective solution for deep-sea oil and natural gas production. Such marine structures are attached to the seabed by anchoring systems composed of, in general, anchors, connectors and mooring chains (Wilson, 2003; Yaghin and Melchers, 2015; Muslim and Kamil, 2017; Kim et al., 2019; Ma et al., 2019; Ozguc, 2020).

The main function of mooring chains is to keep the FPSO in place within acceptable limits, so that various components, such as risers that transport oil from the rock-reservoir to the FPSO, can operate safely.

Turret mooring on FPSO (Figure 1) is defined as a system where a number of mooring chains are attached to a turret, that is essentially part of the vessel, and can be positioned on the bow, stern (external turret) or inside the vessel (internal turret), allowing the free rotation of the hull around the lines. The moorings are connected to the turret by means of the chain table. The turret system has a universal joint that allows the vessel to freely turn 360° around the vertical axis (single point mooring) to align itself with the dominant wind, wave and current conditions.

The mooring chains, as shown in Figure 2, are subject to extremely high tensile forces (their considerable weight, for example) and, in operational practice, to additional tensile forces generated by wind loads and marine currents. These loads are a function of the size and format of the FPSO, the prevailing wind, wave speed at the structure, as well as of factors resulting from the dynamic effects under different sea conditions (Jean et al., 2005; Zanuttigh et al., 2012; Ma et al., 2013; Ma et al., 2019).

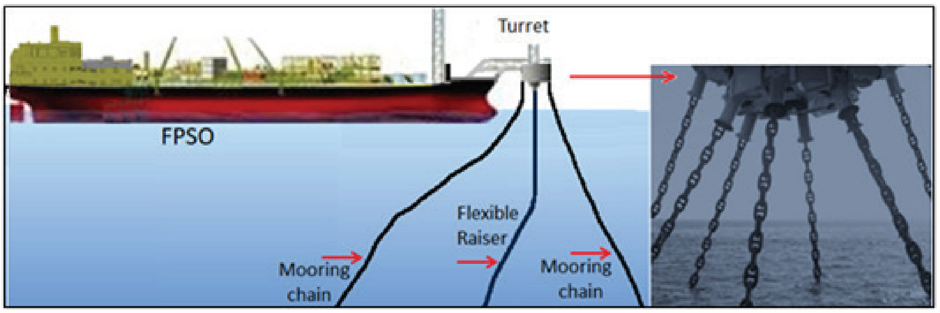

Figure 1.
FPSO with turret mooring, flexible riser, mooring chain and chain table.

Figure 2.
High-strength structural steel mooring chain.

In the last decade, carbon steel mooring chains have also been used in the development of offshore mooring marine techniques and structures for the increasingly popular wind generators, as shown in Figure 4. Such marine structures are fixed to the seabed through anchoring systems composed, in general, of anchors, connectors and mooring chains. Floating marine installations for wind turbines and their components, such as moorings and anchors, are based on those used in oil and gas production.

As wind turbines become increasingly familiar maritime sights, designers of offshore floating platforms take advantage of powerful winds from the sea, seeking to devise technological innovations that would make wind power a major viable source of clean energy (Musial et al., 2006; Butterfield et al., 2007; Breton and Moe, 2009; Erlich et al., 2013; Castro-Santos and Diaz-Casas, 2016; Ng and Ran, 2016).

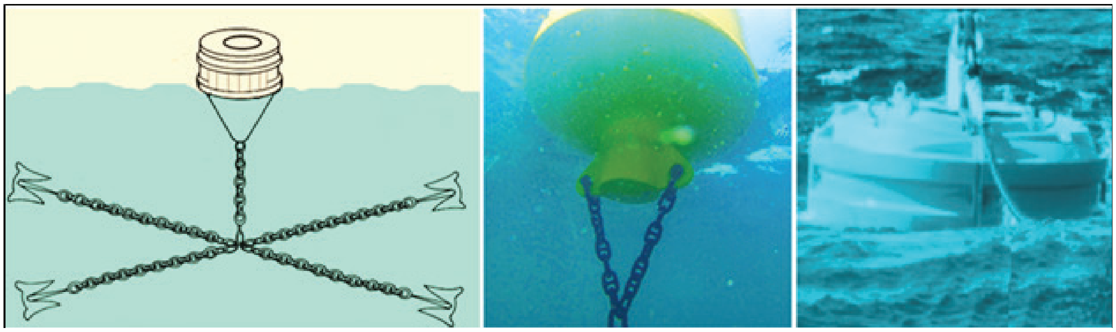

Figure 3.
Buoy mooring systems.

