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OPTIMIZATION OF STRENGTH AND TOUGHNESS ON THE EFFECT OF THE WELDABLE HIGH STRENGTH STEELS (HSS) USED IN OFFSHORE STRUCTURES

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Abstract

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Optimization of high strength and toughness combination on the effect of weldability is very vital to be considered in offshore oil and gas industries. Having a balanced and improved high strength and toughness is very much recommended in offshore structures for an effective production and viable exploration of hydrocarbons.

This thesis aims to investigate the possibilities to improve the toughness of high strength steel. High carbon contents induce hardness and needs to be reduced for increasing toughness. The rare combination of high strength with high toughness possibilities was examined by determining the following toughening mechanism of: Heat treatment and optimal microstructure, Thermomechanical processing, Effect of welding parameters on toughness and weldability of steel.

The implementation of weldability of steels to attain high toughness for high strength in offshore structures is mostly in shipbuilding, offshore platforms, and pipelines for high operating pressures.

As a result, the toughening mechanisms suggested have benefits to the aims of the effect of high strength to high toughness of steel for efficiency, production and cost reduction.

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Sammy-Armstrong Atta-Agyemang

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List of symbols and abbreviations

σ_{ref}	Reference Stress Level
α	Ferrite
γ	Austenite
γ_{rec}	recrystallized austenite
a	Crack length parameter
A	Elongation
+AR	Supply condition ´´As Rolled``
AcC	Accelerated Cooling
A_{c1}	Lower Critical Temperature
A_{c3}	Upper Critical Temperature
A_{cm}	Upper Critical Temperature
AISI	American Iron and Steel Institute
AWS	American Welding Society
Al	Aluminium
B	Boron
C	Carbon
CGHAZ	Coarse Grain Heat Affected Zone
CEV	Carbon Equivalent Value
CE (IIW)	Carbon Equivalent
CSE	Charpy Shelf Energy

CTOD	Crack Tip Opening Displacement
CNV	Charpy V-notch
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
DWTT	Drop-Weight Tearing Test
d	Austenite grain size
EN	European Standards
FPSO	Floating Production Storage and Offloading
FGHAZ	Fine Grain Heat Affected Zone
Fe_3C	Cementite
GMAW	Gas Metal Arc Welding
HRC	Rockwell Hardness on scale C
HR	Hot Rolling
H	Hydrogen
HAZ	Heat Affected Zone
HSS	High Strength Steels
HD	Hydrogen Content
ITT	Impact Transition Temperature
I	Welding Current (Amps)
IIW	International Institute of Welding

ISO	International Organization for Standardization
J	Joule
J2	Impact Energy at Testing Temperature 20 degree Celsius.
L	Liquid
MPa	Mega Pascal (1 newton/mm^2)
M	Meter
MIG	Metal Inert Gas
M_f	Martensite Finish
MMA	Manual Metal Arc
Mn	Manganese
Mo	Molybdenum
M_S	Martensite Start
+M	Thermomechanical rolling
+N	Normalized
NL	Longitudinal Charpy V-notch impacts temp. not lower than -20
N	Nitrogen
Nb	Niobium
Ni	Nickel
P	Phosphorus
P_{cm}	Carbon Equivalent According to Ito Bessyo
PWHT	Post Welding Heat Treatment

kg	Kilogram
kJ/mm	Kilo Joule/ millimeter
Q&T	Quenched and Tempered
Q (kJ/mm)	Heat Input
QL	Quenched and Tempered+ Low notch toughness temperature
RHN	Rockwell hardness number
RHN-B	Rockwell Hardness on scale B
HRB	Rockwell Hardness on scale B
RA	Reduction of Area
S	Interlamellar spacing
S	Sulphur
Sn	Tin
SAW	Submerged Arc Welding
SMAW	Shielded Metal Arc Welding
TM	Thermomechanical
TMCP	Thermo Mechanically Controlled Processing
TMCR	Thermomechanically Controlled Rolling
t	Cementite thickness
UTS	Ultimate Tensile Stress
µ	Micro
YS	Yield Strength

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1. INTRODUCTION

It sticks out a mile that in today's oil and gas industries, the attainment of toughness for high strength steel on the effect of weldability of carbon steels pertaining to offshores structures has received considerable attention of discussion. Impact toughness is one of the most important properties associated with materials used in offshore structures to have adequate energy to resist fracture.

The improvement to achieve toughness for high strength steel used for offshore platforms increases efficiency and productivity. Besides it avoids problems of fractures resulting from Impact load, reduces repair and rework of welding, waste materials would be avoided, which saves cost and time. This causes flexibility, less work done and gives chance for continuous progress and effectiveness.

However, these properties are generally mutually in compatible, even though it is known that in mechanical behaviors of steels carbon plays a dominant role, there is some uncertainty aspect of its microstructural and micromechanical mechanisms. It is notably that while increasing the tensile strength of steel by raising its carbon content, its toughness obviously reduces as well as its weldability and thereby limiting the extent of applications of structural steels [1, 2]. In ferrite-pearlite steel, it may be attributed to the formation of carbides, and some elements which forbids dislocations from moving which induces the crack nucleation [2]. Catastrophic failures are caused by inadequate strength, poor weldability and toughness characteristics of a given material, including both its impact and fracture toughness.

An approach to overcome this problem or the possibility of improving the toughness of steel has been examined by considering several relevant factors. Chapter 2 and 3 reviews types of offshore structures, mechanical properties of steel, environmental conditions in offshore, applications of structural steel used in offshore. Chapter 4 examines the effects of carbon content on toughness of steel and weld. Chapter 5 is also about how to increase the toughening mechanisms of high strength steels. The rest of the chapters examine the effects of welding parameters on toughness and weldability, cracking. Testing methods for fracture toughness including CVN, CTOD, and DWT have been discussed as well.

1.1. Delimitations

This thesis provides an overview of offshore platforms structures. The main material is focus on high carbon steels because of its detrimental effect on toughness of steel resulting from increasing carbon content.

1.2. Aim of the research work

- This research is to compare different High strength steels (HSS) and their usability in welded structures.
- To develop the understanding of toughening mechanism of carbon steels and find the best ways to improve its toughness.
- Also understanding of fracture toughness behavior of carbon steels by knowing what happens, when they do occur by some impact tests methods.
- The effects of welding parameters in achieving a sound weld which is weld defect free such as hydrogen induced cracking.

1.3. History of Offshore hydrocarbon exploration

The rising and establishment of offshore hydrocarbon exploration has driven high interest in oil and gas business today. This has resulted into economic and technical characteristics which are directly related to global investment. The history behind the today global investment in offshore is shortly discussed.

Offshore drilling typically refers to the extraction of oil and gas resources which lie underwater. Also the term describes oil extraction off the coasts of continents, which also applies to drilling in lakes and inland seas [3]. In 1896, the exploration of offshore drilling for oil began off the coast of Summerfield, California, United States. Californian piers were the first offshore platforms for petroleum production. By 1897 this first offshore well was producing oil and 22 companies soon joined in the boom, constructing 14 more piers and over 400 wells within the next five years [4]. About 50 years later, Kerr-McGee oil industries started their first productive drilling in water depth of about 6 meters off the coast of

Louisiana. And during that time wooden drilling structures which were previously used was replaced by steel drilling structures in Summerfield. This replacement improved the structural integrity for rigs and at lower costs as compared to the life of the well. Companies such as Shell and Texaco were the first to use barge drilling, which is towing small mobile platforms to locations where there is oil drilling prospect. In the 1980s the offshore oil and gas explorations and production became more uneconomically viable for shallow water drilling than deep water. This was due to the fact that shallow water exploration posed some challenges like seismic limitations and highly gas prone shelf but beneficial in deeper waters to the greater exploration for larger fields. More significant discoveries in the 1980s developed into producing wells in the 1990s, in deep water Gulf of Mexico. In five years later, deep water rigs worked farther off the coast was producing twice as much as shallow water. An increasing amount of oil was coming from ultra-deep water (1524 m and deeper). Floating platforms made in the 1970s, including semisubmersibles, tension leg platform FPSOs and other structures keeping them above water for drilling deeper turn out to be even better than imagined [5]. Figure 1 shows the federal offshore oil production in the Gulf of Mexico from 1984 to 2009. It illustrates the depth of water throughout every year that amount of barrels of oil drilled and produced. An increasing amount of oil was coming from ultra-deep water (1524 m and deeper) with maximum barrels of oil production. Figure 2 shows world history of oil offshore [6].

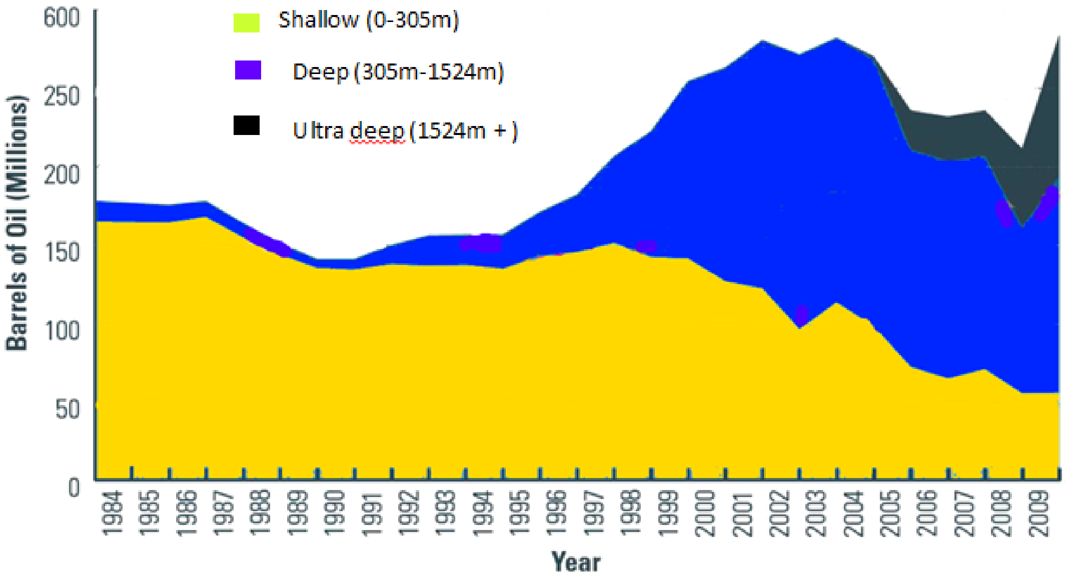


Figure 1 Federal Offshore Oil Production in the Gulf of Mexico [5].

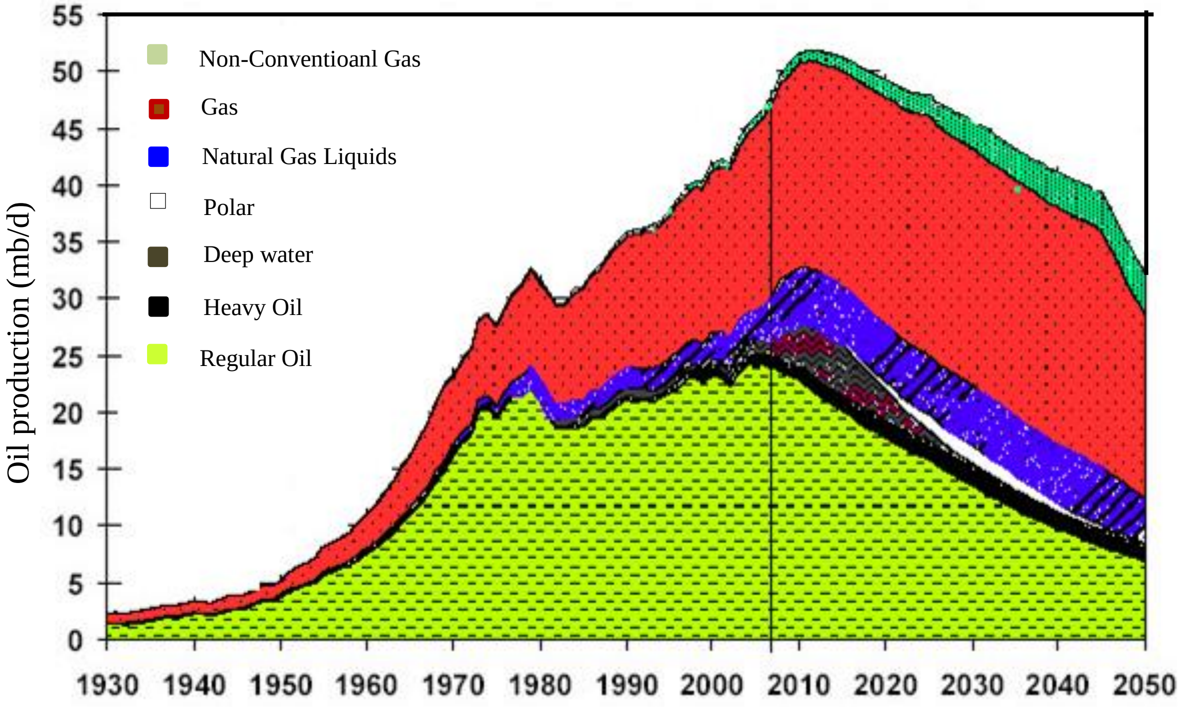


Figure 2 Shows future of worldwide oil and gas production [6, 7].

2. TYPES OF OFFSHORE STRUCTURES

Offshore platforms are used for exploration of oil and gas from under seabed and processing. There are two classifications; fixed and movable structures and each has a number of sub-categories as shown in Table 1. Fixed structures are those extended to the seabed for a long period of time throughout the service of life. The movable structures can be moved from one location to another, float, near the water. The jacket is the most platforms among the offshore structures used in oil and gas industries because it carries production platform with high payload. The Offshore platforms of fixed and movable structures used in oil and gas industries are respectively shown in figure 3 and 4.

Table1 Categories of fixed and floating offshore structures - their uses, advantages and disadvantages [8, 9, 10, 11, 12, 13].

Structure Sub-categories	Uses	Advantages	Disadvantages
Fixed Structures			
Jacket	It provides deck space and supports the foundation piles, conductors, risers.	All have good Stable working environment. The compliant towers use flex legs which reduces resonance and wave forces.	Long lead time. Material cost raises quite sensitive to water depth as its depth increases. It is not economical or practical to have long legs built.
Gravity base	It is a base which supports several vertical columns which supports a deck carrying production facilities.		
Compliant Tower	Its flexibility is enough that the applied forces transmitted to the platform is reduced or resisted. For moderate depths of water 500m-900m.		
Movable Structures			
Tension- Leg platform	Can operate as Ultra deep water.	Ease of relocating and reusing.	Limited payload capacity and lack of storage capability.
Semisubmersible	Used for Ultra deep water about 60m-3,050m		
Spar	Used for ultra-deep water. It supports drilling and production activities simultaneously.		
Jack up	They are used mainly as Drilling units.		
FPSO	Floating production unit for Shallow and deep water.		

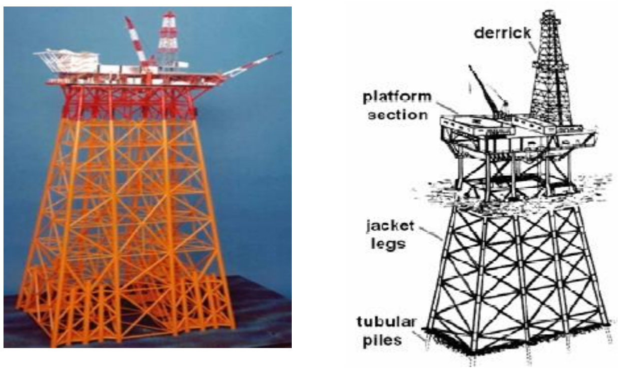
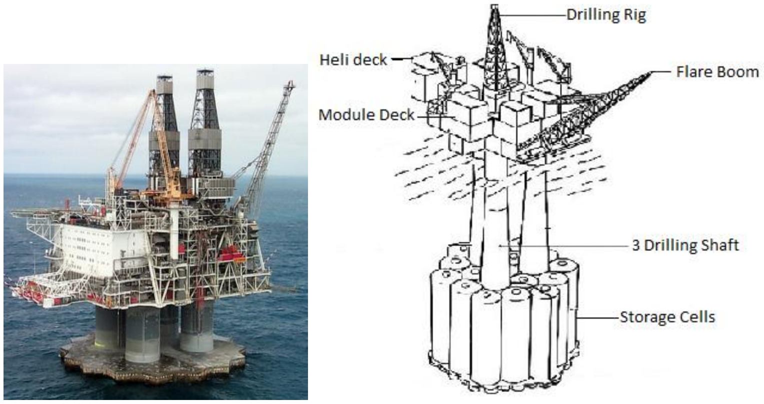
Jacket	
Gravity Base	
Compliant Tower	

Figure 3 Pictures of fixed offshore platforms [8, 9].

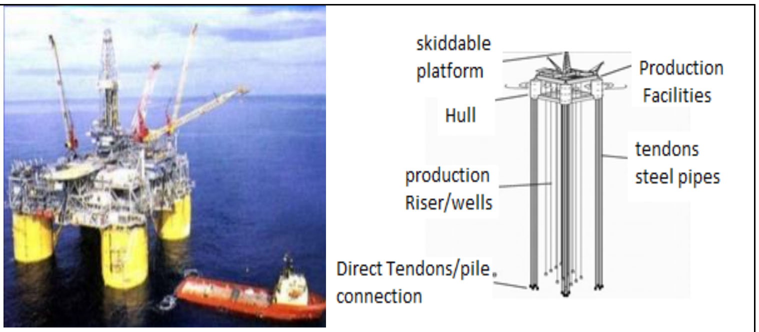
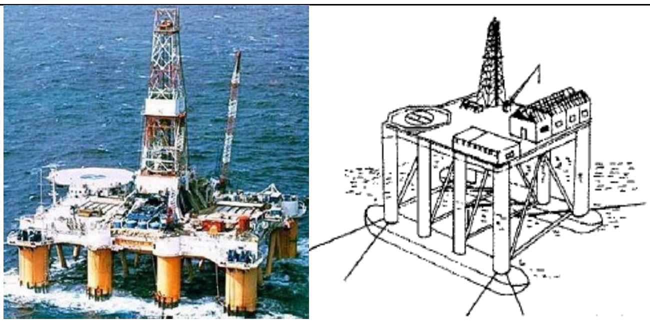
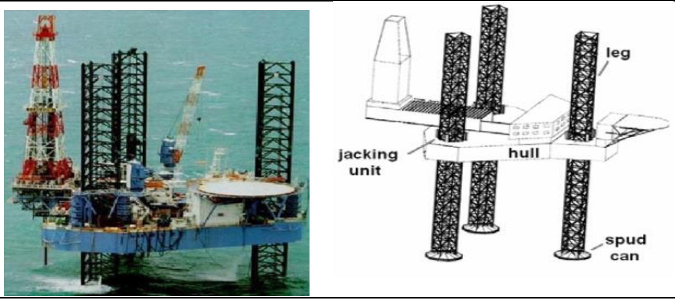
<table>
<tr><td>Tension- Leg platform</td><td> </td></tr>
<tr><td>Semi-submersible</td><td></td></tr>
<tr><td>Jack up</td><td> </td></tr>
<tr><td>Spar
</td><td>FPSO
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Figure 4 Pictures of Movable offshore platforms [8, 9].

