# A REVIEW ON FRACTURE PROPERTIES OF WELDED HIGH STRENGTH STEEL-(HSS) FOR LOW TEMPERATURE APPLICATION

By

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## Abstract

The technological evolution in structural steels are pointing towards high strength steel, especially in the offshore and marine applications. Therefore, there is need to have knowledge on the fracture behaviour of high-grade steel welded joints to improve and contribute to the potential upgrades of the design criteria. Lightweight structures (with reduced cost and weight) that guarantee high-quality/high-strength weld-able joints has become the trend in recent research. Natural gas and oil reservoir which have the potential to boost economic growth and play a vital role in the future energy requirements lie beneath the waters of the world's ocean. This water depths ranges from a few hundred to several thousand metres. Explorations and production activities in these offshore waters have revealed depths of 2000 metres and more. Generally, water depths of 1000m (known as mesopelagic zone) and above have low temperatures of about -2°C. At this temperature, seawater freezes and ductile materials are susceptible to brittle fracture. This has significant effects on installation of oil and gas pipelines at low temperature. This have become challenges, which calls for enhanced engineering techniques to cope with the risks of fatal failures. Due to inherent metallurgical phenomenon, mechanical properties heterogeneity, residual stresses and geometrical defects, cracks propagates easily especially at the welded joints. Studies have been conducted on the fracture properties of the HSS materials. This paper is aimed at reviewing the effects of chemical composition on the microstructural properties of HSS materials in low temperature applications. The concept of fracture mechanics as applied to fracture behaviour of welded joints with focus on the effects of low temperature on HSS materials is presented. The fracture toughness in deep water applications, where temperature at the depth of water is in semblance to the arctic region environment is briefly discussed. In conclusion, API X100 TMCP materials have been recommended as a types of high strength steels (HSS) for structural steel material applicable for low temperature because of the properties, chemical compositions and development methods or manufacturing processes. Also, modern welding techniques often used in the arctic region is suggested to be applied for the deep offshore materials for sustainability, effectiveness and fitness for service requirements.

**Keywords**: Low temperature, deep offshore, Fracture behaviour, Geometrical defects, Pipeline, Welded joints.

## 1. INTRODUCTION

The Federal Government of Nigeria, under the auspices of Nigeria National Petroleum Corporation-NNPC, had opened up a new frontier in Oil and Gas exploration, by allocating some offshore blocks in water depths reaching 2500metres [1]. These water depth and plans for even greater depths than 2500m will undoubtedly impact positively the country's production and reserve blueprint. Fig. 1 shows the Nigeria's deep offshore oil and gas exploration area. The deep and ultra-deep water operations are technically challenging for exploration. Water depths of 1000m and above have low temperatures as seawater freezes at -2°C [2] and at this temperature, ductile materials are susceptible to brittle fracture and this has significant effects on the installation of oil and gas pipelines due to the low temperatures. Early researches revealed that deep offshore pipeline problems are caused by low temperature and high strain rate in the material that resulted to brittle fracture. [3]. For example, betweem 0°C and 5°C, offshore ships (vessels) have broken into two in harbours and bridges have collapsed, while gas storage tanks and pipelines have ripped open [4]. These are some of the common engineering challenges that come with the use of steel pipelines in low temperature region in deep offshores. Brittle failures of metals due to extreme cold, problems of corrosion, large deformation of pipelines as a result of reeling installation defects, microstructure heterogeneity and overloading of facilities due to some other factors in the seabed are examples of potential flaws that leads to pipeline failures.

Expectedly, since most of the deep water activity in Nigeria is in, so called, virgin territory, thereby lacking infrastructural support and services, there is the need to research the deep offshore environment for appropriate pipeline material and welding techniques to be adopted to prevent future structural problems in the Nigeria deep offshore region. This can be likened to the arctic region oil and gas exploration and production technologies. [5], opined that there is need to study the behaviour of newer materials applicable to certain areas, especially the fabrication techniques. The techniques involves welding process which affects the microstructure of the weld material and influence the crack growth behaviour, which occurs in both air and seawater environments. Other factors that affects the behaviour are the type of materials, level of induced residual stresses which depends on material thickness, welding input parameters, and level of expertise employed during welding.

