Scientific Journal of Review (2014) 3(7) 547-554
ISSN 2322-2433
doi: 10.14196/sjr.v3i7.1600

Contents lists available at Sjournals

Journal homepage: www.Sjournals.com

Review article

# Sustainable development of bridge industry with the new generation of high performance steel materials

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A R T I C L E I N F O

*Article history,*
Received 11 June 2014
Accepted 22 July 2014
Available online 25 July 2014

*Keywords,*
High performance steel
Transportation infrastructure
Bridge industry
Sustainable development

A B S T R A C T

The development of transportation infrastructures is one of the main indicators of advancement and welfare of communities. Bridges are essential to road and railway networks as transport links. Thus, extending the life cycle and sustainable development of bridges can increase the quality of human life. Steel is reputed as one of the most sustainable construction materials for its unique characteristic of recyclability without losing qualities. In the past few decades, significant improvements in rolling and heat treatment processes and metallurgical advances have made it possible to produce a new generation of constructional steel material designated as the High Performance Steel (HPS). Higher performance in weldability and toughness of HPS steels compared to conventional high strength steels has increased the cost efficiency, safety and life cycle of bridges. This paper reviews the prospects of the world steel industry and introduces the outstanding steelmaking technologies in leading countries and their impacts on the bridge industry.

## 1. Introduction

The development of transportation infrastructures boosts the dynamism and economic growth of countries and represents advancement and welfare of communities.

Roads and railways are the two major means of transport in many countries. According to Iran's official statistics, as reported in Table 1 (Ministry of Roads and Urban Development, 2011), roads and railway networks carry the largest volume of transportation demands in Iran. Nevertheless, these demands increase annually and further development of road and railway networks are necessary.

**Table 1**
Official statistics of Iran's transportation in 2011.

| Transportation mode | Freight transport (thousand tons) | Percent (%) | Passenger transport (millions) | Percent (%) |
|---|---|---|---|---|
| Road | 580000 | 81 | 913 | 94.30 |
| Rail | 956 | 0.135 | 28.56 | 2.95 |
| Air | 60.256 | 0.0085 | 16.48 | 1.70 |
| Water | 135000 | 18.85 | 10.20 | 1.05 |
| Total | 716016.256 | | 968.24 | |

Bridges are essential to road and railway networks as transport links, ensuring safety and high quality of life. Meanwhile, sustainability is one major concern in the design, construction and maintenance of bridges.

Basic characteristics of sustainability include optimum use of natural resources with minimum environmental damages, as well as high – speed construction and prolonged life cycle. Also, sustainable construction is aimed at reduced lifetime costs and energy consumption rather than lower initial costs (Subramanian, 2011, 116). Steel is worldwide reputed as one of the most sustainable construction materials for its unique characteristic of recyclability without losing its qualities. This valuable trait of steel can play a major role to meet the requirements of sustainable development (Sustainable Steel Council, 2013, 1).

Smooth, economic, safe and sustainable transportation is included as one of the main prospects of Iran's 5th development plan. One basic step to achieve this desire, according to Transportation Committee on Manufacturing and Infrastructural Affairs Commission Affiliated to Secretariat of Expediency Council (2009), is to employ the latest world technologies to construct, develop, use and maintain the country's transportation network. This paper reviews the prospects of the world steel industry and introduces a new generation of high performance steel material as a unique choice to improve the quality of the bridge industry in Iran.

## 2. Development prospects of the world steel industry

Over 1.4 billion tons of steel material are annually produced and used throughout the world. Due to the constructive role of steel in the advancement and welfare of communities, the steel production industry is continually developing in Latin America, Asia and the Indian subcontinent (Worldsteel Association, 2013, 1).

Reducing greenhouse gas emissions is a global necessity to protect the earth and save the environment. Carbon dioxide ($CO_2$) is the most emitted greenhouse gas from the steel industry. On average, 1.8 tons of $CO_2$ are emitted during the production of every ton of steel. According to the International Energy Agency, in 2010, the iron and steel industry accounted for approximately 6.7% of total world $CO_2$ emissions (Worldsteel Association, 2013, 2).