2.1. Environmental Loads in offshore structures

Materials like high strength steels required for offshore structures have to respond properly to its environmental impacts and conditions to exhibit satisfactory weldability characteristics and toughness property. Also for a proper production welding it has to be done under conditions where welding site is protected against detrimental effect of the environment. The environmental factors which act as a limit against long service life of offshore structures and its performance of operation, including transportation, installation, offloading and construction are explained below [11]:

Earth quake: Earth quake phenomena including liquefaction of substance soils, submarine slide, tsunamis and acoustic overpressure shock waves cause ground motion which is problematic to the strength and ductility during the expected life of the structures. These effects on structures located in areas where seismic is active are to be considered [11].

Air temperature: Environmental conditions such as applicable for strength and ductility level needs to be considered because the air and sea temperatures affect the properties of the material [11].

Ice and snow: Offshore structures to be installed especially in artic areas where ice and snow may increase estimates are to be made to the extent to which ice and snow may accumulate on the structures. Large masses like moving icebergs impact a structure and broken ice in moving past the structure are considered as well for the sake of toughness failure [11].

Marine growth: This marine fouling ever occurrence should be considered as well which induces increased forced in motion of sea, hydrodynamic loading due to increase in tubular diameter, surface roughness of members as seen in figure 5. Inspection is carried out to prevent the presence of this marine growth [11, 14].

Figure 5 Marine growth found around offshore platforms [15].

Wind and waves: The dynamic effects of impacts of wind speed and water propagation forces on offshore structures due to cyclical loads induced vibration are to be considered when designing the structures [11].

Water depth at location: The water depth, which is the distance between the seabed and the fluctuating components, must be taken into account due to storm surges, and rise and fall of the water sea [11].

2.2. General properties of plain carbon steel

Steels are alloys of iron and carbon which contains no more than 2% of carbon content with or without other alloy element. Steels which contain only carbon as its alloying element are known as carbon steels. These carbon steels can also contain iron, carbon, less than 1,65% but up to 1,2% manganese, less than 0.6% copper and small amount of silicon, sulphur and phosphorus. In Table 2, carbon steels are classified by chemical composition into four groups.

Table 2 Classification of carbon steels based on carbon content [16, 17, 18, 19].

	% of carbon steels content	Properties
Low-carbon steel	carbon < 0,3	Ductile and soft, good weldability, and good toughness values. Usually bends or deforms.
Medium carbon steel	0.3 < carbon < 0.6	Relatively good strength, moderate ductility as compared to low carbon. Weldability is good.
High-carbon steel	carbon > 0.6	High strength, least ductility, more difficult to weld as compared to low and medium steel. Usually crack under stress. Decreased toughness and poor weldability.
Extra-high carbon steel	Range from 1.25 to 2,0	Seldom welded and metal must be heated before, during and after.

Figure 6 shows macrograph of typical low-carbon, medium-carbon, and high-carbon steels respectively. Each of the micrograph shows the microstructures of ferrite and pearlite phases in the subclasses of plain carbon steels according to the carbon content present [20].

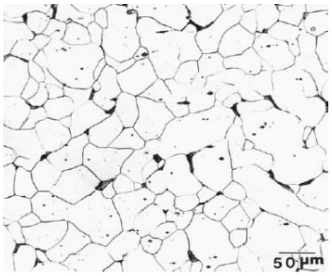
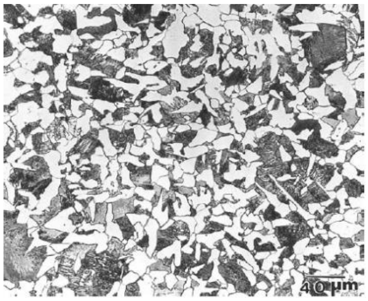
 (a) Micrograph a) is low carbon steel. The white areas are ferrite grains and darker parts are pearlite.	 (b) Micrograph a) is medium carbon steel. The white and dark areas are ferrite grains and pearlite.	 (c) Micrograph c) is high carbon steel showing a matrix of pearlite and some grain-boundary cementite.

Figure 6 Macrograph of low carbon, medium carbon, and high carbon steels [21].

2.2.1. Mechanical properties of carbon steels

The mechanical properties that may be considered more are those that relate its ability to resist external mechanical forces such as sudden impact, bending and twisting. Steels being one of the principal materials used for offshore structures have some features to assure a proper performance under both service and extreme loads. Characteristics and reasons required imposed on the material to perform in offshore environment when subjected to impact conditions over a wide range of temperatures are shown in Table 3.

Table 3 Properties of steels for structural uses in offshore construction and application [22, 23, 24].

Properties	Reason
Ductility	Ability to deform after yielding
Light weight	For high strength
Weldability	Easy to weld and achieve good welds
Impact strength	Notch toughness at low temperature
Shear strength	Prevents sudden fracture
Young modulus	Resistance to deformation

2.2.2. The relationship between strength and toughness

Strength: The word strength is the force per unit area in the field of metals, as in high strength steels refers to the ability of the material to resist outside forces that are trying to break it. That is how much energy it can absorb before failure. Material strength is a combination of mechanical properties such as tensile strength, yield strength, ductility, elasticity and creep resistance.

Toughness: The ability of a metal to absorb energy when there is a sudden impact before fracture is termed as toughness; that is, ability to absorb energy in the plastic range. The tougher the material, the more energy required to cause a crack to grow to fracture. Remember that ductility is a measure of degree of material plastically deform before it fractures, but just because the material is ductile does not make it tough. Impact toughness and percentage elongation are the measures of toughness. It is an established fact that elongation and toughness are proportional to each other: the higher the elongation, the greater the toughness and vice versa [25]. Toughness also depends on carbon content, grain size and inclusion.

Toughness is the combination of both strength and ductility, a material with high strength and high ductility will have high toughness than a material with low strength with high ductility as seen in figure 7.

Strength versus toughness: Toughness falls as strength increases in all cases except where there is toughening mechanism like grain-size reduction, thermomechanical treatment, heat treatment which will increase strength and toughness simultaneously. Strength is of no or little used without toughness and there is kind tradeoff between the two [26, 27, 28].

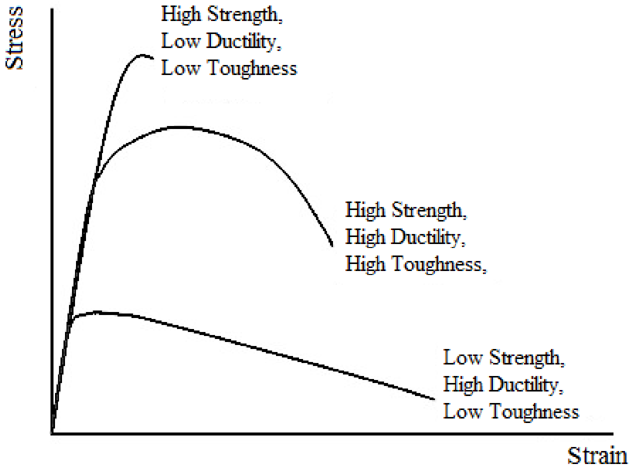


Figure 7 Tensile toughness under stress-strain curve [29].

3. DEVELOPMENT OF HIGH STRENGTH STEELS USED FOR OFFSHORE STRUCTURES

The demand and production of development of high strength steel grades with yield strength and toughness as well as good weldability are determined.

3.1. Chronology and production processes for rolled steels

Toughness as well as weldability is associated with on one hand, quenched and tempered steels with very high yield strengths (460Q/QL, S690Q, S890Q, S960Q) and on the other hand by thermomechanically rolled steels with a more moderate yield strength, but higher toughness (S355M, S460M and S550M). By normalising steel grades with moderate strength and toughness requirements usually ≤ S460N can be produced. The chronology of structural steels during the last decades is illustrated in figure 8.

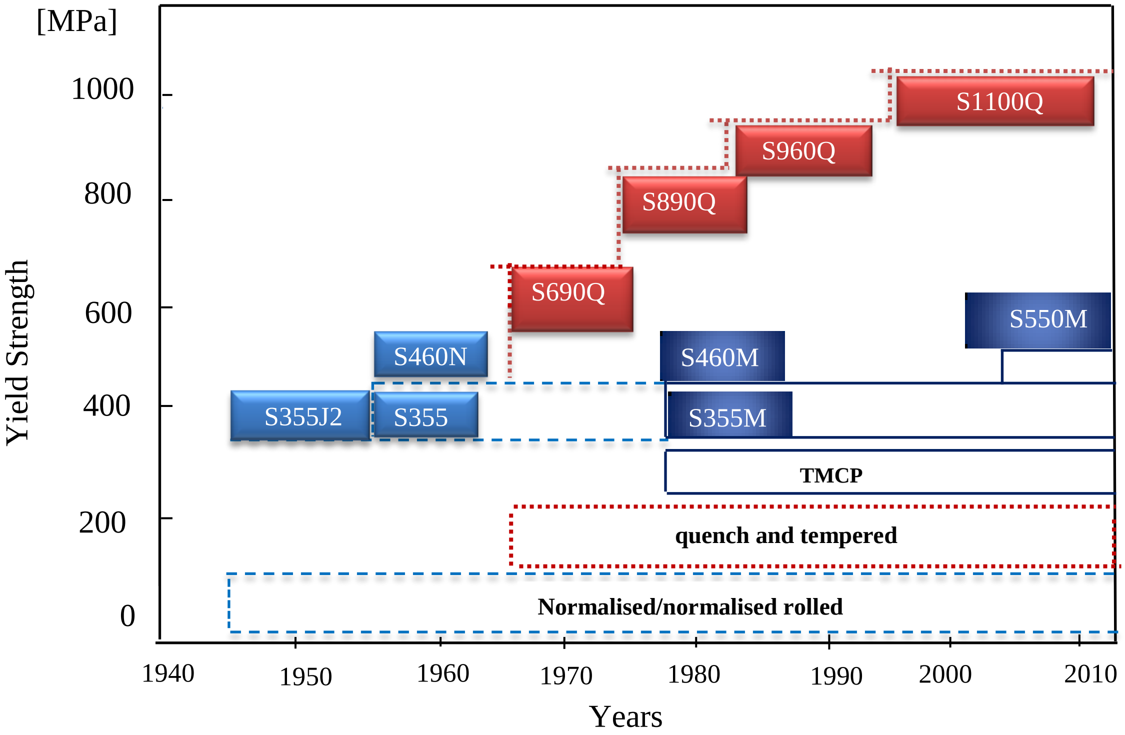


Figure 8 Chronology of structural steels of specific steel grade and its level of strengths [30, 31, 32, 33, 34]

3.2. Applications of High strength steels in offshore structures

Modern offshore steel plates for platform structures and other equipment are generally made of various grades of steel, from high to higher strength steel. They serve a variety of functions, in a variety of water depths, monitoring systems and other sensors. Below are the applications in ships and, oil and gas platforms below:

- Higher strength steels (>550MPa) are usually produced by the Q&T route and are used in mobile jack-up drilling rigs to minimize weight during the transportation stage [35].
- Used in mooring attachments for floating structures such as (TLPs) with a minimum yield strength of 795MPa [36] and provide adequate fracture toughness. Also resistance to both stress corrosion cracking and corrosion fatigue.
- Other floating structures such as semi-submersibles used welded higher strength steel anchor chains or wire ropes as their mooring attachments [37].
- Application of very high strength steels in the fabrication of jack-ups, in legs, rack and pinions and spud cans [37].

Table 4 shows the High strength steel ranges and process routes for high strength steels used in offshore structures applications.

Table 4 High strength steels used in offshore [37]**.**

Strength MPa (grade)	Process Route	Application Area
350- 500	N, TMCP	Jacket structures and topsides
550	Q&T	Structures & Moorings
550-800	Q&T	Jack-ups & Moorings, fabrication of legs, rack and pinions and spud cans.

- Used for exploration and extraction of oil and gas production.
- Used for platform structures serve as loading and unloading.
- Pressure equipment.
- Storage tanks.

- Machinery parts.
- Ice-breakers and ice-going vessels.
- Used for navigation, and to support bridges and causeways services [38, 39, 40].
- TMCP – steels used for offshore platforms of this kind of application is shown in figure 9 Valhall-Platform, Aker Kvaerner Norway.

Figure 9 Valhall-Platform [34].

Another example of TMCP – steels application is the Mayflower TIV ship for erection of offshore windmills of 500 MPa built by Chinese Shipyard as shown in figure 10.

Figure 10 The Mayflower TIV- Offshore windmill constructed [41].

3.3. Processing methods of steels

Most high to higher strength steels are produced today by thermomechanical controlled processing (TMCP), quenching and tempering (Q&T), and direct quenching (DQ) [42]. The process route is to determine the strength of steel controlled by its microstructure. High strength steels available for thick sections (30 – 100 mm) for offshore must exhibit good weldability toughness to avoid the possibility of brittle failure. Production of some higher strength levels may be restricted to TMCP steels due to very high processing thickness but would be production route for Q&T. The choice of steel with high strength but excellent weldability and toughness is achieved by controlled and thermal processing properties.

Structural steel plate is available in many grades and variations designed for use in harsh environments such as offshore structures. An example of steel plates within European standard structural steel of EN 10025: 2004 shows in figure 11.

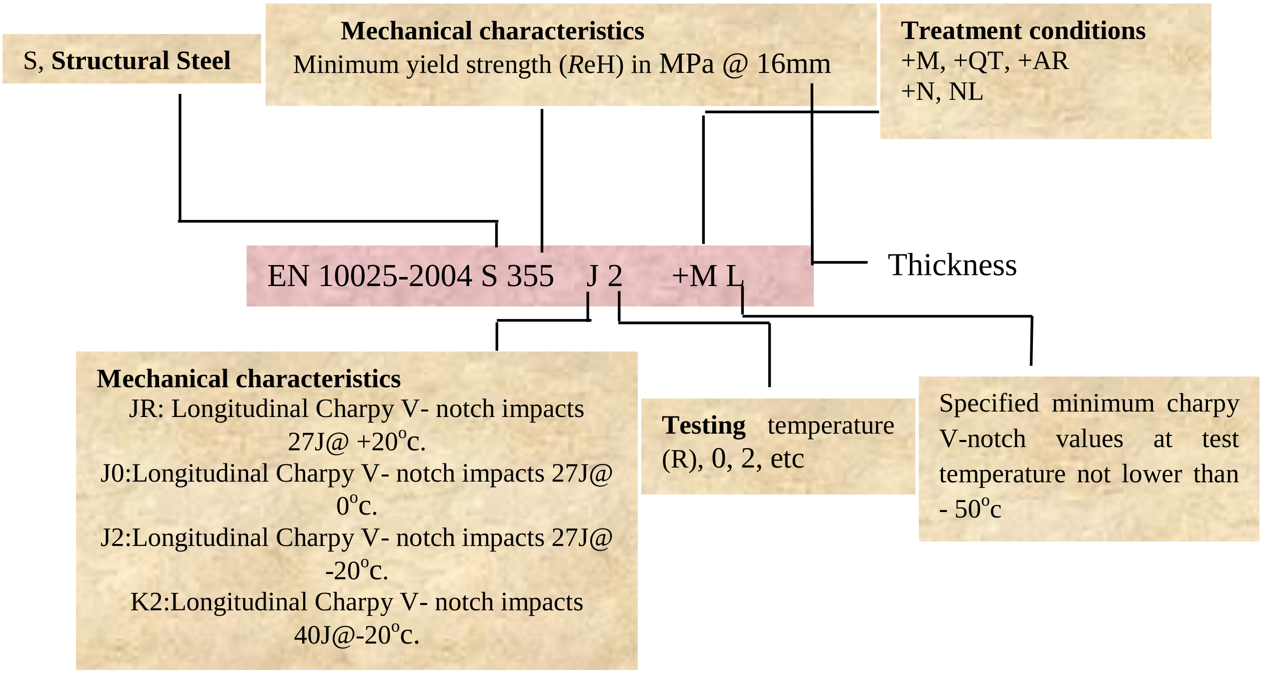


Figure 11 Explanation of symbols used in EN 10025 for structural steel [43].

Plates of G1 to G6 within EN 10225 are designated as group 1 steels, G7 are designated as group 2 steels while the G8-G10 are designated as group 3 steels. The letter G is followed by a maximum of two digits characterizing and indicating the steel grade. An example mechanical properties and chemical composition of offshore steel plate is shown in Table 5.

Table 5 Mechanical properties of S460G1 [44].

S460G1						
Thickness for all grades (mm)	≤16	>16≤25	>25≤40	>40≤63	>63≤80	>80≤100
Yield strength MPa	460	440	420	415	405	400
Tensile strength MPa	540/700	530/690	520/680	515/675	505/665	500/660
Elongation A (%)	17					
Impact energy	60 J at -40°C					

3.4. Metallurgical and Chemical consideration

The chemical composition of offshore steels is very important since it regulates the mechanical properties of the steel material. Therefore it has influenced between strength, toughness and weldability of steel [45]. In the following Tables 6, 7, 8 are the chemical compositions showing an overview over steels grades suitable for applications in offshore structures. Some typical impact toughness requirement in used today for high strength applications is 40J at –40 ^{o}C (for offshore constructions). Temperature requirements are normally set at least 30^{o}C below the expected service temperature in many applications [46, 47].

Table 6 Typical composition and mechanical properties of normalised steels produced in Europe – yield strength range 360 to 460MPa [37].

Thickness	Typical composition (by weight %)												CEV	Typical mechanical yield strength/CVN range
(mm)	C	Mn	Si	S	P	Nb	V	Al	Cu	Ni	Cr	Mo		
25	0.20	1.35	0.42	0.016	0.015	0.028	_	0.022	_	_	_	_	0.43	360MPa/70J@-40°C
20	0.22	1.0-1.6	0.55	0.030 max	0.035	_	_	_	0.3	0.5-0.7	0.2	0.1	0.52	420MPa/70J@-0°C
20	0.22	1.6	<0.6	0.04 max	0.04	0.003 -0.10	0.003-0.20	_	_	_	_	_	0.49	450MPa/60J@-40°C
30	0.13	1.52	0.49	0.005	0.015	0.03	-0.20	0.02	0.45	0.72	_	_	0.50	460MPa/>110J@ -20°C

Table 7 Typical chemical composition and mechanical properties of thermomechanical controlled processed steel – yield strength range 400 to 500MPa, typical average plate thickness 30mm [37].

Thickness	Typical composition (by weight %)											CEV	Typical mechanical yield strength/CVN range
(mm)	C	Mn	Si	S	P	Nb	V	Al	Cu	Ni	Cr		
30	0.10	1.33	0.28	0.002	0.015	0.027	-	-	-	-	-	0.35	400MPa/190J@ -40°C
<32	0.12	1.35	0.30	-	-	-	-	-	0.01	0.02	-	-	398MPa/300J@ -20°C
32	0.07	1.45	0.27	0.001	0.004	-	0.01	0.07	0.19	0.4	-	0.32	400MPa/>300J @-20°C
30	0.04	1.52	0.22	0.003	0.005	-	-	-	0.60	0.49	0.02	0.37	460MPa/220J@ -40°C
30	0.09	1.50	0.3	0.001	0.007		0.04	0.03		-	-	0.35	500MPa/300J@ -30^{0}C

Table 8 Typical chemical composition and mechanical properties of quenched and tempered steels – yield strength range from 460 to 1000MPa [37].