Additionally, freezing temperatures, immense water pressure and pitch darkness all make producing oil and gas from deep water a major technical challenge. Substantial economic losses and negative environmental impacts are the consequential outcome. Therefore, safety and reliability becomes a source of concern to offshore engineering professionals.

Due to the challenges in production activities with oil and gas structures in deep offshore, an enhanced engineering techniques to cope with the risks of fatal failures is required [6].

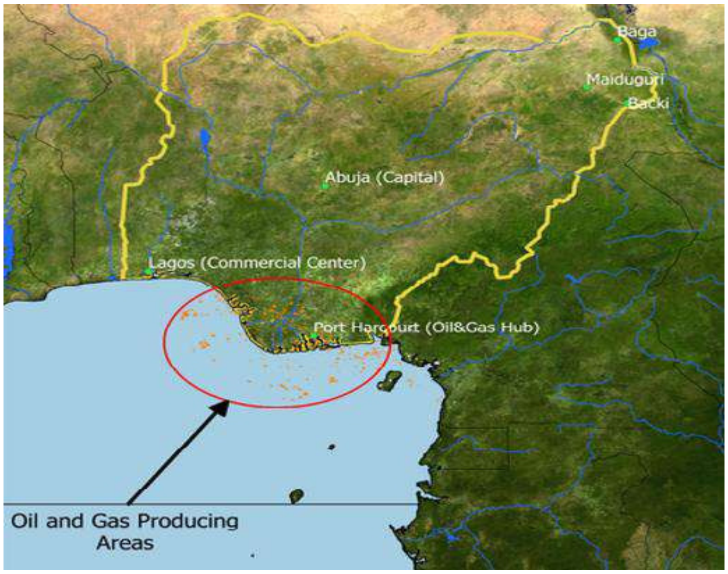

**Fig. 1.** Oil and Gas Producing areas in Nigeria. [7]

## 1.1 Brief introduction to (low temperature) Deep offshores and similarity with arctic region environment

Arctic region is an environments within the globe that has enormous oil and gas resources, but with very harsh and hostile conditions. The similarity to deep offshore is the low temperature that is detrimental to steel materials used in the structural installations. The Arctic environment compared to deep offshore region are both hazardous to structural steels (metals) at low temperatures, because they have increased susceptibility to brittle fracture. Hence, materials with high toughness properties are required to ensure that adequate fracture-resistance at low temperatures are used to build the facilities [8]. Exploration to deep and ultra-deep offshores requires that construction of structures, platforms and many other facilities are capable of operating safely at very low temperature, say -70ºC or lower down till -100ºC. Fortunately, most of these structures, platforms and facilities were built with metals (mostly structural steels and HSS) and joined together by welding. The welded HSS steels used are due to some of the advantages in mechanical properties such as low cost (compared to high cost of titanium alloy materials), ease of fabrication (low carbon content), high strength, and availability of grades that are highly fracture-resistant at low temperatures. [8].

Therefore, the demands in properties of materials used for deep offshore and arctic structures are similar. These includes fatigue property, strength, corrosion resistance, impact resistance, toughness, and transition temperature. Other stringent demands are welding technologies which requires high efficiencies, high productivity, high qualities, for labour savings and low costs etc. [9]. As a result of these special conditions experienced with both Arctic environment and deep offshore, special and advanced welding technologies, with new grades of metallic materials (steels) are inevitable.

## 1.2 Materials Applicable for deep offshore (low temperature) Conditions

Researches into new and higher grades of steel that can satisfy the service conditions of deep offshore structures have become a challenge in recent times. Some of these new materials are steel grades of X80, X100, X120, titanium alloys (Grade 5, Ti-6Al-4V (Ti64)) and upgraded 9% Ni steels. Due to the entirely different environment from the usual moderate temperate region, lower grades of steel cannot be utilised. HSS structures with very high toughness property under extremely low temperature will suffice. In deep offshore region, the minimum ambient temperature recorded falls well below -40°C. This definitely, will account for the minimum design temperature to go down to -60°C. Hence, the need for special grade metals (materials) that can survive the extremely cold region without failing under service conditions.

There is need to investigate the welding technologies for joining the metal structures that can give a satisfactory weldments under low temperature service conditions too. The output quality of material is expected to be high among many other desired characteristics of the welded joints of X100 steel. The yield strengths minimum value should be 690 MPa and above which fall within the acceptable standard materials. The toughness of the material is rated high, as high as 150 J/cm$^2$ for CVN @ -40.

