Stainless Steel in Tunnel Construction and Applications

SUSTAINABLE STAINLESS

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Disclaimer

Stainless Steel in Tunnel Construction and Applications

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Tunnels are a highly efficient way to improve the flow of road and rail traffic and reduce travel times. They are used to transport both people and freight and can range from a few metres to 50 kilometres and more in length.

By definition, tunnels are always underground. However, the conditions that they pass through can vary widely. Some pass under seas, while others are burrowed through mountains. This wide range of conditions means that each tunnel is unique when it comes to the materials that must be utilised in its construction. All tunnels need to function relatively maintenance-free for many decades. The materials chosen for their construction must be able to meet these criteria, in conditions that may be corrosive or hazardous.

The North-South Bypass in Brisbane is Australia's longest road tunnel

The use for the tunnel also affects the materials that can be used inside. As the case studies in this brochure show, atmospheric conditions in tunnels can vary wildly depending on whether it is used by road vehicles or electric trains.

This document provides case studies of existing tunnels from around the world. All utilise stainless steels, and particularly nickel-containing grades, for their improved operating efficiency over the longer term and their significant economic advantages.

Why Use Stainless Steel in Tunnels?

Stainless steel is available in a range of alloys and product forms and can meet the most arduous conditions. It requires no added protection for corrosion resistance and its high strength and fire resistance properties provide a long and durable service life, with little or no maintenance. Tunnel engineers deploy stainless steel in both visible applications, such as fire doors and barriers, and invisible applications such as reinforcing.

Long-term monitoring of the atmosphere and conditions by tunnel operators has led to the mandatory specification of stainless steel in components such as fixings. Failure-proof fixings are crucial for the safe attachment of key components including lighting, ventilation and fire-fighting equipment. A broken fixing can have fatal consequences and lead to disruption or closure of the tunnel. Explicit stainless steel grades are often specified for tunnel fixings as they can withstand severe atmospheric and crevice corrosion – particularly at the junction of the wall or rock face.

The conditions inside the individual tunnel should always determine which materials are specified for construction and interior applications. The level of maintenance the tunnel operator will provide should also be defined during the material specification phase of planning. Advice from a competent corrosion engineer or stainless steel producer should always be sought. Local guidance documentation can also be consulted. A list of reference documents is provided in Appendix A on page 14.

Stainless Steel in Road Tunnels

The most common type of transport tunnel is the road tunnel. They may pass through hard or soft rock and under rivers, lakes and harbours. In the event of an accident inside, the tunnel may be subjected to explosive forces and fire. Even in normal use, road tunnels are subjected to variations in temperature and high levels of corrosive chemicals from emissions and de-icing salts which, in colder climates, are carried into the tunnel on vehicle tyres.

The atmosphere in road tunnels typically contains chemicals such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), and hydrogen sulphide (H_2S) from exhaust emissions (see Table 1). Other emissions include abraded tyre particles, heavy mineral dust deposits, soot, and water soluble chlorides. Measurements in the Mont Blanc Tunnel have shown that the atmosphere contains 3.5% water soluble chlorides. The chloride content of the dust in the tunnel was measured at between 0.1 and 0.7% when periodic cleaning was performed, and 0.7 to 3.5% when no cleaning is done.

The corrosive effect of these chemicals in the atmosphere can cause anchor points to fail. At the junction between a wall and a fixing, a film of acidic chloride solution forms and acts as an electrolyte. The concentration increases as the tunnel goes through periodic drying cycles. Anchor points can be extremely difficult to access, making cleaning expensive or virtually impossible.

The result is crevice corrosion which can lead to the failure of the fixing unless a suitable stainless steel is specified. To eliminate maintenance and enhance durability, operators of the Mont Blanc Tunnel specify that stainless steels with a minimum molybdenum content of 6% must be used.

Road Tunnel Fires

Many lives have been lost in road tunnel fires. As well as fatalities, fires can also cause the closure of road tunnels and necessitate costly repairs. The 1999 fire in the Mont Blanc Tunnel is a typical example. The fire started in a truck transporting flour and margarine and burned for 53 hours. Temperatures reached more than 1000°C and claimed the lives of 39 people. As a result of this fire, the tunnel was closed for three years and cost more than €450 million to repair.

Solutions to prevent or minimise the devastating effects of road tunnel fires inevitably use stainless steel. This is due to its excellent performance at the elevated temperatures generated by hydrocarbon fires.

Fires in road tunnels can cause catastrophic damage to people and tunnels

Case Studies

The following case studies provide information on the use of stainless steel to solve real-life problems in road tunnels around the world. In some cases, the use of stainless steel has been specified in the construction of the tunnel. In other examples, the stainless steel has been retrofitted to solve a problem that is affecting the safe use of the tunnel.