Mooring chains are part of the anchoring systems used for marine structures and in oil and natural gas probing in the ocean in ever deeper waters, as increasingly longer mooring is required to ensure the safety and integrity of the marine structure. Thus, the additional weight of a longer anchor line requires this specific carbon steel mooring to be stronger. In addition, mooring chains are designed for a service life of ~30 years due to material fatigue and being immersed in corrosive seawater (Yaghin and Melchers, 2015; Perez-Mora et al., 2015; Ma et al., 2019).

Figure 4.
Semisubmersible platform for wind turbines.

The steels used in the production of mooring chains can be classified as high strength and low alloy (HSLA), having the chemical composition corresponding to low and medium carbon alloy steels, called grade R3, R4 or R5. As several thermal treatments are conducted to ensure good ductility and high tensile strength of HSLA steels, they are used for offshore mooring due to their excellent mechanical properties (Zhong et al., 2009; Cheng et al., 2013; Zhou et al., 2015; Zhang et al., 2017).

Their chemical compositions are not standardised, conventional or public, with the responsibility of their mechanical properties assumed by steel manufacturers and mooring chain manufacturers. In addition, the components manufactured with these steels are joined by the electrical resistance process of welding (flash butt welding) and heat treated to achieve the final mechanical properties requested (Buzzatti et al., 2019).

In the case of deep-sea oil and natural gas exploitation, floating structures need to have an anchoring system designed to avoid potential failures and the mooring system must maintain its position. Mooring chain failures due to fatigue, mechanical damage, overload and material problems can result in oil leaks with high potential for environmental consequences with high direct costs, such as riser rupture, production outage, need for premature replacements and repair costs. There are also indirect costs, such as penalties imposed by environmental agencies and lost profits (Yaghin and Melchers, 2015; Ma et al., 2019; Canut et al., 2019).

Please note that the International Association of Classification Societies (IACS) requires IACS classification societies to either adopt their Classification Rules (expected), or precisely specify their reservation against the document (not expected). IACS UR W22 (IACS, 2016) unified the specific properties of high strength and hardening steels after heat treatment (quench and tempering) for application in grade R4 steels for offshore moorings, as shown in Table 1. In addition, it prohibited maintenance and repairs of offshore mooring chains by welding, based on past experience (IACS, 2021). Therefore, in case of any defect or failure, mooring chains should be replaced by new ones.

The production of offshore mooring chains based on the development of grade R4 steel and consequently on critical evaluation, in keeping with technical requirements, of acceptable mechanical properties that ensure the integrity of marine structures, requires triangulated certification between the steel manufacturer, the mooring chain manufacturer and the class. After certification, steel normally obtains Type 3.2 Certification BS EN 10204 (BS, 2004).

The experimental ingot based on grade R4 steel for mooring chains or accessories must be manufactured by the selected steel manufacturer who is required to obtain formal class approval for this procedure which must be confidential. Approval can be given only after the full testing of the mooring chain is completed and successful. The rolling reduction ratio must be recorded and be at least 5:1. The rolling reduction ratio may be higher but should not be lower than that specified in the standard (Farneze et al., 2010; Bjørnsen, 2014; IACS, 2016; Jorge et al., 2016; Crapps et al., 2017; Ma et al., 2019).

Ingot casting was used in the production of experimental grade R4 steel ingots with fixed chemical composition and the

Table 1.
Mechanical properties of offshore mooring chain and accessories (IACS, 2016).