## 1.3 The Thermomechanical Controlled Process -TMCP

TMCP technology has enabled the production of excellent steel plate with high-strength and good low-temperature toughness. This process is divided into two, direct quenching and tempering process, and the Interrupted accelerated cooling process. The former involves high cooling rate of plate with water to barely room temperature. The tempering is required to obtain the appropriate ductility and toughness. In the later process, the plate is cooled with water at moderate cooling rate and then subjected to air cooling, only in the transformation temperature region. The self-tempering effect of this process reveals excellent ductility and toughness. The processing conditions in TMCP have to be optimized in order to obtain high-strength and low toughness of the material, since they both depends on the process conditions.

## 2.0 Overview of High Strength Steels (HSS)

High-Strength Steels-HSS are complex, sophisticated materials with carefully selected chemical compositions and multiphase microstructure resulting from precisely controlled heating and cooling process, [10]. They contain ferrite and martensite in the microstructure. The 'high strength' is the major attribute, which enhances the use of thinner steel materials for weight consideration. HSS contains very low carbon content and small amounts of micro-alloying elements, such as Niobium, Vanadium, Titanium and Molybdenum [11-14]. They possess highly refined grain and cleanliness, characterized by the low sulphur content and reduced amount of detrimental second phases such as oxides inclusions and pearlite. They can be seen as advanced variant of HSLA steels. The evolution of HSS steel grades for line pipe in terms of strength and toughness over the last decades is shown in figure 2. The description of the main alloying elements and processing methods are briefly described [14-15].
The improvements in the mechanical properties of high-strength steels lies in the complex thermomechanical controlled processing (TMCP) routes and accelerated cooling (AcC) techniques. The advantages of the final products of higher strength micro alloyed steels and grain refinement is the reduced carbon content for excellent field weldability which are achieved through metallurgical tools of the rolling mills, [11-12].

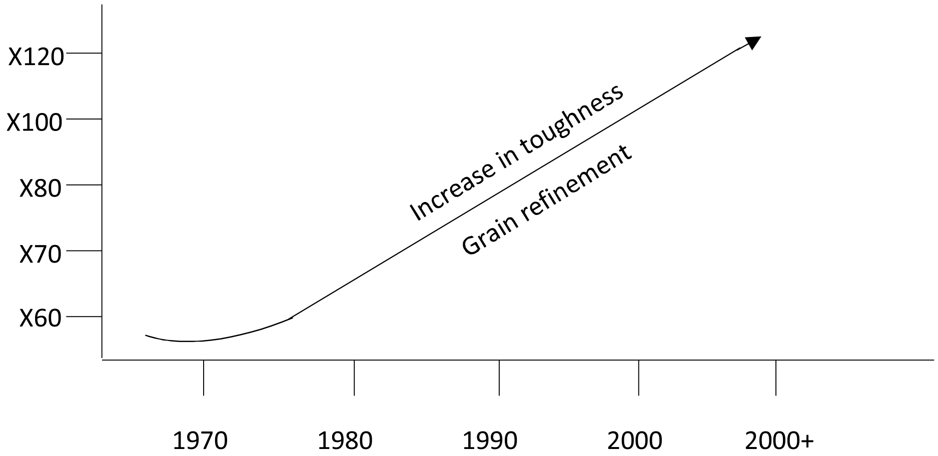

**Fig. 2**: Evolution of steel grades as an example of HSLA steel development. Grain refinement increases the strength and toughness.

## 2.1 Metallurgical Consideration of chemical composition.

The chemical composition of HSS steels may vary for different product for particular mechanical property requirements. This can be based on product specification levels 1 or 2 – (PSL1 or PSL2). Usually, Manganese-Mn (up to 2.0wt % in combination with very low Carbon-C of < 0.10 wt%) and minor additions of other alloying elements such as Niobium-Nb, Vanadium-V, Titanium-Ti, Molybdenum-Mo and Boron-B are the constituents [10]. The additions of the alloying elements serves mainly to strengthen the ferrite by:

- Grain refinement, which depends on the interaction between chemical composition,
- Solid solution hardening which is related to the contents of the alloying element and
- Precipitation hardening which depends on the TMCP process.