Thickness	Typical composition (by weight %)													CEV	Typical mechanical yield strength/CVN range
(mm)	C	Mn	Si	S	P	Nb	V	Al	Cu	Ni	Cr	Mo	B		
6-140	0.18	0.1-0.4	0.15-0.35	0.075	0.015	–	<0.02	0.015	<0.2	2.25-3.25	1-1.8	0.2-0.6	–	0.81	550-690MPa/80J @ - 40 ^{o}C
–	0.2	0.1-0.4	0.15-0.35	0.254	0.025	0.03	–	–	0.25	2.25-3.25	1-1.8	–	–	0.7	690MPa minimum
30	0.10	1.6	0.50	0.005	0.015	0.03	_	_	0.35	0.50	0.15	_	_	0.45	450MPa/>35J@-40^{o}C
50-64	0.12	1.50	0.4	0.005	0.020	–	0.06	_	0.15	0.30	0.10	_	_	0.43	480MPa/>50J@-40°C
50	0.11	0.89	0.26	0.003	0.008	0.02	0.01	0.07	0.15	1.18	0.46	0.38	0.002	0.64	690MPa/>40J@-40°C
30	0.17	1.2	0.26	_	_	_	_	_	_	1.5	0.49	0.5	0.002	0.64	960MPa/>40J@-40°C

4. FACTORS AFFECTING THE WELDABILITY AND TOUGHNESS OF STEELS

The mechanical properties such as ductility, toughness, and its weldability of carbon steel can be influenced by the effect of the following: trace elements, carbon content, pearlitic microstructure and other variables that reduce aforementioned properties in offshore structures.

4.1. Effect of trace elements on steel

Carbon steels contain small amount of residual element also termed as trace element which are undesirable and have negative impacts on steel. Actually in plain carbon steels silicon and manganese are not considered undesirable elements because they present in small amounts [17]. At excessive amounts of alloying elements decrease the impact toughness [48]. The descriptions of the elements as well as their bad effects they cause on steel which reduces weldability and toughness are as follows:

- Increased quantity of carbon and manganese impact higher tensile and yield properties, low ductility, embrittlement, low weldability [49, 50].

- Increased sulphur and phosphorus increase strength, impacts brittleness, which gives low weldability, hot cracking, reduces ductility and impact toughness of steel [49, 50].

- Increased quantity of silicon lowers ductility transition temperature, but also reduces weldability.

- Hydrogen and Oxygen cause brittleness, decrease ductility and toughness of steel [51, 52, 53]. In the case of oxygen is shown in figure 12.

- Nitrogen also a harmful trace element leads to embrittlement which causes a decrease in impact toughness of the steel [51, 52, 53].

- Problems of toughness can also be caused by Sn and reduced plasticity due to inclusions existence [54, 55].
- Copper content in steel may be relatively beneficial to low temperature notch toughness when not undergone precipitation hardening. However, copper produces precipitation hardening and promotes hardness and tensile strength which as a result, may adversely affect toughness [56, 57].

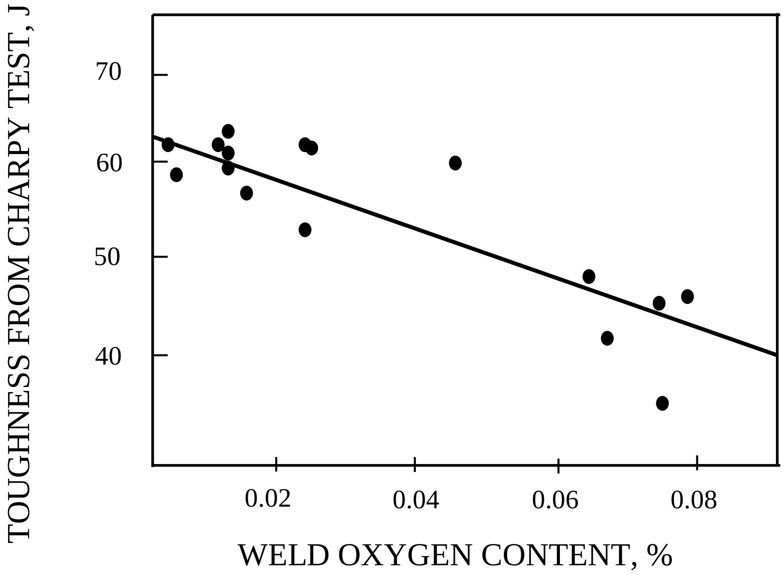


Figure 12 Relationship between the toughness at 20°C and the oxygen content of carbon steel welds [53].

4.2. The effect of pearlitic microstructure on mechanical properties of carbon steel

The effect of toughness of steels also depends on interlamellar spacing, *s,* austenite grain size, *d*, pearlite colony size, and cementite thickness, *t* which are pearlitic microstructures.

The effect of interlamellar spacing on UTS, ductility, impact toughness of high carbon steel is examined [25]. Pearlite inter-lamellar spacing *S,* is the distance from the center of a ferrite or (cementite) plate to the center of the next ferrite or cementite plate in other words the distance between adjacent cementite lamellar, referred to as the interlamellar spacing [58, 59]. Lamellar structure pearlite is made up of ferrite and cementite. Interlamellar spacing is a function of transformation temperature alone so the smaller the transformation temperature the smaller the interlamellar spacing, the stronger the steel [60]. Thick cementite in coarse pearlite shows very low ductility and fracture easily, whereas in fine pearlite the thin cementite appears to be ductile and improves toughness [61, 62]. Ferrite-pearlite steels, the pearlite phase govern the strength while the ferrite phase controls the ductility [25].

The pearlitic microstructure, including interlamellar spacing, nodule and colony size play an important role in controlling the strength, ductility, and toughness in high carbon steels [59]. However, the colons size is not an influential microstructure to control the strength, toughness, or ductility [63]. Figure 13 shows a pearlitic microstructure.

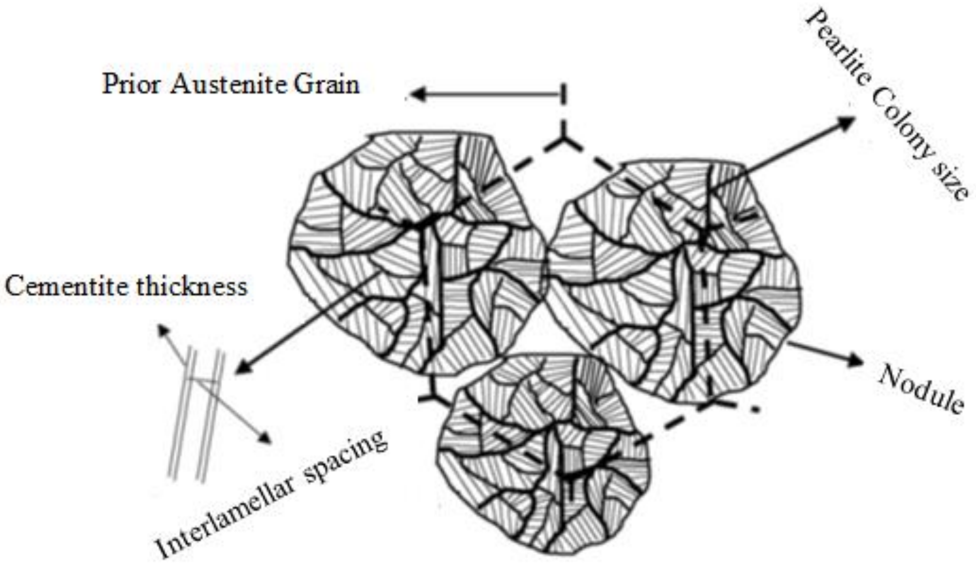


Figure 13 Schematic diagram illustrating the constituents in the pearlitic microstructure [59].

O.P. Modi et al [25] conducted an experiment to examine the effect of interlamellar spacing on UTS, impact toughness and ductility of a 0,65% C hypo- (near-) eutectoid steel. The steel was heat-treated at five different austenitization temperatures in order to vary the interlamellar spacing for a fixed duration of 1h, after which they were cooled in the furnace. The conclusions on the effect of interlamellar spacing on aforementioned mechanical properties are discussed below:

The UTS of the steel samples are plotted as functions of the inverse of the square root of the interlamellar spacing ($S^{-1/2}$) in figure 14. UTS increases linearly up to a certain value of $S^{-1/2}$ (i.e., 38mm $^{-1/2}$) but does not at values greater than 38mm $^{-1/2}$. The UTS of steel increases with a decrease in interlamellar spacing as values of $S^{-1/2}$ increases. It is indicated that up to a critical point the interlamellar spacing decreases further even though there is no additional increase in UTS [25].

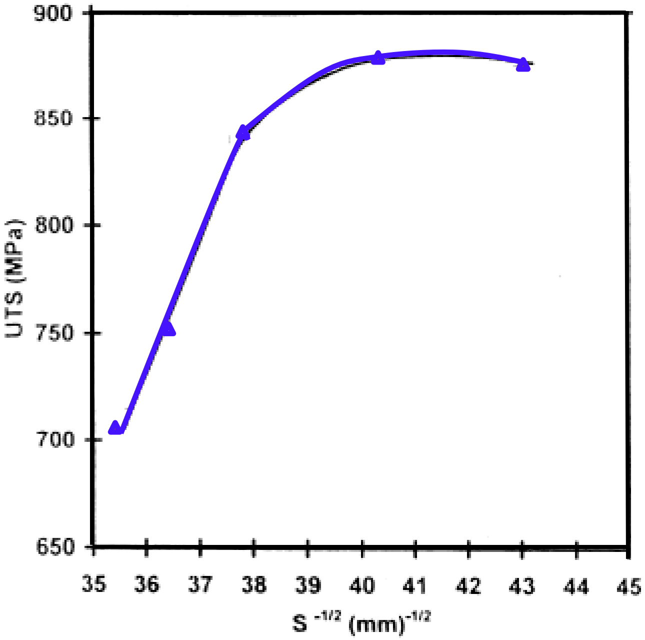


Figure 14 The variation in UTS of steel vs of the inverse of the square root of the interlamellar spacing, S [25].

O.P Modi et al [25] concluded that effect of interlamellar spacing on UTS is that ferrite in pearlite which is soft also deformes during the course of pearlite defomation. The plastic deformation is associated with free movement of dislocations. As a result, when the interlamellar spacing is large, there is large a number of dislocation movement interacting with each other in the ferrite zone and this causes restriction in their movement. This causes ferrite phase to be hardened which in turn increases the UTS and reduces ductility and impact toughness. The ferrite in pearlite becomes completely hardened at the point $S^{-1/2}$ equal to 40 mm$^{-1/2}$. This complete hardening of the ferrite in the lamellar structure leads to a quick crack initiation [25].

With respect to elongation and impact toughness it can be seen in figure 15 that the elongation is reduced marginally with an increase value to 37 mm $S^{-1/2}$ (i.e., S = 735 nm). However, the elongation values decreases suddenly with a further increase in $S^{-1/2}$ from 37 to 40 mm $S^{-1/2}$. The elongation remains constant for $S^{-1/2}$ values greater than 40 mm $S^{-1/2}$. By comparison, the impact toughness is reduced monotonically with increases in $S^{-1/2}$ up to 40 mm $S^{-1/2}$. Above this value, the toughness remains practically unchanged as $S^{-1/2}$ values increase. It is a fact that elongation and toughness are proportional to each other, the higher the elongation the greater the toughness and vice versa. As the values of $S^{-1/2}$ increases the toughness and ductility decreases resulting in an easy crack initiation [25].

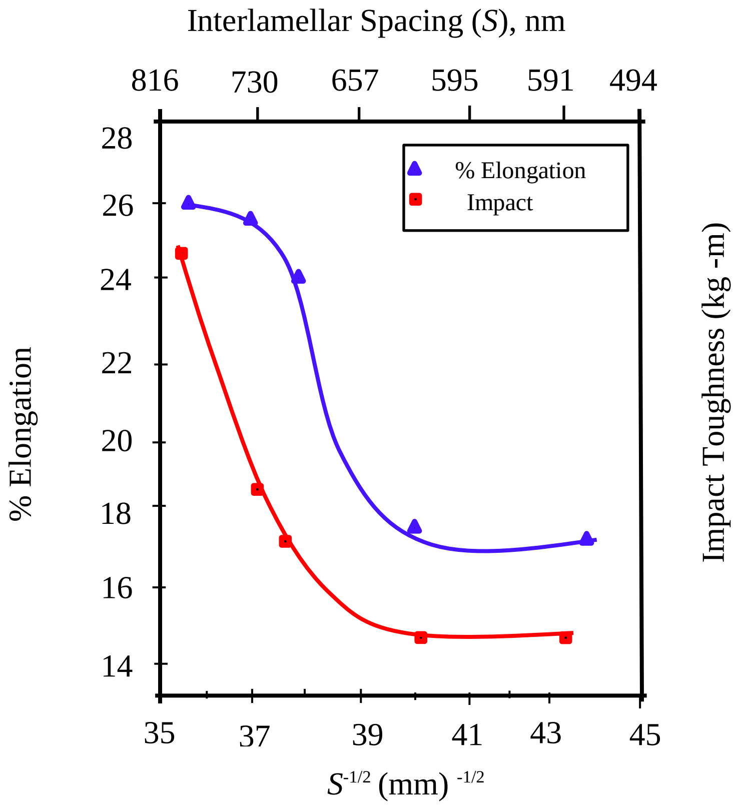


Figure 15 The variation of percent elongation and impact toughness vs. inverse of the square roots of the interlamellar spacing, *S* [25].

It can be concluded by [25] that the effect of interlamellar spacing on impact toughness and ductility decreases with decreasing *S* (as values of $S^{-1/2}$ increases) but when the value of $S^{-1/2} <$ 38 $mm^{-1/2}$ (*S* is greater than 712 nm) saturation of work hardening of the ferrite does not occur so elongation and impact toughness increases. However when *S* is less than 712 nm and becomes low enough (i.e. increasing $S^{-1/2}$) hardness saturation is reached in the ferrite. The ferrite becomes hard enough and this might results in easy crack initiation at the ferrite and cementite interface [25].

Interlamellar spacing is not adequately to explain the behavior of RA in steels [61] because it depends also on the function of transformation temperature. A decrease in transformation temperature was observed to decrease the interlamellar spacing which improves ductility [60, 64]**.** This explains the H.J Sim et al in their experiment.

H. J. Sim et al [61] investigated; figure 16 that the increase of interlamellar spacing, due to high transformation temperatures, causes a monotonous drop in RA for high carbon steel C as compared to medium carbon A and B steels. RA is a reduction area which is a measure of ductility [61].

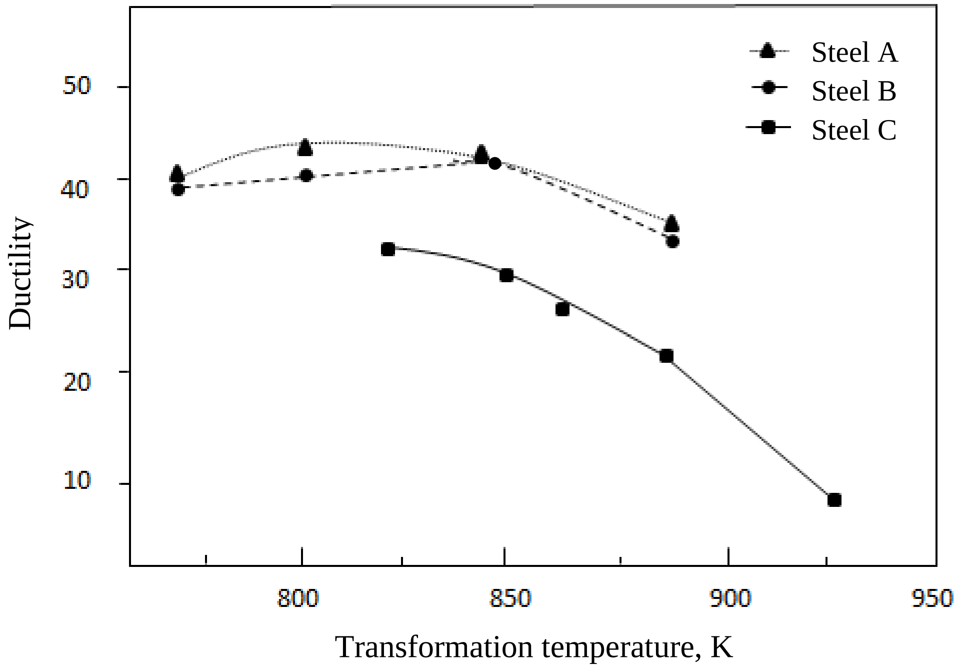


Figure 16 Variation of ductility with transformation temperature in steel [61].

Due to high transformation temperature with increasing interlamellar spacing the high carbon steel C ductility decreases completely while the other steels A and B 5.5% C also slightly decreases as shown in figure 17. The smaller the interlamellar spacing, the higher the ductility and thereby making the steel stronger [61].

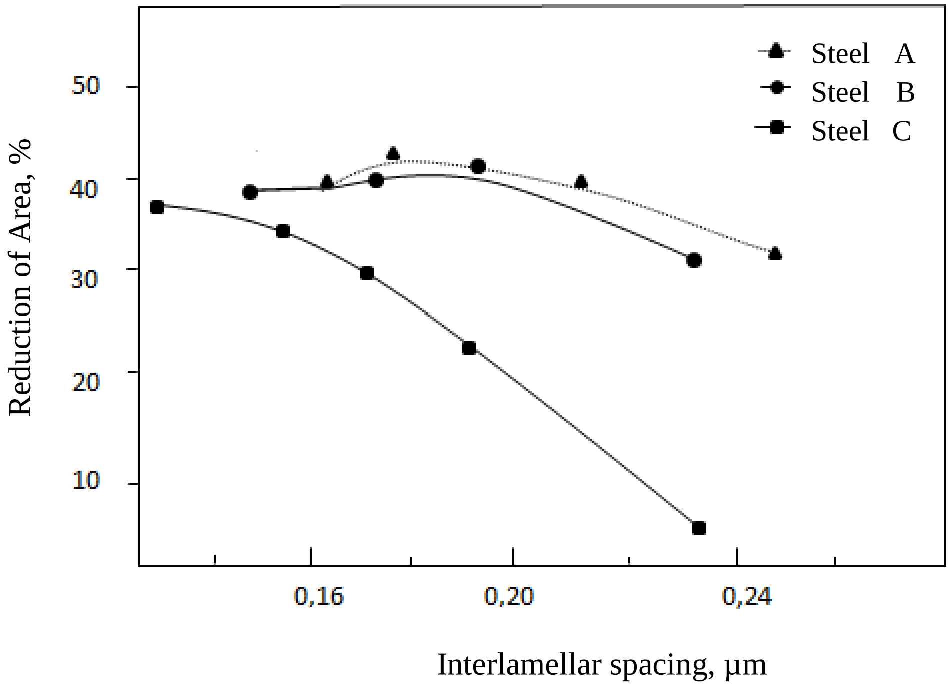


Figure 17 Variation of RA as a function of interlamellar spacing in pearlite [61].

According to *Nakase and Bernstein* [63] investigation, the role of pearlitic structure and their effect of microstructure on strength and resistance to brittle and ductile fracture in carbon steels, concluded that:

- Yield and tensile strength depends on the *S*, *d*, and pearlite colony size which is not an influential microstructural in controlling the strength and toughness [63].
- For ductile fracture, *d* again has the strongest influence with *S*: a decrease in both improves ductility and toughness [63].