Grade	Yield stress N/mm^2 min. (1)	Tensile strength N/mm^2 min. (1)	Elongation, % min.	Area reduction %, min. (3)	Charpy V-notch impact tests		
					Temperature, °C (2)	Avg. energy, Joules, min.	Avg. energy flash weld, Joules min.
R3	410	690	17	50	0 -20	60 40	50 30
R3S	490	770	15	50	0 -20	65 45	53 33
R4	580	860	12	50	-20	50	36
R4S(4)	700	960	12	50	-20	56	40
R5(4)	760	1000	12	50	-20	58	42

NOTES: (1) Target yield tensile ratio value: 0.92 max.; (2) At the option of the classification society, impact testing of Grade R3 and R3S may be carried out at either 0°C or -20°C (See Table 1); (3) Reduction of cast steel area for Grades R3 and R3S: min 40%; for R4, R4S and R5: min. 35%.cf. item 2.4.4; (4) Target maximum hardness for R4S is HB330 and R5 HB340.

metal-mechanical characteristics prescribed by the IACS UR W22 (IACS, 2016) for mooring chains. Testing methodology and the evaluation of experimental ingot results are presented below in section 2.

This paper aims to analyze, based on specific tests, the viability and characterization of a grade R4 steel obtained by ingot casting, which is used as raw material in the production of offshore anchoring chains. After this introduction, the materials and methods used to conduct this study will be presented, followed by results, discussion and finally conclusions.

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Ingot casting was used in the production of experimental grade R4 steel ingots with fixed chemical composition and the metal-mechanical characteristics prescribed by the IACS UR W22 (IACS, 2016) for mooring chains. Testing methodology and the evaluation of experimental ingot results are presented below in section 2.

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2. MATERIALS AND METHODS

2.1. Materials

The material used in this work was grade R4 steel (IACS, 2016) obtained from conventional casting in ingots of 570 × 570 mm. Its chemical analysis is presented in Table 2.

Table 2.
Chemical analysis of grade R4 rolled steel.

Chemical element	% by weight
C	0.212
Mn	1.03
Si	0.24
P	0.015
S	0.008
Cr	1.09
Ni	0.53
Mo	0.26

The IACS UR W22 (IACS, 2016) recommends that grade R4 steel for offshore mooring chains contain a minimum of 0.20% molybdenum.

Subsequently, ingots were homogenised in a heat treatment furnace at 1200 °C for 15 h, rolled in a thinning laminator and then hot rolled until round shape with a nominal diameter of 123 mm was obtained, with the reduction ratio of 28:1.

The temperability of the obtained material was tested by subjecting the specimens to metallographic assays where they were placed in a stationary furnace that maintained the temperature of 900 ºC for 60 min and then cooled in water. The specimens were then heated to 650 ºC for 120 min and cooled in water again.

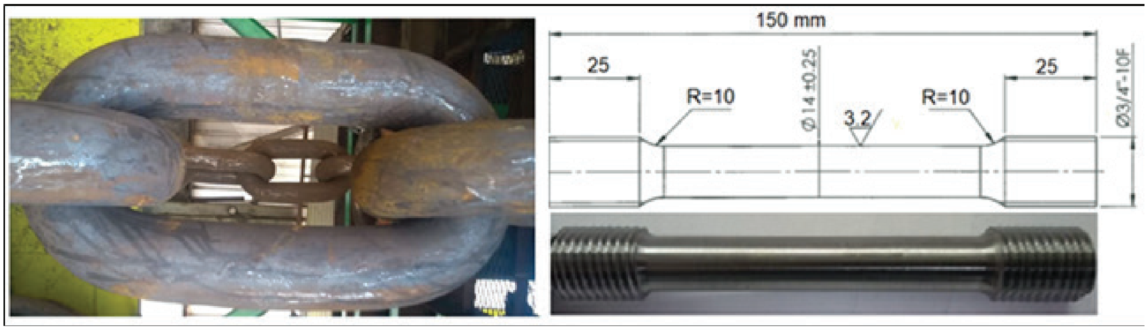

Figure 5.
Mooring chain and tensile testing specimens.

The specimens for tensile tests and Charpy V-notch impact tests were taken from grade R4 steel rolled bars and from mooring links manufactured from those bars, with respect to the value of 2/3 of the bar radius. Specimens were also taken from the welding region of the mooring link (weld proof specimen), as well as from the straight sections of the link opposite the weld region (base material specimens). Samples of the weld region were taken crosswise to the weld line. Tensile test specimens were cylindrical and their longitudinal axis coincided with the direction of bar lamination. Figures 5 and 6 represent, respectively, tensile and Charpy V-notch impact tests (IACS, 2016).