The type and volume fraction of the product formed under given conditions is determined by individual element and cooling rate applied [14, 16].

The increase in strength of steel is related to an increase of the following alloying elements: Molybdenum (Mo), Silicon (Si) and Nickel (Ni) [10]. However, CE and Pcm values are kept almost constant even for increasing steel grades. The alloying elements also exerts influence on transformation temperatures. For example reducing the temperature at which austenite begins to transform to ferrite and/or pearlite during cooling, results in a finer-grain microstructure [14, 16]. Over the years, some strategic alloying combinations have been pursued to meet the increasing demands on strength and toughness without compromising weldability, [17]. The following alloying combination suffices:

- V+Mo+Nb: to produce secondary hardening by forming carbides, nitrides and carbonitrides;
- Ni+Mo: effective addition of microstructure refinement by suppressing austenite recrystallization during controlled rolling and steel strengthening by precipitation hardening and enhancement of hardenability;
- Ni+B: synergistic improvement of hardenability;
- Nb+V: increase strength properties. However, steels based on this combination may require relatively high carbon equivalent design, which can compromise the capability for preheat-free field welding;
- Mo+Nb+Ti: More effective (compared to the formerly applied Nb+V steels) in achieving the strength requirements of X70 and X80 (high Mn steels) particularly in thicker pipe walls; A significantly finer ferrite grain size;

**Table 1**: Effects of alloying elements on HSS.

| Element | wt % range | Effect |
|---|---|---|
| Carbon-C | 0.03 – 0.10 | Strengthens the matrix by precipitation |
| Manganese-Mn | 1.6 - 2.0 | Reduces DBTT, affects fine-grained lower bainite microstructure, substitutional strengthening. |
| Nickel-Ni | 0.2 – 1.0 | Improves the properties without effects on low temperature toughness and field weldability. Increases fracture toughness as it forms less hardened microstructural constituents that is detrimental to low temperature toughness. |
| Vanadium-V | 0.03 – 0.08 | Improves strength. |
| Molybdenum-Mo | 0.2 - 0.6 | Improves hardening |
| Niobium-Nb | 0.03 – 0.06 | Improves strength and toughness by grain refinement. Reduces temperature range between rolling passes. |
| Titanium-Ti | 0.005 – 0.03 | Strengthen the ferrite. Prevents detrimental effect of nickel on hardening. Grain refinement. |
| Silicon-Si | ≤ 0.6 | Improve in strength by solid solution |

## 2.2 Microstructural Consideration

Material properties are finally determined by the microstructure. This must be a key variable in the design to ensure safe and optimal performance under operating conditions [13]. Modern HSS pipe have different and complex microstructural arrangements which depends on the chemical compositions and processing routes, i.e. the TMCP and Accelerated cooling-AcC.

For strain-based design applications, microstructures of different forms and combinations like bainite, martensite and ferrite are formed in order to achieve the target strength, toughness and ductility. These qualities are based on a careful design of the steel chemistry and processing in order to control austenite phase transformations, such as lower bainite and lath martensite [19].

A bainitic microstructure is produced with precise chemical composition (micro-alloying) and low carbon content, aiming at a low Pcm value. The basic alloying system contains Cu, Ni, Cr and Mo and micro-alloying elements such as V, Nb, Ti and B [20]. Subsequently, the rolling and cooling procedures are very effective in achieving a grain structured (low angle boundaries) microstructure which hinders the dislocation mobility, resulting in a perfect combination of strength and toughness. This microstructure is also developed to ensure fully ductile failure behaviour and high crack arresting behaviour at temperatures as low as -40 °C (arctic conditions), [21, 22].

### 2.3 Steel processing

The development of thermo-mechanical controlled process (TMCP) was the real breakthrough to achieve grain refinement. This is the most effective metallurgical mechanism to improve both strength and toughness in high strength steels. According to [11, 14, and 18.] TMCP steels can be precisely controlled to obtain the desired microstructure for higher strain hardening capacity and ductility. In a separate work by [11, 21, 23], higher requirements for strain based design, with respect to strain hardenability, toughness and high strength, a particular cooling process (after rolling), known as accelerated cooling process (AcC) is performed. However, in some cases the steel plate is first hot rolled and soaked (held at a temperature until the desired microstructural changes takes place) and then submitted for inline quenching and tempering (QT) process. Such QT treatment is performed to produce a bainite-martensite microstructure without applying AcC process. By tempering, it is possible to reduce the brittleness of martensite and improve ductility and toughness [19, 24]. Different types of microstructures can be produced by these processing routes, such as: bainite single phase, ferrite-bainite dual phase and lower bainite-lath martensite [13, 19, and 23].