According to the latest news, Iran ranks 15th in the world steel production (Isfahan Metropolis News Agency, 2013). On the other hand, Iran is now the eleventh – highest producer of greenhouse gases in the world(Mehr New Agency, 2013). Thus, Iran emissions are more than expected. Accordingly, the government should identify opportunities to reduce the steel industry's $CO_2$ emissions. The development of new technologies to reduce the emissions associated with the manufacturing of steel products, use of lighter and stronger products and reduce the life cycle energy consumption from the sustainability point of view are examples of these opportunities. In connection with this, Worldsteel has published a framework to reduce carbon footprint associated with the steel industry. This framework recommends four main actions as follows: (1) the increase of research and development funding to identify outstanding steelmaking technologies with reduced $CO_2$ emissions, (2) the development and application of new lighter and stronger steel products to reduce the life cycle energy consumption, (3) moving the performance of all steel plants up to the current available level through technology transfer; and (4) using the standard of ISO 14404 as a measurement and reporting system for steel plant CO2 emissions (Worldsteel Association, 2013, 5).

**3. Steel types**

According to the American Iron and Steel Institute (AISI), various types of steel with different applications are conventionally categorized into four groups as follows depending on their chemical compositions (Bell, 2013, 1):

1- Carbon steels: These steels contain little amounts of alloying elements. They are produced in three forms of low carbon or mild steel (with a maximum of 0.3 % carbon), medium carbon steel (with 0.3 – 0.6 % carbon) and high carbon steel (with more than 0.6 % carbon).

2- Alloying steels: Hardening, tensile strength, corrosion resistance, ductility and weldability of alloying steels are controlled by adding varying proportions of alloying elements such as manganese, silicon, nickel, titanium, copper, chromium and aluminum.

3- Stainless steel: These steels generally contain between 10 – 20 % chromium as the main alloying element which gives high resistance to corrosion. Stainless steels are approximately 200 times more resistant to corrosion than mild steel. Austenitic, Ferritic and Martensitic steels are different kinds of stainless steels with different crystalline structures. Austenitic steels, the most produced stainless steel, generally contain 18 % chromium, 8 % nickel and less than 0.8 % carbon. Austenitic steelsare nonmagnetic and non-heat-treatable and they are often used in food processing, kitchen equipment and piping. Ferritic steels contain negligible amount of nickel, 12 – 17 % chromium, less than 0.1 % carbon, along with other alloying elements such as molybdenum, aluminum or titanium. Ferritic steels are magnetic and they can be hardened by cold – works rather than heat treatment. Martensitic steels contain 11 – 17 % chromium, less than 0.4 % nickel and up to 1.2 % carbon. These magnetic and heat – treatable steels are used to make knives, cutting tools, as well as dental and surgical equipment.

4- Tool steels: These steels contain tungsten, molybdenum, cobalt and vanadium in varying proportions to increase heat resistance and durability. Thus, they are ideal for making cutting and drilling equipment.

Different types of carbon steels and alloying steels are generally used in construction and they are known as constructional or structural steels. For example, mild steel and alloying steels are used to make profiles and plates; and medium carbon steel is used to make steel beams and rails.

**4. The present sustainable development of bridge industry**

The advents of modern technologies and new materials have changed the design and construction methods of bridges. Meeting the challenge of growing demands for transportation infrastructures, requires the new bridges to be constructed faster with no disturbance in the local traffic flow. This makes public agencies and contractors to seek new materials and methods to construct without compromising on safety and durability of bridges (Subramanian, 2011, 116).

All components of steel bridges can be manufactured off – site and delivered to the site, allowing simple and quick assembly and erection. Therefore, the construction time and weather – related delays are reduced. In addition, off – site manufacturing minimizes defects and waste generation (Sustainable Steel Council, 2013, 1).

The new applications of nanotechnology in the field of construction can fix the current construction problems and change the requirements and the organization of the construction process. In fact, the significant growth of nanotechnology and its applications within the last 25 years is relied on the simultaneous advances in physics and chemistry sciences. Generally, nanotechnology is defined as controlling the creation of materials at the level of atoms, molecules and nano – scale structures. Thus, lighter, stronger and more durable materials can be produced (Ge and Gao, 2008, 235).

Today, several new nanotechnology based materials are commercially produced. These modern materials include more durable, so – called high performance materials. High Performance Steel (HPS) is one important type of these products which is introduced in this article. Tensile strength, toughness, weldability, corrosion resistance and ductility of HPS steels are higher than conventional structural steels. These unique characteristics reduce the energy consumption needed for construction, repair and maintenance of bridges. In addition to the need to reduce CO2 emissions in the steelmaking process, life – time energy efficiency and environmental effects of end –

of – life steel products are two important factors to reduce the carbon footprint associated with the steel industry (Worldsteel Association, 2013, 5). One characteristic of HPS steel is its low carbon content which is important to reduce the carbon footprint in the time of destruction and recycling.

