Open your mind. LUT.
Lappeenranta University of Technology

Faculty of Technology

Mechanical Engineering

Laboratory of Welding Technology

Pavel Layus

RUSSIAN METALS FOR ARCTIC OFFSHORE STRUCTURES

Supervisors: Professor Jukka Martikainen

Dr. (Tech.) Paul Kah

ABSTRACT

Author:	Layus, Pavel
Title of thesis:	Russian metals for Arctic offshore structures
Faculty:	Faculty of Technology
Year:	2012
Master`s Thesis:	Lappeenranta University of Technology
	154 pages, 34 figures, 99 tables and no appendices
Examiners:	Prof. Jukka Martinkainen
	Dr. (Tech.) Paul Kah
Keywords:	Arctic, cold-resistant, offshore, Russia, steel

With an increasingly growing demand for natural resources, the Arctic region has become an attractive area, holding about 15% of world oil. Ice shrinkage caused by global warming encourages the development of offshore and shipbuilding sectors. Russia, as one of the leading oil and gas production countries is participating actively in cold resistant materials research, since half of its territory belongs to the Arctic environment, which held considerable stores of oil. Nowadays most Russian offshore platforms are located in the Sakhalin Island area, which geographically does not belong to the Arctic, but has comparable environmental conditions. Russia recently has manufactured several offshore platforms. It became clear that further development of the Arctic offshore structures with necessary reliability is highly depending on the materials employed.

This work pursues the following objectives:

- to provide a comprehensive review on Russian metals used for Arctic offshore structures on the base of standards, books, journal articles and companies reports
- to overview various Arctic offshore structures and its structural characteristics
- briefly discuss materials testing methods for low temperatures

Master`s thesis focuses on specifications and description of Russian metals which are already in use and can be used for Arctic offshore structures. Work overviews several groups of steel, such as low carbon, low alloy, chromium containing steels, stainless steels, aluminiums and nanostructured steels. Materials under discussion are grouped based on the standards, for instance the work covers shipbuilding and structural steels at the different sections. This paper provides an overview of important Russian Arctic offshore projects built for use in Russia and ordered by foreign countries. Future trends in development of the Arctic materials are discussed.

Based on the information provided in this Master`s thesis it is possible to learn about Russian metals used for ships and offshore platforms operated in the Arctic region. Paper can be used as the comprehensive review of current materials, such as various steels, aluminiums and nanomaterials.

ACKNOWLEDGEMENTS

This Master`s thesis has been done at the Laboratory of Welding Technology of the Department of Mechanical Engineering in Lappeenranta University of Technology. The research started in December 2011 and completed in May 2012.

I would like to express my gratitude to the laboratory, where the project was carrying out. It was a pleasure to receive an office room and to get guidance at all stages of my research, as well as a financial support.

This research project would not been possible without support of my supervisors. I wish to express my gratitude to Prof. Jukka Martikainen, who was abundantly helpful and offered invaluable assistance, support and guidance. Deepest gratitude is also due to Dr. (Tech.) Paul Kah, whose expertise, understanding and patience added considerably to my research experience. I appreciate also support from the project manager Mr. Markku Pirinen, who organized the trip to Russian company Prometey, during which I gained the practical understanding of the project.

Very special thanks goes out to my parents Dmitry Layus and Julia Layus, who supported me during the project. I appreciate their understanding of the importance of that thesis for me.

Finally, I would like to acknowledge help of James Wright in English correction and Vasily Kokorev for providing the data for the Arctic map. Moreover, I am grateful for my friends, who understood the importance of this thesis and supported me at different stages of the research.

Pavel Layus

Lappeenranta

20.07.2012

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

°C	Celsius
Al	Aluminium
As	Arsenic
B	Boron
C	Carbon
CE	carbon equivalent
cm	centimetre
Cr	Chromium
CT	compliant tower
CTOA	crack tip opening angle
CTOD	crack tip opening displacement
Cu	Copper
DT	drop weight test
FPS	floating production system
FPSO	floating production storage and offloading
GOST	state Russian standard
J	joule
KCU	fracture toughness parameter of Charpy U impact test

kg	kilogram
LNG	liquefied natural gas
m	metre
mm	millimetre
Mn	Manganese
Mo	Molybdenum
MPa	mega Pascal
N	Nitrogen
NDT	nil-ductility temperature
Ni	Nickel
nm	nanometre
P	Phosphorous
PRE	index of corrosion resistance, %
REE	rare earth elements
RMRS	Russian Maritime Register of Shipping
S	second
S	Sulphur
SAW	submerged Arc Welding
Si	Silicon
t	thickness
Ti	Titanium

TLP	tension leg platform
TU	technical specification paper
V	Vanadium
W	Tungsten
Zr	Zirconium
δ	elongation

1 INTRODUCTION

The Master`s thesis is done as a part of research project named Arctic Materials Technologies Development. The project is carrying out by two entities: Lappeenranta University of Technology (LUT), which represents Finnish side and located in Lappeenranta and Federal State Unitary Enterprise Central Research Institute of Structural Materials Prometey (Прометей), which is representing Russian side and located in Saint Petersburg. There is a chance that some Finnish companies will also join the project later.

Project is aimed to develop new materials for the Arctic environment, as well as define safety and environmental regulations. New materials will find applications in various Arctic structures and machinery, such as offshore platforms, icebreakers and oil related pipelines. As the first part of the project will be over at summer 2012, this Master`s thesis is a preliminary research on the topic.

The main challenge for conventional steels in the Arctic conditions is brittle fracture behavior below the certain temperature. This phenomenon has already caused many serious accidents, as steels for Arctic operation must stay ductile at low temperatures. Therefore, this property of steels should be examined carefully and extensively before choosing the certain steel grade.

The study reviews different Russian steels that are used or can be used for offshore Arctic platforms. In Russian standards, there are several types of materials applicable for Arctic service, such as shipbuilding steels, steels for general use, structural construction steels, stainless steels, cast steels, aluminium alloys and newly introduced nanomaterials. Each group is examined closely and certain materials grades are reviewed.

The paper provides an overview of offshore platforms structure and classification. There are different material requirements for various parts of an offshore platform, therefore there is a need to evaluate these requirements and provide recommendations to materials required properties.

Moreover, the research covers current Russian Arctic offshore projects and provides a description of most significant ones, such as Sakhalin II project, Prirazlomnaya ice-resistant offshore platform, jack-up Murmanskaya and several other projects.

1.1 What is the Arctic?

Geographically, the Arctic areas can be defined as lands to the north from the Arctic Circle, which is situated at the latitude 66˚34'. However, from the engineering point of view this criterion is not so important, since not only geographical location influences the climate and other environmental conditions in the region. According to the definition commonly accepted in engineering practices "Arctic refers to those places at which the average temperature of the warmest month of the year is less than 10˚C" [1]. Based on construction point of view the Arctic region grounds can be divided into: areas with permanent or temporal permafrost and regions without any frozen ground. Fig. 1 shows the circumpolar Arctic region, countries it includes, the most significant oil reserves and the location of the Arctic Circle.

Fig. 1 Map of the Arctic region. The red isothermal line borders the areas with the average temperature of the warmest month below 10˚C [2], [3], Yellow line shows the Arctic Circle; Gray areas indicate the largest oil fields located in the Arctic region [4]

Russian engineering practice uses a special term which can be defined as the Arctic conditions - the Extreme North or Far North. In the Extreme North region welded structures should obey strict requirements and materials should be cold resistant. However, according to [5] some areas of Russia were specified as the Extreme North in favor of attracting workforce there, since salaries are higher in such regions. Fig. 2 shows the areas of Russia that are considered to be the Extreme North. As it can be seen in Fig. 2 the large part of Russia is considered to be the Extreme North. This area is rich with natural resources such as oil, gas and precious metals. Therefore, even despite the extremely cold climate Russians are interested in development of these lands.

Fig. 2 The Extreme North areas in Russia. Drawn from [6]

Nowadays the price of oil and gas is on the rise due to the daily growing worldwide demand. According to forecasts [7], the current reserves of oil will last for several decades, but some of the oil locations are not easily accessible and are expensive to develop. In this realm, the Arctic region plays an extremely prominent role, since it has been estimated that it holds about 5% of oil and more than 20% of natural gas only as proven reserves [8]. Fig. 3 shows proven and estimated Arctic resources as a share of the world reserves.

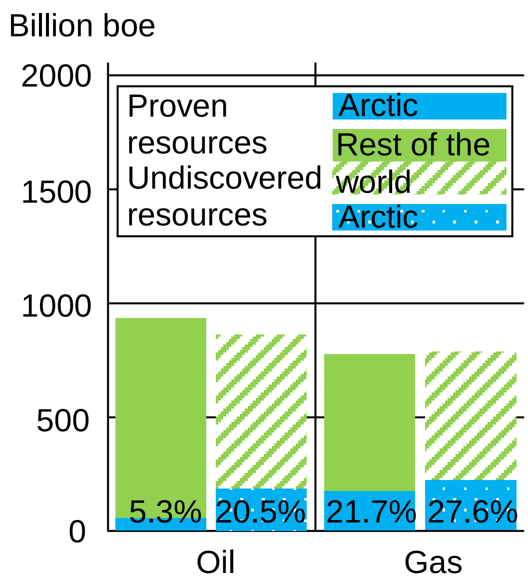

Fig. 3 Percentage of Arctic oil and gas reserves, replotted from [8]

The richness of the Arctic region in oil and gas was discovered about 50 years ago, but a thick ice cap prevented the extraction of oil and natural gas stored beneath the seabed. However, recently the climate change has caused considerable reduction of the ice cover [9]. The shrinkage of the ice cover in the Arctic region helps to access oil and gas resources stored beneath the seabed. This fact boosted political debates about the Arctic region, as well as technical research on low temperature welding processes and materials. Due to discovering more oil beneath the seabed, offshore structures have gained more significance in order to maintain a stable oil supply in the future. Particularly, interest in such areas as the Beaufort Sea, the North Sea, the Sakhalin Island and Arctic shelf areas has increased. As it can be seen in Fig. 4 more and more hydrocarbons are produced from offshore locations. Climate change caused ice melting allows an easier access to oil and gas stored beneath the seabed of the Arctic region with relatively low expenses. So far, the North Sea is a leading offshore oil production region with the largest rigs [10].

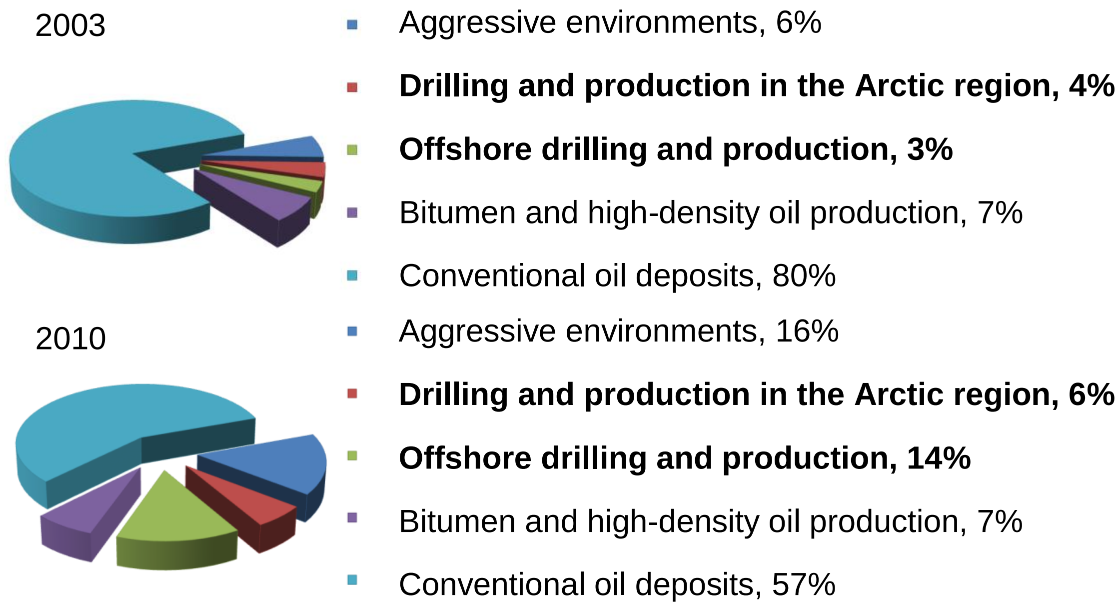

Fig. 4 Change in hydrocarbons production source from 2003 to 2010 [11]

Considering the rising awareness of global warming, more attention is being paid to alternative forms of energy. In this realm, offshore platforms can be employed for the placing of wind power stations. In Europe and the US most of the wind power plant locations on land have already been occupied. As a result, new wind energy plants will typically be placed at seabed. So far only some offshore wind energy farms have been constructed [12].

1.2 Operating conditions in the Arctic region

During winter time in some parts of the Arctic region air temperature may fall down as low as -60˚C. It is obvious that low temperature affects performance of machinery and manual tasks in the region. Working conditions are also affected by strong winds, which have speed of about 5-15 m/s, with maximum up to 50 m/s [13, 14]. Coldest parts of the Arctic are getting little rain or snow.

Fig. 5 illustrates how efficiency of equipment and manual tasks reduces due to low temperature.

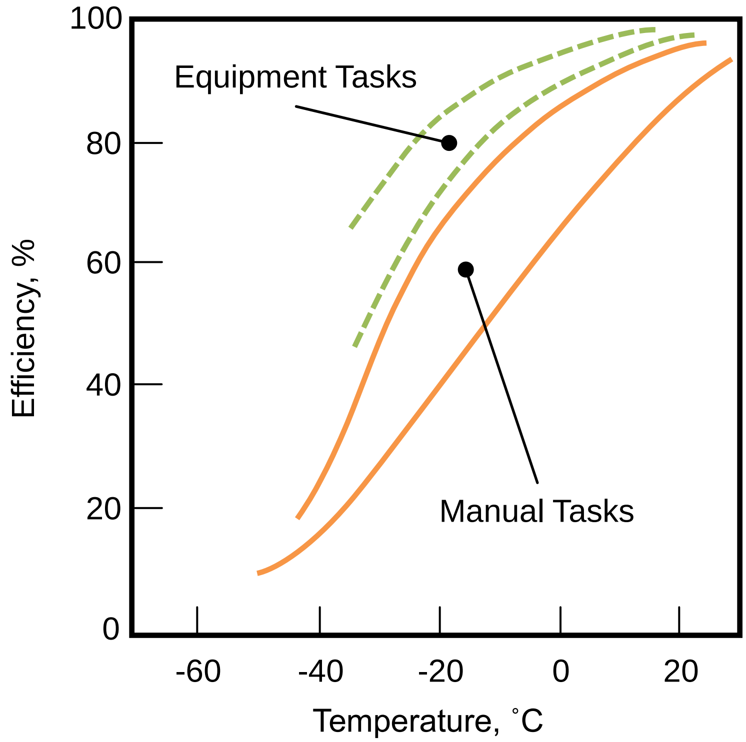

Fig. 5 Effect of temperature on work efficiency, replotted from [15]

Long Arctic winters have a profound effect on steel structures and the equipment, since prolonged periods of relatively cold temperatures are more dangerous than a few hours of extremely intense frost. Normally, as the temperature drops below 0˚C, hardness, yield strength, ultimate tensile strength and modulus of elasticity of the metal increases but ductility decreases [16]. The greatest changes in the properties occur when the metal cools down to extremely low temperatures near the boiling point of liquid hydrogen (-253˚C). However, even at less severe sub-zero temperatures encountered in the Arctic region, carbon steels become embrittled [17].

Not surprisingly, first steps in that development were not successful from the engineering point of view due to numerous failures of industrial machines, pipelines and steel structures during winter season. For instance, service period of cars at the Far North is two times shorter compared to the European part of Russia. Severe winter is particularly dangerous, as excavator and bulldozer part failures occurred 3-6 times more often than during the summer [18].

Reliability also plays a crucial role for energy related applications in the Arctic region, since even a relatively small oil spill may seriously damage the fragile Arctic ecosystem. A disaster, like the recent British Petroleum oil spill in the Gulf of Mexico [19], in the Arctic region will cause a greater devastation. Furthermore, it would be significantly expensive to clean the oil and restore the fragile Arctic ecosystem, which could be damaged even fatally, including fish and other living organisms of the area. Another problem is that modern oil spill cleaning techniques are ineffective in the Arctic conditions, for instance the bacteria cleaning method is not applicable [20]. These risks lead to extensive development and employment of the most reliable, high-quality manufacturing techniques and cold resistant materials for Arctic service.

When it comes to Arctic offshore platforms there are several external environmental parameters that must to be taken into consideration in accordance with Russian Maritime Register of Shipping (RMRS), which are wind, waves, current, ice, soil, seismic conditions and temperature [21]. Now these parameters will be reviewed in more detail.

<u>Wind:</u>

- Average (for 10 minutes observation period) wind speed at the high of 10 m from the ground level. The data should be recorded for a minimum of 20 years. Extreme values of average wind speed should be calculated based on at least 50 years wind speed records

- Numerical value of the relation between average wind speed and height
- Wind impetuosity parameters
- Spectral parameters of wind gustiness

Waves:

- Wave height with 3% exceedance probability
- Individual height of waves, based on 100 years of observations (in case of the absence of the data it can be calculated)
- Average period of waving
- Average frequency of waves

Current:

- Origin of the current (wind or flood-tide)
- Distribution by the depth
- Constancy in time

Current calculations should be combined with wave calculations in order to calculate the required strength of an offshore platform.

Ice:

- Density
- Salinity
- Ultimate ice compression strength
- Ultimate ice bending strength
- Ultimate ice elongation strength
- Module of elasticity
- Ice cracking resistance
- Friction properties of ice

The combinations of wind, current and ice loads might sum up and result in extremely high loads on an offshore structure.

Soil:

- Type of soil (sand, clay)
- Mass of soil in the water
- Modulus of deformation
- Poisson ratio
- Friction value
- Internal friction angle of the soil

Seismic conditions:

Should be considered only if the approximate seismic activity in the area is higher than 6.5 rate (Richter Earthquake Scale). Intensity of seismic activity should be measured for more than 100 years.

Temperature:

Mainly coldest daily average temperature, based on 10 years of observations for the area is taken into consideration. Minimal temperature for underwater platform elements should be taken as -2 ˚C.

2 EVALUATION OF DESIRED STEEL PROPERTIES

The success of engineering solutions largely depends on materials selected. In the Arctic conditions, materials should meet different criteria, which are typically the following: [22, 23]

- Low temperature toughness down to -60˚C
- Yield strength requirements of 235-690 MPa
- Isotropy of properties across dimensions of material
- Resistance to forming brittle fracture

- Reasonable weldability without preheat and postheat treatment (or with minimal preheat temperature required)
- Good corrosion resistance for marine applications
- Capability of withstanding static and dynamic wind and wave loads according to the operational parameters
- High strength to decrease the weight of structures
- Reasonable elongation for constructions working at a wide range of temperatures

2.1 Ductile to brittle translation curve

Brittle fracture is a failure which occurs when steel is subject to load, but dimensions are restrained preventing steel from fully developing its yield potential. This failure is particularly likely to occur in steel structures used for low temperature service. Steel elastic properties and plasticity are significantly lower at low temperatures due to the brittle fracture behaviour. Ductile to brittle curve is shown in Fig. 6.

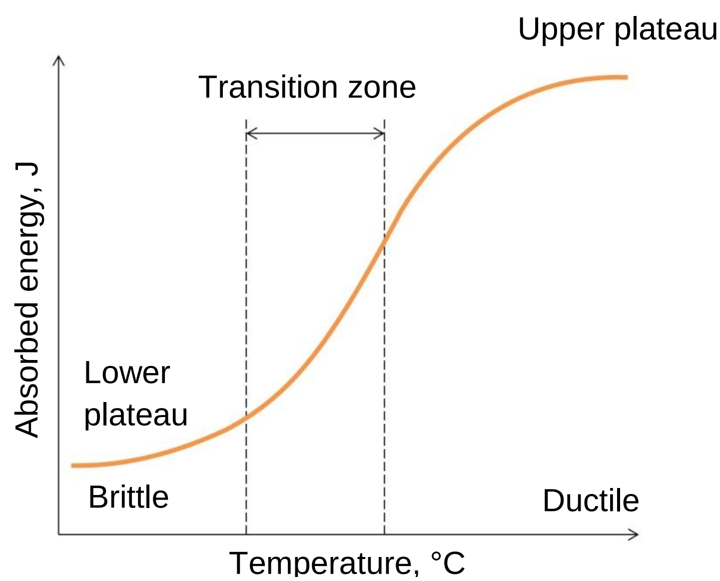

Fig. 6 Typical ductile to brittle translation curve, replotted form [24]

At temperatures below the transition temperature, steel demonstrates the brittle behaviour. There is a parameter which is used to determine steel brittle behaviour, which is the notch toughness. Different approaches might be used to assess the notch toughness of steels, one of which is the Charpy notch test. There are ways to prevent the formation of the brittle fracture and reduce its harmful effect: [25]

- For structures designed for low temperature conditions specific steels should be used
- Design of steel constructions should prevent excessive concentration of stress
- Perform welding with appropriate preheat and postheat treatment, if required

Temperature of ductile to brittle transition of steels depends on many factors. Most prominent among these are: [18]

- Type of lattice
- Grain size and condition of the boundaries
- Alloying elements
- Shape and size of nonmetallic inclusions

The study of the failed shipbuilding plates demonstrates that the value of 20 - 35 J/cm^2 is sufficient to prevent either the initiation or propagation of brittle cracks [26]. However, these values cannot answer some special requirements, and usually impact test values are set for each application individually.

3 TYPES OF OFFSHORE STRUCTURES

Generally, according to [21], offshore structures are devided into fixed and mobile. Each group than can be splitted based on different criteria, such as body material or type of stabililty support. The whole classification is shown in Fig. 7.