In 1998 a new concept of TMCP technology was developed in order to obtain not only high strength by transformation strengthening but also high toughness by refinement of transformed microstructure. This results to a combination of high strength/high toughness steel with reduced alloying elements. The microstructure consists of a bainitic matrix and finely dispersed martensite-austenite constituent (MA) as second phase with a volume fraction above 7%. The process consists of an advanced accelerated cooling device, with the purpose of reaching highest cooling rates and an induction heating equipment for online heat-treatment process (HOP), with high heating capacity to heat thick plates up to 40 mm [25]. This combination enables to reach a novel metallurgical controlling process that cannot be achieved by the 'conventional' TMCP. Some advantages of applying HOP process [23, 25]:

- Precipitation hardening by very fine carbide (reduction of diffusible free carbon content);
- Recovery of the dislocation density;
- Formation of MA constituents which enable the balance high strength / high deformability.

**Table 2:** Microstructure for different processing conditions (14)

| S/No | API 5L | Process used | Microstructure |
|---|---|---|---|
| 1 | X120 | TMCP + AcC | Ferrite + Martensite, Dual Phase, (19) |
| | | | Tempered Lath Martensite (19) |
| | | | Lower Bainite (19) (20) |

| | | | |
|---|---|---|---|
| 2 | X100 | TMCP + AcC + HOP | Ferrite + Bainite, Dual Phase (23) |
| | | TMCP | Ferrite + Bainite (20, 21, 26) |
| 3 | X80 | TMCP + AcC + HOP | Bainite + Martensite-Austenite (23) |
| | | TMCP + AcC | Ferrite + Bainite, Dual Phase (23) |
| | | | Lower Bainite (20) |
| | | | Lower Bainite + Lath Martensite, (27) |
| 4 | X70 | TMCP | Bainite, (13) |
| | | | Polygonal Ferrite + Pearlite Band (28) |
| | | TMCP + AcC + QT | Fine grain Bainite, (29) |
| | | TMCP + QT | Bainite + Martensite + Ferrite (22) |

## 3.0 The API X100 steel.

API X100 steel materials are types of high strength steels (HSS) used for structural steel material especially in the cold region because of the properties, chemical compositions and development methods or manufacturing processes. They are known for increased productivity due to efficiency in the reeling installation processes as a result of weight reduction. The excellent characteristics associated with X100 such as excellent field weldability, high toughness of base material and heat affected zone-HAZ at low temperature and microstructural properties, has made it to overcome the metallurgical problems associated with other forms of steels. The exhibition of these characteristics and the thermochemical controlled process-TMCP of API X100 steel during the development has made it an excellent material for use in the cold or low temperature region such as Arctic, deep and ultra-deep offshore region for energy explorations. The metallurgical problems associated with other forms of steel such as X52, X60 and X70 during development are overcome in the development of X100 steel because of its characteristics. Absolutely, an increase in strength increases the toughness, see figure 2. Figure 3 presents an overview of chemical compositions for typical API X100 TMCP steel. The same figure also shows the parameters that characterize good weldability, known as carbon equivalent (CE) and critical metal parameter for weld cracking (Pcm).