Due to the above mentioned advantages, HPS steel is reputed as the bridge construction material for the new century (FHWA, 2002, 20) and it is rapidly becoming more popular all over the world.

Accordingly, it is clear that developing Iran's steel industry to establish required technologies to produce HPS steels and using such products to construct new bridges are basic steps toward sustainable development; and meeting the qualitative and quantitative aims according to the transportation prospect. The remaining of this article is devoted to representing HPS steels as a proper and unique choice for the bridge industry.

## 5. High performance steels

### 5.1. Introduction

Significant advances in the steel industry within the last few decades have resulted in the production of various grade steels with minimum yield strength of 350 MPa. Taking advantage of this high strength, structural efficiency of bridges is increased. High strength is normally achieved by increasing the proportion of carbon and some other alloying elements. However, high carbon content can result in the formation of some cracks during the construction and service stages. Using precise techniques to preheat plates and controlling energy input before and after welding and temperature between weld passes are used to prevent the cracks. All these measures produce high quality welds in conventional high strength steels. But deviating from the prescribed process and the quality of materials is very probable in the bridge industry as a result of different climate conditions in different geographical regions. Consequently, a higher percentage of welding problems arise in high strength steels than lower ones. On the other hand, complexity of temperature controls increases the cost and welding time. Therefore, bridge owners are usually not willing to risk the potential problems of fabrication with conventional high strength steels; and thus, the use of such steels has been limited in spite of being available for years (FHWA, 1997, 1).

In the last two decades, steelmaking industry in leading countries has tried to find a way to solve the welding problems of high strength steels. It has been decided to decrease the carbon content to prevent the formation of cracks. Significant improvements in rolling and heat treatment processes and metallurgical advances have made it possible to produce low – carbon high – strength steels. One of the important technologies is Thermo – Mechanical Control Process (TMCP) that adequately controls rolling and cooling within the steel plate production in order to generate fine microstructures (Gunther et al, 2005, 1). By the aid of TMCP technology and adding alloy elements such as Manganese in micro scale, the loss of strength which is due to the reduction of carbon content is compensated. Thus, a new generation of high strength steels known as High Performance Steels have been produced without the welding problems. This provides the possibility of exploiting the full strength of steels without the formation of undesired cracks.

In high performance steels, there is an optimized balance between the mechanical properties including strength, weldability, toughness, ductility, corrosion resistance and formability. This ensures the best performance of bridge structures while remaining cost – effective (FHWA, 1997, 1). Superior weldability and toughness of HPS, compared to conventional high strength steel, have several positive effects according to Table. 2. Such actions give cost efficiency and increase the safety and life cycle of bridges.

In the remaining sections of this article, the most important characteristics of HPS steels are introduced and briefly discussed; and the countries that have succeeded to produce such steels are introduced.

### 5.2. Weldability

Proper chemical composition of steel is the main factor to boost the fusion of the base and the filler metal without the formation of cracks or other imperfections. The carbon content is the most suitable criteria to characterize the weldability. In general, lower values of carbon result into better weldability. Concurrent low carbon content and high toughness of HPS material promote the weld quality in the best possible way. Welding HPS to all types of ordinary steel can be performed without preheating or at least at low temperature. Adequate weld quality and reduced volume of welding compared to ordinary steels reduce the fabrication and welding costs to a great extent (Gunther & Kuhlmann, 2005).

### 5.3. Toughness

Toughness of steels is determined with the Charpy – V – Notch (CNV) test. The obtained values must satisfy the AASHTO CVN requirements which are based on climate (zone I, II and III) and use (fracture critical/noncritical). Toughness values of different grades of HPS are 3 to 7 times greater than the minimum requirement for fracture – critical members in the most severe climate. The extraordinary toughness of HPS will allow structures to tolerate large deformations without risk of sudden failure. This is beneficial to resist cracks induced by fatigue or seismic loading and makes designers more confident to use the full strength of steel (FHWA, 1997, 1).