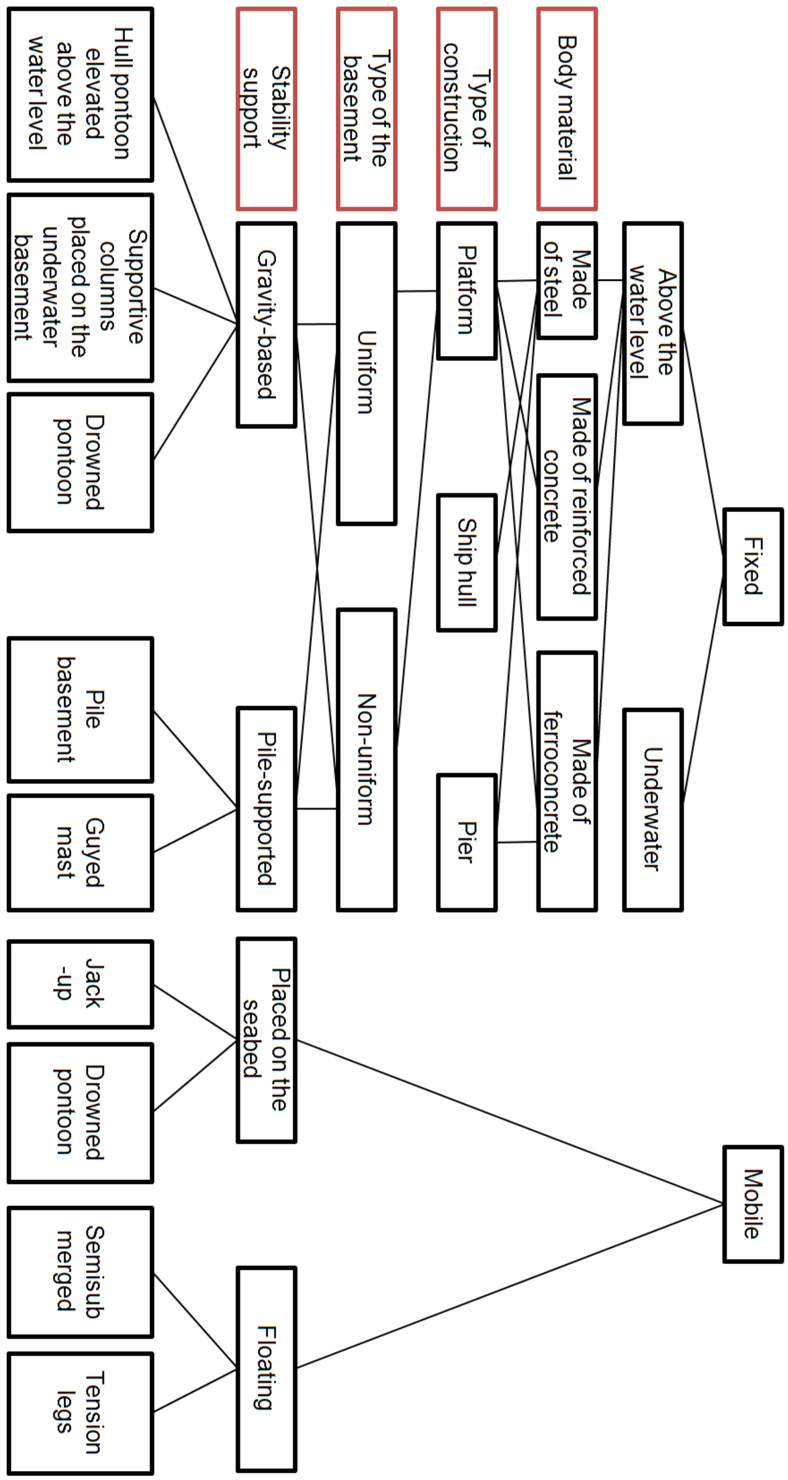

Fig. 7 Classification of offshore platforms, replotted from [21]

Offshore platforms also can be divided by four groups based on the operated depth: shallow (≤30 m), average depth (30-150 m), deepwater (150-350 m) and ultra deepwater (≥350 m). Fig. 8 shows various types of offshore structures and their operation depth. From a structural point of view, an offshore platform can be fixed at the seabed or be buoyant. Typically buoyant platforms are operating at deeper areas.

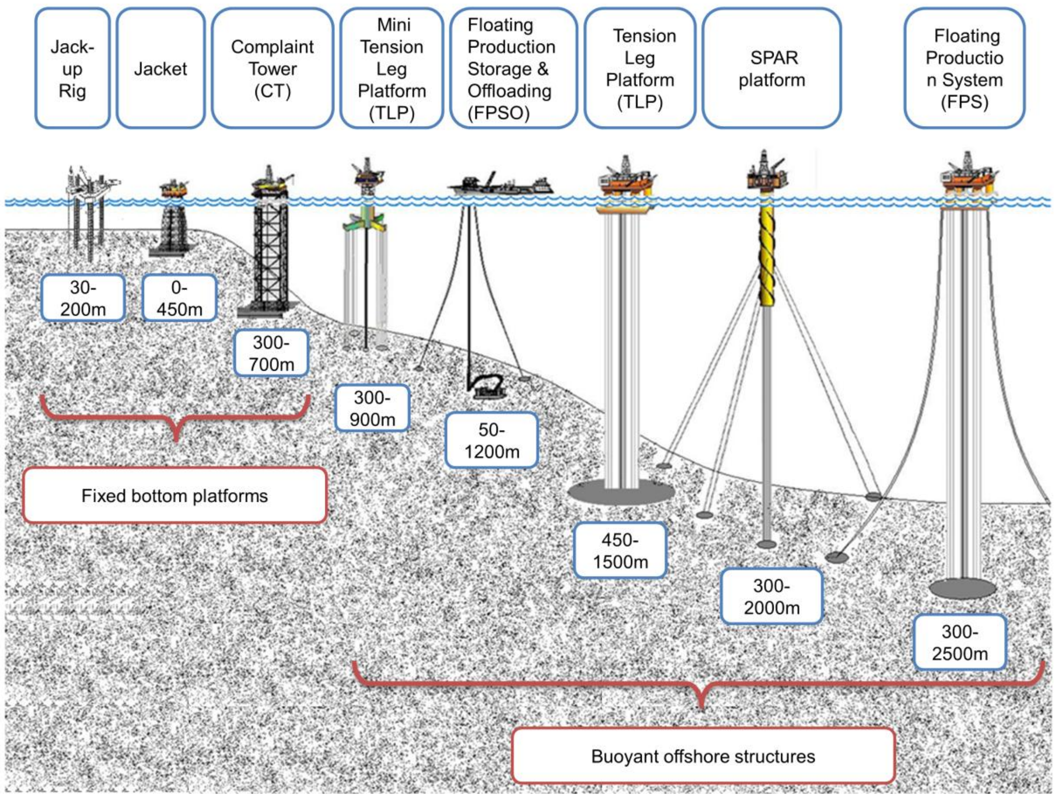

Fig. 8 Different types of offshore structures based on sea depth, replotted from [27]

From an engineering perspective, offshore platforms consist of different components. According to [21] an offshore platform consists of various elements, which play various roles in a platform structure and experience different loads. Table 1 shows classification of offshore platform elements, dividing them into three main groups: elements with special requirements, general construction elements and secondary construction elements.

Table 1 Classification of offshore platform elements [21]

Classification of platform elements	Field of application
Elements with special requirements are responsible for overall strength of a structure and capable of withstanding heavy loads.	Waterline construction elements, connections to a hull floor of the platform. Constructive elements of the ice-resistant girder in case if a platform also stores oil. Elements which are used for connection of platform body parts. Elements which cross-section area changes dramatically. Elements of the platform which are experiencing significant loads.
General construction elements are used to provide general strength of a platform and ensure safety of operations	Outer cover plates of body parts. Cover plates of watertight parts, which are contributing to the overall strength of a platform. Frame beams of a carcass. General cover plates on a deck, bulkhead covers.
Secondary construction elements are elements failure of which will not significantly influence safety and operating conditions	Internal elements which are not related to overall strength of a platform. Secondary set of covers and flooring.

Various parts of offshore platforms are experiencing different environmental conditions. Fig. 9 shows typical environmental conditions for parts of offshore structures, installed in the Arctic region.

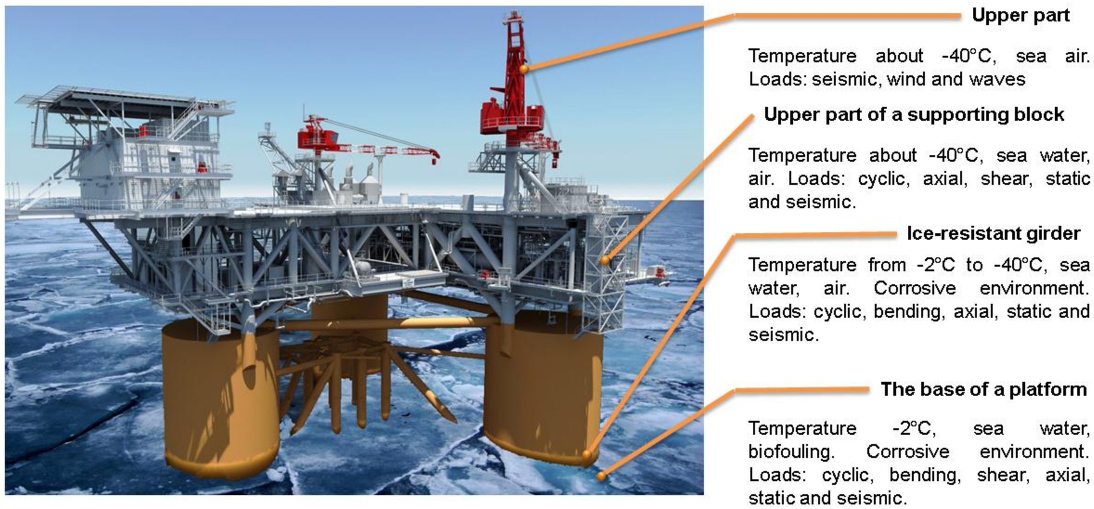

Fig. 9 Environmental conditions experienced by an offshore platform in the Arctic region, replotted from [28]

As elements experience significantly different temperatures and load types, they have different material properties requirements. Recommendations for material selection are given in the Table 2.

Table 2 Material selection for offshore platforms [21]

Type of construction	Steels to apply
Structures below a waterline	Special high-strength cold resistant steels
Parts of the ice-resistant girder (changing waterline)	High-strength clad steels
Constructions located above a water-line	High-strength cold resistant steels
Internal parts	High-strength steels
Internal parts which are not contribute to overall strength of a platform	Steels of normal strength
Constructions of top part of a platform	Steels of normal strength

Materials for underwater parts of offshore structures should be cold resistant only up to -2˚C [29], but have high corrosion resistance against sea water.

Structural desing of offshore platforms is briefly overviewed below. Supportive legs are formed by pipes with diameter of about 1.2-10 m and wall thickness of 15-50 mm, in case of larger pipes, they are made as it is shown in Fig. 10. The leg assembly consists of racks and chords, which are typically welded by SAW welding. Racks length ranges from 8 to 15.5 meters, thicness can vary from 160 mm up to 210 mm and width is from 775 mm up to 1060 mm. Chords have length of 4-6.2 m, thikness can vary from 80 mm to 115 mm and width typically in a range of 380-680 mm. One leg assemly can be up to 25 m long.

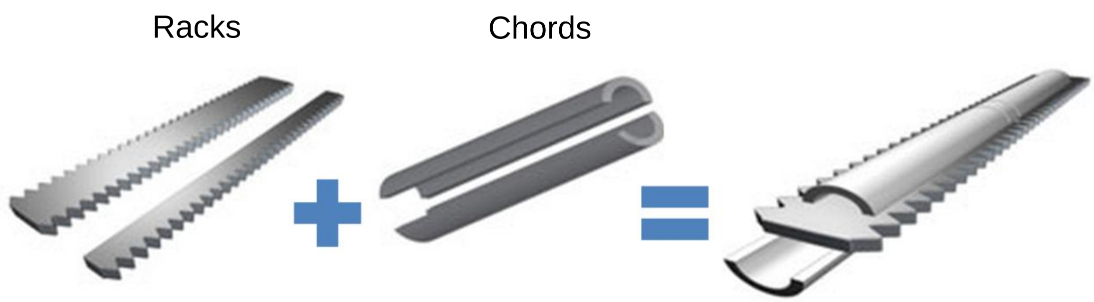

Fig. 10 Elements of jack-up rig welding assembly [30]

Piles for seabed platform fixation are made out of pipes with diameter ranging from 0.92 m to 2.13 m and wall thickness of 38-64 mm and can be hammered to the ground up to 170 m. Piers are usually place on the shallow water, no deeper that 15 m. Major structural element are pipes with diameter of 0.3-0.5 m. Usually all the production facilities are placed on the pier [21].

4 MATERIALS FOR ARCTIC

This chapter covers various materials for the Arctic conditions which are already in use or can be used in the future. As this thesis is focusing on materials, weldability of steels is defined as non-numerical concept and stated as excellent, good or poor. Impact test value is provided as KCU, as this information is mainly available for reviewed standards.

RMRS demands adherence to specification of material testing and usage before welding. Carbon and low alloy carbon steel plates thicker than 60 mm which are used for critical components should be checked with ultrasonic method in order to detect imperfections. Carbon, low alloy and medium alloy steel casts aimed for production of high loaded parts with any dimension exceeding 200 mm and thickness more than 50 mm should be checked with ultrasonic testing method. Tests should cover at least 50% of the cast volume. Steels for offshore structures should obey the following standards: I, II, III [29, 31].

4.1 Low and intermediate carbon steels

Steels of normal quality are designated as Ст (stays for steel) and a digit after, which shows amount of Carbon contained in steel. This thesis covers one steel of that group – Ст3, as that grade is most applicable for cold environments.

Quality unalloyed steels are designated only by number, for instance steel 20 or steel 45. The number shows approximate carbon content, multiplied by 100. This work covers steels 20 and 45.

Low and intermediate carbon steels are typically have high plasticity, reasonable weldability and low corrosion resistance. That steels can be applied at as low as -50 ˚C.

4.1.1 Steel Ст3

This grade of steel is designated by first Ст, which is indicating that it is normal quality steel. The subsequent digit shows the percentage of Carbon. This particular grade is low carbon steel with high plasticity and low strength. These steels are used for welded constructions without significant loads and vibrations. Ст3 can be used for welded structures with plate thickness from 5 mm up to 25 mm at temperatures down to -50 ˚C. Corrosion resistance is low. Chemical composition of Ст3 is shown in Table 3.

Table 3 Chemical composition of steel Ст3, % [IV]

C	Si	Mn	S	P	Cr	Ni	Cu	Ag	N
0.14-0.22	0.15-0.30	0.40-0.65	≤0.050	≤0.040	≤0.03	≤0.03	≤0.03	≤0.080	≤0.010

Steel has a good weldability with any welding process for plates with thickness less than 60 mm. For thicker plates electroslag welding should be used. Mechanical properties of Ст3 are shown in Table 4.

Table 4 Mechanical properties of steel Ст3 [18]

Plate thickness, mm	Tensile strength, +20°C, MPa	Tensile strength, -50°C, MPa	Yield strength, +20°C, MPa	Yield strength, -50°C, MPa	KCU, +20°C, J/cm^2	KCU, -50°C, J/cm^2
≤20	240	420	490	550	70	5
20-40	230	-	450	-	-	-
40-100	220	-	410	-	-	-
≥100	200	-	370	-	-	-

Practical experiments made on Ст3 steel plate of 12-20 mm thickness has shown that lowering sulphur content from 0.040% to 0.008% had not significantly affected its mechanical properties. However, in case of 09Г2С of the same plate thickness reduced amount of Sulphur down to 0.015% has dramatically improved mechanical properties of the steel at low temperatures [32].

4.1.2 Steel 20

It is low carbon steel with low strength, high plasticity and low corrosion resistance. The steel is aimed for constructions with numerous welds, such as cases and vessels. Also pipes can be produced from this steel, but operating pressure should not exceed 2.5 MPa, with working temperature range of -30 ˚C to +450 ˚C. After normalization, this steel is used for producing engine frames, outer parts of bearings and other parts without heavy loads used down to -40 ˚C. Steel has a good formability and excellent weldability up to 60 mm plate thickness [7]. Chemical composition of steel 20 is provided in Table 5.

Table 5 Chemical composition of steel 20, % [V]

C	Si	Mn	S	P	Cr	Ni	Cu	As
0.17-0.24	0.17-0.37	0.35-0.65	≤0.050	≤0.040	≤0.25	≤0.25	≤0.25	≤0.080

Mechanical properties for normalized steel of average plate thickness are listed in Table 6.

Table 6 Mechanical properties of steel 20 [7]

T, °C	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2
20	510	370	80
-40	550	380	30
-70	610	400	10

4.1.3 Steel 45

Steel has low corrosion resistance. It can be used for unloaded parts produced by mechanical cutting, such as caps, bolts and nuts. After quenching and tempering the steel is used for medium parts. Steel can be also used for pipes in temperature range of -50 °C to +150 °C. The steel has excellent formability, but limited weldability, as preheat and further thermal treatment are needed [18]. Chemical composition is given in Table 7.

Table 7 Chemical composition of steel 45, % [V]

C	Mn	Si	S	P	Cr	Ni	Cu	As	N
0.42-0.50	0.50-0.80	0.17-0.37	≤0.040	≤0.035	≤0.25	≤0.30	≤0.30	≤0.08	≤0.008

Mechanical properties for average plate thickness are presented in Table 8.

Table 8 Mechanical properties of steel 45 [33]

T, °C	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2
20	640	390	43
-30	-	-	38
-50	700	500	13
-100	-	-	6

Steel is supplied as:

- Hot-rolled plates without heat treatment of thickness range of 0.5-100 mm [VI]
- Cold-rolled plates with heat treatment of thicknesses 0.5-5 mm [VI]
- Pipes with diameter up to 800 mm [VII, VIII]

4.2 Low alloy steels

Alloyed steels are designated in accordance to its chemical composition by use of corresponding letters, as it is stated in [IX]. However, if the percentage of an alloying element is less than 1.5% the corresponding letter should not be stated. Letters and alloying elements are listed in Table 9.

Table 9 Alloy steels composition designation letters [IX]

Ю	Aluminium	**М**	Molybdenum	**Е**	Selenium
Р	Boron	**Н**	Nickel	**С**	Silicon
Х	Chromium	**Б**	Niobium	**Т**	Titanium
К	Cobalt	**А**	Nitrogen	**Ф**	Vanadium
Д	Copper	**П**	Phosphorus	**В**	Tungsten
Г	Manganese	**Ч**	REE	**Ц**	Zirconium

Sulphur does not have any designation letter in the Russian standard, because it is considered to be an impurity and is not included in a steel name.

Rare earth elements (REE) are sometimes used in cold resistant steel manufacturing as agents to react with non-metallic inclusions in steel and by that improve its quality. However, in certain cases these elements also can be part of chemical composition of steel. Typical RRE used in the steel production in one or another way are Yttrium, Lanthanum, Cerium, Neodymium, Praseodymium and Ytterbium [34, 35].

4.2.1 Steel 09Г2С

Steel has low ductile to brittle transition temperature, satisfactory formability, good weldability and low corrosion resistance. After quenching and tempering it is used for critical structures above -40°C. In case of ordinary structures steel can be used from -70°C up to +425°C [36]. Welding can be done with any process on plate thicknesses less than 60 mm, for thicker section electroslag welding is recommended with preheat of 100-120°C. For better low temperature weld properties, it is advised to add Nickel (up to 1%) to the weld bath. Steel 09Г2С can be replaced with following steels: 09Г2, 09Г2ДТ, 09Г2Т, 09Г2С [33]. Chemical composition is given in Table 10.

Table 10 Chemical composition of steel 09Г2С, % [X, XI]

C	Mn	Si	Cr	Ni	Cu	S	P
≤0.12	1.30-1.70	0.50-0.80	≤0.30	≤0.30	≤0.30	≤0.040	≤0.035

Mechanical properties for various plate thicknesses are listed in Table 11.

Table 11 Mechanical properties of steel 09Г2С [X]

Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -20°C, J/cm^2	KCU, -40°C, J/cm^2
≤4	500	350	-	-	-
5-9	500	350	≥65	≥40	≥35
10-20	480	330	≥60	≥35	≥30
21-32	470	310	≥60	≥35	≥30
33-60	460	290	≥60	≥35	≥30
61-80	450	280	≥60	≥35	≥30
81-160	440	270	≥60	≥35	≥30

Steel plates are supplied according to [X] and [XI].

4.2.2 Steel 10Г2

Steel 10Г2 was specially developed for low temperature applications and constructions. It is recommended for large scale welded sheet metal structures operated at cold environments with temperature as low as -70 °C. The steel has a superb weldability. It is similar to steel 09Г2 [18, 33]. Chemical composition is listed in Table 12.

Table 12 Chemical composition of steel 10Г2, % [X (the same, but nitrogen content: ≤0.012), XI]

C	Si	Mn	S	P	Cr	Ni	N	Cu
0.07-0.15	0.17-0.37	1.20-1.60	≤0.035	≤0.035	≤0.30	≤0.30	≤0.008	≤0.30

Mechanical properties for various plate thicknesses are listed in Table 13. In brackets an actual experimental value of KCU is shown.

Table 13 Mechanical properties of steel 10Г2 [18]

Heat treatment	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -70°C, J/cm^2
After heat treatment [XII]	2-25	265	421	≥118	-	-
Quenching (920 °C) and tempering (600 °C, air) [IX]	10-250	245	420	- (321)	- (304)	- (211)
Normalization (920 °C, air) [XIII]	ø10-100	215	430	≥54 (364)	- (276)	- (185)
	ø100-300	215	430	≥49 (350)	- (266)	- (175)
	ø300-500	215	430	≥44 (330)	- (256)	- (165)

Steel is supplied as:

- Thick sheets [X]
- Thin sheets [XIV]
- Pipes [XII, XV, XVI]

4.2.3 Steel 10Г2С1

Steel 10Г2С1 is low alloyed steel with low ductile to brittle transition temperature. It has an excellent weldability. This steel is usually specified for parts of welded structures which are working at the temperatures as low as -70°C. Moreover, it can be used as a sheet plates parts for vessels operated under pressure at the temperature range of -70°C - +475°C. Steel 10Г2С1 is similar to 10Г2С1Д [18, 33]. Chemical composition of steel 10Г2С1 is given in Table 14.

Table 14 Chemical composition of steel 10Г2С1, % [X (the same, but nitrogen content: ≤0.012), XI]

C	Si	Mn	S	P	Cr	Ni	N	Cu	As
≤0.12	0.80-1.10	1.30-1.65	≤0.040	≤0.035	≤0.30	≤0.30	≤0.008	≤0.30	≤0.08

Mechanical properties of the steel after heat treatment are listed in Table 15.

Table 15 Mechanical properties of steel 10Г2С1 [XI]

Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -70°C, J/cm^2
10-20	480	335	≥59	≥29	≥24
20-32	470	325			
32-60	450	325			
60-80	430	295			
80-100	430	295			

Steel 10Г2С1 is supplied as:

- Sheets [X, XI]
- Bended profiles, strips [X]

4.2.4 Steel 16ГС

It is a high-strength steel which is aimed for low temperature service. It has a good weldability. This steel is used as pipes and elements of welded structures for temperatures as low as -70°C. Steel 16ГС can be replaced by following steels: 17ГС, 15ГС, 20Г2С, 20ГС, 18Г2С [18, 33]. Chemical composition is given in Table 16.

Table 16 Chemical composition of steel 16ГС, % [X (the same, but nitrogen content: ≤0.012), XI]

C	Si	Mn	S	P	Cr	Ni	N	As	Cu
0.12-0.18	1.50-2.00	0.90-1.20	≤0.40	≤0.035	≤0.30	≤0.25	≤0.008	≤0.008	≤0.30

Mechanical properties for various plate thicknesses are provided in Table 17.

Table 17 Mechanical properties of steel 16ГС [18]

Heat treatment	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -70°C J/cm^2
After heat treatment [XI]	≤5	325	490	-	-	-
	5-10	325	490	≥59	≥39	≥29
	10-20	315	480	≥59	≥29	≥24
	20-32	295	470	≥59	≥29	≥24
	32-60	285	460	≥59	≥29	≥24
	60-160	275	450	≥59	≥29	≥24
Normalization [XIII]	100-300	245	470	≥39	-	-
Flat products after heat treatment [X]	≤10	325	450	≥59	≥39	≥29
	10-20	315	450	≥59	≥29	≥24
	20-160	265	450	≥59	≥29	≥24

The steel is supplied as:

- Sheets [X, XI]
- Cast steel [XIII]

4.2.5 Steel 14Г2АФ

Steel 14Г2АФ is a ferrite-pearlite based high-strength steel with low corrosion resistance. This steel is recommended for manufacturing vessels and machinery, which are operated under pressure at the temperature range of -50 °C to +400°C. For improving ductility at low temperatures the steel can be alloyed with Nitrogen and Vanadium during thermal treatment, which are contributing to a smaller grain size. Steel has a good machinability and satisfactory welding for plates thinner than 25 mm. If a plate thickness exceeds 25 mm additional preheat treatment for 150 °C is recommended. Welds remain ductile to as low as -60 °C. Steel 14Г2АФ is similar to steels: 15Г2АФ, 16Г2АФ [33]. Chemical composition is listed in Table 18.

Table 18 Chemical composition of steel 14Г2АФ, % [X]

C	Mn	Si	V	N	Cr	Ni	S	P
0.12-0.18	1.20-1.60	0.3-0.6	0.07-0.12	0.015-0.025	≤0.40	≤0.30	≤0.040	≤0.035

Mechanical properties of the steel after normalization at 930°C are listed in Table 19.