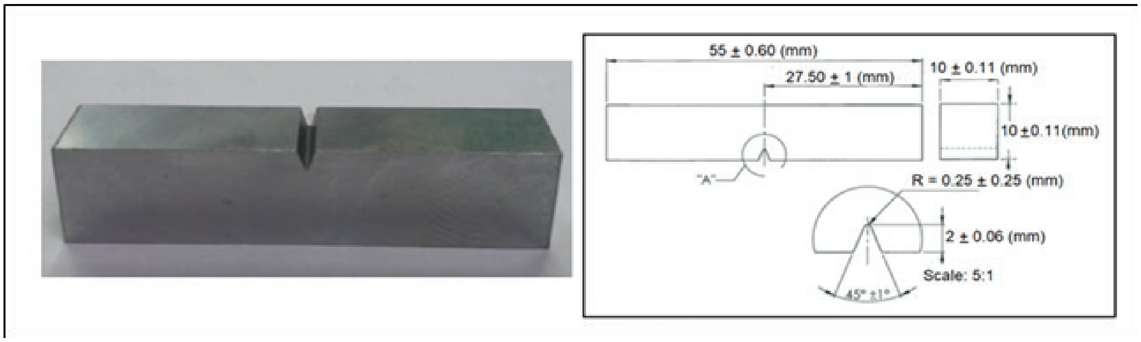

Figure 6.
Specimen for Charpy V-notch impact tests.

2.2. Metallographic Analyses

Metallographic analyses were performed on experimental bar specimens based on the ASTM E3-11 standard (ASTM, 2017a) and using a ZEISS Stemi 2000-C optical microscope. A 2% Nital reagent was used for the metallographic attack.

2.3. Vickers Micro Hardness Determination

The micro hardness tests were performed on experimental grade R4 steel bar specimens as received and after tempering, in keeping with the ASTM E92-17 standard (ASTM, 2017b). The hardness of 100 points was measured, with an interval of 0.1 mm from the surface. The equipment used was the Zwick micro hardness tester for Vickers micro hardness measurements with loads ranging from 200 gf to 5 kgf.

2.4. Tensile Tests

Tensile tests were performed in keeping with the ASTM A370-19 standard (ASTM, 2019). The tensile tests were carried out on a hydraulic machine having the capacity of 60,000 kgf, using a Kratos machine model K60000MP/M030904. All specimens were tested at room temperature and subjected to strain that lengthened them until they fractured to determine yield strength, tensile strength, deformation, reduction of percentage area and ductility in the fracture.

2.5. Charpy V –Notch Impact Tests

The Charpy impact test is a standardised method for measuring impact tenacity, most often used at low temperatures (- 20 °C) to measure the amount of energy absorbed by the impact of a pendulum of known total energy, against a standardized specimen at the specific temperature. Charpy impact tests (with a range from 0 to 300 Joules) using Tension model JB-300B were performed on standardised specimens in keeping with the ASTM A370-19 standard (ASTM, 2019).

3. RESULTS AND DISCUSSION

3.1. Metallographic Analyses

The results show that the microstructure of the bars (as received and heat treated by quenching) was highly homogeneous and the distances between segregated regions small (Figure 7). Microstructure expected after quenching, namely, martensite and bainite (Figure 8), was also checked.

According to Tau et al. (1996), the sliding of crystalline planes is more homogeneous in a primary microstructure, such as martensite, than in a more complex microstructure involving more than one microconstituent, for example, martensite + bainite + ferrite. These microstructural aspects were considered by researchers as being mainly responsible for greater material fatigue resistance.