Table 1: Road tunnels show significant variations in humidity, temperature, and atmospheric conditions

Tunnel	Relative humidity	Temperature range	Atmosphere		
			SO_2	NO_2	H_2S
Gottard (Switzerland)	25 to 81%	3 to 27°C	81 ppm	3 ppm	27 ppm
Mont Blanc (France – Italy)	41 to 95%	6 to 25°C	95 ppm	6 ppm	25 ppm
San Bernadino (Switzerland)	Average: 73%	-20 to 17°C	-	73 ppm	20 ppm
Seelisberg (Switzerland)	7 to 72%	14 to 28°C	72 ppm	14 ppm	28 ppm

Concrete spalling in Italian motorway tunnels

Aggressive atmospheric conditions have caused the deterioration of the concrete linings in many road tunnels on Italy's A7, A10 and A12 motorways. The highly corrosive atmosphere is caused by a combination of factors including: highly concentrated and stagnating sulphurous compounds from vehicle exhaust emissions; the local marine climate; vibration; and extremes of humidity.

On the A10 (Genoa to Savona) alone, 25 tunnels have required extensive repairs to stop spalling concrete falling onto the motorway. Over 12,000 m2 of stainless steel mesh (EN 1.4401/AISI 316) has been used to line the tunnels. The mesh catches any falling lumps of concrete and directs them away from the road surface.

Over 12,000 m^2 of stainless steel mesh protects traffic from spalling concrete

The fixed fire-fighting system in the Kehu Tunnel near Helsinki produces a fine mist which is highly effective at quenching fires

Fixed-fire fighting system in the Kehu Tunnel, Finland

The Kehu Tunnel in Helsinki uses a fixed fire-fighting system which consists of five rows of 16 mm diameter stainless steel piping and spray nozzles. In the event of a fire in the tunnel, the high-pressure system produces a fine water mist which has been proved to be effective in quenching tunnel fires. Stainless steel (EN 1.4404/AISI 316L) is used for the entire system because of its strength, and its corrosion and fire resistance properties. The system not only increases safety, but also reduces damage and disruption to the tunnel in the event of fire.

Stainless Steel in Road Tunnels - Case Studies

Duplex stainless used in smoke and heat extraction system, Australia

The longest road tunnel in Australia is the North-South Bypass (also known as the Clem Jones Tunnel or CLEM7) in Brisbane. Comprised of two 4.8 km twin-lane tunnels, CLEM7 has been built under the Brisbane River. Duplex stainless steel (EN 1.4462/ASTM-UNS S32205/S31803) was specified for use throughout the tunnel due to its ability to withstand the highly corrosive environment. Applications included the use of 33,000 light gauge stainless steel posts as tunnel lining supports.

Brisbane's North-South Bypass uses 33,000 light gauge stainless steel posts as lining supports in a highly corrosive atmosphere

In the event of a fire or explosion, a high-tech ventilation system rapidly extracts smoke to a longitudinal duct above the road tract using 100 jet fans. Massive concrete slabs hang from a stainless steel suspension system to form the ventilation shaft. The system uses grade EN 1.4462 (ASTM-UNS S32205/S31803) which is able to meet the heat-resistance standards required and provide long-term performance, without maintenance, in a corrosive atmosphere.

Stainless steel jet fans in the Mont Blanc Tunnel

To eliminate maintenance and enhance durability, operators of the Mont Blanc Tunnel specify that stainless steels with a minimum molybdenum content of 6% must be used.

Stainless steel (EN 1.4404/AISI 316L) ventilation fans were installed as part of a 2011 renovation programme. Cable ladders in the tunnel are also manufactured from the same grade.

Following a devastating fire in 1999, the Mont Blanc Tunnel was closed for three years. Stainless steel is now used extensively.

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New underpass utilises stainless in deck and upstands, England

The Underpass at Cradlewell is a major coastal link in the north of England. During construction, 256 tonnes of stainless steel (EN 1.4401/AISI 316) were used in the tunnel deck and upstands. Grade EN 1.4401/AISI 316 was selected for its ability to withstand corrosion from the de-icing salts applied in winter periods. Water run-off is carried away by tubes located in the decking. If carbon steel reinforcement had been used instead of stainless steel, any leakage would have been catastrophic and extremely expensive to repair.

Located near the coast, the Underpass at Cradlewell contains more than 250 tonnes of stainless steel to resist corrosion

New stainless steel structure and lining, Scotland

Glasgow's Clyde Tunnel provides a major transport link between north and south parts of Glasgow. Comprised of two 762-metre parallel tunnel tubes, it is utilised by more than 65,000 vehicles each day.

During the Clyde's refurbishment (2005-2010) the original 1950s cast iron primary structure was retained. A new secondary framework was created from nickel-containing stainless steel (EN 1.4401/AISI 316) and attached to the original structure. The secondary framework supports a stainless tunnel lining which, in the event of a fire, is designed to keep the temperature within the tunnel below 300ºC.

A secondary stainless steel framework was added to the Clyde Tunnel (below) to support a stainless steel lining

Stainless Steel in Road Tunnels - Case Studies

Stainless deck joints prevent corrosion

Situated to the east of London, the Dartford River Crossing goes under the River Thames and is a key link between the north and south of the city. It forms part of the M25 London orbital motorway.