The pearlite colony size which is not an influential microstructural in controlling the strength and toughness or ductility [63] by *Nakase and Bernstein* is contravened and corrected by *Gladman et al*. [65] indicating that the refinement of the pearlite colony structure that can occur with decreasing transformation temperature can also contribute to an improvement in the toughness of high carbon steels through the pearlite colony boundaries acting as hindrance to brittle crack propagation. It should also be noted that the cementite thickness decreases with decreased in transformation temperature reduces brittleness which improves impact toughness.

4.3. Effect of carbon content on toughness of steel and weld

Figure 18 shows general variation in mechanical properties of carbon steel as a function of carbon content. Carbon steels contain higher amount of pearlite which has higher tensile strength, more hardness than ferrite and due to that there are some variations in the mechanical properties. The ductility decreases with increasing carbon content and its obviously nil as it goes beyond 1.25% C. Recall that a similar relation to ductility holds true for impact strength also and as hardness increases weldability and toughness decrease as well. The yield and tensile strengths increase with increasing carbon content [17].

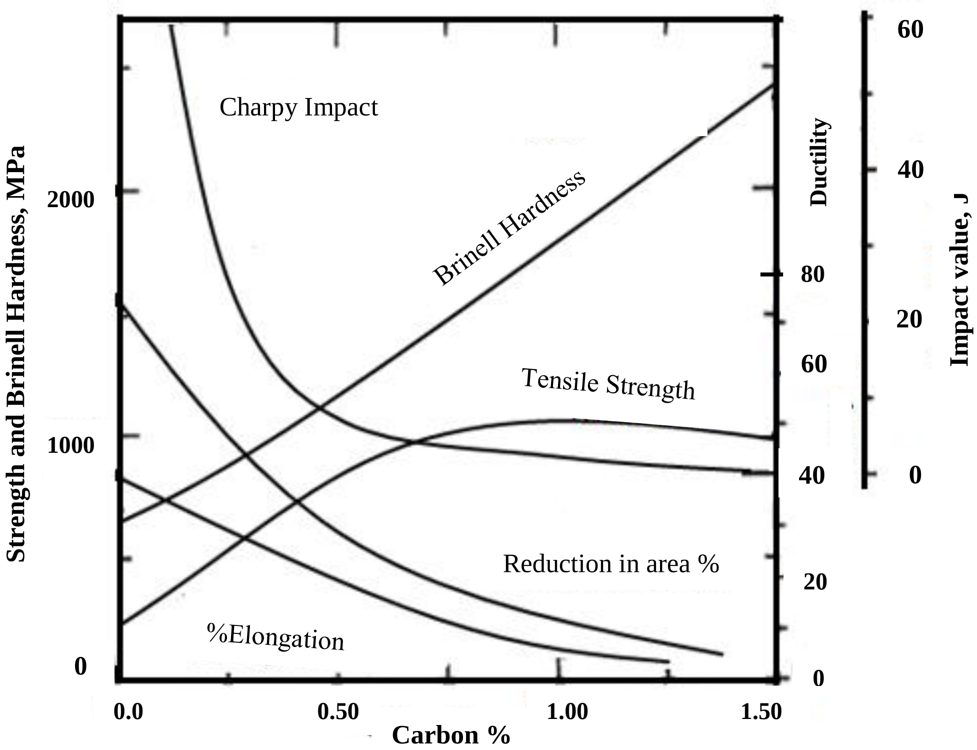


Figure 18 Effect of carbon content on mechanical properties of carbon steels [55, 66].

When the toughness of steel is measured as a function of temperature, high strength carbon steels with large amounts of pearlite have increasing ITT as the carbon content increases and this decreases toughness as impact energy falls. For instance, the upper shelf energy of 0,8% C is 45J which is lower than that of 0,11% C , 200J by comparison. Higher strength steels with carbon above 0.30% begin to lose toughness below room temperature. In figure 19 shows the impact strength of carbon steels of different carbon concentrations as a function of temperature.

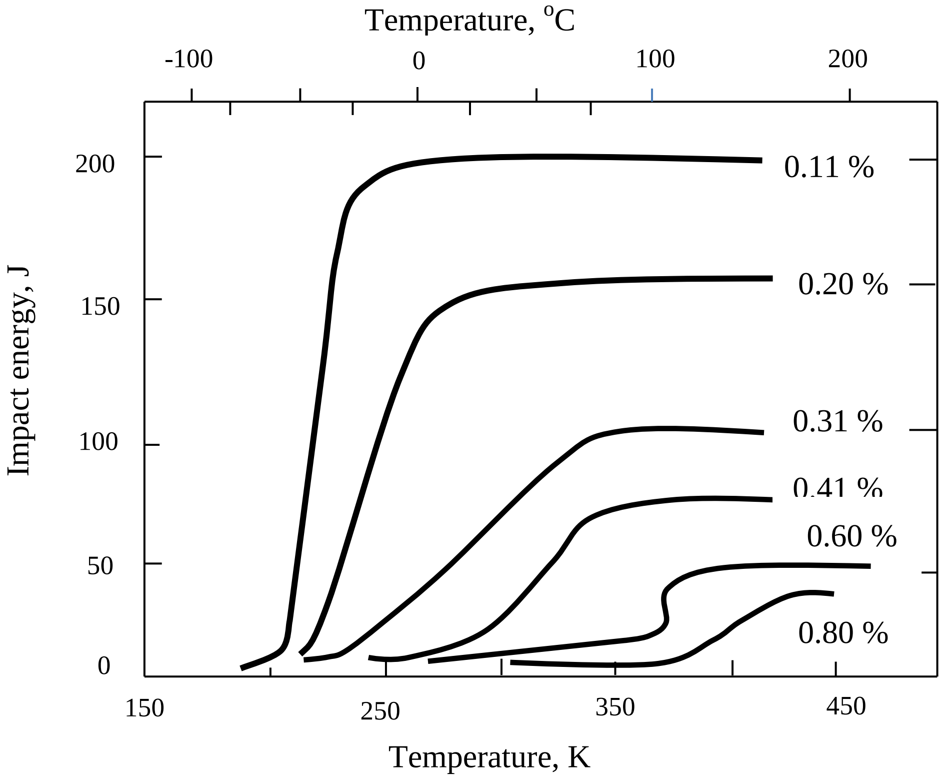


Figure 19 Change in impact transition curves with increasing pearlite content in carbon steel [50, 55].

Increasing the carbon content increases the fraction of iron carbide (Fe_3C) present. However, iron carbide initiate cracks easily so increasing Fe_3C content decreases the fracture toughness. In figure 20 shows a plot of strength against fracture toughness of steel. It can be seen that pure iron is soft but has high fracture toughness. At 0,2% carbon steel has some pearlite which strengthens the steel but decreases the fracture toughness, 0,4% carbon steel has more pea rlite than before and so stronger but has lower toughness. The 0,8% carbon content steel is very strong because almost all the grains are pearlitic and yet has lowest toughness [67].

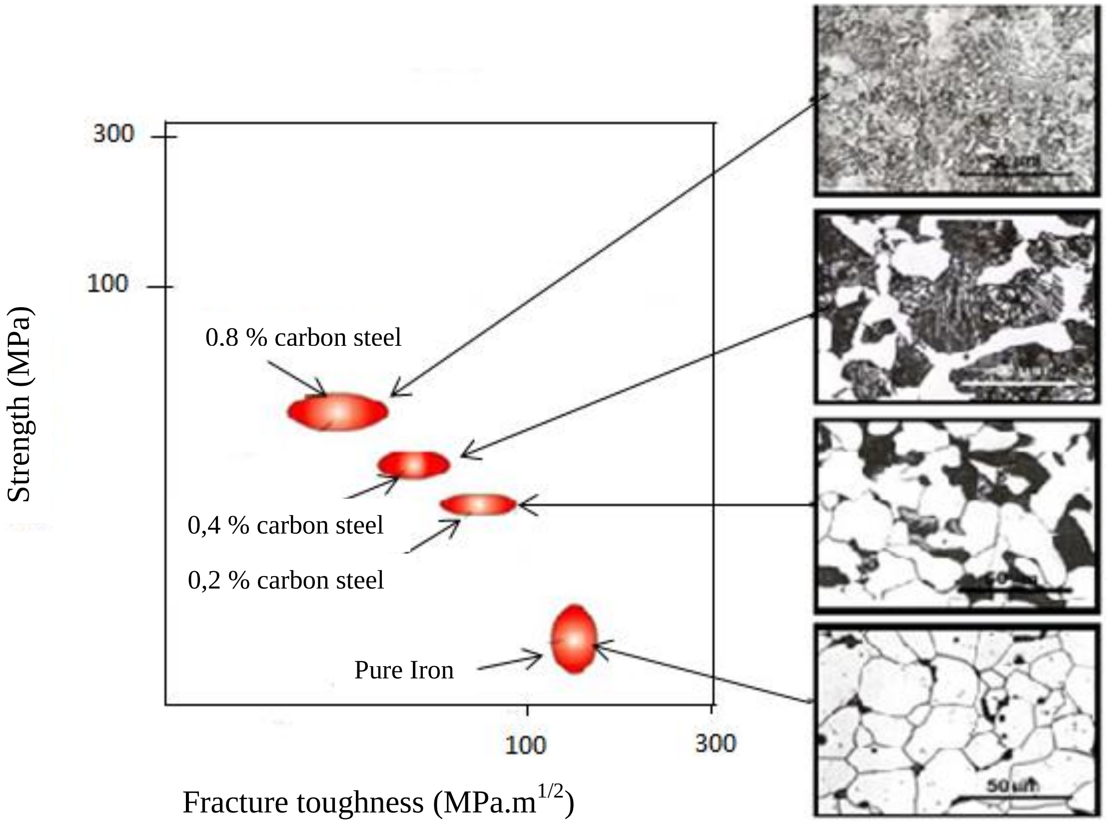


Figure 20 Effect of carbon content on normalized carbon steel [67].

4.4. Other failure modes which contribute to low toughness

The level of toughness required to avoid brittle fracture depends on numerous factors such as service temperature, strength grade, stress level, strain rate, construction detail and material thickness. There are some ductile materials which do behave in a brittle manner to a low toughness and are explained below:

- Rate of loading (i.e. strain rate) of steel under static loads possess enough toughness but fail under dynamic impact or loads. Generally, as the rate of loading increases toughness decrease [28, 68].

- Temperature has a significant effect on the toughness of steel. Most materials at lower temperatures are brittle, the ductility and toughness also decrease but are more ductile at higher temperatures [28, 68].
- The distribution of stress is critical. A material might display good toughness when the applied stress is uniaxial, but when a multiaxial stress state is produced due to the presence of a notch the material might not withstand the simultaneous elastic and plastic deformation in the various directions [28, 68].
- Size of material thickness, may cause a ductile material behaves in a brittle manner when there is sudden impact frequently. Thin parts are likely to fail when overloaded but thicker steel plate behave more like a brittle metal and has lower toughness because; its geometry does not allow stress to be evenly distributed, the microstructures of increased strength and thickness (higher strength steel) is likely to have more brittle phases, making crack initiation much easier [69]. Figure 21 shows fracture at an angle or shear lip becoming smaller as the thickness increases and fracture becomes more brittle.

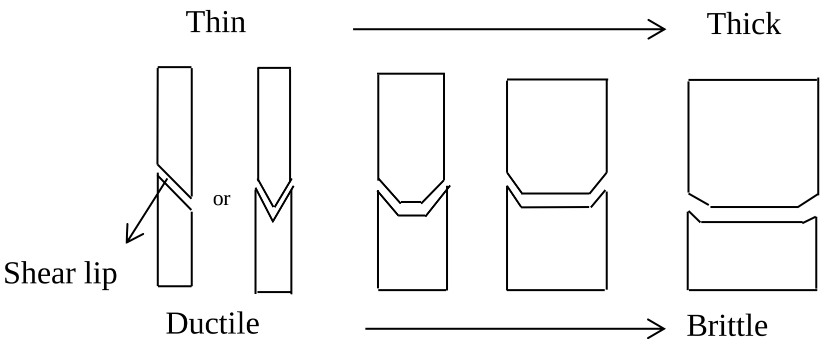


Figure 21 Ductile metals behaving more like a brittle metal [28, 68].

Table 9 summarizes the factors that may contribute to ductile and brittle sudden impact fractures. These frequently occur in the applications of offshore structures for example: If a ductile part has severe stress concentrations from corrosion or improper machining and receives an impact, the results have features of a brittle fracture.

Table 9 Factors affecting ductility of carbon steel to brittle fracture [28, 68].

Factor	Effect	
	Ductile	Brittle
Strength	Lower	Higher
Temperature	Higher	Lower
Rate of loading	Slow	Fast
Stress Concentration	None	More/severe
Material thickness	Thin	Thick

5. PROCESSES OF IMPROVING STEEL TOUGHNESS

This chapter is about heat treatment steel processing routes for production of high strength structural steels refining grain size, achieving a toughness and weldability properties of modern high-performance steel.

Steel toughness also is optimized by combining the application of Heat treatment processes and Controlled rolling. Previously, hot rolling was only to achieve carbon steel strength for plate thickness but as the demand for quality requirement was critical, heat treatment such as N or Q&T was added. As the quality requirement became more critical and severer, TMCP was developed for offshore steel plate. In figure 22 shows the diagram of processing method. TMCP plates are thermomechanically controlled rolled and, also accelerated cooled after rolling which improves weldability, greater strength, and toughness of greater thicknesses than conventional normalized steels at the same or lower cost [70, 71].

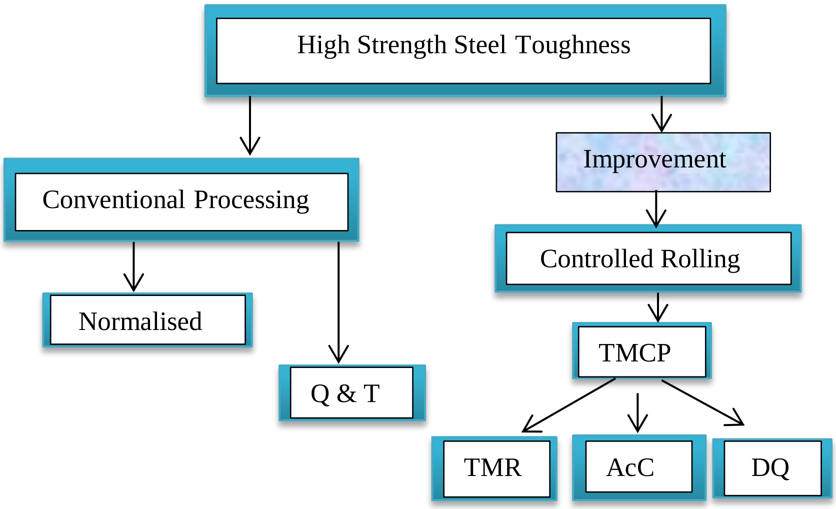


Figure 22 Schematic diagram of processing routes of steel.

5.1. Production processes for High-performance steel

The processing routes for production of modern high strength steels are to make steels ductile, crack resistant at low temperatures, and allow welding without any risk of brittle fracture. The techniques to achieve quality minimum yield strengths of high to higher modern steels are by TMCP and / heat treatment. Higher yield strengths are TM, TM+AcC of 355 – 690 MPa, QT with460 – 1000 MPa, and DQ. To achieve a very high toughness is carried out by TM-rolling + AcC [30]. Figure 23 presents the schematic diagram of time-temperature for different production processes for high-performance steel grades.

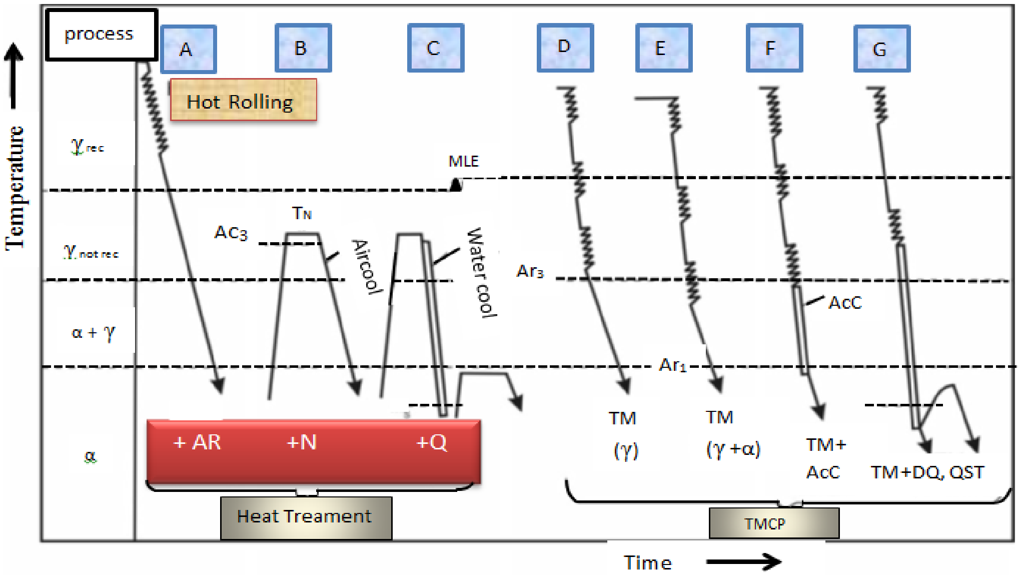


Figure 23 The temperature-time diagrams of steel processing routes of high strength steels [70, 34, 41, 32, 72].

In figure 23, temperature is on the vertical axis, γ_{rec} denotes recrystallized austenite, $\gamma_{not\ rec}$ denotes non recrystallized austenite, α + γ the temperature range for austenite + ferrite and α temperature region for ferrite and pearlite in conventional steels. MLE shows the increase in temperature for recrystallization due to microalloying, and T_N is the normalization temperature.

Process A: +AR

The plate is produced by conventional / hot rolling, carried out at above 950°C and delivered “as rolled” condition (AR) is achieved [70, 34, 41, 32, 72].

Process B: +N

The plate is reheated to get a more homogenous microstructure (approx. 900 °C >Ac_3, depending on the carbon content) and is cooled in air again. By this treatment the steel transforms from ferrite and pearlite to austenite and back again. This leads to a refined microstructure of ferrite and pearlite, which is called the normalised condition (N) which removes the coarse and non-uniform steel structure to a uniform and fine grain structures to improve ductility, toughness and yield strength [34, 41, 72, 32, 73]. However, with this process a higher strength of steel plates is mostly related to higher alloying contents which have negative influence on weldability [32, 72].

Process C: +Q&T

For higher strength – no real thickness restriction. In Q&T process (A+C in Fig 23) the plate is reheated above the transformation temperature (> Ac_3) after hot rolling and cooling, so that carbon can dissolve in austenite, but then cooling is not performed on cool air, but in water (quenching) that cools fast enough, so that there is no diffusion process time for the formation of ferrite and pearlite. Carbon then stays dissolved and at room temperature the microstructure mainly consists of martensite, a distorted structure that has a high strength but a low toughness. The martensite structure of steel is not extremely hard but brittle and its excess hardness is reduced by tempering process which is by reheating the metal to lower critical temperature than was used for hardening and cooled in air [74]. Toughness is increased since the hardness of carbon steel decreases continuously as tempering temperatures increases [34, 41, 72, 32, 73]. In figure 24 shows a variation of hardness of high carbon quenched 0,82% C steel tempered at four different temperatures.