Table 19 Mechanical properties of steel 14Г2АФ [18]

Direction of obtaining the specimen	T, °C	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2
Along with the rolling direction	20	600	460	190
	-40	700	540	180
	-60	700	540	110
Across the rolling direction	20	640	490	100
	-40	700	550	80
	-60	720	580	60

Steel is shipped as:

- Plates of 4-50 mm thickness after being normalized [X]
- Pipes with diameter up to 1220 mm and 12 mm wall thickness

4.2.6 Steel 18Г2Ф

Steel 18Г2Ф is a high-strength low carbon steel with nitrogen hardening and low corrosion resistance. Flat products with thickness up to 30 mm produced from this grade of steel can be used as a strength member of a welded construction, working at variable temperatures ranging from -40°C to +450°C. After heat treatment the steel can work at low temperatures as -60°C, but without significant pressure loads. If a plate thickness exceeds 30 mm, steel plates can be used for welded structures which are operated at -20°C - +450°C without pressure loads. Weldability of that steel grade is limited, as for sections thicker than 36 mm preheat treatment and further heat treatments are recommended. Similar steels are the following: 18Г2АФ, 10ХСНД, 15ХСНД, 15Г2АФД, 16Г2АФ [33]. Chemical composition is given in Table 20.

Table 20 Chemical composition of steel 18Г2Ф, % [X]

C	Si	Mn	S	P	Cr	Ni	V	N	Cu	As
0.14-0.22	≤0.10	1.30-1.70	≤0.040	≤0.035	≤0.30	≤0.30	0.08-0.15	0.015-0.030	≤0.30	≤0.08

Mechanical properties of the steel after heat treatment are listed in Table 21. Standard requirements of impact strength are listed without brackets and are provided for specimen obtained perpendicular to the rolling direction. In the brackets actual values are listed for specimens, which were taken along with the rolling direction.

Table 21 Mechanical properties of steel 18Г2Ф [X]

Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -70°C, J/cm^2
≤10	590	440	-	-	≥44	≥34
12			- (77-198)	- (49-116)	- (41-45)	≥29
20			- (84-178)	- (46-117)	- (35-90)	≥29
30			- (86-167)	- (35-86)	- (30-65)	≥29

The steel can be ordered as:

- Sheets, strip and bended profiles according to [X]

4.3 Chromium containing steels

This chapter covers steels which contain Chromium, but are not stainless steels. These steels are widely in use for low temperature applications, as they are not expensive and can withstand low temperatures, down to – 50 and in some cases even -70°C.

4.3.1 Steel 20X

Steel 20X is a structural high-strength steel with low corrosion resistance. After heat treatment it gains excellent wearing properties as well as it keeps a ductile core. Steel is aimed for manufacturing of middle-sized high-strength parts and pipes operated at the temperature range of -50°C - +500°C. Steel has reasonable formability and weldability. Chemical composition is given in Table 22.

Table 22 Chemical composition of steel 20X, % [IX]

C	Si	Mn	S	P	Cr	Ni	N	Cu
0.17-0.23	0.17-0.37	0.50-0.80	≤0.035	≤0.035	0.70-1.00	≤0.30	≤0.008	≤0.30

Mechanical properties of the steel after heat treatment are listed in Table 23. Standard requirements of impact strength are listed without brackets and are provided for specimen obtained perpendicular to the rolling direction. In the brackets actual values are listed for specimens, which were taken along with the rolling direction.

Table 23 Mechanical properties of steel 20X [IX]

Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
10-80	650	800	≥60 (226-241)	- (172-212)	- (152-165)
80-150			≥54 (226-241)		
150-250			≥51 (226-241)		

The steel is supplied as:

- Hot rolled sheets of thickness range 5-160 mm without heat treatment [III]
- Cold rolled sheets of thickness range 0.5-5 mm after heat treatment [VI]
- Hot and cold rolled pipes of diameter up to 800 mm with and without heat treatment [VII, XVI, XVII]

- Forged steels of diameter up to 500 mm after heat treatment [XVIII, XIX]

4.3.2 Steel 20XH

It is a structural high-strength chromium-nickel steel with large depth of hardening. After hardening the steel gains excellent hardness and wear resistance of an outer layer. It is usually used for gears and other parts which are required large depth of hardening and used for cold climate temperatures (down to -60°C). Weldability of that grade of steel is rather limited. Chemical composition is given in Table 24.

Table 24 Chemical composition of steel 20XH, % [IX]

C	Si	Mn	S	P	Cr	Ni	Cu
0.17-0.23	0.17-0.37	0.40-0.70	≤0.035	≤0.035	0.45-0.75	1.00-1.40	≤0.30

Mechanical properties of the steel after heat treatment are listed in Table 25. Standard requirements of impact strength are listed without brackets and are provided for specimen obtained perpendicular to the rolling direction. In the brackets actual values are listed for specimens, which were taken along with the rolling direction.

Table 25 Mechanical properties of steel 20XH [IX]

Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -20°C, J/cm^2	KCU, -50°C, J/cm^2
5-80	590	780	≥78	- (62)	- (43)
80-150			≥70		
≥150			≥66		

Steel is supplied as:

- Long products [IX]

4.3.3 Steel 40X

It is a structural chromium high-strength steel with low corrosion resistance. The steel is used for manufacturing crankshafts, gears and pipe accessories operated at temperatures as low as -50°C and up to +430°C. Moreover, this grade of steel can be used for bolts and other fasteners for operation at -40°C - +425°C. Weldability is rather poor, as preheat and further heat treatment should be carried out. Chemical composition is listed in Table 26.

Table 26 Chemical composition of steel 40X, % [IX]

C	Si	Mn	S	P	Cr	Ni	Cu	N
0.36-0.44	0.17-0.37	0.50-0.80	≤0.035	≤0.035	0.80-1.10	1.00-1.40	≤0.30	≤0.008

Mechanical properties of the steel are listed in Table 27. Table shows average results for 25 mm bar.

Table 27 Mechanical properties of steel 40X [33]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -50°C, J/cm^2	KCU, -73°C, J/cm^2
Quenching (850°C, oil) and tempering (550°C, water, 1 hour)	1170-1250	1090-1550	≥110	≥70	≥65

Steel can be ordered as:

- Long products with thickness up to 250 mm after heat treatment [XX, XXI]
- Hot rolled sheets of 5-160 mm thickness without heat treatment [III]
- Cold rolled sheets with thickness range of 0.5-5 mm with heat treatment [VI]
- Pipes with diameter up to 800 mm with and without heat treatment [VII, VIII, XVII]
- Forged steels of diameter up to 500 mm after heat treatment [XVIII, XIX]

4.3.4 Steel 40XH

It is a heat hardenable high-strength steel with enhanced ductility and large degree of tempering. Steel has low corrosion resistance. It is aimed for production of heavily loaded parts with impact loads or high speeds, like gears or shafts. Recommended service temperature is -60°C - +430°C. Heat treatment is obligatory before use. Weldability is poor, as preheat and further heat treatment should be carried out. Chemical composition is listed in Table 28.

Table 28 Chemical composition of steel 40XH, % [IX]

C	Si	Mn	S	P	Cr	Ni	Cu	N
0.36-0.44	0.17-0.37	0.50-0.80	≤0.035	≤0.035	0.45-0.80	1.00-1.40	≤0.30	-

Mechanical properties of the steel are listed in Table 29. Table shows average results for 25 mm bar.

Table 29 Mechanical properties of steel 40XH [18]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -50°C, J/cm^2	KCU, -73°C, J/cm^2
Annealed	-	-	≥54	≥33	≥29
Quenched and tempered	1000	800	≥117	≥83	≥61

Steel can be ordered as:

- Long products with thickness up to 250 mm after heat treatment [XX, XXI]
- Hot rolled sheets of 5-160 mm thickness without heat treatment [III]
- Cold rolled sheets with thickness range of 0.5-5 mm with heat treatment [VI]
- Pipes with diameter up to 800 mm with and without heat treatment [VII, VIII, XVII]
- Forged steels of diameter up to 500 mm after heat treatment [XVIII, XIX]

4.3.5 Steel 30XH2MΦA

Steel 30XH2MΦA is a structural high-strength steel with satisfactory ductility and plasticity at cryogenic temperatures. This grade of steel is used for parts of reactors and critical parts of other machinery. It can be applied for temperatures as low as -196°C without significant loads, or for cold climate temperatures with loads. Steel can be welded, but with preheat and subsequent heat treatment. Chemical composition is listed in Table 30.

Table 30 Chemical composition of steel 30XH2MΦA, % [IX]

C	Mn	Si	Ni	Mo	Cr	V	Cu	S	P
0.17-0.34	0.30-0.60	0.17-0.37	2.00-2.40	0.20-0.30	0.60-0.90	0.10-0.18	≤0.30	≤0.025	≤0.025

Mechanical properties are listed in Table 31.

Table 31 Mechanical properties of steel 30XH2MΦA [18]

Heat treatment type	Temperature, °C	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2
Quenching (870°C, oil) and tempering (640°C, air)	-73	890	1040	160
	20	820	940	190

Steel can be ordered as:

- Forged steels [XIII]
- Long products [IX]

4.3.6 Steel 38XH3MΦA

It is a structural high-strength steel which has high degree of ductility and plasticity at low temperatures. The steel is magnetic and has low corrosion resistance. Critical parts are manufactured from this steel, such as shafts, rotors of turbines and shipbuilding screws. The steel has poor weldability, therefore usually is not used for welded structures. Chemical composition is given in Table 32.

Table 32 Chemical composition of steel 38ХН3МФА, % [IX]

C	Mn	Si	Ni	Mo	Cr	V	Cu	S	P
0.33-0.40	0.25-0.50	0.17-0.37	3.00-3.50	0.35-0.45	1.20-1.50	0.10-0.18	≤0.30	≤0.025	≤0.025

Mechanical properties of the steel are listed in Table 33.

Table 33 Mechanical properties of steel 38ХН3МФА [18, 33]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Quenching (850°C, oil) and tempering (600°C, air)	1180	1080	≥70	≥78	≥70
Quenching (850°C,oil) and tempering (550°C, air)	930	785	≥59	≥63	≥57

Steel 38ХН3МФА can be ordered as:

- Forged steels [XIII]

4.3.7 Steel 10ХСНД

It is a structural grade high-strength steel with high ductility and plasticity at low climate temperatures. Moreover, it has good corrosion resistance against atmospheric corrosion. This grade of steel is widely used for manufacturing steel constructions for the Far North region, such as bridges. The steel is also used in shipbuilding (including offshore). Structures from this grade of steel are capable of operating at temperature range of -70°C - +450°C. Steel

10ХСНД can be welded without any limitations. This steel can be substituted by steel 16Г2АФ [18, 33]. Chemical composition is listed in Table 34.

Table 34 Chemical composition of steel 10ХСНД, % [X]

C	Si	Mn	S	P	Cr	Ni	As	Cu	N
≤0.12	0.80-1.00	0.50-0.80	≤0.040	≤0.035	0.60-0.90	0.50-0.80	≤0.008	0.40-0.60	≤0.012

Mechanical properties of the steel are listed in Table 35.

Table 35 Mechanical properties of steel 10ХСНД [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, -40°C, J/cm^2	KCU, -70°C, J/cm^2
Hot rolled or normalized [IX]	8-15	390	530-685	≥39	≥29
	16-32		530-670	-	
	33-40		510-670	-	
Long hot rolled or heat treated product [X]	≤10		510	≥44	≥34
	10-15			≥39	≥29
	15-40			≥49	

Steel 10ХСНД can be supplied as:

- Long products [X, XXII]
- Sheets [X, XXII]

4.3.8 Steel 12ХН3А

This grade of steel is a high-strength surface hardening steel with satisfactory plasticity and low corrosion resistance. It can be used for shafts, pump shafts and various cases. It is recommended to use the steel after quenching and tempering. Temperature range is rather wide: -125°C - +152°C. Also, pipes can be made from this steel and in that case recommended temperature range is -60°C - +150°C. The steel can be mechanically cut, forged and pressed. Weldability of this grade is limited as it is recommended to carry out quenching and tempering prior the welding. Chemical composition is given in Table 36.

Table 36 Chemical composition of steel 12XH3A, % [IX]

C	Mn	Si	Ni	Cr	Cu	S	P
0.09-0.16	0.30-0.60	0.17-0.37	2.75-3.15	0.60-0.90	≤0.30	≤0.025	≤0.025

Mechanical properties of the steel are listed in Table 37.

Table 37 Mechanical properties of steel 12XH3A [18]

Heat treatment type	T,°C	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2
Quenched (860°C, water) and tempered 600°C	20	910	850	≥78
	-83	1220	1160	
Normalized at 870°C	20	800	440	≥70
	-183	1200	920	

The steel can be supplied as: [33]

- Long products [IX]
- Pipes [VIII, XIII, XVII]

4.3.9 Steel 12X2H4A

It is an alloyed structural surface hardening steel which combines high-strength at room temperature with plasticity and ductility at low climate temperatures, down to -60°C. Steel 12X2H4A has poor corrosion resistance. The steel is mainly aimed for large parts which should be able to withstand heavy loads, and have high degree of plasticity and a ductile core. Chemical composition is listed in Table 38.

Table 38 Chemical composition of steel 12X2H4A, % [IX]

C	Mn	Si	Ni	Cr	Cu	S	P
0.09-0.15	0.30-0.60	0.17-0.37	3.25-3.65	1.25-1.65	≤0.30	≤0.025	≤0.025

Mechanical properties of the steel are listed in Table 39.

Table 39 Mechanical properties of steel 12X2H4A [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2
Quenched (850°C, oil) and tempered (200°C, 1h).	≤80	1130	930	102	91
	80-150				
	≥150				

Steel 12X2H4A can be supplied as: [33]

- Long products [IX]
- Pipes [XXIV]

4.3.10 Steel 20XH3A

This is a structural high quality steel with good wear resistance and a ductile core. The steel has good resistance to impact load, it is magnetic and has low corrosion resistance. Wide range of parts can be produced from that steel, such as gears, shafts and fastenings. Weldability of that grade is limited. Chemical composition is shown in Table 40.

Table 40 Chemical composition of steel 20XH3A, % [IX]

C	Mn	Si	Ni	Cr	Cu	S	P
0.17-0.24	0.30-0.60	0.17-0.37	2.75-3.15	0.60-0.90	≤0.30	≤0.025	≤0.025

Mechanical properties of the steel are listed in Table 41.

Table 41 Mechanical properties of steel 20XH3A [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2
Quenched (850°C, oil) and tempered (560°C, 1h).	≤80	930	735	108	69
	80-150			97	58
	≥150			92	-

The steel can be supplied as: [33]

- Long products [IX]
- Pipes [XXIV]

4.3.11 Steel 18X2H4MA

It is a structural alloyed surface hardening steel. The steel has low corrosion resistance. Typically the steel is used for non-welded critical parts, which operated under heavy loads at temperature range of -73°C - +397°C. Steel can be welded, but with limitations, as preheat and further heat treatment are required. Chemical composition is listed in Table 42.

Table 42 Chemical composition of steel 18X2H4MA, % [IX]

C	Mn	Si	Cr	Ni	Mo	S	P	Cu
0.14-0.20	0.25-0.55	0.17-0.37	1.35-1.65	4.00-4.40	0.30-0.40	≤0.025	≤0.025	≤0.30

Mechanical properties are listed in Table 43. A specimen had a diameter of 7 mm and it was heat treated (quenching at 950°C, water and tempered at 620°C, water for 2 hours).

Table 43 Mechanical properties of steel 18X2H4MA [33]

T,°C	Tensile strength, MPa	Yield strength, MPa
20	840	680
-100	970	800

Steel 18X2H4MA is supplied as:

- Forged steels with diameter ≤100 mm [XXV]

4.3.12 Steel 15ХСНД

Steels 15ХСНД is a structural high-strength steel with high ductility at low climate temperatures. Steel has a superb corrosion resistance against atmosphere corrosion and widely used for low temperature constructions, such as bridges and ships. It should be used for welded constructions with high-strength requirements and mass limitation. The steel is suitable for use at as low temperature as -70°C. Also steel 15ХСНД can be applied for pressed parts at the temperature range of -40°C - +450°C [37]. Steel 15ХСНД is similar to following grades are: 16Г2АФ, 15ГФ, 14ХГС, 16ГС, 14СНД [33]. Chemical composition is given in Table 44.

Table 44 Chemical composition of steel 15ХСНД, % [X]

C	Si	Mn	S	P	Cr	Ni	As	Cu	N
0.12-0.18	0.40-0.70	0.40-0.70	≤0.040	≤0.035	0.60-0.90	0.30-0.60	≤0.008	0.20-0.40	≤0.012

Mechanical properties of the steel are listed in Table 45.

Table 45 Mechanical properties of steel 15ХСНД [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Hot rolled or normalized [XXII]	8-32	390	490-685	-	≥29	≥29
	33-50	335	470-670			
Long hot rolled or heat treated product [X]	≤10	345	490	≥64	≥39	≥29
	10-32			-	≥29	≥29

The steel is supplied as:

- Long products [X, XXII]
- Sheets [X, XXII]

4.3.13 Steel 15XM

The steel was developed for oil and gas pressure pipes which are used at the Far North region. An allowed temperature range for this steel is -40°C to +560°C. Steel 15XM has a good weldability, however preheat and further heat treatments are recommended. Chemical composition is listed in Table 46.

Table 46 Chemical composition of steel 15XM, % [IX]

C	Si	Mn	S	P	Cr	Ni	N	Cu
0.11-0.18	0.17-0.37	0.40-0.70	≤0.035	≤0.035	0.80-1.10	≤0.30	0.40-0.55	≤0.30

Mechanical properties of the steel are listed in Table 47.

Table 47 Mechanical properties of steel 15XM [IX]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2
Normalized (880°C), tempered (650°C)	≤80	275	440	118
	80-150	335	470-670	106
	≥150	345	490	100

Steel 15XM can be supplied as:

- Long products [IX]
- Pipes [XXVI]
- Forged parts [XIII]

4.3.14 Steel 20XГР

This is a low carbon steel which has high surface hardness and wear resistance after surface hardening. Steel 20XГР can withstand large impact loads. Corrosion resistance of this grade of steel is low. The steel is aimed to be used in manufacturing of gears, shafts and similar parts. Weldability of this steel is limited. Chemical composition is given in Table 48.

Table 48 Chemical composition of steel 20ХГР, % [IX]

C	Si	Mn	S	P	Cr	Ni	B	Cu	N
0.18-0.24	0.17-0.37	0.70-1.10	≤0.035	≤0.035	0.75-1.05	≤0.30	0.005	≤0.30	≤0.008

Mechanical properties of the steel are listed in Table 49.

Table 49 Mechanical properties of steel 20ХГР [18]

Heat treat-ment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Quenching (865-895°C, oil) and tempering (150-250°C, air or oil)	≤80	980	785	78	-	-
	80-150			70		
	150-250			65		
Quenching (860°C, oil) and tempering (200°C, oil)	-	-	-	62	63	61
Quenching (860°C, oil) and tempering (500°C, oil)				133	122	119

The steel can be supplied as:

- Long products [IX]

4.4 Cast steels

Cast steels have higher degree of initial imperfections comparing to other steels. That fact is especially important to consider for low temperature environments, as imperfections affect ductile to brittle transition temperature in a dramatic way. The amount of defects in cast steels depends on manufacturing methods and techniques. Cast steels have not only larger grain size, which affects low temperature material behavior, but also size of a grain differs significantly across the steel composition. Moreover, traditional methods of reducing a grain size such as heat treatment are not effective. For obtaining homogeneous grain size composition, heat treatment with subsequent normalization is recommended. However, such heat treatments are extremely hard to implement for large scale casted parts. It is a common practice to expose such parts only with normalization. Large grain size is not the only problem with cast steels. After heat treatment, regardless of a grain size an oxide film will form at grain boundaries. These films are dangerous, as they help cracks to spread across metal easier comparing to the base metal.

Alloying elements can significantly affect a grain size, however in some cases an oxide film will still form. Reviewed steels have satisfactory properties at low climate temperatures, and some of them can operate in sea water. Often, for improving low temperature impact test results Aluminium or Titanium are added as alloying elements in quantity of about 0.03-0.06%. Moreover, there are REE introduced to cast steels in quantity of about 0.05% [18].

Cast steels are also subject of a porosity problem. There are two types of porosity can occur in cast steels:

- due to gases – smooth bubbles
- due to shrinkage – rough voids

To prevent porosity from gases atmosphere should be controlled by creating vacuum or using gases with less solubility. It is important to provide proper venting to let gases out of a cast. Moreover, appropriate design of runners and gates should be implemented to avoid turbulence. Sometimes, to reduce porosity metallic elements can be added to react with gases. This will result in killed steels (highly deoxidized (Al, Si)).

Shrinkage porosity can be prevented or reduced by using piping, that will help to remove the inside gas. Moreover, it is important to design flow as so no part freezes early. To reach that large channels and flexible molds should be used. Also, controlling heating or cooling in certain areas can be done in order to maintain uniform cooling [38].

Cast steels are designated in the same way as alloy steels, there is only letter Л added at the end of a designation.

4.4.1 Steel 20Л

It is a low carbon alloyed-free cold resistance cast steel, with low corrosion resistance. This kind of steel used for manufacturing parts of pipelines and welded constructions with large amount of welds. This steel can work under pressure at temperature range of -40°C - +450°C. Chemical composition is provided in Table 50.

Table 50 Chemical composition of steel 20Л, % [XXVII]

C	Si	Mn	S	P
0.17-0.25	0.20-0.52	0.45-0.90	≤0.045	≤0.040

Mechanical properties of the steel are listed in Table 51.

Table 51 Mechanical properties of steel 20Л [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -20°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (880-900°C, air) and tempering (630-650°C, air)	≤100	412	216	49	-	-
Normalized (870-890°C, air) and tempering (630-650°C, air)	30	-	-	55-83	41-64	6-12

Steel 20Л is supplied as:

- Castings [XXVII]

4.4.2 Steel 20ГЛ

It is a structural low alloyed cold resistance weldable steel. Corrosion resistance of this grade of steel is low. This steel can be used for manufacturing of gear rims and other parts, which demands high strength and ductility, and are subject of static and dynamic loads. Chemical composition is given in Table 52.

Table 52 Chemical composition of steel 20ГЛ, % [XXVIII]

C	Si	Mn	S	P	Cr	Ni	Cu
0.17-0.25	0.30-0.50	1.10-1.40	≤0.030	≤0.030	≤0.030	≤0.030	≤0.030

Mechanical properties of the steel are listed in Table 53.

Table 53 Mechanical properties of steel 20ГЛ [18]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, -60°C, J/cm^2
Normalized (920-940°C, air)	300	500	≥29
Quenching (820-940°C, water) and tempering (600-620°C, air)	400	550	≥29

The steel is supplied as:

- Castings [XXVIII]

4.4.3 Steel 30ГЛ

Steel 30ГЛ is a structural low alloyed cold resistance steel. The steel weldability is limited, as preheat and subsequent heat treatments are recommended. This steel can be used for manufacturing of gear rims and other parts which demand high strength and ductility and are subject of static and dynamic loads. Also, this steel is particularly suitable for excavator buckets. Chemical composition is listed in Table 54.

Table 54 Chemical composition of steel 30ГЛ, % [XXVIII]

C	Si	Mn	S	P
0.30-0.40	0.20-0.40	1.20-1.60	≤0.040	≤0.040

Mechanical properties of the steel are listed in Table 55.

Table 55 Mechanical properties of steel 30ГЛ [18]

Heat treatment type	Thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (880-900°C, air) and tempered (600-650°C, air)	≤100	294	540	≥29 (80)	16
Quenching (850-860°C, water) and tempering (600-650°C, air)	≤100	343	589	≥49	-

Steel 30ГЛ is supplied as:

- Castings [XXVII]

4.4.4 Steel 30ХЛ

It is a structural low alloyed cold resistance steel. The steel weldability is limited, as preheat and subsequent heat treatments are recommended. Steel 30ХЛ is normally used for critical parts, with wall thickness no more than 50 mm and overall weight less than 80 kg. Chemical composition is listed in Table 56.