**Table 2**
Positive effects of HPS compared to conventional high strength steels

| | |
|---|---|
| Associated with proper weldability | 1- High quality welds with significant reduction in cracks and volume of required field inspections.<br>2- Facilitated welding without any need for complex processes of temperature controls<br>3- Reduced or omitted preheat<br>4- The ability of in – situ weld repairs due to omitted difficulties in welding<br>5- Reduced costs of welding |
| Associated with high toughness | 6- Delayed fatigue crack propagation which provides more time for repairs<br>7- Much lower transition temperature between ductile and brittle behavior, reduced danger of brittle fracture and higher safety<br>8- High energy absorption and the ability to carry high seismic forces<br>9- Higher capacity to tolerate construction flaws and errors. |

### 5.4. Fatigue

Low temperature in combination with repeated loading and unloading accelerates the formation and propagation of cracks. Thus, the bridge design is usually based on the requirements of fatigue limit state. Since the fatigue resistance is not affected by the type and strength of steels, and depends on welding details, stress range and stress concentration only, low quality of welds can spoil the benefit of the high strength of steel. Therefore, it is needed to seek a way to promote fatigue resistance in HPS bridges. This necessitates application of modern methods of welding and proper design of weld details (Gunther & Kuhlmann, 2005).

### 5.5. Weathering characteristic

One other main property of HPS materials is their high resistance against corrosion, which is due to increasing the content of some alloying elements such as nickel, copper, chromium and molybdenum. Surface layer of these steels corrodes and forms a shield that blocks further penetration of oxygen, wet and other contaminants. This provides the possibility of omitting or reduction of painting and other corrosion protection techniques and reduces the bridge maintenance costs (Gunther & Kuhlmann, 2005).

### 5.6. Producing countries

In a joint research program between FHWA, AISI and the U.S. Navy, production of a special low – carbon, high – performance steel for bridges was launched in the United States in 1992. Different grades of high performance steels in the U.S. are designated by three letters of HPS in the beginning of the steel's identity name. This follows the minimum yield strength in ksi or MPa and a letter "W" representing the weathering capability of the steel. HPS 70W (or HPS 485W) was the first commercial production of the steel industry. The bridge industry welcomed the unique effects of this product. Thus, two other grades identified as HPS 50W (or HPS 345W) and HPS 100W (or HPS 690W) were gradually produced and commercialized until the end of 2002. Different grades of HPS are now allowed to be used to construct bridges in homogeneous or hybrid forms (using identical or different grades in web and flanges) per the AASHTO LRFD Specifications (Lwin et al, 2005). The driving force for development of high performance steels in Japan and Korea was the need to minimize the costs associated with bridge construction and maintenance. Japan's commercial productions so far, include two grades of BHS500 and BHS 700 (BHS: Bridge High – performance Steel) and Korea has commercialized two grades of HSB500 and HSB600 (HSB: High – performance

Steel for Bridges). The most valuable achievement of Japanese researchers is the development of Low Transition Temperature (LTT) welding technology to improve the fatigue performance. Moreover, because of the environmental conditions in Japanese coastal regions, lots of research work has been carried out to improve corrosion resistance by adding up nickel content (Gunther & Kuhlmann, 2005).

In Europe, two grades of high performance steels identified as S460M and S690Q are produced and the researchers are trying hard to set up advanced design rules for HPS in all kinds of structural applications, not only in bridge design, and to include them within Eurocodes (Gunther & Kuhlmann, 2005).

Table. 3 represents the mechanical properties of different productions of the above – mentionedcountries. According the reported data in this table, in European steelmaking standard the minimum yield strength varies with the plate thickness. The ratio between yield strength and tensile strength in high performance steels is high and their minimum elongation at fracture is 14%, which is a much better value compared to ordinary steels.

Table. 4 represents the chemical composition of these steels in terms of maximum alloy contents. Carbon (C) is the main alloy controlling the strength. In comparison to ordinary steels which their maximum carbon contents are between 18 % and 25 %, this range reduced to between 10 % and 18 % in high performance steels. Better toughness and weldability of HPS is mainly attributed to the reduction of the maximum sulfur level down to 0.006 %.