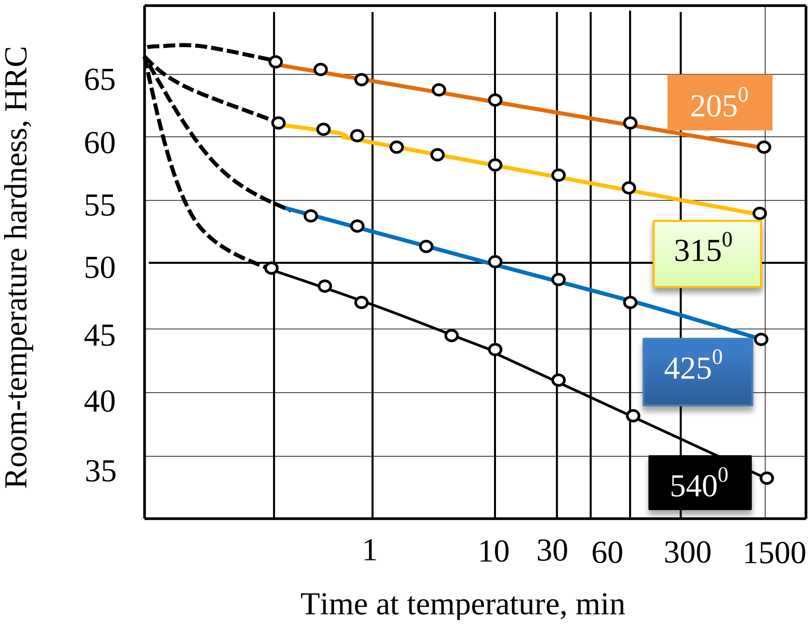


Figure 24 Effect of tempering temperatures on hardness of quenched 0,82% carbon steel [75, 76].

It can be seen that the quenched high carbon steel hardness is then reduced by tempering at different temperatures. Although there are no actual figures of tempering temperatures for the figure 25, but $A_1 - A_4$ are the tempering temperatures. A_1- A_4 shows an increasing trend from lowest to highest respectively to improve impact toughness as shown in figure 25.

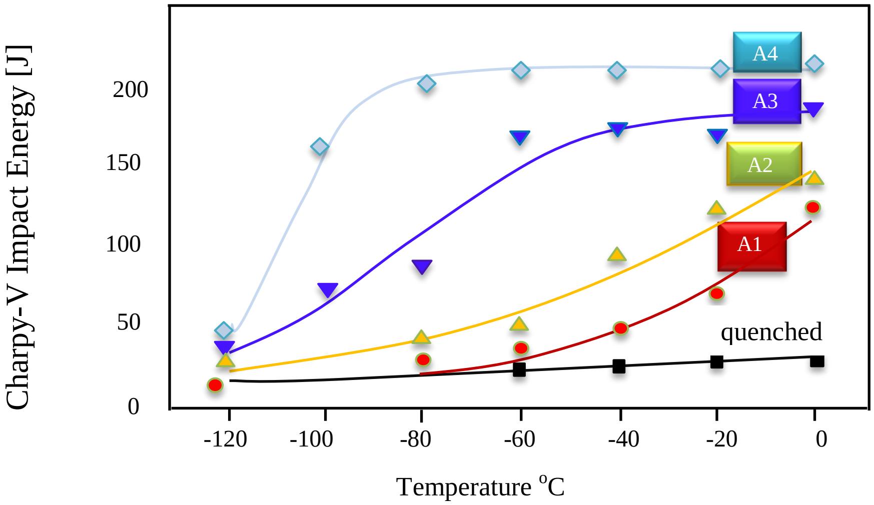


Figure 25 Influence of increasing tempering temperatures on the Charpy V transition at A_1°C, A_2°C, A_3°C, A_4 °C after quenched- S890QL, 60mm [34, 72].

Figure 26 shows variation of hardness with tempering temperature and the effect of ductility for high carbon steel.

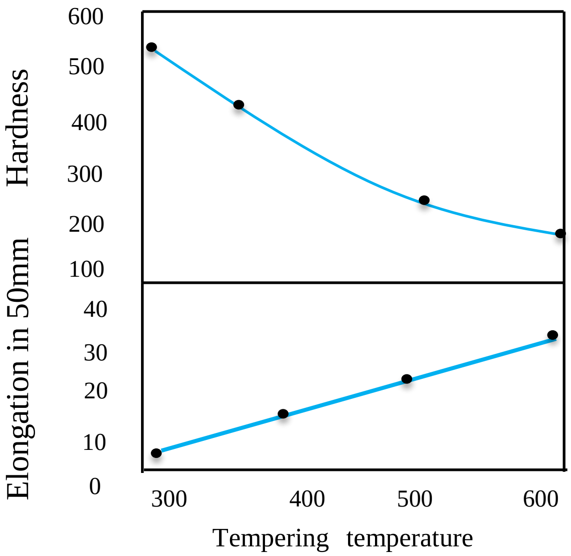


Figure 26 Effect of tempering temperature on hardness and ductility of high carbon steel [75, 76].

Process D-G: Thermo-Mechanical Control Process (TMCP)

A more convincing way to get high toughness steel with high strength is to create a microstructure with an extremely fine grain. TMCP is a method which results a very fine grained microstructure by combination of rolling steps at particular temperatures and a close temperature control (Processes D-G in Figure 23). TM steels are the best weldable due to their lower carbon equivalent and it is further explained in the subsequent chapters.

Accelerated cooled (AcC)

This is performed after the rolling pass to achieve the most suitable microstructure. To overcome the limitations of the TM-rolling, AcC process has higher positive influence on strength as well as on toughness properties and lowers alloy content compared to TM-rolling. For very thick plates and higher yield strength steel a tempering process can be used after accelerated cooling [34, 72, 77, 78].

Figure 27 shows the grain microstructures of figure 23 processes. The typical microstructure of normalised steel is dominated by ferrite and pearlite. Two main differences of TMCP structures are shown. First, there are less pearlite, a result of the lower carbon content and second, the smaller grain size, which is smallest when AcC is performed and it is an evident that TMCP steel is very fine and uniform and a major advantage when compared to normalized. Quenched and tempered steel shows different appearance. The martensite that is formed by diffusionless transformation shows an acicular microstructure [34, 41, 79, 72, 73].

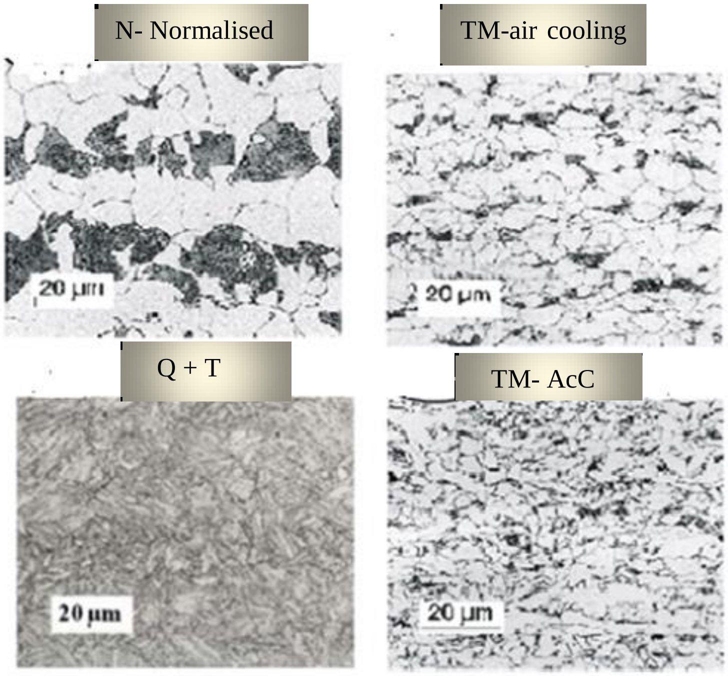


Figure 27 Grain microstructure of QT and TMCP compared to normalised N [34, 41, 79, 72, 73].

Summary of relevant stages in figure 23 processes and their respective features related to them is presented Table 10.

Table 10 Overview of HSS production stages and features.

Processing Methods	Features
N	•Transformed coarse to fine and uniform grain size.
TM	• To produce better refined grain microstructure.
	• Smaller carbon content and grain size than "N"
	• Better ductility and toughness.
TM + AcC	• To achieve most suitable microstructure.
	• Enhances grain refinement of ferrite.
	• Prevents formation of pearlite during cooling.
	• Smallest grain size.
	• Lower carbon content.
	• Highest toughness and higher strength than "N"
Q&T	• Reduce excess hardness and residual stresses.
	• Reduce brittleness of martensite.
	• Improved ductility and toughness, and highest strength.

5.2. Comparison of TMCP to Conventional steel

Thermomechanical steel grades exhibit high toughness and excellent ductility. This means a higher material strength for impact and seismic loading [33].

Thermomechanical Controlled Processed (TMCP) is a thermomechanical treatment in which the final deformation is carried out in a temperature range which cannot be achieved significantly by heat treatment alone [80]. The final fine grain ferrite-pearlite microstructure obtained by TMCP with AcC processing properties allows reducing effectively the carbon and alloying content of the TM-steel, decrease of CEV, weldability improved, compared to normalised steel of the same grade or yield strength as shown in figures 28 and 29**.**

In figure 28, at C, a normalized N formed has the lowest YS (460) MPa and the highest carbon equivalent of 0,47% as compared with B and A, TM and TM+ AcC respectively. Higher strength steels formed at B and C achieves a better weldability due to their smaller carbon equivalents [34, 73, 32, 41, 30].

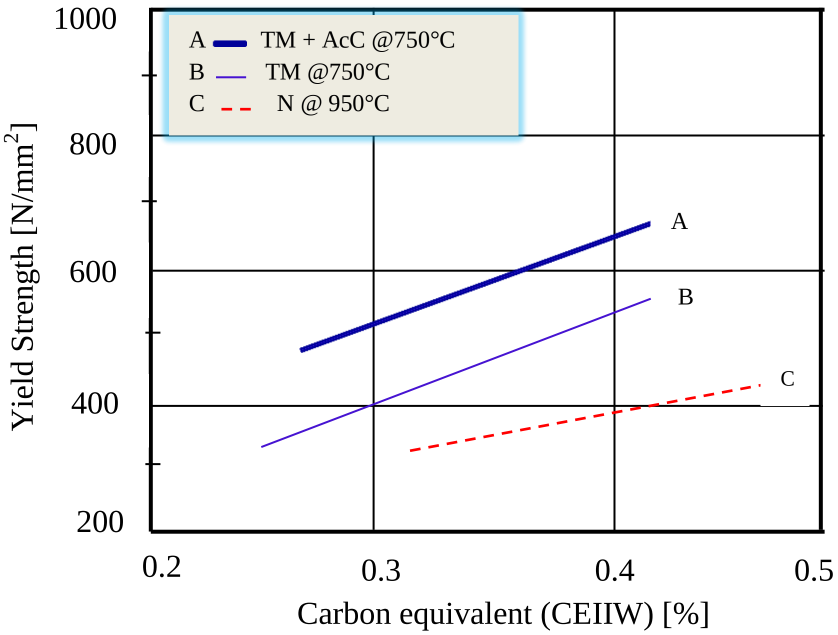


Figure 28 Shows a decreased carbon equivalent value by thermomechanical rolling and accelerated cooling [81, 30]**.**

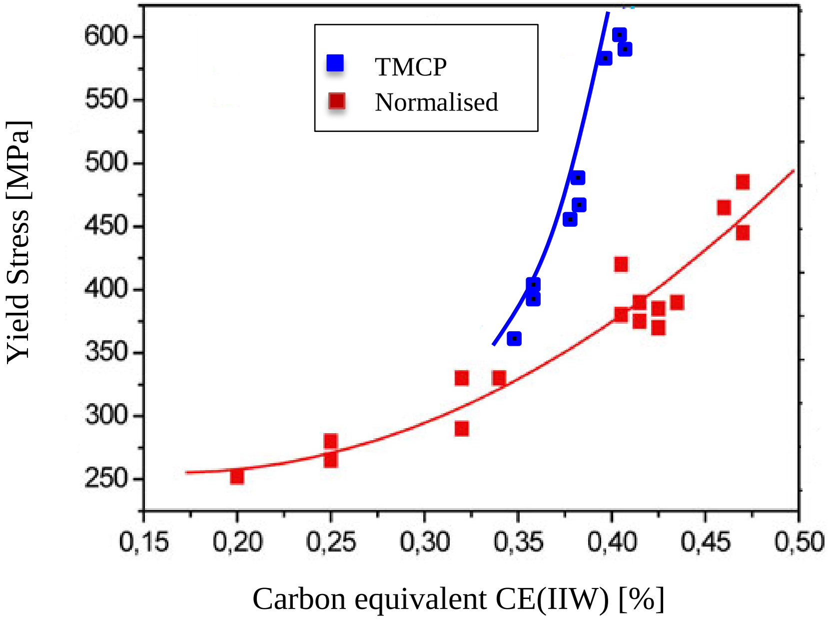


Figure 29 Comparison of N and TMCP carbon equivalent CE (IIW) [34, 41, 32, 73].

Carbon equivalent (CE) is a measure of carbon content and other alloying elements to estimate weldability of a base materials and needed heat treatments of carbon steels. The purposes of these carbon equivalent formulae are as follows [82, 83]:

- Indication of carbon content predicting steel strength.
- Assessing the hardenability of steel.
- HAZ hardness.
- Indication of hydrogen-induced cold cracking susceptibility of steel.

There are several commonly used equations for expressing carbon equivalent for carbon steels. The International Institute for Welding (IIW) adopted a CE (IIW) which is generally the measure of steel weldability [84] and can be seen in equation 1. The other common ones are Pcm, CET, and Ceq. The carbon equivalent value is usually expressed as CE (IIW) or CET in accordance with the equations below.

$$CE(IIW) \text{or CEV} = \mathrm{C} + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5} \ (\%) \qquad \text{Eq. 1}$$

$$CET = \mathrm{C} + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40} \ (\%) \qquad \text{Eq. 2}$$

$$Ceq = \mathrm{C} + \frac{Si}{25} + \frac{Mn + Cr}{16} + \frac{Cr + Ni + Mo}{20} + \frac{V}{15}\ (\%) \qquad \text{Eq. 3}$$

In Japan, the Ito-Bessyo composition characterizing parameter (Pcm) is also used but to assess the weldability of low carbon steels as expressed in equation 4.

$$Pcm = \mathrm{C} + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \qquad \text{Eq. 4}$$

The carbon equivalent of weldability is determined between typical normalized S355J2 + N and one of the thermomechanically rolled S355ML as shown Table 11.

Table 11 Carbon equivalent values for a typical S355J2+N and S355ML.

Steel grade	CET	CE (IIW)
S355J2+N	0.34	0.43
S355ML	0.25	0.36

The higher the carbon equivalent value, the faster the cooling rate, the higher the tendency for hard, brittle phases to form. In general the result of carbon equivalent value (CEV) is considered as follows:

- If CEV is up to 0.35, then is Excellent.
- If CEV value is below or equal 0,40: good weldability, no need for PWHT.
- If CEV exceeds 0,40 but below 0,50: Fair weldability, might need heat treatment with thick materials because it is susceptible to hydrogen cracking.
- Above 0,50: Poor, usually pre heat treatment is needed.

The carbon equivalent allows the determination of the necessary preheating temperature Tp for welding, taking into account the avoidance of hydrogen-induced cold cracking. According to EN 1011-2 Tp is preheating temperature which involves heating the base metal either entirely or just around the joint to a specific temperature and is given by:

$T_p = 700\ CET + 160\tanh(t/35) + 62\ HD^{0.35} + (53\ CET - 32)\ Q + 330$ Eq. 5

Where:

Tp = Preheating temperature; HD = Hydrogen (ml/100g-ISO 3690); Q = Heat input (kJ/mm);

t = Plate thickness (mm).

It is understood that TMCP does not only have smaller carbon equivalent than normalised of the same yield strength but it also has excellent toughness behavior. Figure 30 illustrates the transition curves of the Charpy-V absorbed impact energy against test temperature for TM-steel S355ML and conventional steel S355J2G3. At room temperature, the toughness value of TM-steel exceeds 300J which is much higher and has very low transition ductile to brittle fracture behavior when compared to S355J2G3 [33, 72].

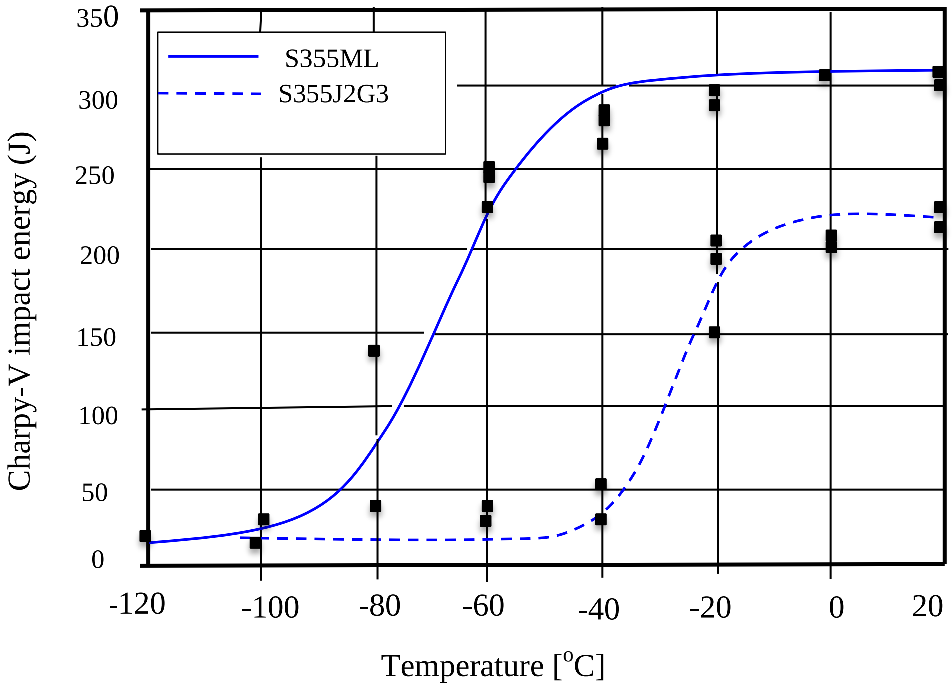


Figure 30 Comparison of the Charpy-V transition curves for TM-steel S355ML and normalized S355J2G3 steel grade (plate, 60 mm thickness) [33, 72].

5.2.1. Properties and characteristics of TMCP to Conventional steels

Today's offshore steel plates are produced not only by the ordinary rolling method, but also by TMCP technology. TM plates compared with conventional steel grades are their outstanding better weldability and toughness. The following advantages below are obtained when in used compared to conventional steels [41, 72, 79, 85]:

- TMCP steels have a higher strength and superior toughness.
- Low CEV**:** Toughness has been improved.
- Preheating of thicker TM plates is significantly reduced or neglected which allows great savings in fabrication time and cost.
- High toughness values and low hardening in the HAZ after welding.
- Weldability is greatly improved.
- Due to the low CEV level (weld sensitivity composition), the preheating temperature of welding time is lower than that of conventional HSS.
- The high hardness of the welded joints is lower than that of conventional HSS.
- Higher strength is produced by the TMCP rolling technique without increasing the alloying content.
- Improved toughness of welded joints.
- The mechanical material properties are less deteriorated by linear heat.
- Even at the same CEV level, the strength of TMCP steels is higher than those of conventional steels.