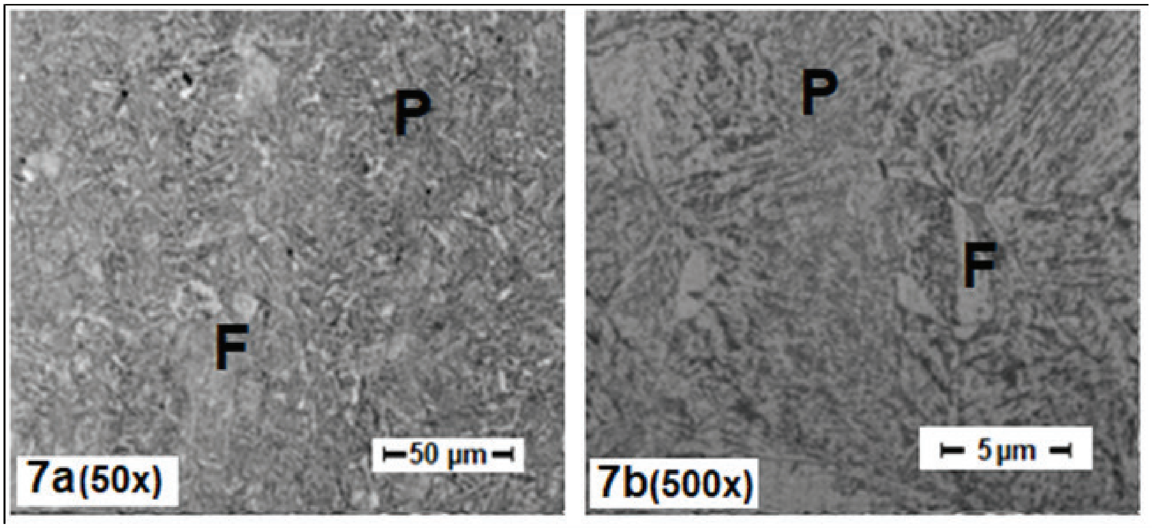

Figure 7.
Metallography of R4 rolled bars as received at 1/3 of the radius. Ferrite (F) and Perlite (P), with 2% Nital reagent.

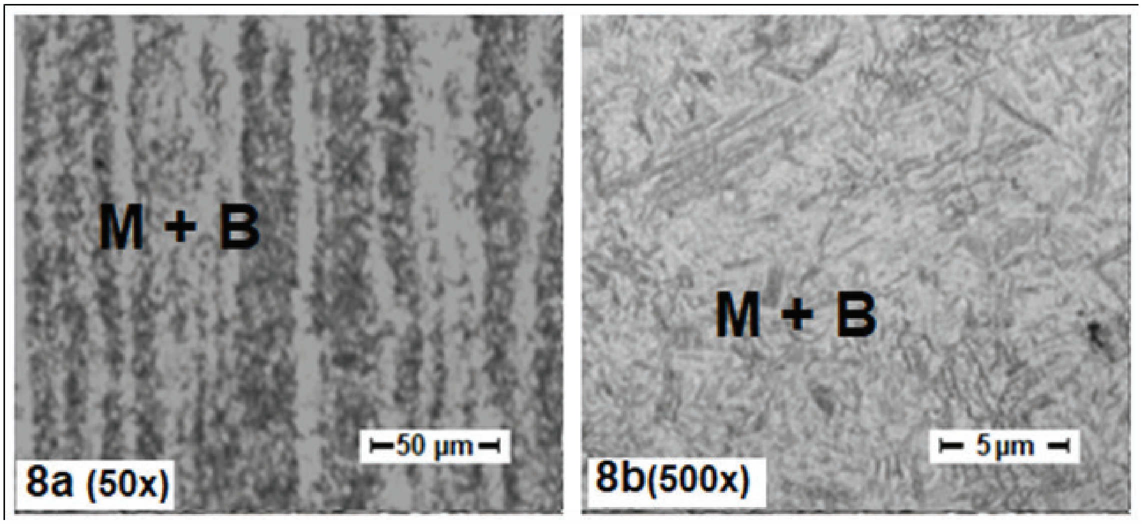

Figure 8.
Metallography of R4 rolled bars after tempering at 1/3 of the radius.
Martensite (M) and Bainite (B), with 2% Nital reagent.

3.2. Vickers Micro Hardness Determination

Both maximum and minimum micro hardness of R4 steel rolled bar specimens is presented in the as-received state, with few variations, in Table 3. The relationship between standard deviation and the mean was ~5%. The micro hardness of rolled bars is quite high in specimens subjected to heat treatment (quench), with hardness values between 398.5 and 513 Vickers micro hardness. The ratio between standard deviation and the mean for quenched specimens was ~5%.

Figures 9 and 10 show variations in Vickers micro hardness in rolled specimens subjected to heat treatment (quench), that corroborate metallographic tests that show the presence of martensite responsible for harder microstructures. The results show the variations of micro hardness in specimens of 20 and 50 mm.