**Table. 3**
Mechanical properties of HPS steels.

| **Producing country** | **Steel grade** | **Production process** | **Thickness** | **Yield strength** | **Tensile strength** | **Min. elongation at fracture** | **Required toughness** | |
|---|---|---|---|---|---|---|---|---|
| | | | **(mm)** | **(MPa)** | **(MPa)** | **(%)** | **Temp** | **Impact energy** |
| | | | | | | | **(°C)** | **(J)** |
| The United States | HPS485 | Q & T | ≤100 | 485 | 586-760 | 19 | -23 | 48 |
| | | TMCP | ≤50 | | | | | |
| | HPS690 | Q & T | 6-64 | 690 | 760-895 | 18 | -34 | 48 |
| Japan | BHS500 | TMCP | 6-100 | 500 | >570 | 19 | -5 | 100 |
| | BHS700 | TMCP | 6-100 | 700 | >780 | 16 | -40 | 100 |
| Korea | HSB500 | TMCP | ≤16 | 380 | 500 | 15 | -5 | 47 |
| | | | ≤40 | | | 19 | | |
| | | | >40 | | | 21 | | |
| | HSB600 | TMCP | ≤16 | 450 | 600 | 19 | | |
| | | | ≤20 | | | 26 | | |
| | | | >20 | | | 20 | | |
| Europe | S460M | TMCP | ≤16 | 460 | 540-720 | 17 | -20 | 40 |
| | | | 17-40 | 440 | 540-720 | | | |
| | | | 41-63 | 430 | 530-710 | | | |
| | | | 64-80 | 410 | 510-690 | | | |
| | | | 81-100 | 400 | 500-680 | | | |
| | | | 101-120 | 385 | 490-660 | | | |
| | S690Q | Q & T | 3-50 | 690 | 770-940 | 14 | -40 | 30 |
| | | | 51-100 | 650 | 760-930 | | | |
| | | | 101-150 | 630 | 710-900 | | | |

(Yoon, 2008, 12-14); (Lwin et al, 2005, 11); (Gunther & Kuhlmann, 2005, 147).

**Table. 4**
The chemical composition of HPS steels in terms of maximum alloy contents.

| Producing country | Steel grade | C | Si | Mn | P | S | Cu | Cr | Ni | Mo | V |
|---|---|---|---|---|---|---|---|---|---|---|---|
| The United States | HPS485 | 0.11 | 0.30-0.50 | 1.10-1.35 | 0.020 | 0.006 | 0.25-0.40 | 0.45-0.70 | 0.25-0.40 | 0.02-0.08 | 0.04-0.08 |
| | HPS690 | 0.11 | 0.15-0.35 | 0.95-1.50 | 0.015 | 0.006 | 0.90-1.20 | 0.40-0.65 | 0.65-0.90 | 0.40-0.65 | 0.04-0.08 |
| Japan | BHS500 | 0.11 | 0.50 | 2.00 | 0.020 | 0.006 | 0.30-0.50 | 0.45-0.75 | 0.05-0.30 | - | - |
| | BHS700 | 0.14 | 0.50 | 2.00 | 0.015 | 0.006 | 0.30 | 0.45-0.80 | 0.3-2.00 | 0.60 | 0.05 |
| Korea | HSB500 | 0.18 | 0.65 | 1.80 | 0.020 | 0.006 | 0.10-0.50 | 0.45-0.75 | 0.05-0.80 | - | - |
| | HSB600 | 0.10 | 0.65 | 1.80 | 0.020 | 0.006 | 0.10-0.50 | 0.45-0.75 | 0.05-0.80 | - | - |
| Europe | S460M | 0.16 | 0.60 | 1.70 | 0.025 | 0.020 | 0.55 | 0.30 | 0.80 | 0.20 | 0.12 |
| | S690Q | 0.20 | 0.80 | 1.70 | 0.020 | 0.010 | 0.50 | 1.50 | 2.00 | 0.70 | 0.12 |

(Yoon, 2008, 12-14); (Lwin et al, 2005, 11); (Gunther & Kuhlmann, 2005, 147)

## 6. Summary

The development of advanced steelmaking technologies beside the modification of alloying contents has led to the production of a new generation of steel materials with high performance and enhanced properties (such as high strength, high toughness, proper weldability and good corrosion resistance) in leading countries. The main application of high performance steels so far is in the field of bridge construction. Some important and valuable effects follow a proper bridge design and construction by the use of HPS steels. These effects include reduced weight and cost, reduced depth and plate thickness and enhanced architectural appearance as a result, longer spans and fewer piers, smaller welding volume and reduced related costs, lower preheat requirements, facilitated handling due to weight reduction, minimized risk of sudden failure, increased cracking tolerance and structural reliability, long durability without the need for painting and lower life – cycle costs. In addition, lower costs related to the pier foundation and reduced use of natural resources all cause HPS steels to be raised as one of the main factors towards sustainable development of the bridge industry. Therefore, the development of Iran's steelmaking industry toward the production of HPS steels and the application of such products in the bridge industry is recommended as one of the main steps directed to the sustainable development of infrastructures to fulfill the qualitative and quantitative aims according to the country's transportation prospects.

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