Table 56 Chemical composition of steel 30ХЛ, % [XXVII]

C	Si	Mn	Cr	S	P
0.25-0.35	0.20-0.40	0.40-0.90	0.50-0.80	≤0.050	≤0.050

Mechanical properties of the steel are listed in Table 57.

Table 57 Mechanical properties of steel 30ХЛ [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (900°C, 2-2.5 h)	20	-	-	≥51	≥13	≥8
Quenching (890-910°C, oil) and tempering (620-660°C, air)	≤100	638	441	≥49	-	-
Quenching (water) and tempered (650°C, water)	20	-	-	80	67	58

The steel is supplied as:

- Castings [XXVII]

4.4.5 Steel 08Г2ДНФЛ

It is a low alloyed cold resistance weldable steel. Corrosion resistance of this grade of steel is rather poor. The steel can be used down to -60°C. Most common applications for this grade of steel are large parts for shipbuilding with wall thickness up to 800 mm and overall weight less than 90 000 kg. Also the steel can be used for heavy loaded welded constructions. In case of large amount of welding, subsequent tempering is recommended. Chemical composition is given in Table 58. REE content should be in a range of 0.02-0.05%.

Table 58 Chemical composition of steel 08Г2ДНФЛ, % [XXVIII]

C	Si	Mn	Cu	Ni	V	S	P
0.05-0.10	0.15-0.40	1.30-1.70	0.80-1.10	1.15-1.55	0.02-0.08	≤0.20	≤0.020

Mechanical properties of the steel are listed in Table 59.

Table 59 Mechanical properties of steel 08Г2ДНФЛ [XXVIII]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (930-970°C, air)	≥800	500	400	-	-	≥40
Normalized (920-930°C) and tempering (580-600°C)	-	-	-	71-176	68-169	43-51

Steel 08Г2ДНФЛ can be ordered as:

- Castings [XXVIII]

4.4.6 Steel 12ХГФЛ

It is a structural low alloyed cold resistance weldable steel. This grade of steel has low corrosion resistance. Chemical composition is provided in Table 60.

Table 60 Chemical composition of steel 12ХГФЛ, % [XXVIII]

C	Si	Cr	Mn	V	S	P	Ni	Cu
0.10-0.16	0.20-0.50	0.20-0.60	0.90-1.30	0.05-0.10	≤0.020	≤0.020	≤0.30	≤0.30

Mechanical properties of the steel after normalization (930-950°C) are listed in Table 61.

Table 61 Mechanical properties of steel 12ХГФЛ [33]

Tensile strength, MPa	Yield strength, MPa	KCU, -60°C, J/cm^2
340	470	≥30

The steel is supplied as:

- Castings [XXVIII]

4.4.7 Steel 14Х2ГМРЛ

It is an engineering low alloyed cold resistance steel. This grade of steel has limited corrosion resistance and rather poor weldability. The steel is used for heavy loaded welded parts with large cross-section area, such as excavator parts operated at the Far North. In case of large amount of welding subsequent tempering is recommended.

Chemical composition is given in Table 62.

Table 62 Chemical composition of steel 14Х2ГМРЛ, % [XXVIII]

C	Si	Mn	S	P	Cr	Ni	Mo	B	Cu
0.10-0.17	0.20-0.42	0.90-1.20	≤0.020	≤0.020	1.40-1.70	≤0.30	0.45-0.55	≤0.004	≤0.30

Mechanical properties of the steel are listed in Table 63.

Table 63 Mechanical properties of steel 14Х2ГМРЛ [18]

Heat treatment type	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Quenched (920-930°C, water or oil), tempering (630-650°C, air)	-	700	600			≥40
Normalized (940-950°C, air), quenching (940-950°C, air), tempering (610-640°C, air)	≤100	690	590	-	-	≥49
Normalized (930°C), quenching (930°C, water) and tempering (640°C)	30-60	-	-	134	93	61
	100			127	43	33
	140			121	61	53

The steel can be supplied as:

- Castings [XXVIII]

4.4.8 Steel 20ФЛ

This weldable cold resistance steel is microalloyed with Vanadium. Corrosion resistance of this grade is low. Mainly this steel is used for railroad coaches and in mining machines. Welding of steel 20ФЛ can be performed without limitations, but it is recommended to implement preheat and subsequent heat treatment. Chemical composition is listed in Table 64.

Table 64 Chemical composition of steel 20ФЛ, % [XXVII]

C	Si	Mn	S	P	Cr	Ni	V	Cu
0.14-0.25	0.20-0.52	0.70-1.20	≤0.050	≤0.050	≤0.30	≤0.30	0.06-0.12	≤0.30

Mechanical properties of the steel are listed in Table 65.

Table 65 Mechanical properties of steel 20ФЛ [XXVII]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (920-960°C, air), tempering (600-650°C)	491	294	≥49	-
Normalized (1170°C, air), normalized (940°C), tempering (650°C)	690	590	-	≥25

The steel is supplied as:

- Castings [XXVII, XXIX]

4.4.9 Steel 20ХМЛ

It is a structural cold resistance steel with limited weldability. Corrosion resistance of this grade is low. In case of welding it is recommended to implement preheat and subsequent heat treatment. Steel is aimed for production of gears, cylinders and other parts working at temperature range of -40°C - +540°C. Chemical composition is given in Table 66.

Table 66 Chemical composition of steel 20ХМЛ, % [XXVII]

C	Si	Mn	Cr	Mo	S	P
0.15-0.25	0.20-0.42	0.40-0.90	0.40-0.70	0.40-0.60	≤0.040	≤0.030

Mechanical properties of the steel are listed in Table 67.

Table 67 Mechanical properties of steel 20ХМЛ [33]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2
Normalized (880-890°C, air), tempering (600-650°C, air)	441	245	≥29

The steel is supplied as:

- Castings [XXVII]

4.4.10 Steel 25Х2НМЛ

It is a structural cold resistant steel with limited weldability. Corrosion resistance of this grade is low. It is aimed for critical welded and casted parts of machinery. The steel is capable of operating at temperature as low as -70°C. Chemical composition is listed in Table 68.

Table 68 Chemical composition of steel 25X2НМЛ, % [XXVIII]

C	Si	Mn	Cr	Ni	Mo	S	P	Cu
0.22-0.30	0.20-0.40	0.50-0.80	1.60-1.90	0.60-0.90	0.20-0.30	≤0.020	≤0.020	≤0.30

Mechanical properties of the steel are listed in Table 69.

Table 69 Mechanical properties of steel 25X2НМЛ for castings which diameter less than 100 mm [18]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, -60°C, J/cm^2
Quenched (880-890°C, water), tempering (600-650°C, air)	800	700	≥30

The steel is supplied as:

- Castings [XXVIII]

4.4.11 Steel 35ХМЛ

It is a structural cold resistant high-strength steel with limited weldability. This grade of steel has low corrosion resistance. This steel is able to operate under heavy loads. It is aimed for critical welded and casted parts of machinery, such as mining equipment. Operation temperature for this grade is as low as -60°C after welding. Welding should be done with preheat and subsequent heat treatment. Chemical composition is listed in Table 70.

Table 70 Chemical composition of steel 35ХМЛ, % [XXVIII]

C	Si	Mn	Cr	Mo	S	P	Ni	Cu
0.30-0.40	0.20-0.40	0.40-0.90	0.90-1.10	0.20-0.30	≤0.020	≤0.020	≤0.30	≤0.30

Mechanical properties of the steel are listed in Table 71.

Table 71 Mechanical properties of steel 35ХМЛ for castings which diameter less than 30 mm [33]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -40°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (870-890°C, air), tempering (600-630°C, air)	589	392	≥29	24-38	9-30

Steel can be supplied as:

- Castings [XXVII, XXVIII]

4.4.12 Steel 20Н3ДМЛ

Steel 20Н3ДМЛ is a structural cold resistant high-strength steel with limited weldability. This steel is corrosion resistant against air. Steel 20Н3ДМЛ is able to operate under heavy loads. It is aimed for critical welded and casted parts of machinery, such as gas industry equipment and shipbuilding. Operation temperature can be as low as -50°C. Welding should be done with preheat and subsequent heat treatment. Chemical composition is listed in Table 72.

Table 72 Chemical composition of steel 20H3ДМЛ, % [XXX]

C	Si	Mn	Ni	Cu	Mo	S	P	Cr
0.17-0.22	0.17-0.37	0.40-0.70	2.50-4.00	0.60-1.25	0.25-0.65	≤0.025	≤0.025	≤0.40

Mechanical properties of the steel are listed in Table 73.

Table 73 Mechanical properties of steel 20H3ДМЛ for castings which diameter less than 30 mm [XXX]

Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -60°C, J/cm^2
Normalized (900°C, air), tempering (600°C, air)	590	491	≥49	39
Quenched (900°C, water) and tempered (600°C, air)	687	589	≥88	59

The steel is supplied as:

- Castings [XXX]

4.5 Stainless steels

Stainless steels contain more than 11% of Chromium. Steels are extremely good in corrosion resistance, as an oxide film covers all surface of a steel part. Stainless steels are classified by predominant crystal phase as austenitic, ferritic, martensitic and duplex.

Austenitic steels have austenite as their primary phase. These steels have a face centered cubic crystal structure. These steels are containing Chromium and Nickel (sometimes also Manganese and Nitrogen). Austenitic steels are not hardenable by heat treatment. Austenitic steels are the best for cryogenic equipment, as they remain ductile at temperatures close to the absolute zero. These steels are sometimes used for Arctic environments, but usually they can be replaced by cheaper materials. Therefore, the main applications are cryogenic equipment. Steels of that class are quite good weldable. One particular example of these steels is steel 08Х18Н10. That steel has about 18% of Chromium and 11% of Nickel and less than 0.08% of Carbon.

Martensitic steels are low carbon steels with about 10% Chromium and 0.12% Carbon. Martensite gives steel great hardness, but it also reduces its toughness and makes it brittle, so few steels are fully hardened. These steels can be tempered and hardened. An example of martensitic steel used in Russia is 03Х9К14Н6М3Д. That steels contains 9% Chromium, 14% Cobalt and 6% of Nickel, as well as 0.03% of Carbon. That steel can operate at temperatures as low as -196°C as heavy loaded parts of cryogenic equipment.

There are also steels of austenitic-martensitic class, such as steel 07Х16Н6. That steel has about 16% of Chrome, 6% of Nickel and about 0.07% of Carbon. This steel is used for cryogenic equipment operated at as low temperature as -253°C.

High cost of Nickel boosted the development of steels with low nickel content and substitution it with Manganese, as it is done in steel 10Х14Г14Н4Т. That grade has about 14% of Chromium, 3.5% of Nickel, 14% of Manganese and less than 0.1% of Carbon. That steel can be used for cryogenics for temperatures as low as -203°C, and it has about 15% of ferrite.

Duplex stainless steels are termed that way because they have a two-phase microstructure consisting of grains of ferritic and austenitic stainless steel. They can provide a wide range of corrosion resistance to fit a lot of applications. These steels are usually used for machinery operated to as low as -80°C. It can be weldable with limitations for thick plates. This kind of steels is not widely in use in Russian offshore industry.

4.5.1 Steel 20X13, 30X13 and 40X13

Steels of that group are martensitic. Steel 20X13 has a good corrosion resistance (but not against sea water), usually used for applications which demand high plasticity and experience impact loads. Steel is suitable for production of fastenings and other parts used in atmospheric and humid environments. Recommended temperature range is -50°C to +480°C. Weldability is rather limited. Before welding steel should be annealed, during the welding steel should be heated up to 350-600°C (depends on the complexity of the weld). After welding it is necessary to do tempering.

30X13 and 40X13 steels are aimed for parts demanding high strength, mainly fastenings, operated at the range of temperatures -30°C - +480°C. Weldability is rather poor, so these grades are not used for welded structures. Chemical compositions of steel grades are given in Table 74.

Table 74 Chemical composition of steels 20X13, 30X13 and 40X13, % [XXXI]

Steel grade	C	Cr	Mn	Si	S	P
20X13	0.16-0.25	12.0-14.0	≤0.8	≤0.8	≤0.025	≤0.030
30X13	0.26-0.35					
40X13	0.36-0.45					

Mechanical properties of steels are listed in Table 75.

Table 75 Mechanical properties of steels 20X13 and 30X13 [XXXI]

Steel grade	Heat treatment type	Tensile strength, MPa	Yield strength, MPa	KCU, +20°C, J/cm^2	KCU, -50°C, J/cm^2	KCU, (-60°C for 20X13; -78°C for 30X13), J/cm^2
20X13	Normalized at 1000°C, and then tempered at 680-750°C	710-820	540-590	78	50	42
30X13	Normalized at 1050°C (water), and then tempered at 550°C	990-1100	840-950	50	40	20

Supplied as:

- Hot rolled sheets [III]
- Cold rolled sheets [VI]

4.5.2 Steel 12X18H10T

This steel is part of the most wide spread group of corrosion resistant austenitic stainless steels, which is known in the world practice as 18-10 (18% of Cr and 10% of Ni). This grade of steel is used for welded constructions, which are operating at low corrosive environments, such as air. The steel can be used also for cryogenic equipment. The steel has a good weldability [39]. Chemical composition is listed in Table 76.

Table 76 Chemical composition of steel 12X18H10T, % [XXXI]

C	Si	Mn	Cr	Ni	S	P
≤0.12*	≤0.8	≤2.0	17.0-19.0	9.0-11.0	≤0.020	≤0.035

*amount of Carbon can be reduced by special requirements

Mechanical properties of steel 12X18H10T are listed in Table 77. Specimen is a bar of diameter 18-25 mm after quenching at 1050°C in water.

Table 77 Mechanical properties of steel 12X18H10T [18]

Temperature, °C	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2
20	620	280	250
-70	1130	360	-

4.6 Aluminium and aluminium alloys

Aluminium alloys are used for wide range of applications, such as construction, aerospace, shipbuilding, rail road, oil and gas, chemical and other industries. Amount of aluminium supplied for low temperature applications is the highest after steels.

Aluminium has certain advantages regarding use in offshore structures. As face centered metal, aluminium does not have certain transition temperature, therefore, does not demonstrate brittle fracture behavior even at the cryogenic temperatures. Aluminium has relatively good corrosion resistance in comparison to structural steel, and usually works fine in air, and some grades are greatly suitable for use in sea water. That fact, along with its small weight makes aluminium a perfect choice for ship hulls and offshore structures. There are also some disadvantages of aluminium. Aluminium has low strength and it is relatively expensive. The coefficient of thermal expansion is rather high. Moreover, weldability of aluminium is not always as good as steels. Tensile strength of alloyed aluminium might exceed 500 MPa [18] with density of just 2.85 g/cm^3. There are different aluminium alloys used for low temperature applications. Most of aluminium alloys used in Russia are listed in Table 79.

Table 78 Classification and designations of Russian aluminium alloys with corresponding ISO number [40, 41], [XXXII]

Alloy characteristics	Designation		Alloying elements
	Russian	European	
Low strength alloys with high plasticity, weldable and with good corrosion resistance	АД0	1050A	Pure Aluminium
	АД1	1230	
	АД, А5, А6, А7	-	
	АМц	3003	Al–Mn
	Д12	3004	
	ММ	3005	
Alloys with moderate strength and high plasticity, weldable and with good corrosion resistance	АМг2	5251	Al–Mg
	АМг3	5754	
	АМг5	5056	
	АМг6	-	
Alloys of moderate strength and high plasticity, weldable	АД31	6063	Al-Mg-Si
	АД33	6061	
	АД35	6082	
	АВ	6151	
Alloys of normal strength	Д1	2017	Al-Cu-Mg
	Д16	2024	
	Д18	2117	
	В65, Д19, ВАД1	-	
Weldable alloys of normal strength	1915	7005	Al-Zn-Mg
	1925	-	
High-strength alloys	В95, В93	-	Al-Zn-Mg-Cu
Heat resistant alloys	АК4-1,	-	Al-Cu-Mg-

	АК4		Ni-Fe
	1201	2219	Al-Cu-Mn
	Д20	-	
Forged alloys	АК6	-	Al-Cu-Mg-Si
	АК8	2014	

The most used aluminium alloys for cryogenic and low temperature applications include Magnesium as the main alloying agent. That composition shows good combination of strength, plasticity, weldability and corrosion resistance. Increase of magnesium content leads to improved strength, but, practically, alloys usually do not include more than 7% of Magnesium. Aluminium and magnesium alloy AMr5 (Al + 5% of Mg) is the most used one. The reason for that is it has better weldability comparing to AMr2 (Al + 2% of Mg), and at the same time it has almost the same strength as AMr6 (Al + 6% of Mg).

Heat-treatable aluminium alloys are used as well. These alloys are usually includes Copper, Magnesium, Manganese, Silicon, Zink and other. Tensile strength of these alloys after heat treatment can be up to 400 MPa, and yield strength is up to 500 MPa. However these alloys have a tendency to corrosion under pressure.

There are also cast alloys, but these have low tensile strength of about 140 MPa and mainly used for parts with complicated shapes. Alloying with Titanium, Beryllium and Magnesium can raise tensile strength up to 390 MPa.

Following subchapters will discuss the most used Aluminium alloys in Russia for moderately cold temperatures (down to -70°C). Aluminium alloys used only in cryogenic applications are not discussed, as they are not suitable for offshore platforms.

4.6.1 Al-Mg alloys

Al-Mg alloys have good formability and can be heat-threatened. These have reasonable corrosion resistance along with good weldability. Chemical composition are listed in Table 79.

Table 79 Chemical composition of Al-Mg alloys, % [XXXII]

<table>
<tr><th>Alloy name</th><th>Cu</th><th>Mg</th><th>Mn</th><th>Zn</th><th>Fe</th><th>Si</th><th>Ti</th><th>Cr</th><th>Be</th></tr>
<tr><td>AMr2</td><td rowspan="6">≤0.1</td><td>1.8-2.6</td><td>0.2-0.6</td><td>≤0.1</td><td>≤0.4</td><td>≤0.4</td><td rowspan="2">≤0.1</td><td rowspan="2">≤0.05</td><td rowspan="2">-</td></tr>
<tr><td>AMr3</td><td>3.2-3.8</td><td>0.3-0.6</td><td rowspan="5">≤0.2</td><td>≤0.5</td><td>≤0.5</td></tr>
<tr><td>AMr4</td><td>3.8-4.5</td><td>0.5-0.8</td><td>≤0.4</td><td>≤0.4</td><td rowspan="3">0.02-0.10</td><td rowspan="3">0.05-0.25</td><td rowspan="3">0.0002-0.005</td></tr>
<tr><td>AMr5</td><td>4.8-5.8</td><td>0.3-0.8</td><td>≤0.5</td><td>≤0.5</td></tr>
<tr><td>AMr6</td><td>5.8-6.8</td><td>0.5-0.8</td><td rowspan="2">≤0.4</td><td rowspan="2">≤0.4</td></tr>
<tr><td>AMr61</td><td>5.5-6.5</td><td>0.7-1.1</td><td>-</td><td>0.02-0.12 Zn</td><td>0.0001-0.003</td></tr>
</table>

AMr2 and AMr3 are used for lightly loaded welded structures which are working in the corrosive environment at temperature range of -250°C - +150°C. Alloys AMr4, AMr5 and AMr6 have better tensile strength, as magnesium content is higher. These also can be used for welded structures and pipelines. Alloy AMr61 is widely used in shipbuilding industry.

Mechanical properties for 2 mm sheet after heat treatment are listed in Table 80.

Table 80 Mechanical properties of Al-Mg alloys [18]

Alloy name	Tensile strength, MPa		Yield strength, MPa		δ, %		KCU, +20°C, J/cm^2
	+20°C	-70°C	+20°C	-70°C	+20°C	-70°C	
AMг2	190	200	100	-	23	-	40
AMг3	230	230	120	95	23	29	40
AMг5	300	310	150	160	20	24	30
AMг6	340	350	170	-	19	26	30

The alloy is supplied almost in any shape, plate thickness up to 200 mm.

4.6.2 Al-Mg-Si alloys

Al-Mg-Si alloys are heat-treatable alloys with set of useful properties as good corrosion resistance, high plasticity, and also these alloys can be easily enameled and colored. These alloys are similar to 6000 series and called aluminium extrusion alloys. Chemical compositions are provided in Table 81.

Table 81 Chemical composition of Al-Mg-Si alloys, % [18]

Alloy name	Cu	Mg	Mn	Si	Zn	Fe	Ti
АД33	0.14-0.15	0.8-1.2	0.4-0.8	-	≤0.25	≤0.7	≤0.15
АД35	-	0.8-1.4	0.5-0.9	0.8-1.2	≤0.2	≤0.5	
AB	0.1-0.5	0.45-0.9	0.15-0.35	0.5-1.2			

АД33 alloy is used for parts with normal tensile strength, up to 270 MPa. This alloy has good corrosion resistance against air and sea water, which allows it to be used in shipbuilding. Alloy АД35 has similar properties and applications. AB alloy has better tensile strength, up to 300 MPa and mainly used for aerospace industry. Alloys have reasonable weldability. There is a hot cracking problem with aluminium alloys. This problem can be reduced by using the following procedures: [42]

- Use appropriate filler alloy
- Prepare edges correctly
- Use high welding speed
- Design a structure to reduce residual stress

Mechanical properties are listed in Table 82.

Table 82 Mechanical properties of Al-Mg-Si alloys [18]

Alloy name	Plate thickness, mm	Tensile strength, MPa		Yield strength, MPa		δ, %	
		+20°C	-70°C	+20°C	-70°C	+20°C	-70°C
АД33	2	300	330	250	270	15	16
АД35		300	310	250	250	12	10
АВ	20	250	-	160	-	23	-

Alloys are supplied as:

- Sheets [XXXIII, XXXIV]
- Plates [XXXV]

4.7 Nanotechnology materials

Materials with a grain size less than 100 nm are termed to be nanomaterials. The development of technology was so rapid, that a forecast made in 1988 predicted mainstream use of nanotechnology was not earlier than in 30 years; however already after 4 years these materials were industrial-scale produced. In 2005 the amount of nanomaterials market was about 100 billion dollars, and by 2015 it is forecasted to increase by ten times [18].

There are several ways to produce nanomaterials. Methods of production are chemical, physical and mechanical. Chemical method is based on various chemical reactions, such as precipitation reaction, thermal decomposition reaction and others. This approach allows to produce particles of about 10-30 nm. Physical methods based on evaporation of metal with subsequent condensation. This process is often carried out in vacuum or inert gas. Size of particles can vary a lot depending on the process parameters. Mechanical method of producing nanomaterials is performed using the grinding mill. Fig. 11 shows typical grinding mill equipment for producing nanopowder. The end size of particles depend on material type, as for Tungsten or molybdenum it is possible to obtain particles of 5 nm, but for ferrite steels only sizes of 10-20 nm are achievable [18].

Fig. 11 A typical grinding mill for nanomaterials production [43]

Nanomaterials can be employed in various applications, such as electric components, smart coatings, materials for medical needs, military applications, armor and other [44].

As this study is about metals for offshore structures, nanomaterials which concern structural needs will be discussed.

One of the central problems with metals is the inverse relationship of strength and toughness. In the other words, with an increase in strength, toughness drops. So far, the only method which can contribute to both characteristics simultaneously is grain refinement. Commonly, the yield strength of metals respects Hall-Petch equation: [45]

$$\sigma_y = \sigma_i + k_y d^{-1/2}, \quad (1)$$

where σ_y is the yield strength, σ_i is the internal friction, d is the grain size and k_y is the Hall-Petch slope representing the resistance against the slip propagation across a grain boundary [46].

Also, there are studies which show exactly the same relation for the temperature of the ductile-brittle translation [47]. Knowing equation (1), it is clear that reducing the grain size will lead to the desired combination of strength and plasticity. Fig. 12 illustrates this.