Figure 31 shows the relationship between tensile strength and CE (IIW).

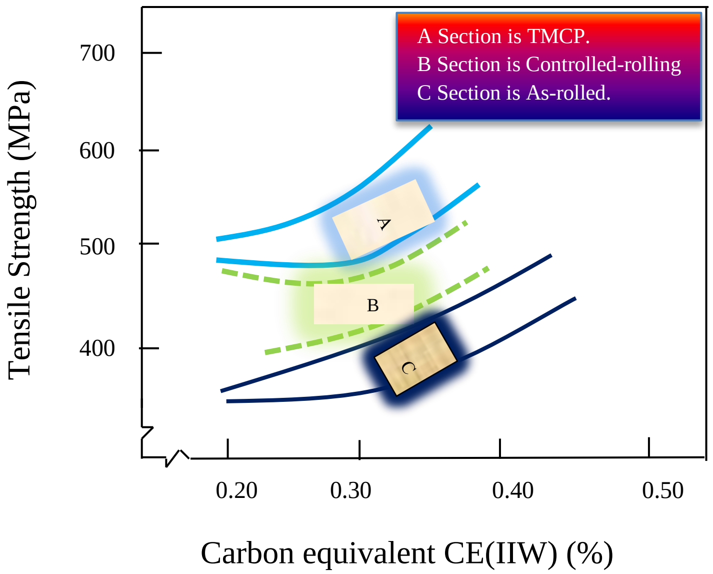


Figure 31 Relationship between the conventional manufacturing process and the TMCP Process in terms of CE (IIW) [79].

5.3. Properties of modern high-performance steel

TMCP plates show a very ´´slender`` chemical composition resulting in very good weldability than conventional steel as shown in Table 12. On the other hand, quenched and tempered steel as S690QL has higher alloying content resulting in carbon equivalent demand for welding such as preheating, limited heat input to avoid too long cooling times etc [32].

Table 12 Effect of changes in chemical compositions and processing steel plates of grades 460ML, 690QL compared to 355J2 [32, 30, 86].

		Typical composition (by weight %)													Carbon equivalents		
EN 10025	Process	C	Mn	Si	S	P	Nb	V	Al	Cu	Ni	Mo	Cr	B	CE	Pcm	CET
S355J2	Normalised Old	≤0.22	≤1.60	≤0.55	≤0.025	≤0.025	_	_	0.02	≤0.55	_	_	_	_	0.47	_	_
S355J2	Normalised New	0.17	1.50	0.45	0.015	0.018	_	_	0.03	_	_	_	_	_	0.42	0.26	0.32
S460ML	TMCP Old	≤0.16	≤1.70	≤0.60	≤0.020	≤0.025	≤0.05	<0.12	0.02	≤0.55	≤0.80	≤0.20	≤0.30	_	0.42	_	_
S460ML	TMCP New	0.08	1.65	0.45	0.002	0.011	<0.04	_	0.03	0.17	0.19	_	_	_	0.38	0.19	0.26
S460QL	Q&T Old	≤0.20	≤1.70	≤0.80	≤0.010	≤0.020	≤0.06	≤0.12	0.02	≤0.50	≤2.0	≤0.70	≤1.50	≤0.050	0.47	_	_
S460QL	Q&T New	1.60	1.50	0.45	0.005	0.012	0.017	_	0.03	_	_	0.115	_	_	0.39	0.19	0.26
S690QL	Q&T Old	≤0.20	≤1.70	≤0.80	≤0.010	≤0.020	≤0.06	≤0.12	0.02	≤0.50	≤2.0	≤0.70	≤1.50	≤0.050	0.65	_	_
S690QL	Q&T New	0.16	1.30	0.30	0.005	0.012	<0.04	_	0.03	0.08	0.15	0.37	0.40	<0.003	0.54	0.29	0.35

CE = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15

Pcm = C + Si/30 + (Mn + Cr + Cu)/20 + Ni/60 + Mo/15 + V/10 +5B

CET = C + (Mn + Mo)/10 + (Cr + Cu)/20 + Ni/40

Figure 32 shows a typical transitions curves for the Charpy-V energy against the test temperature for a S460 ML, and S690QL steel in comparison with conventional steel, S355J2. The TMCP plate results in high strength and also due to their beneficial properties as stated They are convenient for offhshore platform and shipbuiding [32].

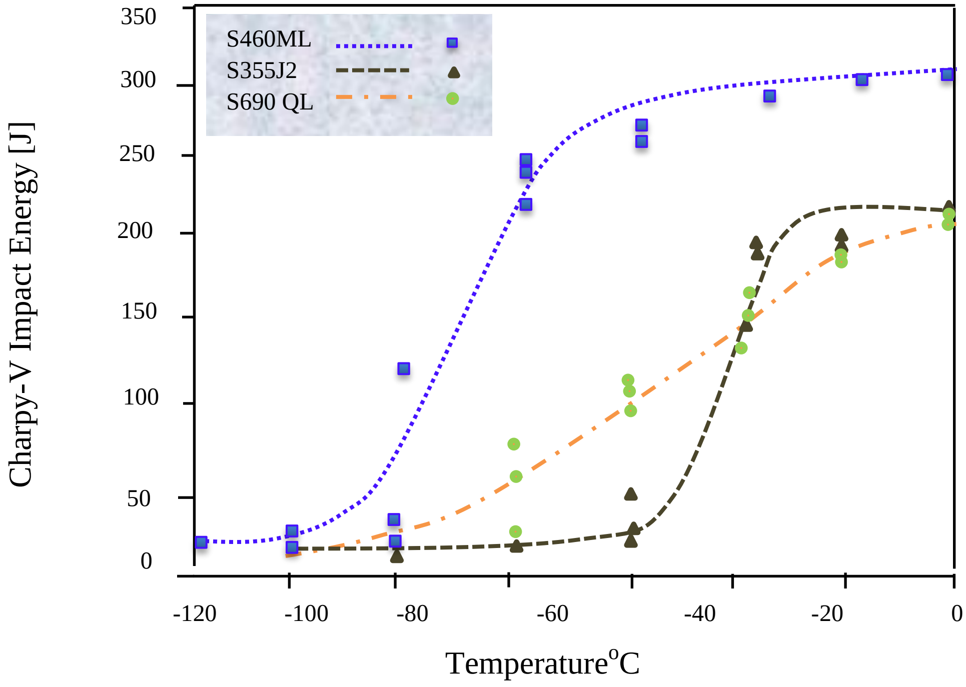


Figure 32 Charpy V- temperature transition curves for S460ML and S690QL with S355J2 for comparison [32].

6. WELDABILITY OF CARBON STEEL

Weldability basically means the ability to produce a sound weld by taking into account the material, structure and processing methods [87]. Many welding processes have been modified and enhanced to improve weldability as well as productivity, better penetration, and accuracy of welded joints. Understanding and ensuring good behavior of welded structures requirements such as strength, high toughness, heat–affected zone regions, better microstructure and durability of the weldable steels are considered.

6.1. Effecting factors of steel weldability

The following are some of the most common factors that affect the weldability of steel structures [87]:

- Chemical composition and type of alloying elements
- Material hardness (amount of carbon content)
- Welding process
- Heat input
- Joint design
- Thermal conductivity of the material
- Environment
- Microstructure (martensite)
- Stress
- Cracks (present of hydrogen and residual stresses)
- Resistance of weld metal to hot crack formation.

Carbon steels are weldable if they have good strength properties and toughness in the service life. Materials which have high tendency to form hard and brittle areas in the HAZ using fusion welding with the susceptibility of forming defects such as hydrogen induced cold cracks, is said to have poor weldability [86]. Residual stresses in the weld metal may cause distortion and uneven load distribution which will eventually result in a crack. Ductile steel (with more granular ferrite microstructure) is very resistant to internally induced crack formation. Grain refinement can suppress stresses in the welded structure.

A good weld preparation and avoidance of defects such as lack of penetration or fusion can lead to sound weld for all common structural steels. However other steels may need special treatments to be able to get quality and sound welds. Figure 33 shows the features affecting the weld quality.

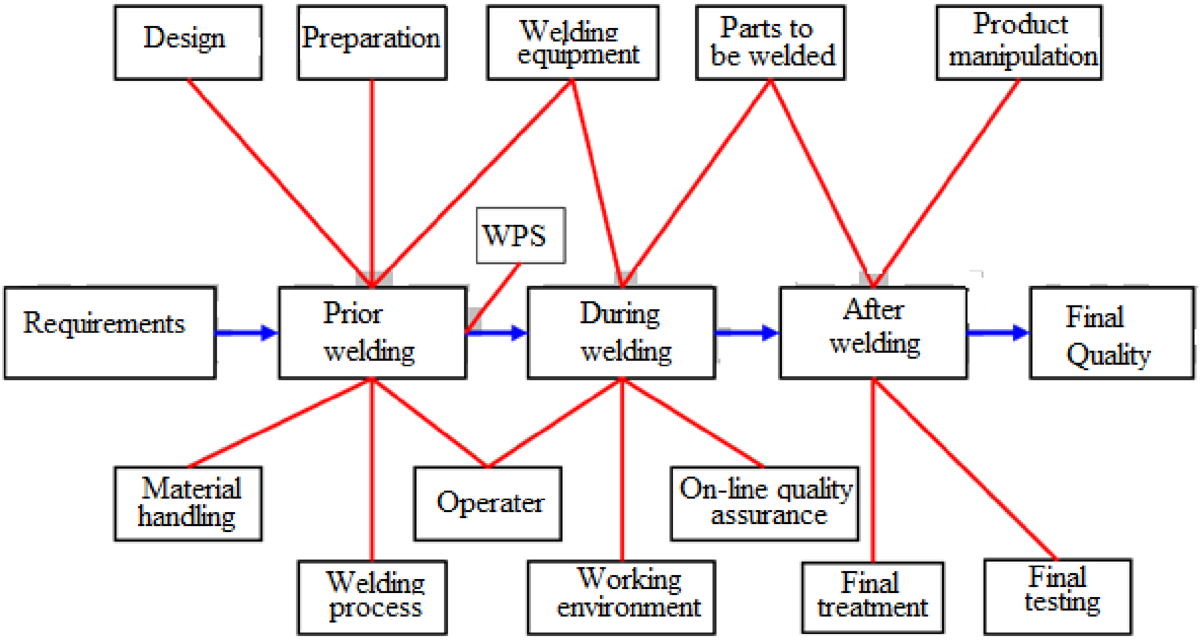


Figure 33 Features affecting the weld quality [88], modified.

6.2. The effect of welding parameters on toughness and weldability of steel

To overcome weldability issues, analyze weld joint failures and evolve safe welding procedures for fabrication. There is the need to control welding parameters such as the heat input, electrode diameter, voltage, current, preheat, etc, in order to get a robust welded structured of steel because they can give problems in welding such as cracking tendencies in the HAZ, longitudinal or transversal cracking in weld metal, welding distortion, residual stresses and loss of mechanical properties of welds [89].

6.2.1. The effect of Heat Input

The welding heat input has a great influence on the weldment properties. The heat input used in the welding should be restricted to lower range but not too low. Due to the slower cooling rate at higher heat input, microstructure of weld metal and HAZ changes, coarsening of prior austenite grain and undesirable phases occur leading to the deterioration of tensile strength and impact toughness of steel [90, 91, 92]. The change in toughness is not significantly influenced only by the heat input but also the weld bead size. Increase of heat input gives appearance of proeutectoid ferrite and Widmanstatten ferrite, which affect toughness negatively. As the bead size increases, due to higher heat input, the notch toughness tends to decrease. If the beads are smaller, more grain refinement occurs, resulting in better notch toughness [93]. Figure 34 shows a macro photograph of different zones of a welded joint, the fusion line, the HAZ, and the buildup of the runs.

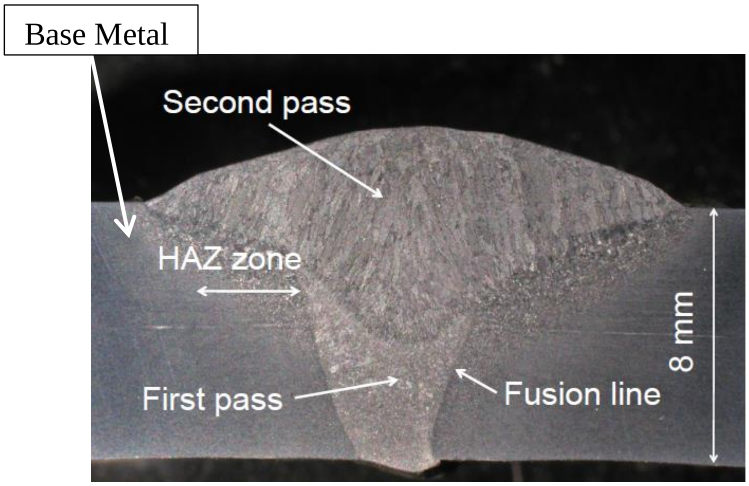


Figure 34 A picture of location of different zones of welded joint [42].

According to P. K. Kishore et al [94] samples of multipass welded joint steel were experimented and tested for hardness, fracture toughness, HAZ of the welded joint at different heat input of multipass SAW. The energy transfer per unit length of weld is a function of heat input, which in turn can alter the mechanical properties of the welded zone. The heat input can be calculated as shown in equation 6, [95, 96].

$$Q=\frac{U\times I\times 60}{v\times 1000}\,, \qquad \text{Eq. 6}$$

Where Q is the heat input (kJ/mm); U the voltage (V); I the current (A); and v is the travel speed (mm/min).

The results of the samples welded joints tested are graphically presented in figure 35 showing the effect of heat input on mechanical properties of a welded joint. Below are the explanations:

- The lowest toughness values were obtained for specimen (CL5252, CL5255) are 38 and 60 J at the heat input of 2.1J/mm and 3 J/mm. It shows that this loss of toughness is associated with the presence of Widmanstatten ferrite and martensite in the microstructure due to rapid cooling rate. On the contrary, for a low heat input of 1,764 J/mm, specimen (CL5251) demonstrated the highest toughness 82 J because of ductile phase such as ferrite and pearlite in the microstructure.

- Hardness of the welded sample was slightly reduced at low heat input and was steadily until CL5254 for high heat inputs, and reduced again.

- Hardness of fractured sample was high at low heat input and it decreased for high heat input.

- In some cases due to the rate of increase in heat input increases the hardness of fractured surface of weld metal while decreases the hardness of weld metal, this happens due to the increase of thermal cycles from the weld metal to base metal tending to sufficient cooling, which results in such type of change in hardness and the increase in ferrite phase in the microstructure [94].

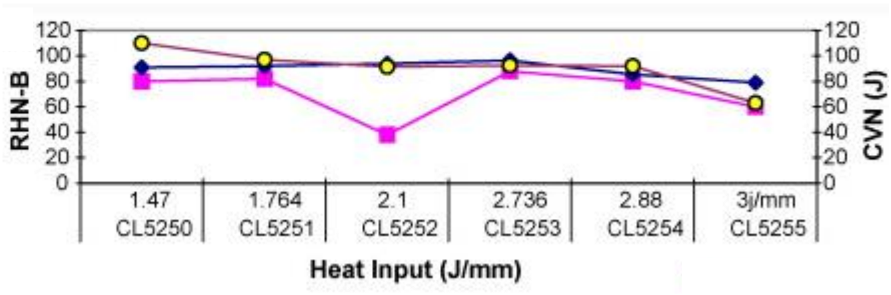
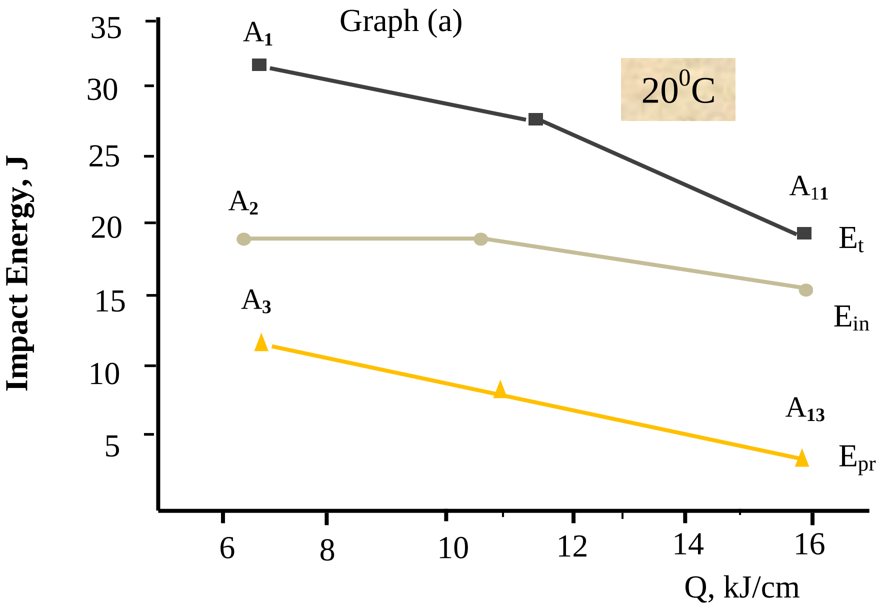


Figure 35 The influence of heat input on toughness and strength of a weld joint [94].

Popović et al [93] explained further the influence of welding heat input on the weld metal toughness of high-carbon steel surface welded joint. The total impact energy, as well as crack initiation and crack propagation energies, were estimated at three testing temperatures (20^0C, -20^0C and -40^0C).

Figure 36 presents dependence heat input vs. impact energies at testing temperatures; 20^0 C, for samples A_1, A_2, A_3 tested for Et, Ein, and Epr respectively, at -20^0 C, samples B_1, B_2, B_3 for Et, Ein, and Epr respectively and at -40^0 C, samples C_1, C_2, C_3 for Et, Ein, and Epr respectively.