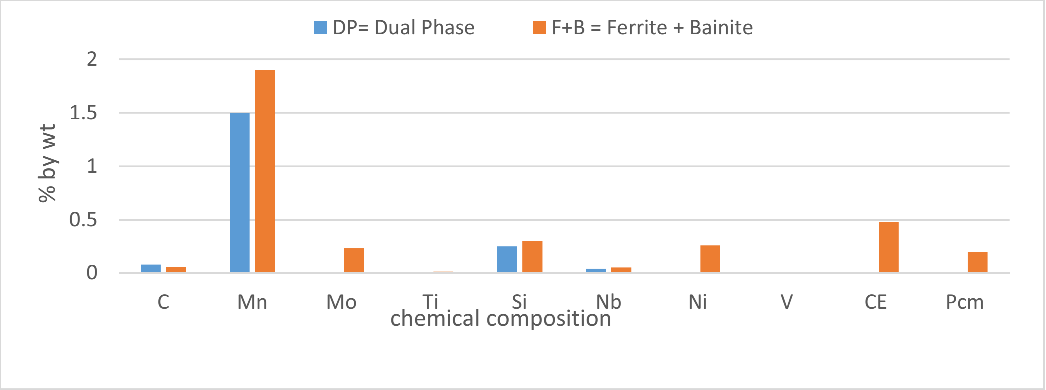

**Fig. 3:** Typical chemical composition of API X100 steel grades and weldability parameters.

### 3.1 Improving the strength of X100 steel for low-temperature toughness

Before the advent of X100, offshore structures are constructed with less strength thick plates such as X65 and X70 materials. The thickness ranges from 40 mm to 120 mm and even more. Due to the increased thickness, the tendency for brittle failure increases. The toughness of the welded joints are measured using Charpy V-notch test and CTOD, there is a minimum toughness value required for metal alloys or their welded joint to be suitable for low temperature use.

Toughness and Strength values have influence on weldability, improved by the TMCP process. The weld joints have well refined microstructures, high toughness and strength value, narrow HAZ and low distortion.

Precipitation hardening, Slid solution hardening and Transformation strengthening are the three major methods of strengthening steel. High and ultra-high strength steel such as X100 is often developed with the three methods. Transformation strengthening is the most important of the three and is normally achieved by micro-alloying and TMCP technology. Importantly, refining the austenitic structure by thermomechanical rolling and inhibiting the austenite grain coarsening during slab reheating by Titanium nitride (TiN) particles improves the low temperature toughness of the base material.
Thermo-mechanical control process (TMCP) and cladding are part of the processes used to improve the properties for high strength materials. Increase in strength and toughness are aided by TMCP, while increased corrosion and wear resistance has been aided by Cladding.

The extremely low-temperature, water depth, and water pressure that renders the pipeline materials to failure risks needed an enhanced technology to overcome the challenges and bring them under control. One of the quality descriptions of any material is the design temperature. Generally, steels are prone to brittle fracture at low temperatures. Their ductility property changes to brittleness, often known as 'transition temperature'. Therefore, the design temperature of 20°C below the minimum expected service temperature and/or ambient temperature is often allowed in the design. In deep offshore region, the minimum ambient temperature recorded falls well below -40°C. This definitely, will account for the minimum design temperature to go down to -60°C. Hence, the need for special grade metals (materials) that can survive the extremely cold region without failing under service conditions.

### 3.2 Weldability

Welding of X100 steel material has become an essential part of developmental process to explore and develop materials for low temperature energy resources. However, there are several challenges with it and due to these challenges, an advanced welding technologies are applied to ensure a good weldment that can satisfy and survive the low temperature conditions.

Several welding methods have been used such as Narrow Gap Welding (NGW, or narrow groove welding), Laser welding, Laser-arc hybrid welding, Tandem, Metal Inert Gas/Metal Active Gas (MIG/MAG) welding and multi wire Submerged Arc welding (SAW). The welding method that will be recommended for this work shall be based on local factors.

## 4.0 Conclusions

The development within the field of Materials Technology is very vital to ensure success in reaching the aim of safe exploration, development and production of low-temperature region energy resources. A significant progress has been achieved during last years in the development of HSS line pipe steels, especially for strain-based design applications. Development of optimum microstructures (e.g. ferrite-bainite DP and/or bainite-martensite/austenite) which provides the required mechanical properties for high strain capacity applications, such as higher strain hardening and uniform elongation are significant improvement for HSS development. High strength steel grades are showing improvements in mechanical properties. Increase in strength has been identified with proportions of basic chemical compositions such as Mo, Si and Ni contents. It can be observed that the characterizing parameters for good weldability (i.e. CE and Pcm) are maintained and practically unchanged. The TMCP processing routes are effective in order to produce steels with lower Y/T ratio and sufficient toughness.

The choice of API X100 TMCP steel materials needs further research to appropriately achieve the desired aim especially at the welded joints for low temperature applications. Narrow gap welding technique ensure good field weldability.

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