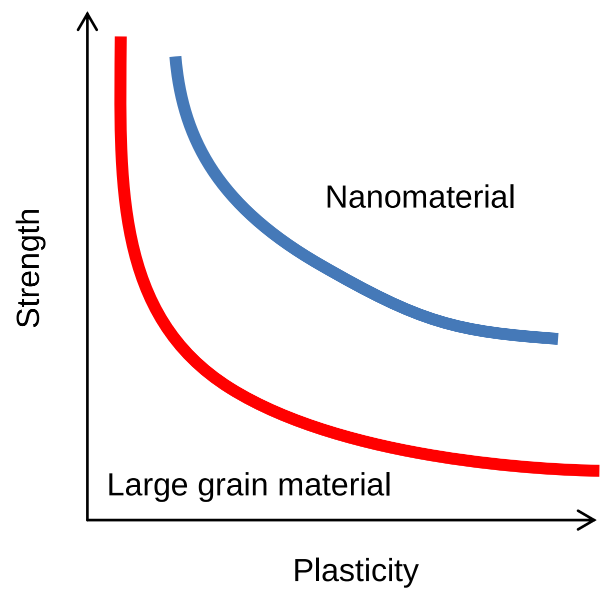

Fig. 12 Nanomaterials properties [18]

For instance, an experiment conducted with copper confirms Fig. 12. It has been shown that plasticity and strength of nanostructured copper is 4 times exceeds the same characteristic of large grain size copper [18].

Table 83 presents a comparison of three methods with and without grain refinement. The table shows clear increase in yield strength of nanostructural materials compared to materials with conventional grain size.

Table 83 Properties of nanomaterials compared to conventional materials [18]

Material	Grain size, µm	Yield strength, MPa	δ, %
BT6 (chemical composition, %: Al: 5.3-6.8; V: 3.5-5.3; Zr: ≤0.3; S: ≤0.1; Fe: ≤0.6; O: ≤0.2; H: ≤0.015; N: ≤0.05; C: ≤0.1)	10	1050	9
	0.4	1300	7
Alloy Al-Mg-Li-Sc-Zr	10	450	5
	0.2	600	6
Steel (chemical composition, %: C: 0.12; Cr: 25; TiO: 0.2)	50	485	26
	0.2	730	17

One more example is steel 12X18H10T, which grain sizes were mechanically reduced to 100 µm has the yield strength of 1340 MPa at room temperature, which is 6 times larger than the same steel has after normal heat treatment. Also, plasticity remains relatively high – 27%. For nanostructured aluminium it is possible to rich ultimate strength up to 800 MPa, which is more than typical steel has [23].

Nanostructural carbon steels can have higher corrosion resistance than special stainless steels. Mainly adding Molybdenum in quantity of 5-10% can significantly increase corrosion resistance of nanomodified carbon steels [18].

Moreover, nanotechnology is used as coatings. For instance, Prometey developed and produced corrosion resistant anode plates of type AKL-2MU for Prirazlomnaya offshore platform. These plates are made of Platinum and Niobium, in particular Platinum coating of particles about 5 nm was applied. These plates can significantly reduce corrosion in sea water by about 3-4 times comparing with conventional methods. These plates are shown in Fig. 13, where they are already installed on the platform. Fig. 13 shows platform during manufacturing, as at an operation mode these plates are hidden underwater [48].

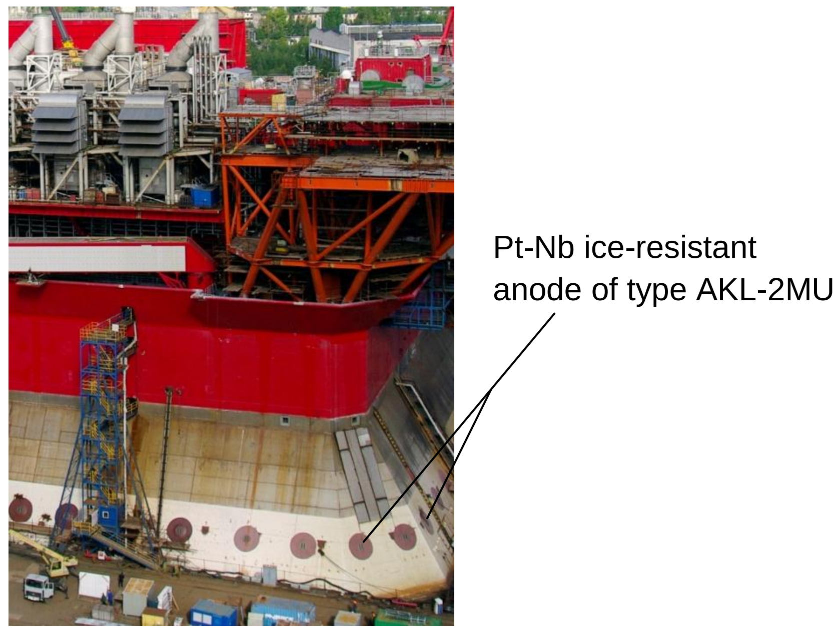

Fig. 13 Corrosion resistant anode plates of type AKL-2MU installed on Prirazlomaya offshore platform [49]

Promising direction of nanomaterials is mixing its particles with liquid metal, as well as adding nanopowder to metal powder during backing manufacturing process. For instance, while manufacturing Nickel-Molybdenum steel (ПХ17Н2) Nickel carbide substitution by nanopowder of Nickel carbide improved strength by 1.5 times and plasticity by 4 times. Another example is steel Х17Н2. Adding nanopowder of 0.5% Nickel, (0.5-1) % Copper and 0.3% Carbon resulted in impact values 1.5 times larger than without modifications.

Nanostructural steel of yield strength of 355-690 MPa was produced for offshore platforms Prirazlomnaya and Arcticheskaya by Severstal and Prometey.

4.8 Shipbuilding steels

Standard [XXXVI] describes shipbuilding steels products norms. Steels for various applications are covered in the standard, also including Arctic off-shore platforms. Standard was developed together with Russian Maritime Register of Shipping (RMRS).

There are ten groups of steels classified in the standard, as it is shown in Table 84. Three groups of steels are specially designed for low temperatures: steels of normal, improved and high strength with increased resistance to lamellar tearing and improved weldability for low temperature environments. There also three groups of steels which can be applied to offshore platforms operated at moderately low temperatures, these are:

- Steel of improved strength
- Steels of improved strength with increased resistance to lamellar tearing
- High-strength steels with increased resistance to lamellar tearing

For each level there are four categories (A, B, D, E, F) set by the impact test value at different temperatures: where A means that steel impact value is not controlled, B means an impact value should be controlled at 0°C, D stays for controlled impact value at as low as -20°C, E specify impact value control at -40°C and F -60°C. A number, which is following after first letter of a steel designation specifies impact values KV in Joule for a plate of 10 mm thickness or thicker.

Table 84 Steel categories and grades defined by [XXXVI]

Steel category	Steel grades
Steels of normal strength	A, B, D, E
Steels of normal strength with increased resistance to lamellar tearing	BZ25, DZ25, EZ25, BZ35, DZ35, EZ35
Steels of normal strength with increased resistance to lamellar tearing and improved weldability	BW, DW, EW
Steels of normal strength with increased resistance to lamellar tearing and improved weldability for low temperature environments	FW
Steel of improved strength	A27S, A32, A36, A40, D27S, E27S, D32, E32, D36, E36, D40, E40, A40S, D40S, E40S
Steels of improved strength with increased resistance to lamellar tearing	A27SZ25, D27SZ25, E27SZ25, A27SZ35, D27SZ35, E27SZ35, A32Z25, D32Z25, E32Z25, A32Z35, D32Z35, E32Z35, A36Z25, D36Z25, E36Z25, A36Z25, D36Z25, E36Z25, A36Z35, D36Z35, E36Z35, A40Z25, D40Z25, E40Z25, A40Z35, D40Z35, E40Z35
Steels of improved strength with increased resistance to lamellar tearing and improved weldability	A27SW,D27SW, E27SW, A32W, D32W, E32W, A36W, D36W, E36W, A40W, D40W, E40W, A40SW, D40SW, E40SW

Steels of improved strength with increased resistance to lamellar tearing and improved weldability for low temperature environments	F32W, F36W, F36SW, F40W, F40SW
High-strength steels with increased resistance to lamellar tearing	D460W, E460W, D500W, E500W
High-strength steels with increased resistance to lamellar tearing and improved weldability for low temperature environments	F460W, F500W

S means that steel properties are not answering to RMRS criteria. Steels of normal and improved strength can also have an increased resistance to lamellar tearing, which is indicated by letter Z. Letter W shows that steel has an improved weldability. As this work is focusing on Arctic service steels, most important steels to evaluate are E and F graded steels.

This chapter will describe steel grades from mentioned groups in more details. Steels can be delivered as plates with length from 4500 to 12000 mm, wideness of 1000 up to 3200 and thickness starting from 5 (7.5 for F grades) and up to 70 (80 for 500W grades) mm.

Table 85 shows chemical composition of steels of various groups.

Table 85 Chemical composition of shipbuilding steels, % [XXXVI]

Steel grade	C	Mn	Si	Cr	Cu	Ni	Mo	Al	V	Nb	S	P
E	≤0.18	0.60-1.00	0.15-0.35	≤0.30	≤0.35	≤0.40	-	0.020-0.060	-	-	≤0.025	≤0.025
E27S		0.60-1.40							0.05-0.10	0.02-0.05		
E32		0.90-1.60	0.15-0.50									
E36, E40							≤0.08				≤0.015	≤0.020
E40S	≤0.12	0.50-0.80	0.80-1.10	0.60-0.90	0.40-0.60	0.50-0.80						
EZ25, EZ35	≤0.18	0.60-1.00	0.15-0.35	≤0.30	≤0.35	≤0.40	-		-	-	≤0.008	≤0.010
EW, FW	≤0.12										≤0.005	
E27SW		0.60-1.40	0.15-0.35	≤0.20			≤0.08		0.05-0.10	0.02-0.05		
E32W, E36W, E40W		0.90-1.60										
E40SW		0.50-	0.80-	0.60-	0.40-	0.50-						

		0.80	1.10	0.90	0.60	0.80						
F32W	0.07-0.12	0.60-0.90	0.15-0.35	≤0.30	≤0.35	≤0.40			0.02-0.05			
F36W, F40W	0.07-0.11	1.15-1.60	0.10-0.40	≤0.20	≤0.35	≤0.80			0.02-0.10			
F36SW, F40SW	0.08-0.11				≤0.25	0.65-1.05						
E460W, F460W					0.30-0.60				0.02-0.06			
E500W, F500W	0.08-0.12	0.45-0.75	0.20-0.40	1.05-1.30	0.35-0.65	1.85-2.15	0.10-0.18	0.010-0.050				

Mechanical properties of steels are provided in Table 86 (KCU is listed for 10 mm sheet thickness).

Table 86 Mechanical properties of shipbuilding steels [XXXVI]

Steel grade	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCV, -40°C, J/cm^2	KCV, -60°C, J/cm^2
E	≤50	400-520	235	≥27	
	50-70			≥34	
E27S	≤50	400-540	265	≥31	
	50-70			≥38	
E32	≤50	440-570	315	≥31	
	50-70			≥38	
E36	≤50	490-630	355	≥34	
	50-70			≥41	
E40	≤50	510-660	390	≥39	
	50-70			≥46	
E40S	5-50	530-690		≥36	
EZ25	≤50	400-520	235	≥27	
EZ35	50-70			≥34	
EW	≤70			≥40	
FW				-	≥40
E27SW		400-510	265	≥50	-
E32W		440-570	315	≥50	
E36W		490-630	355	≥50	
E40W		510-660	390	≥50	
E40SW	≤50	530-690		≥60	
F32W	≤70	440-570	315	-	≥50
F36W		490-630	355		≥50
F40W		510-660	390		≥50

F36SW		490-630	355		≥80
F40SW		510-660	390		≥80
E460W	-	570-720	460	≥80	-
F460W				-	≥80
E500W		610-770	500	≥80	-
F500W				-	≥80

According to [31] there are certain guidelines in material selection for various elements of an offshore platform. These guidelines are listed in Table 87.

Table 87 Material selection guidelines for offshore platforms [31]

Classification of the platform elements	Steel grade [XXXVI]	Calculated temperature for construction element				
		-20°C	-30°C	-40°C	-50°C	-60°C
		Thickness of steel plate (no more than), mm				
Secondary construction elements	B	20	10	-	-	-
	D	45	35	25	15	-
	E	50	50	45	35	25
	F	50	50	50	50	45
	AH	20	10	-	-	-
	DH	45	35	25	15	-
	EH	50	50	45	35	25
	FH	50	50	50	50	45
	AQ	10	-	-	-	-
	DQ	35	25	15	-	-
	EQ	50	45	35	25	15
	FQ	50	50	50	45	35
General construction elements	B	10	-	-	-	-
	D	30	20	10	-	-

	E	50	40	30	20	-
	F	50	50	40	30	25
	AH	10	-	-	-	-
	DH	30	20	10	-	-
	EH	50	40	30	20	15
	FH	50	50	50	40	30
	AQ	25	15	-	-	-
	EQ	45	35	25	15	-
	FQ	50	50	45	35	25
Elements with special requirements	D	10	-	-	-	-
	E	35	25	15	-	-
	F	50	45	35	25	15
	DH	10	-	-	-	-
	EH	35	25	15	-	-
	FH	50	50	40	30	20

H stays instead of numerical value for enhanced strength steels, and Q for high-strength steel grades.

Most of the discussed steels can be obtained from Russian factory Severstal, which is producing steel grades listed in Table 88.

Table 88 Severstal steels [50]

Steel grade	Standard	Plate thickness, mm	Wideness, mm	Length, mm
PC F40W, PC F36SCBZ25, PC F36SCB, PC F36SW, PC E40CB, PC E40W, PC E40, PC E36CBZ25, PC E36CB, PC E36W, PC E36, PC D40CB, PC D40W, PC D40	[XXXVI]	7-50	1400-2530	4000-12100
PC F40W, PC F40SW, PC F36W, PC F36SW		15-60	1500-4000	4500-16000
PC F40CB, PC F36CB, PC E32CBZ25, PC E32CB, PC E32Z35, PC E32Z25, PC E32W, PC E32, PC D32CBZ25, PC D32CB, PC D32Z35, PC D32Z25, PC D32W, PC D32, PC A32CBZ25, PC A32CB, PC A32Z35, PC A32Z25, PC A32W, PC A32	[XXXVII]	10-70	1500-3200	2000-17000

There was a joint project METAL (2003-2006) in Russia where Prometey and couple of local factories were involved. The aim of the project was to develop new grades of cold resistant steels for offshore structures and other marine or general applications. The project was resulted in several patents, but the most importantly in document [XXXVII]. That document provides recommendations and corrections to [XXXVI] which was reviewed before. In particular the new document has stricter requirements to amount of Sulphur and Phosphorus, as it can be seen in Fig. 14. Amount of Sulphur should be 7 times smaller and amount of Phosphorus should be decreased by 3.5 times [28].

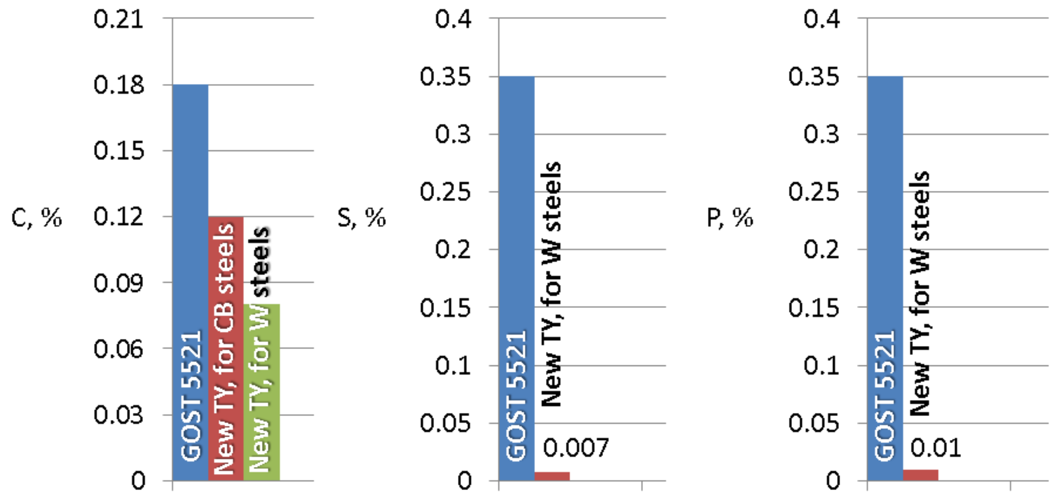

Fig. 14 Comparison [I] to newly developed [XXXVII], replotted from [28]

The new document imposes stricter requirements on Carbon Equivalent (CE) to improve weldability of steels. New grade of steel was introduced as well – it is CB grade which has improved weldability. Also, steels with higher strength were introduced, such as F690W. The stricter requirements are also demand ultrasonic control of long product quality. Table 89 below shows characteristics of steels which were developed during the project.

Table 89 Steel developed by Prometey [28]

Steel grade	Tensile strength, MPa	Yield strength, MPa	KCU, at corresponding T °C*, J/cm^2	CE
DCB, ECB, FCB	400-520	235	≤40	≤0.26
D32CB, E32CB, F32CB, D32W, E32W, F32W	440-590	315	≤50	≤0.34
D36CB, E36CB, F36CB, D36W, E36W, F36W	490-620	355	≤50	≤0.36
D40CB, E40CB, F40CB, D40W, E40W, F40W	510-650	390	≥50	≤0.38
D500CB, E500CB, F500CB, D500W, E500W, F500W	610-770	500	≥60	≤0.28
D690W, E690W, F690W	770-900	690	≥78	≤0.32

*KCU impact test had been done at -20°C for D steels, -40°C for E steels and -60°C for F steel grade.

These steels are recommended to use for icebreaker ships, ice-resistant offshore structures and other marine or general structures operated in the Arctic region. Fig. 15 shows how newly introduced steels compared to conventional shipbuilding steels in fulfilling crack tip opening displacement (CTOD) standard requirements at low temperatures.

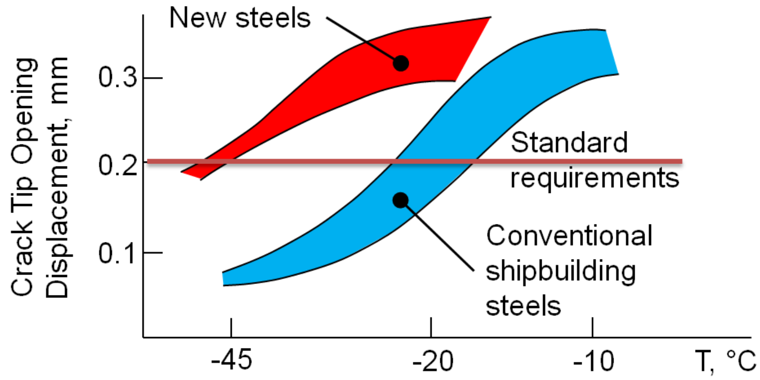

Fig. 15 Comparison of new steels to conventional shipbuilding steels, replotted from [28]

Certain kind of clad steels were also developed during the project. In particular the steel consisting of two layers – outer layer made from stainless steel (316L, 317L or 317LN), and inner layer made from cold resistant steel F36SZ. Advantages of that combination are that an outer level prevents corrosion, while an inner level reduces overall price and prevents brittle fracture to form at low temperatures. Such steel is usually used for ice-resistant girders of offshore platforms or icebreakers, as it is shown in Fig. 16.

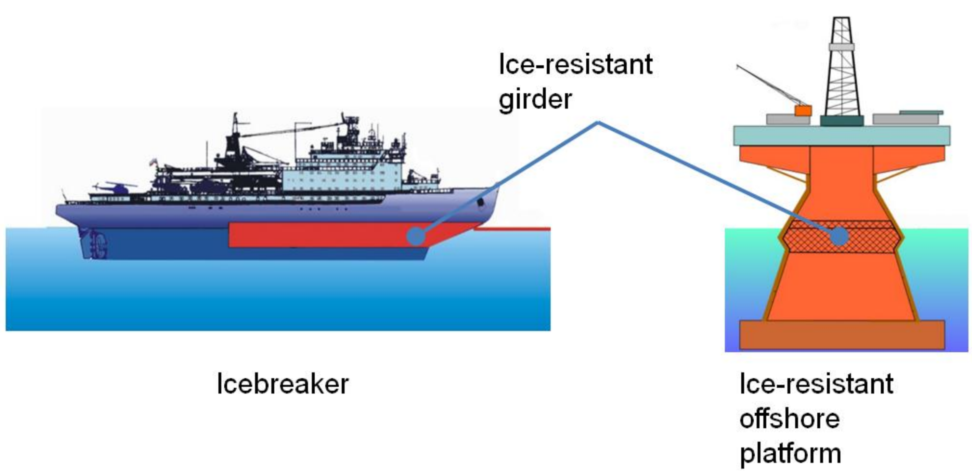

Fig. 16 Possible applications of cold and corrosion resistant clad steels, replotted from [28]

There is a clear improve in corrosion resistance properties of clad steels over conventional ones. It can be seen from Fig. 17 that even after 3 years of exploitation clad steels do not show visible signs of corrosion destruction, as conventional steels have corrosion penetration of about 1.5 mm.

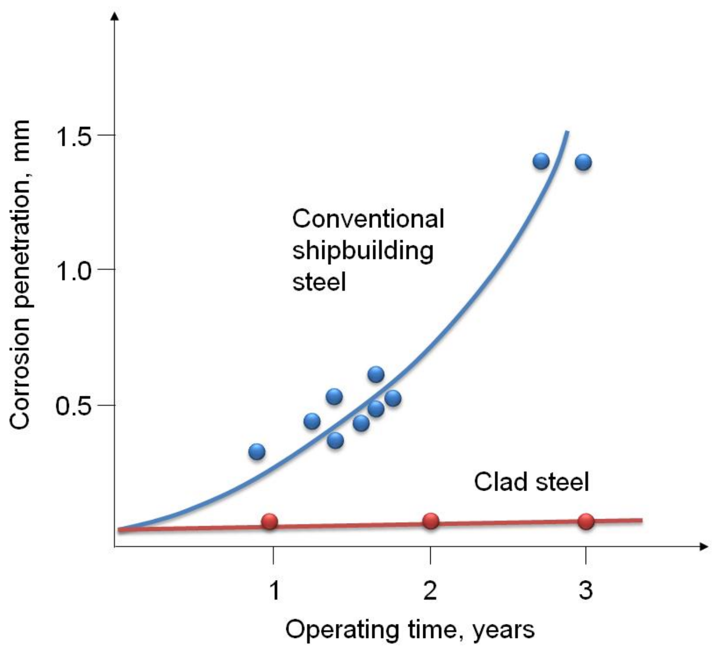

Fig. 17 Corrosion resistance of clad and conventional shipbuilding steels, replotted from [28]

Table 90 shows parameters of clad steels developed by Prometey.

Table 90 Clad steels developed by Prometey [28]

Steel grade	Tensile strength, MPa	Yield strength, MPa	KCU, corresponding T °C*, J/cm^2	Index of corrosion resistance, PRE**, %
F36SП	490-620	355	≥50	33-36.7
E500П	610-770	500	≥60	
F500П				

*Impact test had been done at -40°C for E steels and -60°C for F steel grade.

**PRE=Cr+3.3Mo+16N

Bending tests results show that a clad layer is strongly connected with an inner level during both kind of bending tests, as it is shown in Fig. 18.