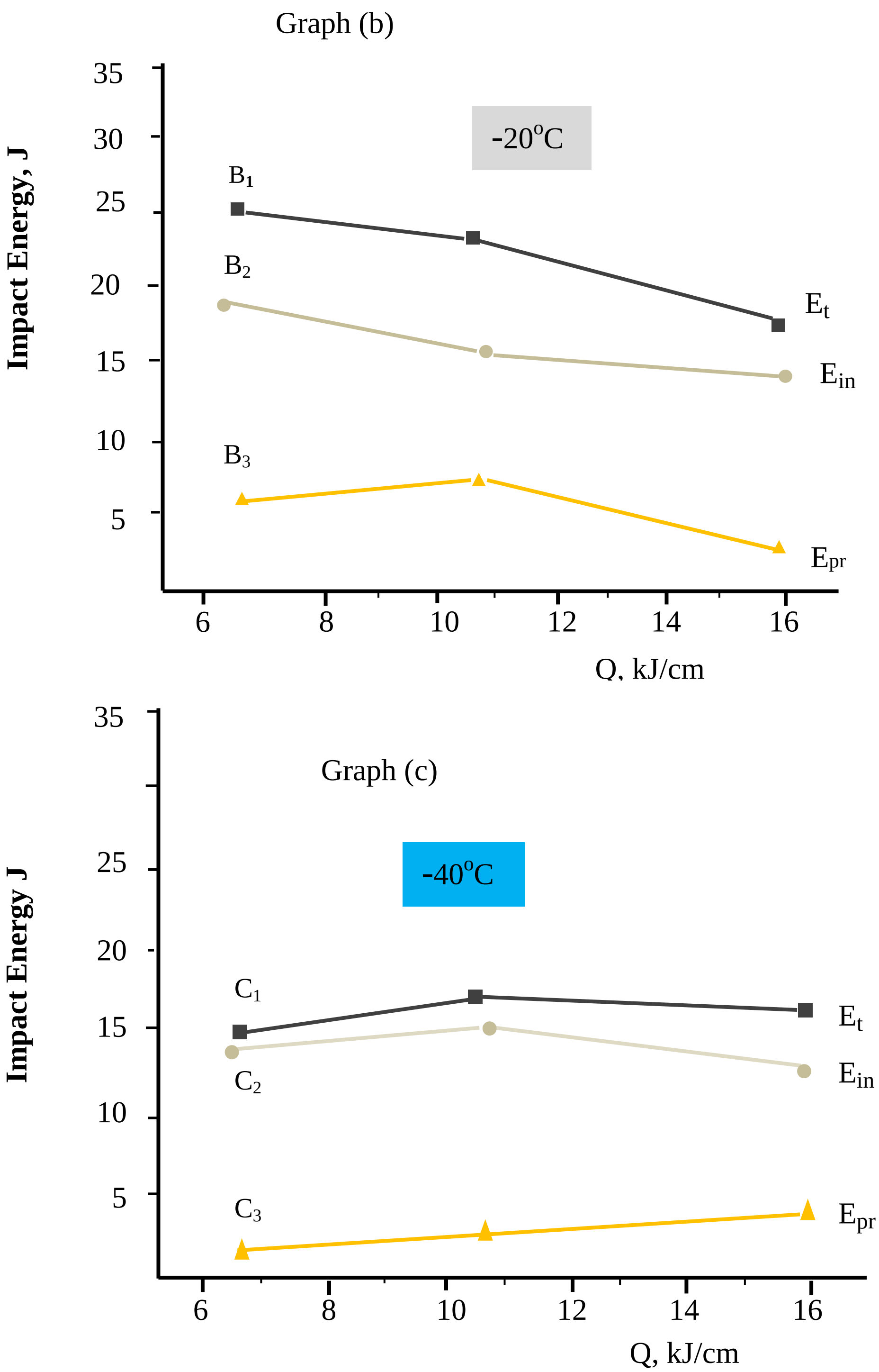


Figure 36 Dependence heat input vs. impact energies at testing temperatures 20°C, -20°C, -40°C for graphs (a), (b), (c) respectively [93].

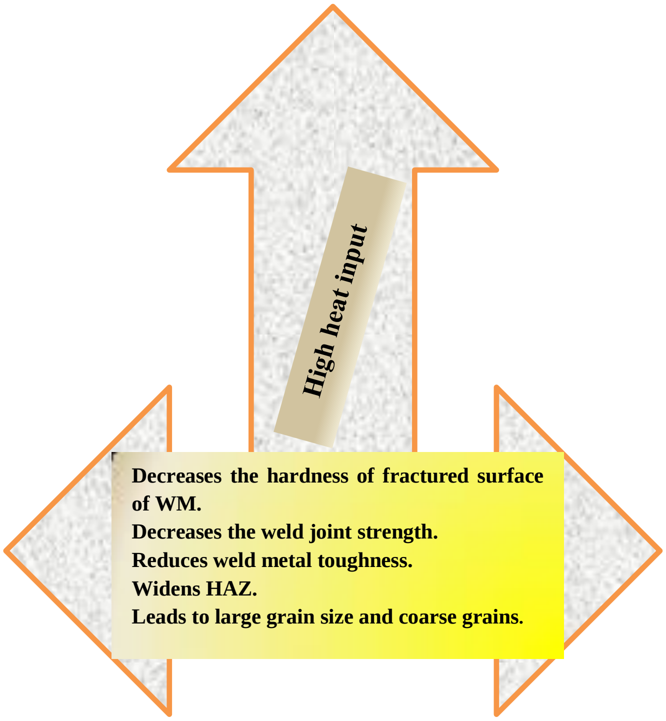
From figure 36**, graph (a):** explains at room temperature, the highest total impact energy, $E_{t,}$ of sample A_1 is 32J at the lowest heat input. Toughness then decreases to 21J of E_t at A_{11}. Crack propagation energy, E_{pr}, for A_3 and A_{13} amounts to 4 J and 12 J, respectively, and has lower than the crack initiation energy, E_{in}, in all cases.

Graph (b): -20 ^{0}C, impact energy E_t dropped from 25-18 J with the lowest to highest heat input respectively. Crack initiation Ein energy is equal to 15-19 J. it is noted that most of total impact energy is spent on the crack initiation, while the magnitude of crack propagation energy is minimal.

Graph (c): at -40 ^{0}C E_t amounts to 15-17 J and proportion of crack propagation energy at this temperature is negligible. Due to the insensitivity of crack initiation energy to temperature decrease, these joints have satisfactory and safe exploitation up to -40^{0}C (15 J) [93].

Generally, it can be concluded that the toughness decreases with an increase of heat input in all cases, so the value of 7 kJ/cm can be recommended as optimal. Increase of heat input brings out appearance of more proeutectoid ferrite and Widmanstatten ferrite, which affect to toughness decrease.

The effect of heat input on a welded joint of its microstructure and mechanical properties is summarized in figure 37.



Decreases the hardness of fractured surface of WM.
Decreases the weld joint strength.
Reduces weld metal toughness.
Widens HAZ.
Leads to large grain size and coarse grains.

Figure 37 Effect of heat input on welded steel [93, 94, 96].

TMCP steels result in good impact toughness in welded joints with a wide range of welding heat inputs without deterioration of the toughness. Under many conditions welded constructions built from TMCP plates is already sufficiently tough and moderate HAZ hardness [86].

6.2.2. The effect of Voltage and Ampere

Increasing voltage causes an increase grain area in HAZ which as a result, hardness and toughness decline significantly. Generally, the mechanical properties of welded specimen declined when voltage and amperage are increased in welding process [96]. It was observed in figure 38 that the range of impact strength shows a downward trend in the impact energy values of 92.3 and 40.8 kJ after welding at 130 A/20 V, and 180 A/30 V respectively as voltage increases.

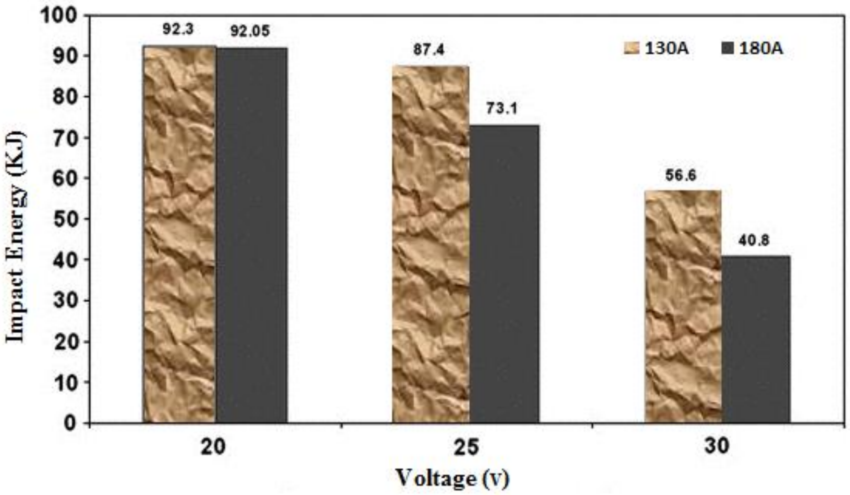


Figure 38 Absorbed Charpy impact energy of weld metal with different welding amperes and voltage [96].

6.2.3. The effect of welding electrodes

The weld metal deposited by welding electrode with higher weld tensile strength than the tensile strength of steel base metal being welded is called “overmatching”. Overmatching protects the weld deposit from the presence of weld flaws. However, using welding consumables, overmatching of high strength steels because of high carbon content may involve expensive preheating, interpass during welding to resist HAC and will be uneconomical and less productivity. Overmatched is an option to use only when it offers enough toughness and it is cost effective [97].

The weld metal deposited by welding electrode with lower weld tensile strength than the tensile strength of base metal being welded is called “undermatching”. Undermatched welds have proven to be effective with HSSs and leads to [98, 99]:

- Reduction of residual stresses which might occur in weld metal, in HAZ in the base metal.
- High potential of reducing crack initiation or tendencies which might occur in the weld metal or as lamellar tearing in the base metal.
- Reduction of preheating requirements.

- Lower weld metal strength will be more ductile than higher strength weld metal.

Due to an increased electrode diameter heat input increases and also prolongs weld cooling times, e.g. from 800–500 ^{0}C [86]. Additionally, fewer weld layers are needed to fill the welded joint, see figure 39. Hardness depends on the amount of columnar area present within the weld metal. Increasing the electrode size increases the amount of columnar region and its widths and thereby promoting strength. The bigger the electrode diameter, the higher the strength since it increases the number of runs deposited within the weld joint, while the toughness declines at low temperatures [27]. Figure 40 shows the effect of large electrode on high strength steel.

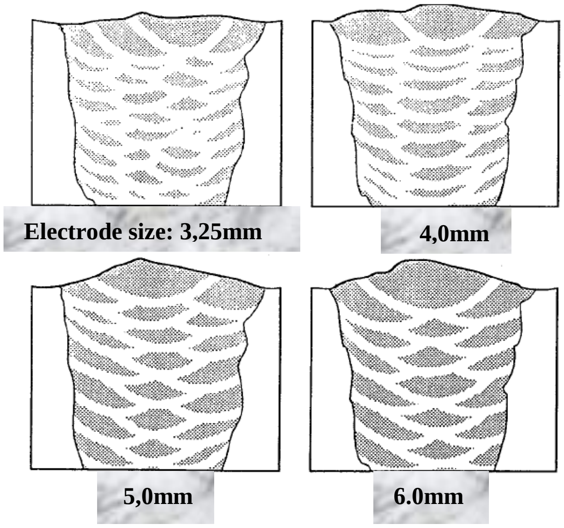


Figure 39 Effect of electrode size on weld metal in multipass welding. Cross sections as a function of weld diameter, white areas represent re-austenitised and tempered weld metal [27].

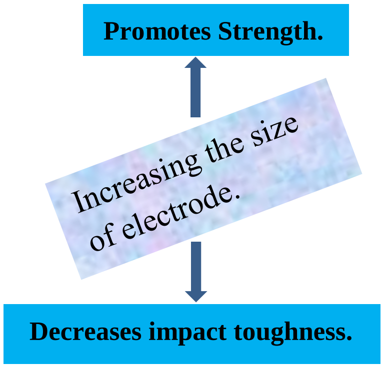


Figure 40 The effect of large electrode on high strength steel.

Factors to consider when selecting electrodes for welding high strength steels to enhance weldability performance, good toughness and productivity are as follow [97]:

- Chemical composition to minimize the potential adverse effects of base metal dilution.
- Processing.
- Microstructures type and size distribution which depends on cooling rate and chemical composition.
- Weldability may be looked up to recreate or retain to achieve desired microstructures.
- Design specific requirements for a welded structure.

6.3. Preheating temperatures for welding

The operation of heating metal either, entirely or just the region surrounding the joint to a specific desired temperature before engaging in actual welding is called preheating [100, 101]. Welding of high strength steel usually caused HAZ crack by insufficient preheat as seen in figure 41. The importance of preheating or reasons to utilize preheats are [100, 102, 103]:

- It raises some steels above the temperature at which brittle fracture would occur in fabrication.
- Reduction of shrinkage stresses after welding in welds and adjacent base metal.
- Thickness of the base metal increases and with the rigidity of the welded structure because of the rapid self-quenches capability and the derived constraints respectively.
- It can prevent cracking and/or ensure specific mechanical properties such as notch toughness.
- A higher ductility with higher resistant to cracking is produced since it lowers the cooling rate in the weld metal and base metal.
- Preheating may avoid cold cracking by lowering the cooling speed and allowing a complete diffusion of the hydrogen [86].

Figure 41 HAZ crack caused by insufficient preheat [86].

Factors to determine whether to preheat or not prior to welding depends on the following [100, 103]:

- Chemistry and condition of base metal.
- Section thickness.
- Constraint level.
- Ambient temperature.
- Filler metal.
- Hydrogen content and
- Previous cracking problems.
- Code requirements.

There is higher carbon content in QT HSS and conventional S355J2 G3 than in TMCP HSS content of C in the weld. TMCP HSS has lower alloying elements compared to QT and conventional steel and consequently has much lower carbon equivalent enabling safe and satisfactory welding process without any danger of cold cracking. TMCP is normally not preheated if EN 1011-2 is applied for the calculation of preheating temperatures [86, 104].

Different welding processes and their preheating temperatures based on plate thickness of TMCP HSS in comparison of preheating temperatures with normalized steel are shown in figure 42.

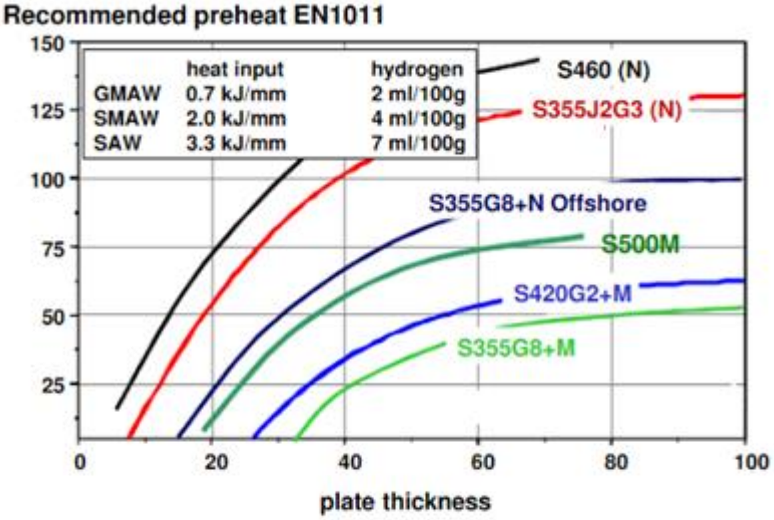
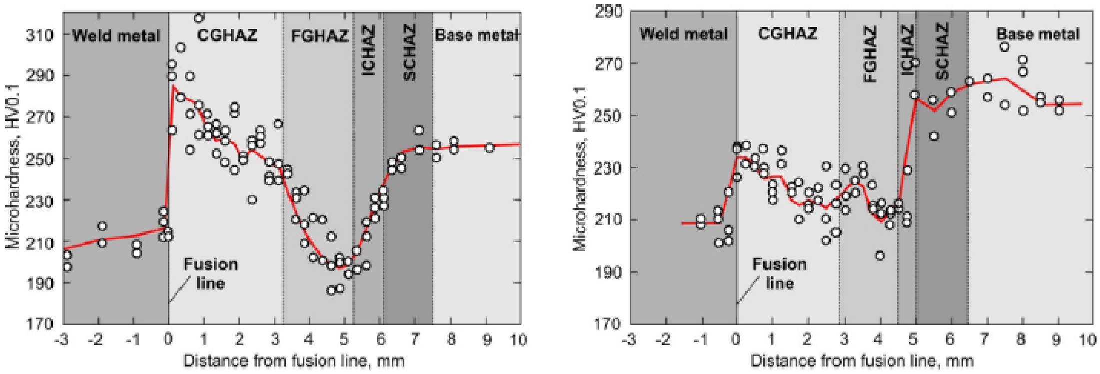


Figure 42 Comparison of preheating temperatures according to EN 1011-2 between S460N and higher strength S500M [86].

6.3.1. HAZ microstructure of steels QT and TMCP

Comparison of welded joint TMCP and QT steels are characterized by the softening in the HAZ but the lowest hardness relates to the weld metal. Formation of the quenched structures in the HAZ of QT steel can lead to cold cracking during welding and deterioration of the toughness of CGHAZ [42].

In general TMCP steel HAZ decreases more in hardness as compared to the HAZ of QT steel as seen from figure 43.



a) **QT HSS**

b) **TMCP HSS**

Figure 43 Micro hardness distribution in the weld joint of a) QT and b) TMCP HSSs [42].

It is observed in CGHAZ, the HAZ of QT welded joint has the highest hardness reaching 290-317 HV in comparison with TMCP steel welded joint, 230-240 HV. This is because of the increased carbon content in the base metal and a strong grain growth due to welding thermal cycle. The decrease in the hardness of TMCP in relation to the base metal is due to low level of alloying elements and carbon content. The lowest hardness in the HAZ of the both steels corresponds to the FGHAZ. It is explained by the formation of the polygonal ferrite in this area [42].

6.3.2. Hydrogen induced cold cracking

Hydrogen cracks may form up to several days after welding in the heat affected zone (HAZ), where there is martensite, accumulation of hydrogen and high stresses. However, for high strength steel weld metals, the cracks often form in the weld metal instead and are generally transversal to the welding direction. The conditions hydrogen cracking can occur are [105, 46]:

- The presence of hydrogen;
- High residual stresses;
- A susceptible microstructure like martensite that has a low ductility.

In figure 44 shows the procedure of minimization of risk of hydrogen cracking in weld joint

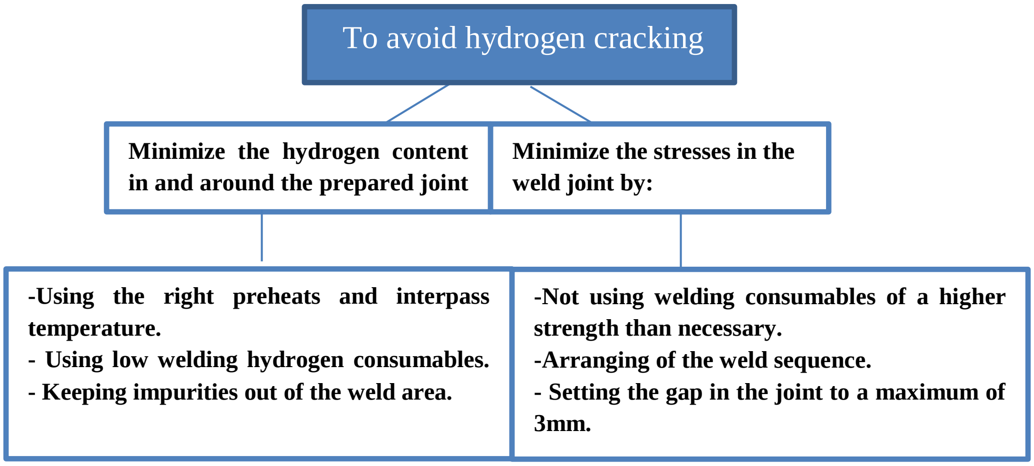


Figure 44 Minimization of risk of hydrogen cracking in weld joint [104, 106].