Table 3.
Results of Vickers micro hardness determined in experimental R4 steel barsas received and after heat treatment (quench).

Test conditions (Micro-hardness HV (0.3 kgf)	Specimens as received	Specimens after heat treatment (quench)
Minimum	268.0	398.5
Maximum	351.5	513.0
Average	309.0	458.0
Standard deviation, (%)	16.5	25.0

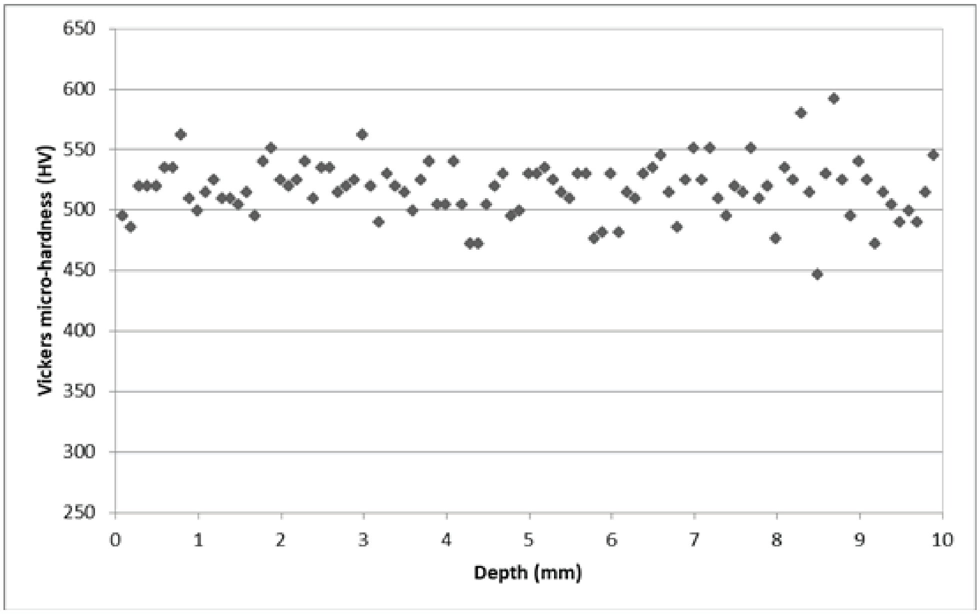

Figure 9.
Vickers micro hardness variations (0.3 kgf) for R4 steel rolled bar specimens after heat treatment (quench) at the depth of 10 mm.

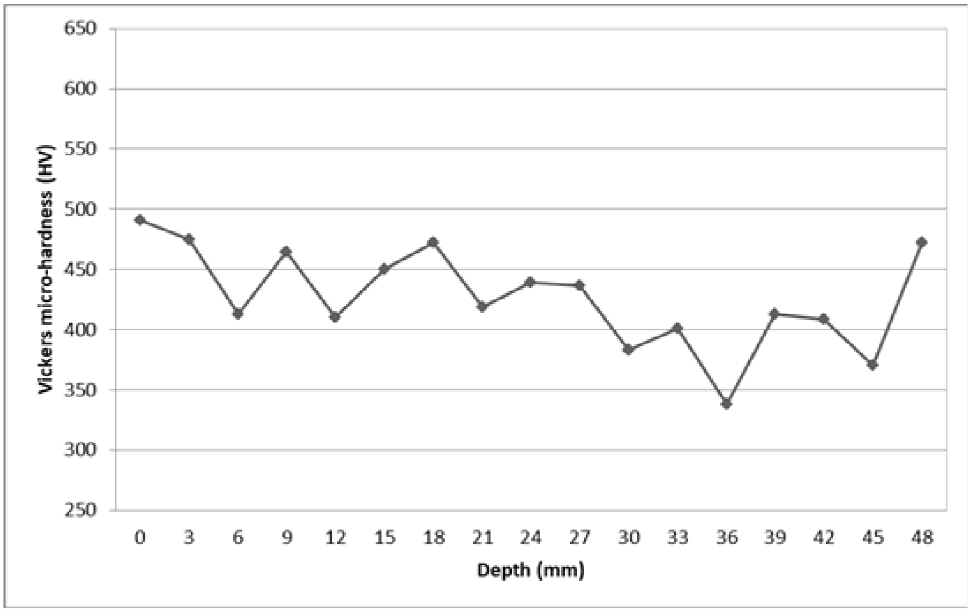

Figure 10.
Vickers micro hardness variations (0.3 kgf) for R4 steel rolled bar specimens after heat treatment (quench) at the depth of 50 mm.