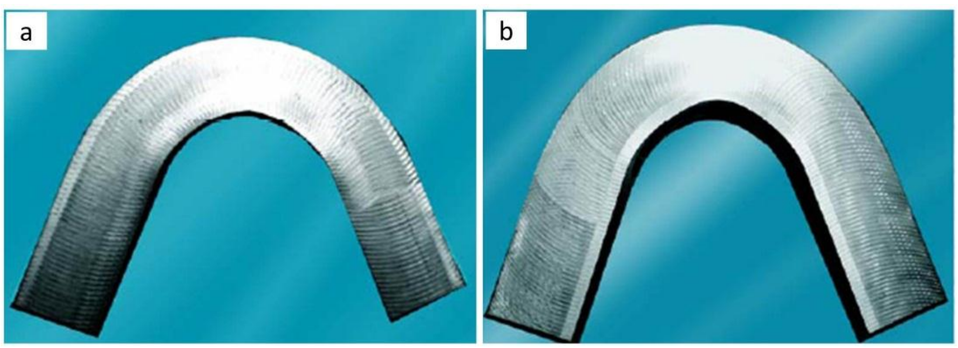

Fig. 18 Specimens after bending test. a - clad layer on outer side; b - clad layer on inner side; replotted from [28]

4.9 Structural construction steels

Structural construction steels are designated by letter C and by digits, which are showing minimum yield strength, according to [XXXVIII]. Some grades have also a letter at the end of the designation. There are some letters available – K stays for improved corrosion resistance, Д indicated higher copper content.

Structural construction steels are used for various constructions, such as buildings, pipelines, heavy machinery and bridges. Steels are divided by 7 groups, based on these yield strength. There are 225, 285, 325, 390, 440, 590 and 735 MPa. Structural construction steels which are used for low temperature environments are usually additionally alloyed with 6 or 9 % of Nickel [51].

Chemical composition of typical structural construction steels are listed in Table 91.

Table 91 Chemical composition of structural construction steels, % [XXXVIII]

Steel grade	C	Si	Mn	S	P	Cr	Ni	Cu	V	Other
C285	≤0.22	0.05-0.15	≤0.65	≤0.050	≤0.040	≤0.30	≤0.30	≤0.30	-	
C375	≤0.15	≤0.80	1.30-1.70	≤0.040	≤0.035	≤0.30	≤0.30	≤0.30	-	
C345K	≤0.12	0.17-0.37	0.30-0.60	≤0.040	0.070-0.120	0.5-0.8	0.30-0.60	0.30-0.50	-	Al 0.08-0.15
C390	≤0.18	≤0.60	1.20-1.60	≤0.040	≤0.035	≤0.40	≤0.30	≤0.30	0.07-0.12	N 0.015-0.025
C390K	≤0.18	≤0.17	1.20-1.60	≤0.040	≤0.035	≤0.30	≤0.30	0.20-0.40	0.08-0.15	N 0.015-0.025
C440	≤0.20	≤0.60	1.30-1.70	≤0.040	≤0.035	≤0.30	≤0.30	≤0.30	0.08-0.14	N 0.015-0.025
C590	≤0.15	0.40-0.70	1.30-1.70	≤0.035	≤0.035	≤0.30	≤0.30	≤0.30	0.07-0.15	Mo 0.15-0.25
C590K	≤0.14	0.20-0.50	0.90-1.40	≤0.035	≤0.035	0.20-0.50	1.40-1.75	≤0.30	0.05-0.10	Mo 0.15-0.25 N 0.02-0.03 Al 0.05-0.10

Steels that do not have % of Nitrogen specified must have less than 0.008% of Nitrogen, all the steel must contain less than 0.08% of Arsenic. Mechanical properties of structural construction steels are listed in Table 92.

Table 92 Mechanical properties of structural construction steels [XXXVII]

Steel grade	Plate thickness, mm	Tensile strength, MPa	Yield strength, MPa	KCU, J/cm^2		
				-20°C	-40°C	-70°C
C285	4-10	400	285	≥29	-	-
	11-20	390	275	≥29		
C375	4-10	510	375	-	≥39	34
	11-20	490	355		≥34	29
	21-40	480	335			-
C345K	4-10	470	345	-	≥39	-
C390	4-50	540	390	-	-	≥29
C390K	4-50	540	390	-	-	≥29
C440	4-30	590	440	-	-	≥29
	31-50	570	410	-	-	≥29
C590	10-36	685	590	-	≥34	-
C590K	10-40	685	590	-	-	≥29

*Steels C735 is not listed in the table, as it is not applicable for low temperature use.

5 COMBINED TABLE OF MAJOR MATERIALS

Table 93 shows combined table of most used materials reviewed in this thesis. It can be seen that work provides a comprehensive review of materials which can operate at low temperature environment. The table shows materials of all groups mentioned before in chapter 4. Table 93 provides only short explanation, as more detailed information can be obtained from chapter 4. Yield strength values are listed as average for different material conditions, such as quenched and tempered or normalized, as well as it is an average value for different materials thickness. Operation temperature is also stated as approximate, as for different parts and manufacturing processes it can be different. Weldability is stated as ++ for superb result, + for good weldability, +/- for relatively good weldability and – for poor or non-weldable materials.

Table 93 Combined table of major steels mentioned

Steel grade	Operating temperature, °C	Weldability	Applications	Yield strength, MPa	KCU, J/cm^2, (-40°C -70°C)
Ст3	-50	+	Constructions without significant loads	450	≥5
20	-30-40	++	Cases, vessels, pipes	400	n/a
45	-50	+/-	Pipes, nuts, bolts	400	n/a
09Г2С	-70	+	Steel structures	300	≥30
10Г2	-70	++	Sheet metal structures	420	150
16ГС	-70	+	Pipes, welded structures	480	≥25
14Г2АФ	-50	+/-	Vessels	530	n/a
18Г2Ф	-30-60	+/-	Steel structures	440	29
20Х	-50	+/-	Wearing applications, pipes	800	150
40ХН	-60	-	Heavy loaded structures, gears	800	≥40
30ХН2МФА	-70-196	+/-	Critical parts	950	160
38ХН3МФА	-70	-	Critical parts, rotors	850	≥60
10ХСНД	-70	++	Shipbuilding, ship hulls	600	≥35
12ХН3А	-60-125	+/-	Shafts, pipes	800	≥70
12Х2Н4А	-60	n/a	Large parts	930	91

20ХН3А	-40	-	Gears, fastenings	735	62
18Х2Н4МА	-73	-	Critical parts under heavy loads	700	n/a
15ХСНД	-40-70	+	Corrosion resistant shipbuilding parts	500	≥29
15ХМ	-40	+	Oil/gas pressure pipes	450	n/a
20ХГР	n/a	-	Gears, shafts	785	60
20Л	-40	++	Pipes	216	8
30ХЛ	n/a	+/-	Critical parts less than 80 kg	450	≥20
08Г2ДНФЛ	-60	+	Large shipbuilding parts	400	≥40
12ХГФЛ	n/a	+	n/a	470	≥30
14Х2ГМРЛ	n/a	+/-	Heavy loaded parts with large cross-section	600	≥50
20ФЛ	-50	+	Mining and railroads parts	400	≥25
25Х2НМЛ	-70	+	Welded and casted parts	700	≥30
35ХМЛ	-60	+/-	Heavy loaded parts, mining	392	15
20Н3ДМЛ	-50	+/-	Heavy loaded shipbuilding parts	530	45
20Х13	-50	-	Fastenings with corrosion re-sistance	550	42

30X13	-30	-	Fastenings with corrosion resistance	850	20
12X18H10T	-70-180	+	Welded constructions	300	n/a
АМг5	-180	+	Pipelines, shipbuilding	150	n/a
АД35	-180	+/-	Corrosion resistant shipbuilding parts	250	n/a
E40SW	-40	+	Shipbuilding	390	n/a
F500W	-60	+	Shipbuilding	500	≥80
C590	-40	+/-	Bridges, buildings	590	≥34

6 TESTING METHODS OF MATERIALS PROPERTIES

Under the effect of cold temperatures materials and welded constructions can rapidly fracture in an unstable manner due to welding defects and fatigue cracks occurring in the stress-concentrated areas of weldments under unexpectedly low loads. Brittle fractures can occur in short periods of time prior the end of the service life of a structure. Brittle fracture hence can cause serious damage of a welded construction, especially in the Arctic region.

There are several tests, which can be used to determine toughness of materials at low temperatures. Most common in Russian practice are Charpy U notch test, Crack Tip Opening Displacement (CTOD) or Crack Tip Opening Angle (CTOA) and Nil-Ductility Temperature (NDT) or Drop weight Test (DT) or Drop Weight Tear (DWTT). All tests show the amount of energy requited to crash the specimen at a specific temperature.

6.1 Charpy U-notch test

The test involves striking a standard sized specimen with a pendulum of a certain weight and speed. After the collision the amount of energy absorbed by the specimen is recorded. This shows the notch toughness of the material tested.

Charpy U-notch test illustrates amount of energy required to fail the standard sized material specimen at different range of temperatures. Results are plotted on two axes - temperature and amount of energy at the failure point of the specimen. The schematic view of test procedure is shown below in Fig. 19.

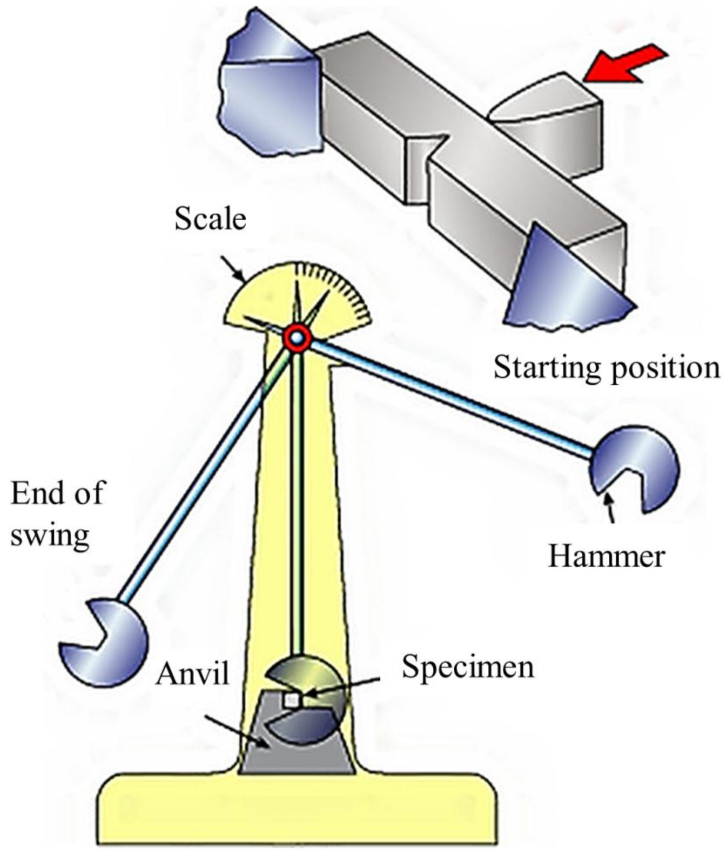

Fig. 19 Charpy U-notch test procedure [52]

The standard specimen used for this test is shown below in Fig. 20.

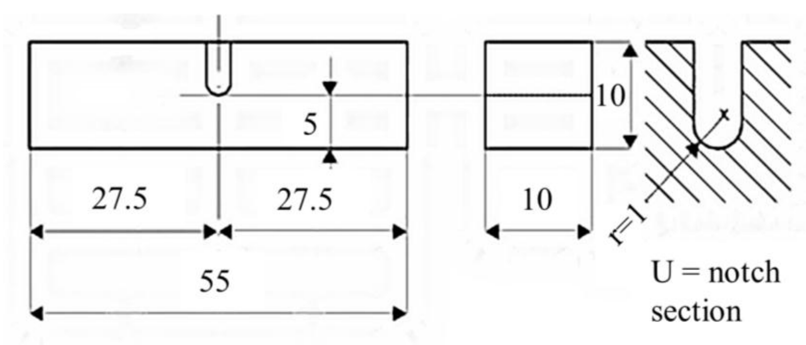

Fig. 20 Charpy U-notch test specimen, replotted from [53]

It is important to highlight that this test is qualitative, so results can only be compared with each other or with requirements of a specification. Most common practice is to plot average value from three material specimens, as it can be seen in Fig. 21.

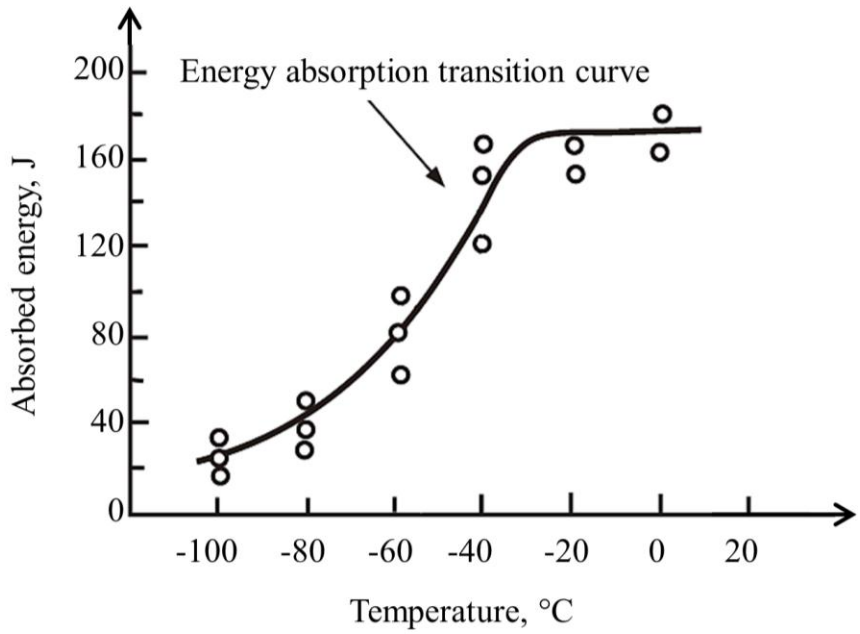

Fig. 21 Typical results of the Charpy U-notch test, replotted from [54]

Transition region is the area where the fracture behavior changes from ductile to brittle. The “S curve” is typical for most of low alloy and alloy steels, though the shape of the curve is affected by the composition, welding parameters and heat treatment conditions.

The chart in Fig. 21 show that brittle fractures might happen if the temperature is in the lower plateau area. Steel composition have a significant effect on the transition temperature, particularly strong influence is produced by carbon content, phosphorus content, manganese Carbon ratio and nickel content.

6.2 Crack Tip Opening Displacement test

The main advantage of the Crack Tip Opening Displacement (CTOD) test over Charpy U-notch test is the ability to use a full size specimen with a crack under loading that corresponds to real service loads. Moreover it is possible to evaluate current condition of equipment in service to make replacement or repair work if necessary.

The CTOD test usually performed for carbon-manganese and low alloy steel in the ductile/brittle transition range [55].

There is also Crack Tip Opening Angle (CTOA), which is not that different from CTOD. The only different is the shape of the notch made on a specimen. The different shapes are shown in Fig. 22.

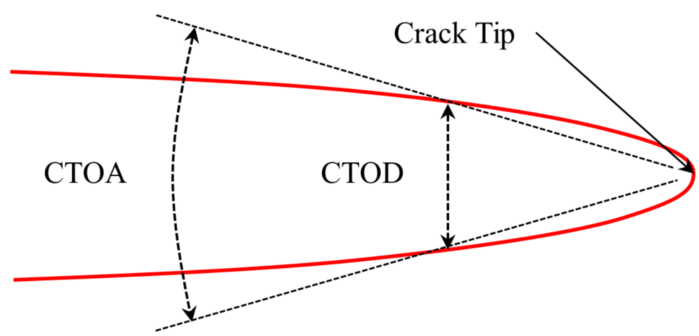

Fig. 22 Difference between CTOA and CTOD tests specimens replotted from [56]

CTOD test is performed by placing a specimen into three point bending machine and measuring the amount of crack opening after applied load. The measuring is done by means of a strain gauge attached to a clip placed between two accurately positioned knife edges at the mouth of the machined notch [57]. The process of the test is shown in Fig. 23.

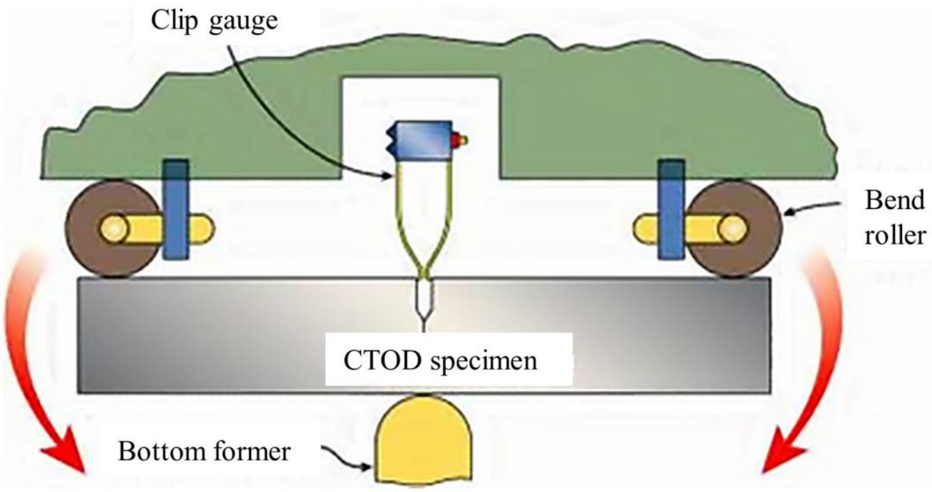

Fig. 23 Schematic view of the CTOD test procedure [57]

A specimen for CTOD test is full sized, but dimensions are interrelated to each other making test piece proportional, as it is shown in Fig. 24.

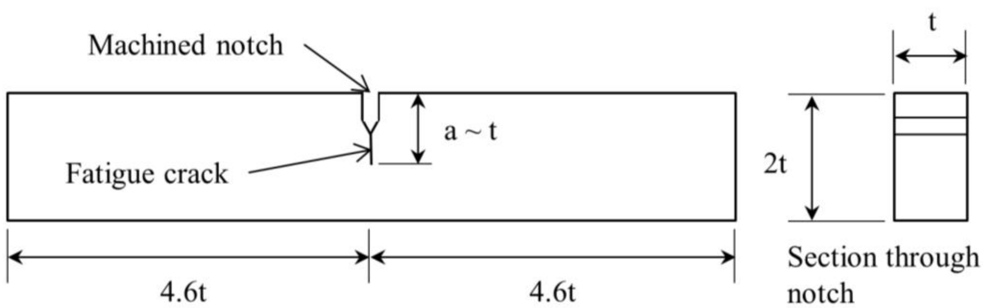

Fig. 24 The CTOD test specimen with proportional dimensions replotted from [57]

The result of the test is a chart of load over crack opening distance. The CTOD value of some part illustrates the degree to which the part is safe under applied forces when it contains a crack. Large CTOD result shows that the structure can accommodate a longer crack or larger loads. Fig. 25 shows a schematic plotted chart.

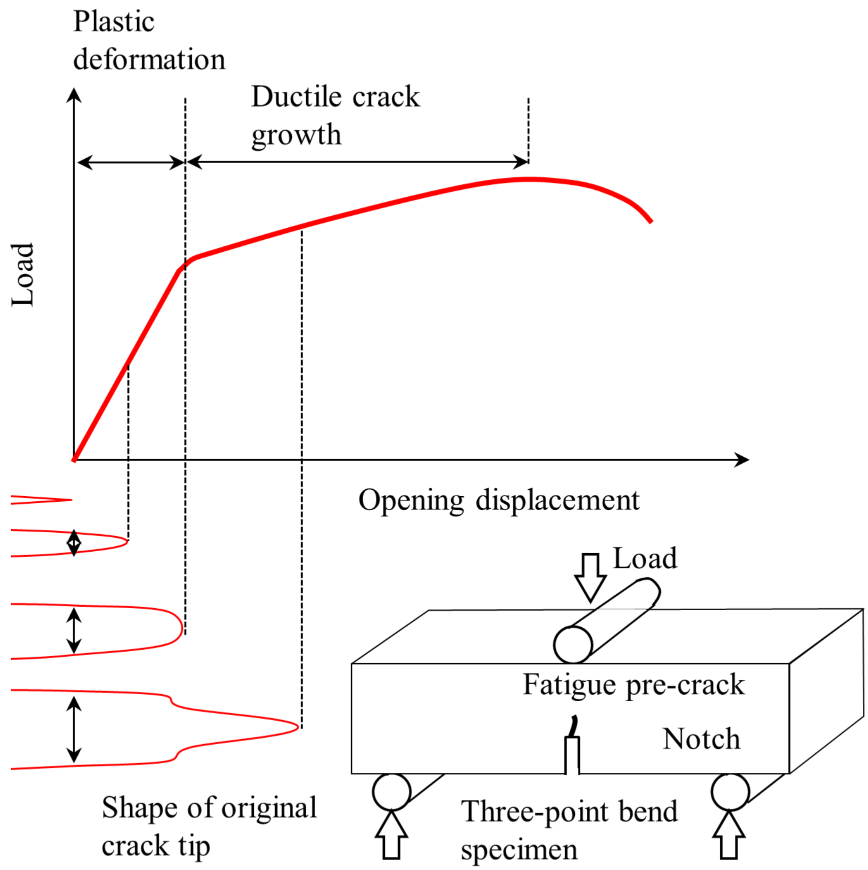

Fig. 25 CTOD test results plotted replotted from [55]

The major guideline for an appropriate CTOD value is the size between 0.1mm and 0.2mm at the minimum service temperature. This test becomes used frequently for welds evaluations of North Sea offshore structures [55].

6.3 Nil-ductility temperature test or drop weight test

Drop weight test can be used to compare weld parts with each other or to answer the “nil-ductility temperature” value specified by requirements. The test utilizes range of standard sized specimens which sizes are related to the thickness of the part being tested. For example, according to the specification a 20 mm thick sheet of steel should be tested as 125 mm by 50 mm and 20 mm dimensioned specimen [58].

Test procedure requires machining a notch in the welded deposit before the part will subject to loads. The next step is to place tested specimen on two fixed supports notch down. Finally the standard weight hammer applied to load the specimen as it is shown in Fig. 26.

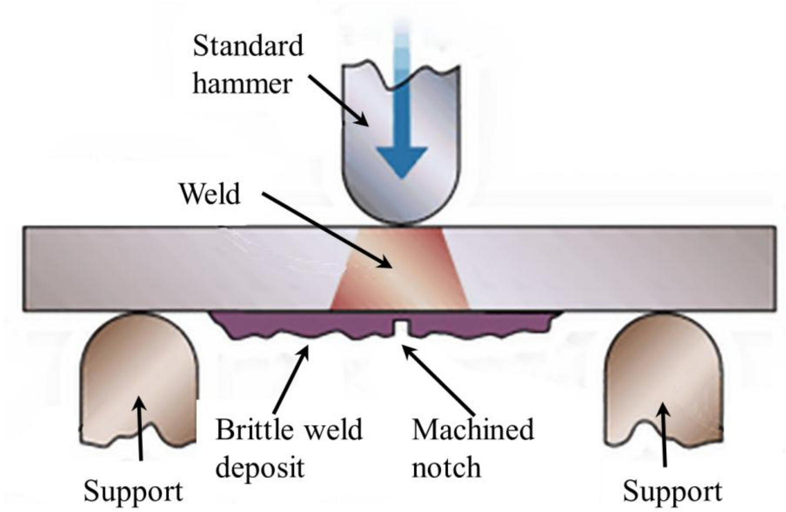

Fig. 26 Drop weight test procedure [58]

“The test is carried out on a number of samples at progressively lower temperatures until the test piece breaks. This temperature is known as the “nil-ductility temperature”. A further two tests are carried out at a temperature 50°C above the NDT to demonstrate that complete failure does not occur” [58].