7. TEST METHODS FOR FRACTURE TOUGHNESS

Testing is done before to know whether the material has high energy or elongation or plastic deformation or little or no plastic deformation to produce a fracture in a material. The quantity of energy can be used as a measure of the toughness of the material, higher absorption of energy indicates better toughness.

7.1. Charpy impact Test- generally

Toughness of steels is characterized by two parameters; the Charpy Shelf Energy (CSE) and the Impact Transition Temperature, ITT (or ductile-to-brittle transition temperature, DBTT). Charpy impact test is a measure of the toughness of a material and the total energy that is absorbed during the test is referred to as CSE. The ITT is the temperature at which such a ductile to brittle transition occurs in steel [55].

The purposes of this specimen test are as follows [107, 108, 109]:

- It measures the amount of energy absorbed during fracture of a specimen in a standardized test;
- It measures the metal’s resistances to fracture in the presence of a flaw or notch and fast loading conditions;
- Impact resistance measured for weld deposit and HAZ;
- Often applies to steel welded structures which exhibit temperature dependent behavior.

The idea of carry out this process is explained below:

The test piece with a notch is struck on the opposite face of the machined notch by a hammer of the pendulum at a certain height and speed. The specimen will absorb energy until it yields. The specimen will begin to undergo plastic deformation at the notch. The work hardens at the plastic zone at the notch as the test specimen continues to absorb energy. Fracture occurs when the specimen can absorb no more energy. The amount of energy absorbed by the specimen is recorded and shows the notch toughness of the material tested [109]. Figure 45 shows the Charpy V-notch test machining.

Carbon steels exhibit ductile to brittle transition as the temperature decreases [107]. Transition region is the area where the fracture behavior changes from ductile to brittle. This behavior gives “S curve” when impact energy is plotted as a function of temperature shown in figure 46. The behavior of the curve shows a rapid declining of impact energy as the temperature decreases. The factors steel composition, welding parameters and heat treatment conditions affect this behavior of the curve. For a high notch toughness required the aforementioned factors must be controlled.

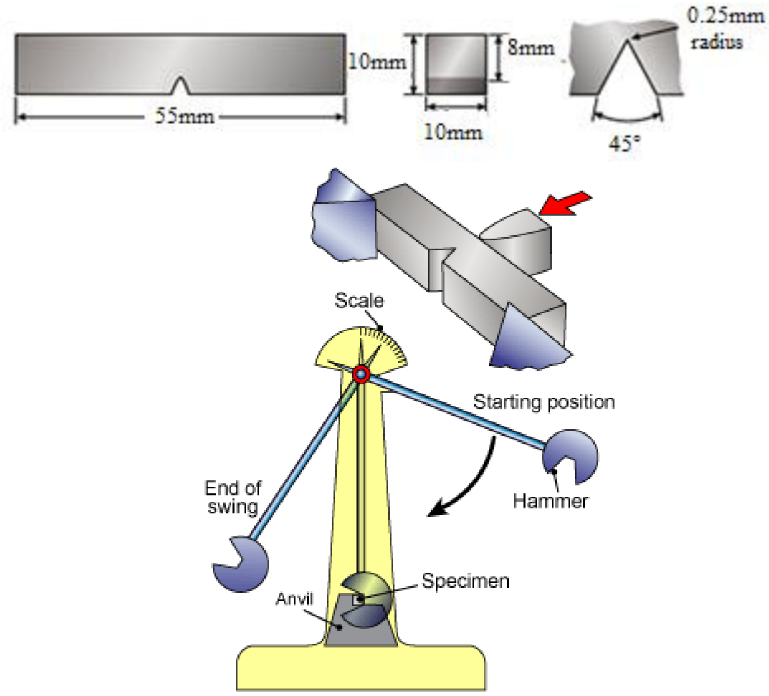


Figure 45 The Charpy V-notch specimen and testing machine [108].

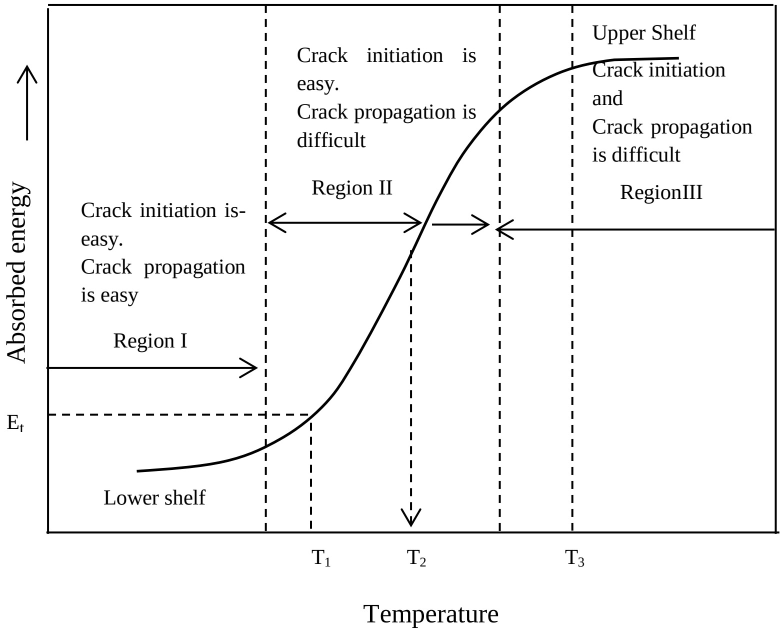
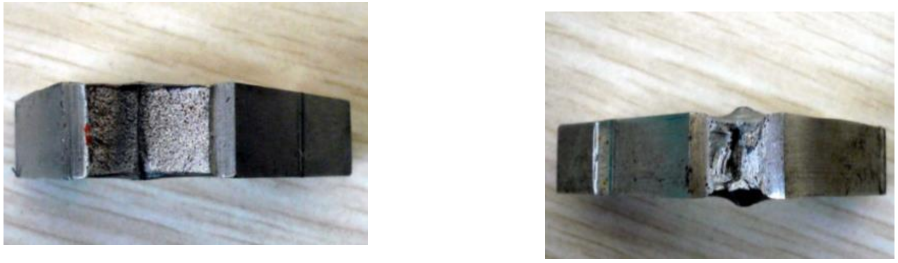


Figure 46 Graph of the temperature dependence on the Charpy V-notch impact energy [110, 111].

The testing shows the amount of energy absorbed in fracturing a piece gives an indication of notch toughness of the test material.

Figure 47 shows two tested sample fracture that metals can be classified as being either brittle or ductile.



a) Crystalline, shinning brittle fracture, absorbing little energy on impact.

b) Fibrous, dull ductile fracture, absorbing relatively large amount of energy on impact.

Figure 47 Tested samples fracture appearance [107].

7.2. Crack Tip Opening Displacement (CTOD)

It is mostly written in many articles that specimen measurement size 55x10x10mm for Charpy impact test piece is enough to measure the metal's resistances to fracture. However, by analyzing and comparing the test piece size, this does not prove so right to some extent because a little bit thicker sizes are used in offshore platforms. For thicker sizes used in Offshore structures CTOD test must be used for better results.

Measuring accurately the fracture toughness in a way that can be related to tolerable flaw size is the job for CTOD. Unlike Charpy test specimen small and inexpensive, CTOD specimen takes the full thickness of the material [112].

The purposes of CTOD test are as follows [113, 114]:

- Measures the resistance of a material to the growing of a crack.
- Used to determine the fracture mechanics properties of ductile materials.
- Show some plastic deformation before failure occurs causing the tip to stretch open.

The procedure used in testing the specimen is explained below [115, 112]:

To prepare a specimen for a CTOD test, a notch is machined in the center of the specimen and then an actual fatigue crack is induced at the base of the notch. The crack must be long enough to pass through any area displaying plastic deformity caused by the machining process. Figure 48 shows the details of the CTOD specimen.

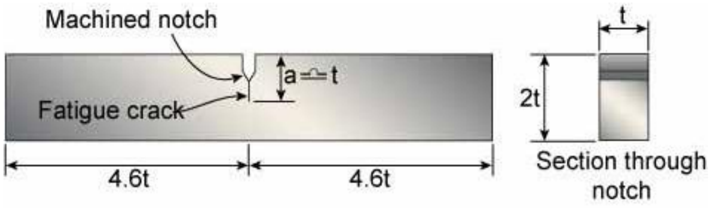


Figure 48 The CTOD test piece details [112].

The specimen is immersed in a bath of cooled liquid that has required test temperature. A load is applied to the specimen to bend and induce a concentrated stress at the tip of the crack and a clip gauge gives a reading of the increase in width of the mouth of the crack as the load is gradually increased.

A very tough steel weldment will allow the mouth of the crack to open widely by ductile tearing at the tip of the crack whereas a very brittle weldment will tend to fracture when the applied load is quite low and without any extension at the tip of the crack. Figure 49 shows a schematic of CTOD test.

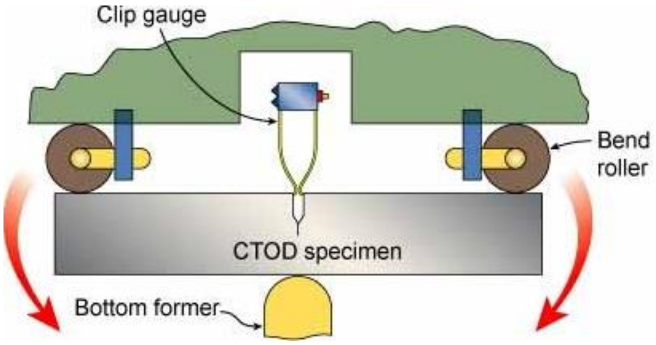


Figure 49 Picture of CTOD testing machine [112].

The CTOD test describes the specimen fracture behavior in figure 50. The CTOD values a, b, c are obtained as there is amount of opening displacement (mm) measured when brittle fracture at the initial stage of loading (**a)** or (**b)** a brittle fracture occurring following slow crack growth occurs, or (**c)** at the maximum load a slow (ductile) crack growing to fracture the specimen occurs under the condition of stable crack growth as shown in figure 50 [116]**.** From the initial stage to maximum load causing each certain amount of opening displacement at the tip of the crack gives the different shapes. With a larger CTOD value, the structure can accommodate a longer crack or larger loads. A graph of load is plotted against opening displacement. Figure 50 shows description of how CTOD value is determined [116].

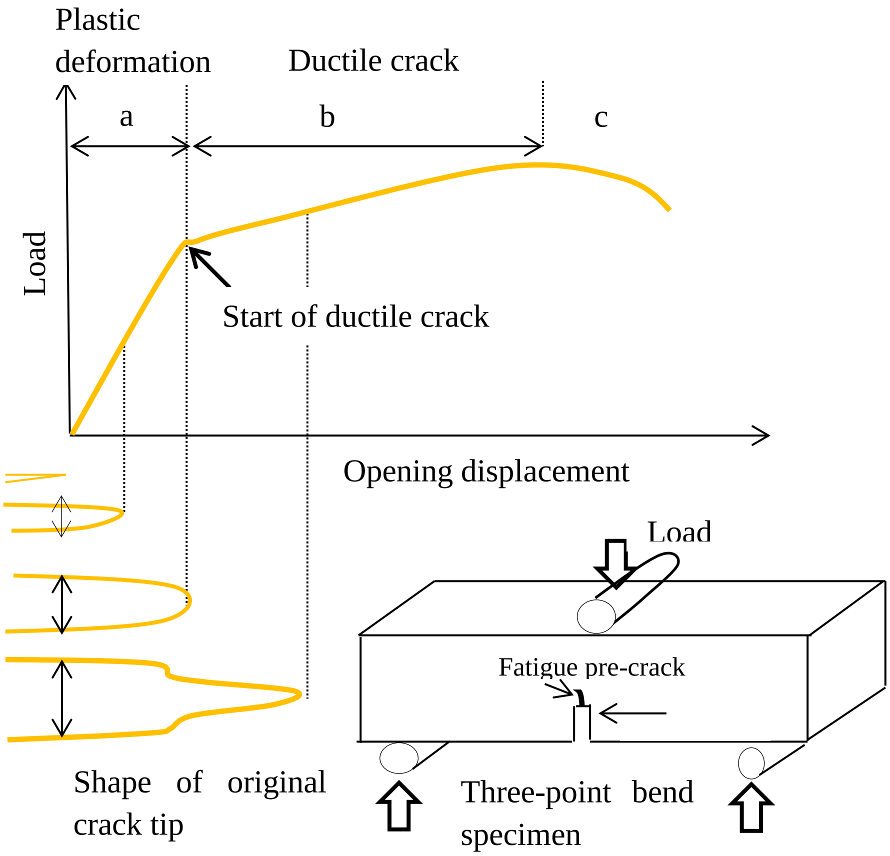


Figure 50 CTOD test result plotted [116].

7.3. Drop Weight Test (DWT)

The drop-weight test was developed at Naval Research Laboratory, Washington DC, as a method often referred to as 'Pellini' test [117].

The need to carry out the tests is to determine [118]:

Material characteristics such as:

- Fracture resistance,
- Nil-ductility transition temperature (NDTT) and
- Steel suitable for a specific application.

The NDTT is defined as the maximum temperature at which the brittle crack spreads completely across one or both of the tension surfaces on either side of the brittle weld bead.

The principle of conducting this test is described below [119]:

A specimen depending on the thickness with a brittle weld bead is made on one side of the surface. A notch is made on the weld from which a crack is initiated by impact loading. The specimen supported is struck on the opposite side of brittle crack in a standard way. Tests are carried and are cooled or heated over a range of temperatures in order to determine the highest temperatures at which the sample fractures. Below this Nil-Ductility Transition temperature the material will consistently fracture, but above the material does not. The test is carried on a number of specimens at progressively low temperatures until the test piece breaks in brittle fashion. Figure 51 shows the how Drop Weight Test or nil tests is carried out.

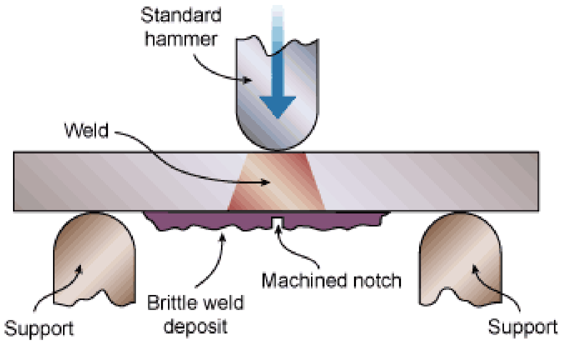


Figure 51 Drop Weight testing (DWT) of weld [119].

Figure 52 shows a real situation of a tested brittle weld specimen procedure by Drop Weight testing.

a) The test piece with brittle weld bead

b) The opposite side of the test piece to be struck.

c) The test piece is struck

d) Nil test done

Figure 52 Weld metal being tested [120].

8. CONCLUSIONS AND SUMMARY

The paper gave an overview of the different kinds of structural steels and their delivery conditions to optimize the toughness and its weldability of steel strength. Offshore structures fabrication formerly has been moderate strength steels with yield strengths up to 350 MPa by normalising route. However, today, thermomechanical rolling has been developed over the last years to produce plates with extraordinary toughness values and a yield strength class of a S500 in thicknesses up to 100 mm. TMCP is the key to a new generation of fine-grained steel grades with high strength, good toughness and excellent weldability, it lowers alloys and CE (IIW) value, a combination of material properties which cannot be achieved by traditional production techniques is thermomechanical rolling processes.

In-depth investigation in offshore construction shows the superiority of TM-steels, particularly for welding in the fields of safety, efficiency and cost reduction. Lower alloy content and the whole range of material thicknesses can be obtained by combining TMCR rolling and accelerated cooling and with lowest alloy content, a combination of TMCR rolling and quenching and self-tempering (QST). By this process route steels have excellent weldability due to their low alloy content when compared to traditional hot rolling process.

Summary physical metallurgy principles used to improve toughness for high strength structural steels are listed:

- Increasing the amount of acicular ferrite by controlling the alloying elements reduces grain size.
- Reduction of carbon content to improve weldability and toughness.
- The presence of dissolved gases such as oxygen and nitrogen (in excess) and too many inclusions that contribute to "a poor weld" can deteriorate weld metal toughness. Proper control of shielding gas during welding and the use of clean steel technology is important to be considered.
- Strict control of impurity elements like S, P, Sn, As, Sb, and N helps to prevent embrittlement of the structure.
- Toughness and ductility increases with increasing interlamellar spacing according to [25] while hardness increases with decreasing interlamellar spacing up to a critical value. On the other side of the coin, with respect to transformation temperatures ductility increases with decreasing interlamellar due to high transformation temperatures of high carbon steel (hyper-eutectoid) [61]. There seems to be a little contradiction between [21] and [53] with respect to interlamellar spacing and ductility.

Heat input

Considering performed examinations the following is concluded:

The welding heat input affects the structure and properties of the weld metal. Weld metal toughness is extremely sensitive to the welding heat input. The change in toughness is not just bound to the heat input, but is also influenced by the weld bead size. As the bead size increases, which corresponds to a higher heat input, the notch toughness tends to decrease. More grain refinement occurs if the welding beads are smaller, resulting in better notch toughness.

TM plates result in good impact toughness and allow even for S500M a wide range of welding heat inputs without deterioration of the toughness. Under many conditions welded constructions built from TM plates do not need to be PWHT because the welded condition is already sufficiently tough and HAZ hardness moderate.

Welding electrode

Carbon equivalent (CE) is a measure of carbon content and other alloying elements. The equation below shows how to assess hydrogen-assisted crack (HAC) sensitivity [121]. The higher the CE (IIW), the lower is the resistance to HAC.

$$CE(IIW) = \mathrm{C} + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5}\ (\%) \qquad Eq\ 7$$

It is essential to select welding electrodes with carbon content lower than that of the steel to be welded. But lowering carbon content must be compensated for by other alloy elements to maintain CE (IIW). A 0.12 wt-% for carbon in high-strength steel welding electrodes is considered an upper limit, as twinned martensite, which has poor resistance to HAC, may form above this limit.

Also the used of basic consumables gives low amount of oxygen, which leads to a low volume fraction of inclusions. Overmatching of high strength steels using welding consumables, may involve expensive preheating, interpass during welding to resist HAC and will not be economical and less productivity. Overmatched is an option to use only when it offers enough toughness and it is cost effective.

The application of undermatched welds to HSSs is more important and practice than overmatching. It leads to the reduction of minimum preheating temperatures and thus prevents cold cracking on the weld metal.

The bigger the electrode diameter, the higher the strength since it increases the number of runs deposited, while the toughness declines at low temperatures.

Fracture Toughness

Research studies were also carried out aiming to rationalize the selection of steel with resistance to brittle fracture.

It was demonstrated that more effective toughness is needed for:

- Structural elements under fatigue load.
- Lower service temperature.
- Higher yield strength.
- Thicker products.

Fracture toughness generally depends on temperature, environment, loading rate, the composition of the material and its microstructure. It is preferable to determine fracture toughness in CVN, CTOD and DWT.

These different testing methods measure the behavior of materials, to reveal the temperature where material´s fracture mode changes from ductile to brittle. Other testing methods for example crack tip opening displacement (CTOD), crack tip opening angle (CTOA) methods, usually they are executed with full-size (actual size or thickness) test piece, but the results are difficult to compare and there are no standardized demands for these tests in Europe.

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