3.3. Tensile Tests

The results of tensile tests for both R4 steel rolled bars and for the links manufactured from the same R4 grade steel were satisfactory and their mechanical properties above the minimum required by IACS UR W22 (IACS, 2016). The results are presented in Tables 4 and 5, respectively.

Table 4.
Results of tensile tests of grade R4 steel rolled bars.

Tensile tests	
Yield stress, N/mm2	937.4
Tensile strength, N/mm2	856.7
Elongation, %	16.1
Reduction of area, %	64.0

Table 5.
Results of tensile tests of links manufactured from grade R4 steel.

Tensile tests	Link 01	Link 02	Link 03
Yield stress, N/mm^2	937.4	957.5	974.7
Tensile strength, N/mm^2	859.2	871.6	891.2
Elongation, %	18.9	17.7	18.0
Reduction of area, %	62.5	62.3	63.1

3.4. Charpy V –Notch Impact Tests

Table 6 shows that the results of the Charpy V-notch impact test specimens are double the value of the average energy minimum in IACS UR W22 (IACS, 2016), i.e. 50 J.

Table 7 presents the results for specimens removed from the manufactured links (three impact specimens taken across the flash weld with the notch centred in the middle, three impact specimens taken across the unwelded side and three impact specimens taken from the bend region).

Table 6.
Results of Charpy V-notch impact tests conducted on grade R4 steel rolled bar specimens.

Charpy-impact tests	Joules
Impact specimen 1	122.0
Impact specimen 2	110.0
Impact specimen 3	114.0
Average energy	115.3
Standard deviation, (%)	6.1

Table 7.
Results of Charpy V-notch impact tests conducted on grade R4 steel specimens removed from fabricated links, welded links and link bend.

Charpy impact tests	Across the unwelded side, Joules			Across the flash weld with the notch centred in the middle, Joules			Bend region, Joules		
Impact specimen 1	76.0	56.0	70.0	43.0	36.0	37.0	57.0	50.0	68.0
Impact specimen 2	51.0	53.0	50.0	38.0	37.0	42.0	58.0	59.0	52.0
Impact specimen 3	52.0	79.0	54.0	39.0	36.0	41.0	52.0	55.0	50.0
Average energy	59.7	62.7	58.0	40.0	36.3	40.0	55.7	54.7	56.7
Standard deviation, (%)	14.2	14.2	10.6	2.6	0.6	2.6	3.2	4.5	9.9

The results of fabricated links and the link bends have been shown to correspond to the minimum average energy of 50 Joules, prescribed by IACS UR W22 (IACS, 2016). Similarly, the values for specimens removed from welded links are compatible with the average energy flash weld of 36 Joules. Kim et al. (2009) showed that values above 36 J for the average energy in Charpy impact tests are satisfactory for chain mooring.

In addition, the Ishikawa Diagram shown in Figure 11, (Dobrusskin 2016; Doshi et al.,2012), also known as the Fishbone Diagram for having a shape similar to a fishbone, has been used in the study to evaluate and identify the likely causes of errors, defects or prospective problems that may affect the manufacturing process and at the same time be inserted in the technical-social-environmental view of this processing in the global context.