7 CURRENT PROJECTS OF ARCTIC OFFSHORE STRUCTURES

During Soviet times there were three universities who worked on development of arctic offshore platforms mainly focusing on Sakhalin Island and Pechora sea area: SakhalinNIPIneftegaz, Gipromorneft, VNIPImorneftegaz (Moskow). University VNIPImorneftegaz has developed the design for Astrohanovskaya, Astohskaya-1, Lunskaya, Lunskayaa-1 and Prirazlomnaya. There were different designs developed which has gravitational or piled basement, made from steel or reinforced concrete [60]. There are 3 platform where built in sea of Azov on the depth only 2-8 meters, Kislogypskaya moving electro station in Barents sea and some other less significant projects.

However, mainly offshore platforms were constructed after Soviet Union collapsed. Russia was not the first country who constructed arctic offshore platforms and partially experience of such projects were gained from Canadian and Japanese companies, who constructed first arctic platforms in Beaufort Sea. Nevertheless, the ice conditions on the shelf of Barents Sea and Sakhalin Island seem to be more severe than on Beaufort Sea shelf [44].

Considering the fact that offshore platforms should operate for many years, for every certain case deep engineering analysis is needed. Moreover, designers are not always wanted to take a risk related to use of new materials because of the lack of practical observations. These factors slow down the use of innovative materials [60].

7.1 Sakhalin II

Sakhalin II project is a massive integrated oil and liquefied natural gas (LNG) facility located in the far east of Russia. The project started at 1994 when a joint venture - Sakhalin Energy Investment Company Ltd was formed to develop the Piltun-Astokhskoye oil field and the Lunskoye gas field in the Sea of

Okhotsk. Sakhalin II includes the first Russian arctic offshore platform, which operates in harsh sub-Arctic environment. It is also the first Russian project to sell oil to Asia-Pacific region. The project location and phases are shown in Fig. 27.

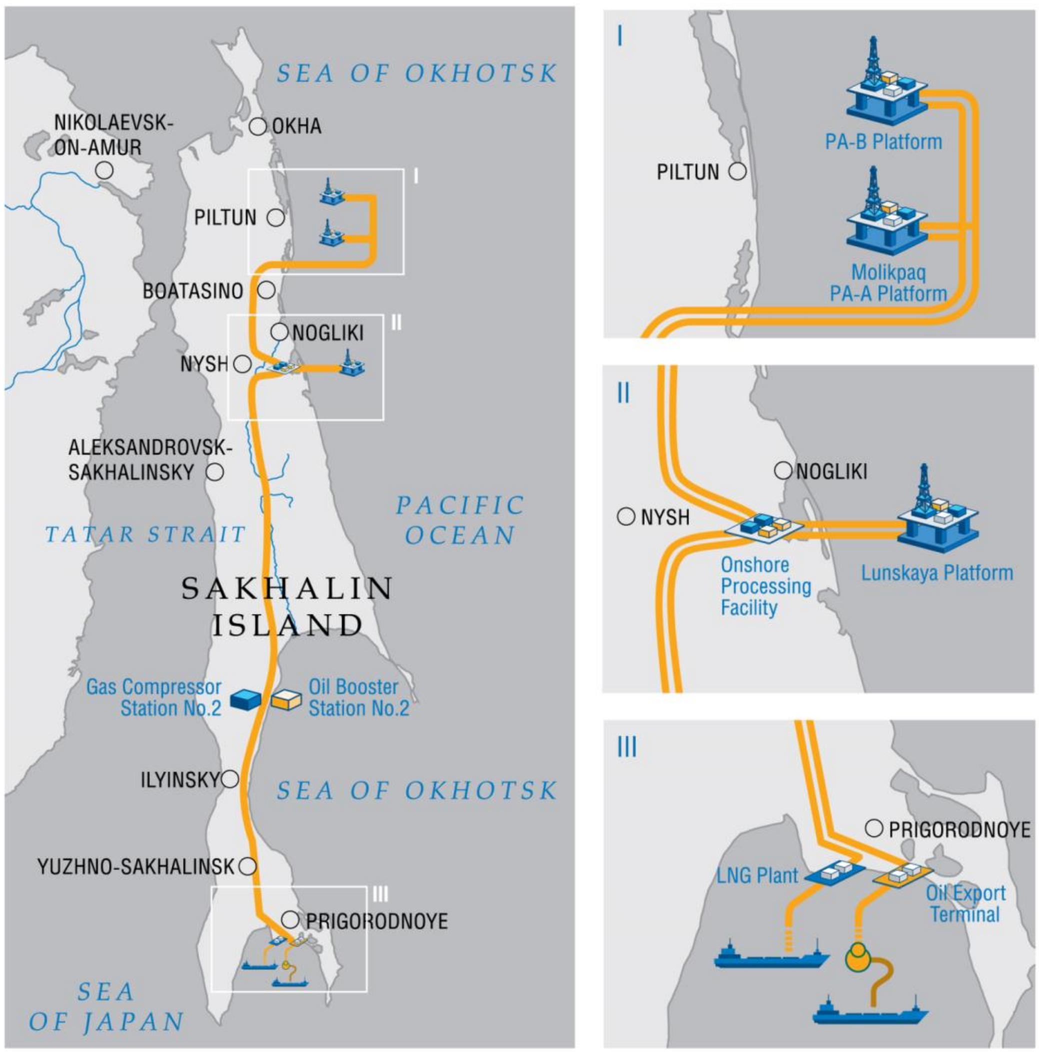

Fig. 27 Sakhalin project overview [61]

North of Sakhalin Island was not a developed place before this project and the absence of infrastructure meant that everything was built from scratch in sub-Arctic environment. Moreover, Sakhalin project is located at the place which is prone to earthquakes. Sea areas where platforms are installed are frozen most time of year. Despite all challenges, the project was completed and in past 10 years about 150 million barrels of oil were produced. Now Sakhalin II is the major new source of energy for Asia. The project delivers significant benefits to Sakhalin Island area. In addition to direct income from taxes the project provides plenty new jobs, local contracts and new technology. Moreover, there are direct benefits from improved infrastructure such as roads, railways, ports, hospitals and two airports. The Arctic ice-resistant offshore platform is shown in Fig. 28.

Fig. 28 Sakhalin II platform in ice (Lunskoye Platform) [62]

During 2008 and 2009 Sakhalin II won three awards from industry peers and the Russian Government for its achievements in environmental performance, safety management and engineering design. The project shares are owned by: Gazprom (50% +1 share), Shell (27.5% -1 share), Mitsui (12.5%) and Mitsubishi (10%) [62].

7.2 Offshore platform CS50

Sevmash Production Association has built CS50 offshore platform for Moss Arctic Productions Inc (Norway) with the amount of a contract of about 35$ million. Platform has an upper deck, which is capable of carrying topside construction weighing 20000 kg and is adapted for installation of dynamic positioning systems, as well as an anchor positioning stabilization system or an combined stabilization system. Depending on installed equipment, platform CS50 can be used in depths from 80 to 2500 meters [63, 64]. The offshore platform is shown in Fig. 29.

Fig. 29 CS50 platform for MOSS [65]

Multipurpose platform Moss CS50 is the 6th generation of semi-submersible platforms, designed by «Moss Maritime AS» (Norway). The platform of catamaran type is placed on two pontoons and the body is supported by six stabilizing columns. Depending on a purpose, the platform can be equipped with any equipment - extractive, drilling, crane and living facilities. Technical specification of the platform is listed in Table 94.

Table 94 Technical specification of CS50 offshore platform [64]

<table>
<tr><td colspan="2" rowspan="2">Pontoons</td><td colspan="2">Columns</td><td rowspan="2">Deck</td></tr>
<tr><td>Corner</td><td>Center</td></tr>
<tr><td>Length, m</td><td>111.56</td><td>12.80</td><td>12.80</td><td>83.2</td></tr>
<tr><td>Width, m</td><td>15.73</td><td>13.44</td><td>13.44</td><td>72.7</td></tr>
<tr><td>Hull Height, m</td><td>10.15</td><td colspan="2">-</td><td>-</td></tr>
<tr><td>Weight, t</td><td>5200</td><td colspan="2">3838</td><td>14508</td></tr>
<tr><td>Total weight, t</td><td colspan="4">14508</td></tr>
<tr><td>Total displacement, t</td><td colspan="4">498000</td></tr>
</table>

7.3 Jack-up rig Murmanskaya

The platform is capable of operation at temperature range of +20°C - -20°C (even -40°C at a downtime). A purpose of the platform is to drill wells of up to 6000 m depth at sea depth from 12 to 100 m. Also, the platform has an ability to withstand earthquakes that occur around once every 200 years. The platform use the largest friction pendulum bearings ever manufactured. The platform is shown in Fig. 30 and its technical specification is listed in Table 95.

Fig. 30 Murmanskaya offshore platform [66]

Table 95 Technical specification of Murmanskaya offshore platform [67]

Total length, m	109
Total width, m	77
Total height, m	146
Distance between axes of columns, m	52
Width of a pontoon, m	33.6
Hull height, m	9.7

Long pipeline was built to transfer the oil as well. Environmental impact was reduced considerably by using innovative approach of allowing pipeline movement in the frozen ground. Engineers from Sakhalin Energy Investment

Company Ltd. used technology and traditional knowledge to address environmental concerns related to that project. It helped secure the construction of two 800 km pipelines in a sustainable way. These pipelines cross around 200 rivers classified as sensitive areas for salmon spawning. In addition, the river valleys serve as home to reindeer and bears. Pipelines were laid in mountain areas where melting snow and rainfall causes landslides. Each river and stream was crossed in winter when the ground was frozen. In some places, engineers built tunnels under rivers and bays using directional drills and pulling pre-welded pipeline segments through. Some tunnels were up to 1800 m long. Furthermore, Sakhalin Energy rerouted offshore pipelines to avoid the feeding grounds of rare Western Grey Whales [67].

7.4 Ice-resistant platform Prirazlomnaya

Ice-resistant drilling platform Prirazlomnaya had been started at the plant in 1997 and was designed for oil production on the shelf of Arctic seas. Steels have been manufactured by Severstal [50] according to new [XXXVII] developed by Prometey during project METAL in 2006 [23]. Ice-resistant drilling platform Prirazlomnaya of weight about 85 000 tons and height of about one hundred meters was completed in 2004. Fig. 31 a shows almost finished platform under construction. Modules are collected from sections, and sections combined to superblocks, as it is shown in Fig. 31 b. Sevmash specialists have found the block solution to reduce the cost of construction.

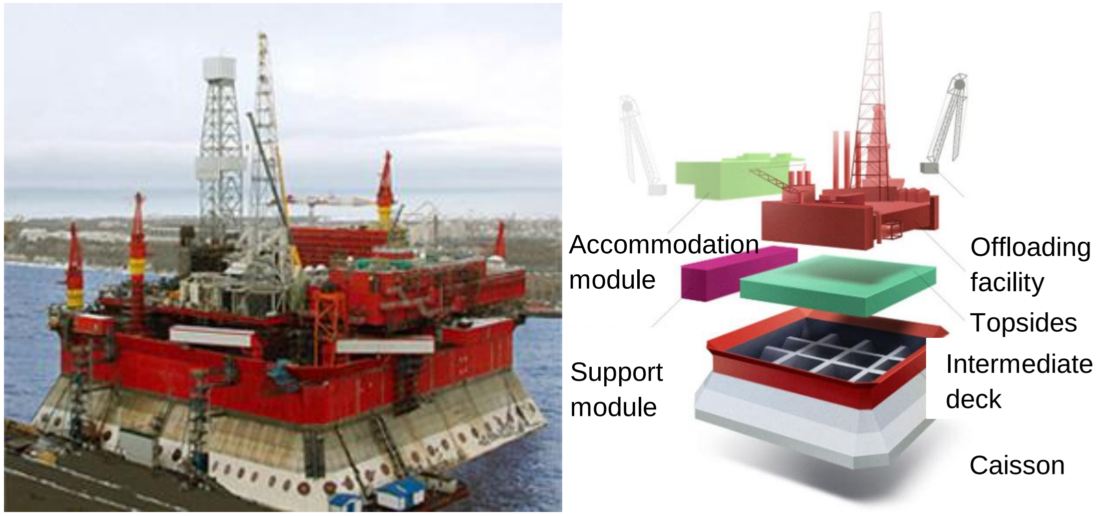

Fig. 31 a - Prirazlomnaya offshore platform under construction; b - Components of Prirazlomnaya offshore platform [68, 69]

In Severodvinsk the bottom base was made by 800 specialists from Sevmash. The top is made from Norwegian platform Hutton, which worked in the North Sea oil fields for 12 years. In Murmansk demolition work at the top of the Hutton was successfully completed by more than a hundred specialists from Severodvinsk. Contracting company Severmorneftegaz expressed satisfaction with the implementation of a unique project [69].

Designed for year-round drilling for oil vertical and horizontal methods in the field Prirazlomnaya will be placed in the Pechora Sea at a distance of about 60 km from a shoe. Caisson is a steel base, which serves as a support for topsides, which include equipment and facilities for oil extraction and refining. It is square in shape, with sloping sides and chamfered corners. At the bottom its dimensions are 126 × 126 m, which are decreasing at the top to 102 m × 102 m. From a structural perspective the caisson is divided into 16 sections of transverse and longitudinal cofferdams. These sections form storage tanks of crude oil with nominal capacity of 136 000 m^3, sea boxes and wellhead areas. For corrosion protection a bottom part of caisson in the impact zone of ice is made from stainless steel with a clad layer. The topsides have facilities for drilling wells, operating, preparation and shipment of crude oil, as well as for personnel placement. Technical parameters of the platform are listed in Table 96.

Table 96 Technical specification of Prirazlomnaya offshore platform [69]

Length, m	126
Width, m	126
Height, m	99
Weight without ballast, t	110000
Weight with ballast, t	506000
Amount of wells	48
Volume of oil produced per day, m^3	19000
Autonomy, days	60
Service life, years	25

7.5 Fixed platform Arcticheskaya

Arcticheskaya is designed for exploration and development drilling on the continental shelf of Arctic seas to a depth of 6500 m, with water depths of 10 to 30 meters. The rig has a water displacement of 16 350 kg and stands on three cylindrical pillars with a diameter of 6 m and height of 72 m with three toothed racks each. The rig is shown in Fig. 32.

Fig. 32 Arcticheskaya offshore platform [70]

Steels have been manufactured by Severstal [50], according to new [XXXVII] developed by Prometey during project METAL in 2006 [23]. In the fore part the residential complex and helicopter landing are situated. The drilling unit is located on the sliding console in the rear of the unit. The size of the platform is 88 x 66 m and the total weight is 14 800 kg. General designer of the rig is factory CDB Coral, Ukraine. By the Sea Register of Shipping Russian platform belongs to the jack-up class. Technical specification of the platform is shown in Table 97.

Table 97 Technical parameters of Arcticheskaya offshore platform [71]

Length, m	106,2
Width, m	75
Height, m	75
Pontoon width, m	33,6
Hull height, m	9,7
Total displacement, t	15240

7.6 Jack-up rig 6500/100

The jack-up rig is aimed for drilling of exploratory wells for gas and oil to a depth of 6500 m at seabed depths of 20 to 100 m. The main areas of operations are the Barents and the Okhotsk Sea. Fig. 33 shows jack-up rig 6500/100.

Fig. 33 Jack-up rig 6500/100 [72]

The jack-up stays on three pillars of height of 146 m, it has the residential complex and a landing place for helicopters, as well as a drilling unit. Technical parameters and dimensions are shown in Table 98.

Table 98 Technical parameters of jack-up rig 6500/100 [73]

Length, m	109.0
Width, m	77.0
Height, m	146.0
Autonomy, days	30

7.7 Ice-resistant platform LPP 15-25 and jack-up rig 6500/10-30 for exploratory drilling

Ice-resistant platform LPP 15-25 and jack-up rig 6500/10-30 are year-round drilling complex for oil and gas production, installed on sea depths of 15-25 m. This complex is capable of drilling wells up to 6500 m. The model of the complex is shown in Fig. 34.

Fig. 34 Model of ice-resistant platform LPP 15-25 and jack-up rig 6500/10-30 for exploratory drilling [74]

The complex consists of two separate structures:

- ice-resistant submerged platform 15-25, serves as a support unit for the rig
- self-elevating floating drilling rig 6500/10-30 (or jack-up project 15 402)

Drilling of wells is done by the jack-up rig. Technical specification can be seen in Table 99.

Table 99 Technical specification of ice-resistant platform LPP 15-25 and jack-up rig 6500/10-30 for exploratory drilling [74]

Water depth, m	15-25
Number of wells	24
Maximum wind speed, m/s	46
Maximum wave height, m	11.3
Maximum ice thickness, m	1.6
Autonomy, days	60

8 FUTURE TRENDS OF ARCTIC MATERIALS DEVELOPMENT

Large scale development of Russian Arctic shelf oil and gas reserves defined the direction of shipbuilding industry for the next decade. There are three main trends in modern cold resistant steel development: [23]

- improving the quality of already developed and used materials
- creating new steel grades, including high-strength, improved weldability and other useful properties
- improving the steel manufacturing process in order to rise the quality and lower the costs

These trends will be encouraged by an increasing interest of oil and gas production industries to the Arctic region. Moreover, as it was mentioned earlier, the Arctic region has good conditions for wind turbines operation, which can be placed offshore.

9 CONCLUSIONS

The main objective of the research is to review Russian metals used for Arctic offshore structures. In order to gain a better understanding of the Arctic conditions, these are briefly overviewed. The work covers various metals, such as wide range of steels, aluminiums and nanostructured materials. To indicate possible applications of the materials the most important current offshore projects were introduced and briefly described. The paper reviews different offshore platform designs and provides examples of certain types of materials applications.

The importance of the Arctic cannot be underestimated since it holds about 5% of proven oil reserves and about 20% of undiscovered reserves. The Arctic region is also rich with gas. Nowadays, there are just few offshore platforms installed in the Russian part of the Arctic region, but more projects are planned. There has been an increase of more than 10% in oil obtained from offshore locations compared to ground over the period from 2003 to 2010.

The work provides the description of the conditions in the Arctic region. There are several climate characteristics which have to be considered. The most prominent factor which affects material behavior is the low temperature encountered in the Arctic region. During winter season temperature in the Russian part of the Arctic might drop as low as -60 ˚C. Nevertheless, even such low temperatures are not as harmful for steels as the prolonged periods of moderately low temperatures which stay for long months in the Arctic. Such conditions result in the brittle fracture behaviour of steels. In addition, the Arctic ecosystems are extremely fragile, and that fact greatly increases the reliability requirements of Arctic offshore platforms.

This Master`s thesis looks at the desired metal properties for the Arctic conditions. It is clear that metal should have a satisfactory toughness down to -60˚C. For most applications, materials with yield strength of 235-690 MPa are sufficient, however there is a trend to increase the strength. It is extremely important that the material shows isotropic properties across all the dimensions. In the case of metals being placed underwater, they should have reasonable corrosion resistance. As offshore structures are operated for the whole year, temperatures encountered during the summer season are much warmer than during the winter time, so materials should have reasonable elongation value to prevent failures. From the manufacturing point of view, metals should be reasonably weldable without preheat and postheat treatment (or with minimal preheat temperature required).

There are various types of offshore structures manufactured nowadays. Some of them are fixed (jack-up rigs, jackets, compliant towers) or buoyant (tension leg platforms, floating production storage and offloading ships, SPAR platforms and floating production systems), the main body can be made of steel or reinforced concrete. Platforms parts experience different environmental conditions. For example, an upper deck metal might experience tempertaures as low as -60˚C, while supporting legs are dealing only with -2 ˚C underwater, but also with harsh corrosive environment and biofouling. These conditions should be examined more closely when materials are selected.

Low carbon steels reviewed are Cт3 and steel 20. These steels have chemical composition of about 0.5% of Manganese and 0.2% of Silicon. Both of them have low strength and high plasticity. Steels can be welded by any welding process for plates where the thickness does not exceed 60 mm. Generally they can be used at as low temperatures as -40˚C. Tensile strength of these steels is about 400-550 MPa and KCU is about 10 J/cm^2 at -50˚C. Corrosion resistance of these steels is low.

Intermediate carbon steels have up to 0.5% of Carbon. Chemical composition also includes Manganese of 0.5-0.8% and Silicon of 0.2%. There is only one steel reviewed – steel 45. Steel 45 has a low corrosion resistance. After quenching and tempering the steel is used for medium-sized parts. Steel can be also used for pipes at temperatures as low as -50°C. The steel has excellent formability, but limited weldability, as preheat and further thermal treatment are needed. Tensile strength is about 650 MPa, and KCU at -50°C is 13 J/cm^2.

Low alloy steels which were specially developed for low temperatures are reviewed. Generally, steels of that group (09Г2С, 10Г2, 10Г2С1, 16ГС, 14Г2АФ, 18Г2Ф) can be applied for as low as -70°C, however steels 14Г2АФ and 18Г2Ф can be used only for -40°C. Steels mainly have low corrosion resistance. The carbon content is low, usually about 0.15%. Major alloying elements are Manganese and Silicon. Manganese is usually added in quantity of 1.5% and Silicon is about 0.5% or 1%. However, steel 18Г2Ф has only 0.1% of Silicon. Weldability of all steels is good, but some grades requite preheat for thick plates. Tensile strength of steels is in the range of 400-650 MPa and KCU exceeds 25 J/cm^2 at the operational temperature.

Chromium steels reviewed are 20Х, 20ХН, 40Х, 40ХН, 30ХН2МФА, 38ХН3МФА, 10ХСНД, 12ХН3А, 12Х2Н4А, 20ХН3А, 18Х2Н4МА, 15ХСНД, 15ХМ and 20ХГР. Steels typically contain about 0.2% or less of Carbon (0.1 for 12ХН3А). Silicon content is the same (0.25%) for most of the steels from this group, only certain grades, as 10ХСНД has about 0.9% of Silicon. Nickel and chromium contents ranges from 0.3% to 4% and 0.5-1.5% respectively. Also Manganese is present in all the steels of quantity about 0.5%. Generally, steels can be used at as low as -70°C, and even lower for certain grades, as for 30ХН2МФА and 12ХН3А. Steels mainly have low corrosion resistance (except 10ХСНД and 15ХСНД). Weldability is quite poor (except 15ХМ and 10ХСНД). Some have good wear properties, such as 20Х, 20ХН, 20ХН3А and 20ХГР. The range of steels among the group have a large depth of hardening, for instance 20ХН and 40ХН. Tensile strength for most of the steels is about 1000 MPa, but 20Х and 20ХН have about 600 MPa, 10ХСНД, 15ХСНД and 15ХМ have only about 400 MPa. KCU at -70°C for most steels exceeds 60 J/cm^2, except 10ХСНД, 15ХСНД and 15ХМ who have just 30 J/cm^2.

Cast steels have larger grain size, which affects low temperature material behavior, also the size of the grain differs significantly across the steel composition. Alloying elements can significantly affect the grain size. In this group the following steels are introduced: 20Л, 20ГЛ, 30ГЛ, 30ХЛ, 08Г2ДНФЛ, 12ХГФЛ, 14Х2ГМРЛ, 20ФЛ, 20ХМЛ, 25Х2НМЛ, 35ХМЛ, 20Н3ДМЛ. Carbon content of the steels do not exceed 0.3%, silicon content is less than 0.5%. Some steels alloyed with Manganese, where content is typically about 0.5-1.5%. Also Chromium and Nickel are included in some grades (30ХЛ, 08Г2ДНФЛ, 14Х2ГМРЛ and others) in quantity of 0.5-1.5% of Chromium and up to 3% of Nickel. 08Г2ДНФЛ and 20Н3ДМЛ alloyed with Copper of 1%. Steels have a low corrosion resistance, except 20Н3ДМЛ. Weldability varies from grade to grade, but generally it is limited. Steels can be applied to temperatures as low as – 60°C. Tensile strength is typically in the range of 300-600 MPa, and KCU at -60°C is more than 15 J/cm^2 (40 J/cm^2 for some grades).

Stainless steels 20Х13, 30Х13 and 40Х13 have a carbon content varying from 0.2% to 0.4%, chromium content is 13%. Steels can be used at -30°C and sometimes as low as at -50°C (for 20Х13). Tensile strength is up to 1000 MPa, KCU at -60°C is about 20 J/cm^2. Steels of that group have fair corrosion resistance and limited weldability. Steel 12Х18Н10Т is used for welded constructions, which are operating at low corrosive environments. Carbon content is 0.12%, Chromium: 18% and Nickel is 10%. The steel can be used also for cryogenic equipment. The steel has a good weldability. Tensile strength is about 600 MPa.

Aluminium does not have a certain transition temperature, therefore remains ductile even at the cryogenic temperatures. The most used aluminium alloys for low temperature applications include magnesium as the main alloying agent. That composition shows good combination of strength, plasticity, weldability and corrosion resistance. Increase of magnesium content leads to improved strength, but, practically, alloys usually do not include more than 7% of Magnesium. Tensile strength of these alloys is about 300 MPa. Heat-treatable aluminium alloys are used as well. These alloys are usually includes Copper, Magnesium, Silicon, Manganese and other elements. Al-Mg-Si (1% of Manganese and 1% of Silicon), such as АД33 or АД35 alloys have good corrosion resistance, high plasticity and tensile strength is up to 300 MPa.

Nanomaterials were also reviewed in the paper. Materials with grain size less than 100 nm are considered to be nanomaterials. One of the central problems with metals is the inverse relationship of strength and toughness. Also, there are studies which show exactly the same relation to the temperature of the ductile-brittle translation. So far, the only method which can contribute to both characteristics simultaneously is grain refinement. Steel 12X18H10T, where the grain sizes were mechanically reduced to 100 nm has a yield strength of 1340 MPa at room temperature, which is 6 times larger than the same steel has after normal heat treatment. For nanostructured aluminium it is possible to reach an ultimate strength of up to 800 MPa, which is more than typical steel has. Nanostructural carbon steels can have higher corrosion resistance than special stainless steels. Nanostructural steels with a yield strength range of 355-690 MPa were produced for offshore platforms Prirazlomnaya and Arcticheskaya by Severstal and Prometey.

The standard on shipbuilding steels was developed together with Russian Maritime Register of Shipping. There are six groups of steels divided by the yield strength limit: 420, 460, 500, 550, 620 and 690 MPa. For each level there are 4 categories (A,D,E,F) set by the impact test value at different temperatures. Letter E specifies impact value control at -40°C and F at -60°C. The chemical composition of steels is typically 0.1% Carbon, about 1% Manganese, 0.5% Chromium, sometimes Copper of 0.4% and the amount of

Nickel depends on the grade, varying from 0.3% to 2%. KCU is over 30 J/cm^2 at the specified temperature. Institute Prometey in 2006 developed the special technical regulation, which improved properties of shipbuilding steels in a dramatic way, in particular the amount of Sulphur and Phosphorous was reduced by more than 3 times. Moreover, Prometey has developed clad steels, which are perfect for ice-resistant girders of offshore platforms and icebreakers, as they combine superb corrosion resistance and low temperature properties.

<u>Structural construction steels</u> are used for various constructions, such as buildings, pipelines, heavy machinery and bridges. Steels are divided into 7 groups, based on the yield strength. These are 225, 285, 325, 390, 440, 590 and 735 MPa. Structural construction steels which are used for low temperature environments are usually additionally alloyed with 6 or 9% of Nickel. These steels typically have a low carbon content, which does not exceed 0.2% and a manganese content of about 1.5%.

The thesis discusses several tests, which can be used to determine toughness of materials at low temperatures. It is important because brittle fracture behavior can cause serious damage of a welded construction, especially in the Arctic region. Charpy U-notch test, crack tip opening displacement or crack tip opening angle as well as drop weight test or drop weight tear test are most common in Russian practice. All tests show the amount of energy required to crash a specimen at a specific temperature. These tests are mainly in use to determine properties of materials which are aimed for cold regions.

The paper provides an overview of the most important Arctic offshore projects. Nowadays, the main focus of Russian companies is the Sakhalin Island, as the largest projects are located there (Sakhalin II, Arcticheskaya). However, there is a tendency to develop oil fields located at the North-West of Russia, as Prirazlomnaya offshore platform is installed there. Offshore platforms installed in the Russian Arctic region have faced severe challenges from the harsh climate, as the conditions are more severe there than in the Canadian Arctic region.

Future trends of low temperature materials development could be the following. Improving of the quality of known materials by reducing the amount of impurities and employing better quality control. The other trend is to create new grades of steels with higher strength, improved weldability and other useful properties. Finally, it is possible to improve steel manufacturing processes in order to raise the quality and lower the costs. Nanomaterials development will also contribute to the future of low temperature materials.

10 SUMMARY

Russia, as one of the leading oil and gas production countries is interested in the Arctic region, as it holds significant share of these natural resources. Need for active exploration of the Arctic region boosted research on cold resistant materials and structures. Nowadays there are several offshore platforms already installed on Arctic seas shelf and several other projects are at the initial stage. This paper defines required materials properties suitable for the Arctic region. Metals there should have a satisfactory toughness down to -60˚C. Generally, materials with yield strength of 235-690 MPa are sufficient, however there is a trend to increase the strength. It is extremely important that the material shows isotropic properties across all the dimensions. As offshore structures are operated for the whole year, temperatures encountered during the summer season are much warmer than during the winter time, so materials should have reasonable elongation value to prevent failures. From the manufacturing point of view, metals should be reasonably weldable without preheat and postheat treatment.

The work provides a comprehensive review on Russian materials that are in use or can be potentially used for Arctic offshore platforms. The thesis covers various groups of metals, such as low carbon, low alloy, alloy, chromium, stainless steels, as well as aluminiums and nanostructural steels. In each group particular grades are described including chemical composition, mechanical properties at low temperatures and typical applications. Also testing methods for evaluating mechanical properties of steel at low temperatures are briefly discussed.

Moreover the thesis provides information about current offshore projects in Russia. Nowadays, the major focus of Russian companies is the Sakhalin Island area, where conditions are closed to Arctic ones, as the largest projects are located there (Sakhalin II, Arcticheskaya). Nevertheless offshore platforms are also used to develop oil fields located at the European Arctic seas, as Prirazlomnaya offshore platform is installed there in the Barents sea.

Future trends of low temperature materials development improving of the quality of materials by reducing the amount of impurities, to create new grades of steels with higher strength and improved weldability as well as to improve steel manufacturing processes in order to raise the quality and lower the costs. Nanomaterials will play one of major roles in that development, as they can improve low temperature properties in a very significant way.

BIBLIOGRAPHY

1 Freitag D. R. and McFadden T. T. 1997. Introduction to cold regions engineering. ASCE Publications, p.2, 110.

2 Brown J., Ferrians Jr O.J., Heginbottom J.A., and Melnikov E.S. 1998. revised February 2001. Circum-Arctic map of permafrost and ground-ice conditions. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital Media.

3 Ahlenius H. 2008. Arctic, topography and bathymetry (topographic map). UNEP/GRID-Arendal. [Online]. [Accessed 30.05.2012] Available at http://www.grida.no/graphicslib/detail/arctic-topography-and-bathymetry-topographic-map_d003.

4 Arctic Oil and Natural Gas Resources: United States Energy Information Administration, www.eia.doe.gov. December 2011.

5 Russian Federal law № 122 from 24 of August 2004.

6 Resolution № 12 of Ministry Council USSR from 3 of January 1983.

7 Roberts P. 2005. The end of oil: on the edge of a perilous new world, p. 24-98.

8 Lindholt L. 2006. Arctic Natural Resources in a Global Perspective, The Economy of the North, p. 27-28.

9 Linkin M. E. 2008. North Pacific climate variability and Arctic sea ice. Matyland: ProQuest, p. 144.

10 Kobe steel. 2003. Welding of offshore structures part 1: How to select welding consumables, KOBELCO welding today, no. 6, January, p. 4.

11 Exxon mobil. Financial report 2010.

12 Lancaster J. 1997. Handbook of Structural Welding: Processes, Materials and Methods Used in the Welding of Major Structures, Pipelines and Process Plant, pp. 253-254.

13 Przybylak R. 2003. The climate of the Arctic. Atmospheric and oceanographic sciences library. Springer, vol. 26. p.25.

14 Gorshkov S. G. 1980. Military Sea Fleet Atlas of Oceans: Northern Ice Ocean [in Russian]. USSR: Ministry of Defense, p. 184.

15 Abele L. G., Kim W. 1986. An Illustrated Guide to the Marine Decapod Crustaceans of Florida, Environmental Regulation Technical Series. Florida State Universit, Tallahasse, p. 8.

16 Kaushish J. P. 2008. Manufacturing Processes, PHI Learning Pvt. Ltd., p. 128.

17 Davis J. R. 1994. ASM International. Handbook Committee, Stainless steels, ASM International, p. 495.

18 Solntsev Y.P., Ermakov B.S., Sleptsov O.I. 2008. Materials for low and cryogenic temperatures. St.Petersburg: Himizdat, p.13, p.20, p.111-141.

19 Farrell C. 2011. Gulf of Mexico Oil Spill, ABDO, p. 56-86.

20 Wang Z., Stout S. A. 2007. Oil Spill Environmental Forensics: Fingerprinting and Source Identification. Academic Press, p.368.

21 Novitsky I. G., Portnoy A. S., Razuvaev V. N. 2009. Design of offshore platforms. Requirements of standards. [in Russian] SPBGMTY, pp. 8-10, 48-54, 72-75,112-113.

22 Odessky P.D. 2006. Microalloying of steels for the North and unique metal structures. [in Russian] Moscow: Intermet Engineering, p.28.

23 Gorynin V., Malushevskiy P. 2007. Creating and introducing of new materials. [in Russian], Morskoy vestnik, no. 3(6), p. 74-77.

24 KOBELCO, "Offshore structures exploring deeper seas demand higher quality filler metals," KOBELCO welding today, vol. 11, no. 4, October 2008.

25 McFadden T. T., Bennett F. L. 1991. Construction in cold regions: a guide for planners, engineers, contractors, and managers. John Wiley and Sons, 1991, p. 110.

26 Tsinker G. P. 1995. Marine structures engineering: specialized applications.: Springer.

27 Kobe steel, Meething the requirements of 610 MPa high tensile strength steel and low temperature service , KOBELCO welding today, no. 14, 2011, p.1.

28 Presentation of Prometey for Rybin factory, 2007.

29 Russian Maritime Register of Shipping, 2011.

30 ArcelorMittal. 2011, October. [Online].
http://www.industeel.info/activities/products/welded-components.aspx

31 Rules of oil and gas equipment for offshore platforms, 2009, St. Petersburg, p.82.

32 Steels of high strength for cold resistant metal constructions. Collection of scientific publications. [in Russian] Moscow, 1987, p.127.

33 Zubchenko A. S. 2003. Handbook of steels and alloys. Moscow, Pub.: Mechanical Engineering-1, pp.23, 54-62, 89, 102, 129-133, 707-710.

34 Rincón J. M., Romero M. 1999. Characterization Techniques of Glasses and Ceramics. Berlin:Springer, pp. 4-6.

35 The Rare Earth Elements: Chemistry and Applications [online], [Accessed 01.07.2012] Available at: http://www.rareearthelements.us/the_17_elements.

36 Steel 09Г2С. Central Russian metal portal, [in Russian]. [Online]. [Accessed 30.05.2012] Available at http://metallicheckiy-portal.ru/marki_metallov/stk/09G2S.

37 Shishkov M.M. 2002. Handbook of steels and alloys. [in Russian]. Donetsk, p.211-218.

38 Various cast defects [online], [Accessed 03.07.2012] Available at: http://www.old.me.gatech.edu/jonathan.colton/me4210/castdefect.pdf.

39 Steel 12X18H10T. Central Russian metal portal, [in Russian]. [Online]. [Accessed 30.05.2012] Available at http://metallicheckiy-portal.ru/marki_metallov/stk/12X18H10T.

40 Properties of Aluminium alloys [online], [in Russian], [Accessed 04.07.2012] Available at: http://normis.com.ua/index.php?option=com_content&view=article&id=17&Itemid=24.

41 ISO 209-1:2007 Wrought aluminium and aluminium alloys -- Chemical composition and forms of products -- Part 1: Chemical composition.

42 How to Avoid Cracking in Aluminum Alloys [online], [Accessed 05.07.2012] Available at: http://www.esabna.com/us/en/education/knowledge/qa/How-to-Avoid-Cracking-in-Aluminum-Alloys.cfm.

43 The Virtual Industrial Exhibition, Direct industry [online], [Accessed 05.07.2012] Available at: http://www.directindustry.com/industrial-manufacturer/laboratory-mill-81324.html.

44 Hosono H. 2006. Nanomaterials: From Research to Applications, p 7.

45 Heinz S. at all. 2009. Nanomaterials: Mechanics and Mechanisms, Springer, p.138.

46 Guo Z., Tan L. 2009. Fundamentals and Applications of nanomaterials. London: Artech House, pp. 229-233.

47 Gorynin I. V. and Khlusova E.I., Nanostructural steels for developing the shelf of the Arctic, [in Russian]. Vestnik Rossiiskoi Akademii Nauk, 2010, Vol. 80, No. 12, pp. 1078–1084.

48 Gorynin I.V., Research and development FGYP CNII KM Prometey in the area of structural nanomaterials. Russian nanotechnology, vol 2, №3-4, 2007, pp.52-55.

49 Russian Marine Industry, Prirazlonaya offshore platform [online], [Ac-cessed 05.07.2012] Available at: http://rus-shipping.ru/upload/news/rtf/857_platforma_prirazlom111.jpg.

50 Severstal catalog of the production, [in Russian], 2012, p. 53.

51 Amiraslanov Z. A. 2011. Scientific basis of design of offshore platforms, [in Russian], OOO «CenterLitNefteGaz», Moscow, ISBN 978-5-902665-56-4, p.9, p.119.

52 Mathers G. 2004. Mechanical testing - notched bar or impact testing. [Online], [Accessed 05.07.2012] Available at: http://www.twi.co.uk/content/jk71.html.

53 Charpy U-notch specimens. [Online], [Accessed 05.07.2012] Available at: http://www1.veristar.com/veristar/bvrules/D_1_s2_4_3.htm.

54 KOBELCO, "Welding of offshore structures part 1: How to select welding consumables," *KOBELCO welding today*, no. 6, January 2003.

55 KOBELCO, "CTOD," *KOBELCO welding today*, vol. 8, no. 1, January 2005.

56 Mahmoud S., Lease K. 2001. The effect of specimen thickness on the experimental characterization of critical crack-tip-opening angle in 2024-T351 aluminum alloy. [Online], [Accessed 05.07.2012] Available at: http://www.sciencedirect.com/science/article/pii/S0013794402001303.

57 Mathers G. 2005. This Job Knowledge: CTOD Testing. [Online], [Accessed 05.07.2012] Available at: http://www.twi.co.uk/content/jk76.html.

58 Mathers G. 2005. The Job Knowledge: Compact tension and J integral tests. [Online], [Accessed 05.07.2012] Available at: http://www.twi.co.uk/content/jk77.html.

59 What is the drop-weight tear test? [Online], [Accessed 05.07.2012] Available at: http://www.twi.co.uk/technical-knowledge/faqs/structural-integrity-faqs/faq-what-is-the-drop-weight-tear-test/.

60 Danilov G.I. and Leonov V. P. Substantiation of standardized cold resistance requirements to steel for ice-resistant fixed rigs being operated on the Arctic shelf. [in Russian], Voprosu materialovedenia, 1996 №2(5) p.5-19.

61 Map of Sakhalin II project, [online], [Accessed 30.05.2012] Available at www.gazprom.ru.

62 Sakhalin II — Russia’s First LNG Project. [online], [in Russian], [Accessed 30.05.2012] Available at http://gazprom-sh.nl/sakhalin-2/.

63 Shell in the Arctic, Royal Dutch Shell plc., 2011, p.4.

64 Finishing of the offshore platform construction [online], [in Russian], [Accessed 30.05.2012] Available at http://shipbuilding.ru/rus/news/russian/2002/04/24/platforma/.

65 Seadrill Orders Another Harsh Environment Semi, Wins $235M Contract from Chevron [online], [Accessed 30.05.2012] Available at http://gcaptain.com/seadrill-orders-harsh-environment/?45902.

66 Murnanskaya offshore platform [online], [in Russian], [Accessed 30.05.2012] Available at http://www.mvkursk.ru/press/21510.html.

67 Arctic platform Murmanskaya, technical data. [online], [in Russian], [Accessed 30.05.2012] Available at http://www.amngr.ru/index.php/ru/services/fleet/murmanskaya.

68 Gazprom has finished building of Prirazlomnaya. [online], [in Russian], [Accessed 30.05.2012] Available at http://sdelanounas.ru/blogs/6699/.

69 Gazprom neft shelf [online], [Accessed 30.05.2012] Available at http://www.gazprom.com/about/subsidiaries/list-items/gazprom-neft-shelf/.

70 Offshore platform Arcticheskaya. [online], [in Russian], [Accessed 30.05.2012] Available at http://www.gazflot.ru/fotogallery/photo_137.

71 Arcticheskaya in the sea! [online], [in Russian], [Accessed 30.05.2012] Available at http://www.gazflot.ru/gazflot_v_presse/news_131/.

72 Offshore platform, [online], [in Russian], [Accessed 30.05.2012] Available at http://www.gubkin.ru/images_dep/51/platb_f_murmanskaja.jpg.

73 Jack-up rig 6500/100, technical data. [online], [in Russian], [Accessed 30.05.2012] Available at http://www.gubkin.ru/.

74 LPP 15-25 + SPBU 6500/10-30 Ice-resistant exploratory/production drilling integrated installation. [online], [Accessed 30.05.2012] Available at http://www.cdbcorall.com/en/3/49/.

LIST OF GOST STANDARDS, OST STANDARDS AND TU

I. GOST 5521-93 Rolled steel for shipbuilding. Specifications, [Прокат стальной для судостроения. Технические условия]

II. GOST 14637-89 Rolled plate from carbon steel of general quality. Specifications, [Прокат толстолистовой из углеродистой стали обыкновенного качества. Технические условия]

III. GOST 19903-74 Hot-rolled steel sheets. Dimensions, [Прокат листовой горячекатаный. Сортамент]

IV. GOST 380-2005 Common quality carbon steel. Grades, [Сталь углеродистая обыкновенного качества. Марки]

V. GOST 1050-88 Carbon structural quality steel gauged bars with special surface finish. General specifications, [Прокат сортовой, калиброванный, со специальной отделкой поверхности из углеродистой качественной конструкционной стали. Общие технические условия]

VI. GOST 19904-90 Cold-rolled steel sheets. Dimensions, [Прокат листовой холоднокатаный. Сортамент]

VII. GOST 8732-78 Seamless hot-deformed steel pipes. Range of sizes, [Трубы стальные бесшовные горячедеформированные. Сортамент]

VIII. GOST 8734-75 Seamless steel tubes cold deformed. Range of sizes, [Трубы стальные бесшовные холоднодеформированные. Сортамент]

IX. GOST 4543-71 Structural alloy steel bars. Specifications, [Прокат из легированной конструкционной стали. Технические условия]

X. GOST 19281-89 Rolled steel with increased strength. General specifications, [Прокат из стали повышенной прочности. Общие технические условия]

XI. GOST 5520-79 Rolled carbon low-alloy and alloy steel sheets and plates for boilers and pressure vessels. Specifications, [Прокат листовой из углеродистой, низколегированной и легированной стали для котлов и сосудов, работающих под давлением. Технические условия]

XII. GOST 550-75 Seamless steel tubes for petroleum processing and petrochemical industry. Specifications, [Трубы стальные бесшовные для нефтеперерабатывающей и нефтехимической промышленности. Технические условия]

XIII. GOST 8479-70 Construction carbon and alloy steel forgings. General specification, [Поковки из конструкционной углеродистой и легированной стали. Общие технические условия]

XIV. GOST 17066-94 Rolled sheet of high-strength steel. Specifications, [Прокат тонколистовой из стали повышенной прочности. Технические условия]

XV. GOST 8731-74 Seamless hot-deformed steel pipes. Specifications, [Трубы стальные бесшовные горячедеформированные. Технические требования]

XVI. GOST 8733-74 Seamless cold and warm deformed pipes. Specifications, [Трубы стальные бесшовные холоднодеформированные и теплодеформированные. Технические требования]

XVII. GOST 9567-75 Precision steel tubes. Range of sizes, [Трубы стальные прецизионные. Сортамент]

XVIII. GOST 7505-89 Steel stamping forgings. Tolerances, allowances and forging laps, [Поковки стальные штампованные. Допуски, припуски и кузнечные напуски]

XIX. GOST 7829-70 Carbon and alloyed steel forgings fabricated by hammer forging. Allowances and tolerances, [Поковки из углеродистой и легированной стали, изготовляемые ковкой на молотах. Припуски и допуски]

XX. GOST 2590-2006 Round hot-rolled steel bars. Dimensions, [Прокат сортовой стальной горячекатаный круглый. Сортамент]

XXI. GOST 2591-2006 Square hot-rolled steel bars. Dimensions, [Прокат сортовой стальной горячекатаный квадратный. Сортамент]

XXII. GOST 6713-91 Low-alloyed structural rolled stock for bridge building. Specifications, [Прокат низколегированный конструкционный для мостостроения. Технические условия]

XXIII. GOST 21729-78 Cold-deformed and hot-deformed structural carbon and alloyed steel tubes. Specifications, [Трубы конструкционные холоднодеформированные и теплодеформированные из углеродистых и легированных сталей. Технические условия]

XXIV. OST 14-21-77 Carbon, low alloy and alloy steel tube ,[Заготовка трубная из углеродистых, низколегированных и легированных сталей]

XXV. GOST 7062-90 Carbon and alloyed steel forgings fabricated by press forging. Allowances and tolerances, [Поковки из углеродистой и легированной стали, изготовляемые ковкой на прессах. Припуски и допуски]

XXVI. TU 108-754-78 Sharply-bent tubes, Трубы крутоизогнутые

XXVII. GOST 977-88 Steel castings. General specifications, [Отливки стальные. Общие технические условия]

XXVIII. GOST 21357-87 Cold-resistant and wear-resistant steel castings. General specifications, [Отливки из хладостойкой и износостойкой стали. Общие технические условия]

XXIX. GOST 22703-91 Moulded pieces of automatic coupler equipment for 1520 mm gauge railway rolling stock. General specifications, [Детали литые автосцепного устройства подвижного состава железных дорог колеи 1520 мм. Общие технические условия]

XXX. TU 54.41-866-96 Castings, [Отливки]

XXXI. GOST 5632-72 High-alloy steels and corrosion-proof, heat-resisting and heat treated alloys. Grades, [Стали высоколегированные и сплавы коррозионно-стойкие, жаростойкие и жаропрочные. Марки]

XXXII. GOST 4784-97 Aluminium and wrought aluminium alloys. Grades, [Алюминий и сплавы алюминиевые деформируемые. Марки]

XXXIII. GOST 21631-76 Sheets of aluminium and aluminium alloys. Specifications, [Листы из алюминия и алюминиевых сплавов. Технические условия]

XXXIV. GOST 13726-97 Aluminium and aluminium alloys strips. Specifications, [Ленты из алюминия и алюминиевых сплавов. Технические условия]

XXXV. GOST 17232-99 Aluminium and aluminium alloys plates. Specifications, [Плиты из алюминия и алюминиевых сплавов. Технические условия]

XXXVI. GOST P 52927-2008 Rolled stock of normal, increased- and high-strength steel for shipbuilding. Specifications, [Прокат для судостроения из стали нормальной, повышенной и высокой прочности. Технические условия]

XXXVII. TU 5.961.11679-2005 Rolled weldable plates from steels of normal, increased and high strength. Specifications, [Прокат толстолистовой свариваемый из стали нормальной, повышенной и высокой прочности. Технические условия.]

XXXVIII. GOST 27772-88 Rolled products for structural steel constructions. General specifications, [Прокат для строительных стальных конструкций. Общие технические условия]