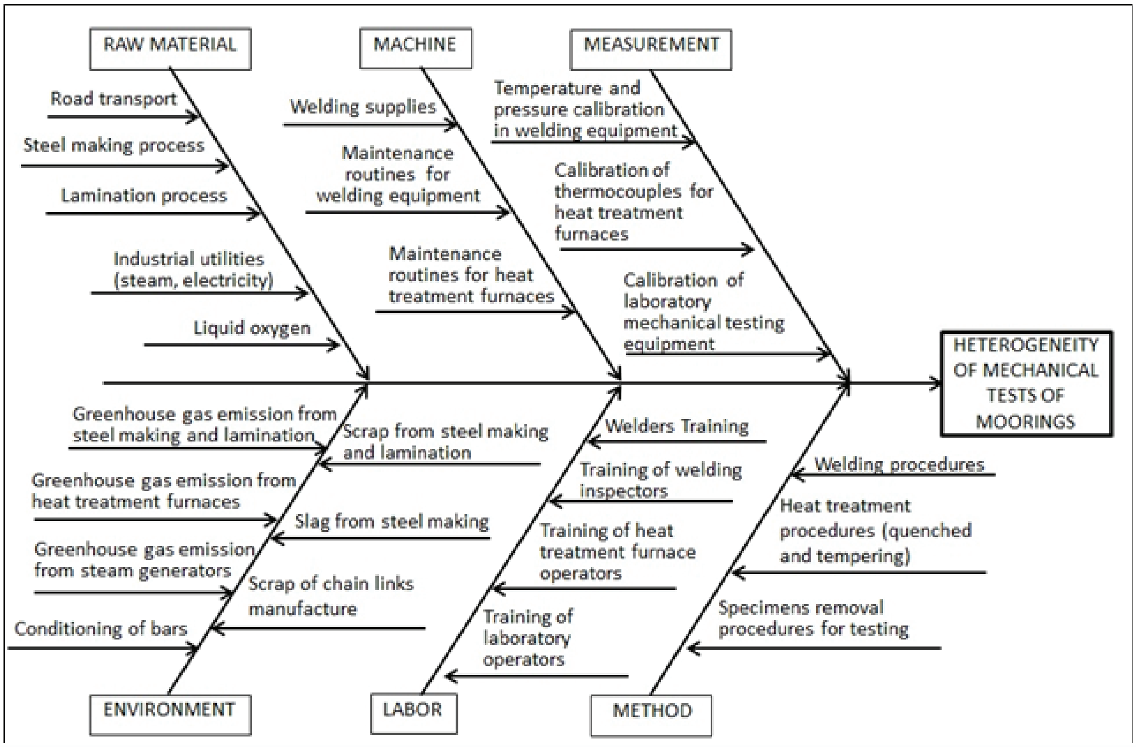

Figure 11.
Ishikawa diagram of offshore mooring chain manufacturing process.

Of the six events that make up the Ishikawa Diagram, three that are representative of the qualification of the chain mooring production process, namely method, laboratory and environment, were emphasized:

- METHOD: welding procedures, heat treatment procedures (quenching and tempering), specimen removal procedures for testing;
- LABOR: training of welders, welding inspectors, heat treatment furnace operators, laboratory operators;
- ENVIRONMENT: greenhouse gas emission from steel making and lamination, greenhouse gas emission from heat treatment furnaces and steam generators, bar conditioning, scrap from the production of chain links, slag from steel making, scrap from steel making and lamination.

4. CONCLUSIONS

Tests suggest that this study achieved its objective of verifying the feasibility and characterization of R4 grade steel manufactured by casting and used as raw material in the production of offshore anchor chains. R4 grade steel laminated bars manufactured by casting with the reduction ratio of ~28:1 have been found to have microstructural homogeneity with minor variations in hardness in the cross section and in the mechanical properties that are compatible with the desired application of offshore mooring chain having the diameter of 120 mm.

In addition, tensile test results were satisfactory and its mechanical properties have been found to be above the minimum prescribed by IACS UR W22. Please note that the results of the Charpy V-notch impact specimens are twice the defined value of 50 J.

The influence of the bar rolling rate of reduction and the influence of the cooling and reheating process have been verified. Both factors improve product quality, mainly with respect to the central segregation and homogeneity of laminated bars.

To obtain the mechanical properties compatible with the mooring manufacturing standard, the use of a more homogeneous raw material obtained from large ingots homogenised in an oven (1200 ºC, 15 hours at a time) and subjected to a rough rolling sequence, with a higher reduction ratio, which also contributes to the reduction of segregation, is recommended.

These results demonstrate that grade R4 steel straps obtained by casting are reliable raw materials for use in offshore conditions and resistant to potential failures. Therefore, this information can be helpful to the main players in the oil and gas production industry and, in case of placement of offshore turbines, for the selection of inputs and their suppliers.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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