Refurbishment became necessary after only 20-years of service as the carbon steel road deck reinforcement had corroded. This was largely because chloride-bearing water (from the de-icing salts which are applied during winter) had penetrated into the slab, causing the carbon steel reinforcing to corrode.

To prevent the edges of the slab breaking up and allowing more water to penetrate, 396 tonnes of austenitic stainless steel (EN 1.4401/AISI 316) deck joints were incorporated into the concrete slabs at 4.5 m intervals.

Stainless steel deck joints were installed in the Dartford River Crossing to counter the corrosive effect of de-icing salts

Fire escape routes and ventilation systems

In the Lioran Tunnel in France, stainless steel (EN 1.4404/AISI 316L) is utilised in the fire escape doors. The grade has excellent corrosion resistance and good mechanical properties when subjected to heat.

Stainless steel was used for the fire escape doors leading from the tunnel to the safety area, and in the doors connecting the safety area to the escape route.

The covers of ventilation shafts in road tunnels are subjected to high levels of corrosive atmospheric gases. The covers of the ventilation shafts which extract the air from the tunnel are most affected. However, fresh air inlets are also subject to atmospheric corrosion. The Lioran Tunnel utilises covers made from stainless steel (EN 1.4404/AISI 316L) to prevent corrosion.

Stainless steel is extensively used in the Lioran Tunnel in ventilation and fire safety applications (below and right)

Reducing the effect of fire in the Elb Tunnel, Germany

To minimise the effects of a fire, the Elb Tunnel in Hamburg was lined with 1,500 tonnes of stainless steel plate (EN 1.4571/AISI 316Ti). The plate was attached to the tunnel using 60 tonnes of fixing bolts and screws which were made from the same grade.

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Stainless Steel in Rail Tunnels

To meet the demand for passenger transport and alleviate traffic congestion, urban planners are increasingly turning to underground rail systems. High-speed rail networks are also becoming important links between major urban populations and even between countries.

In many developing countries, rapid growth in rail networks is already underway. In China for example, 21 cities plan to develop light railway systems. Construction of these networks has already begun in at least seven of these urban areas. During 2012, China will also take delivery of an additional 120 high-speed trains to run on the country's 6,000 km of high-speed track that has already been laid. India is another country which is developing its urban rail infrastructure with metro networks announced or under consideration in at least a dozen cities.

This section outlines the different considerations for tunnels on metro (or underground), railway and long undersea train lines and how stainless steel contributes to their long and safe working life.

Metro Tunnels

Trains using underground networks in cities are usually powered by electricity, so atmospheric corrosion is less of an issue than in road tunnels. However, local environmental factors may impact the materials that are selected for tunnel construction. These include the chemicals in the rocks or earth surrounding the tunnel, and seepage of water from roads, rivers, or even the city's sewage and water supply networks.

During use, metro tunnels can also be affected by fire and this should also be considered during the specification phase of the project.

Case study: London Underground

Parts of the London Underground are 67 m below street level and 21 m below sea level. Water seepage in the tunnel network contains a chloride ion that is highly corrosive and damaging.

Following the disastrous Kings Cross Station fire in 1987, London Underground began to specify the use of materials which do not give off smoke or toxic fumes in the construction and renovation of the underground network. As stainless steel meets these requirements, it has been significantly utilised in new work on the network as these examples show.

Jubilee Line Extension

Stainless steel was extensively used in the tunnels and stations of London's Jubilee Line when it was extended to the revitalised docklands area to the east of the capital.

London's Underground network has 270 stations and relies on stainless steel to keep people moving - and safe!

Each station can be visually identified by the finish of the stainless steel. While the different finishes give every station its own aesthetic individuality, the stainless steel also has a functional purpose. It is also economical in the long term as the stainless steel only requires occasional washing to retain its appearance.

Victoria Line seepage

During refurbishment of the Victoria Line, sinusoidal-shaped sheeting was used extensively in the arched passenger tunnels to divert this seepage water into drainage gullies. Over 560 tonnes of 1.2 mm thick austenitic stainless steel (EN 1.4401/AISI 316) was used. In the event of a fire, the stainless steel will retain its strength for longer periods than other metals without giving off smoke or toxic fumes.

Northern Line: Old Street upgrade

At Old Street Station on London Underground's Northern Line, acid soil conditions caused severe corrosion of the original cast iron tunnel linings. They were replaced by 3,500 cast curved segments using around 750 tonnes of a proprietary super-duplex stainless steel which contains 8% nickel. The tunnel segments were bolted together using 20,000 stainless steel (EN 1.4501/ASTM-UNS S32760) fasteners.

Stainless Steel in Railway and Sub-sea Tunnels

Railway Tunnels

Railway tunnels must accommodate either electric or diesel powered trains, and sometimes both. While electric trains are relatively clean, diesel-powered engines emit sulphur dioxide fumes which may corrode or damage materials utilised within the tunnel. The level of emissions depends on factors such as the frequency of trains, speed they will travel, the length of tunnel, and what equipment has been installed in the tunnel to control temperature and humidity. Local pollution and atmospheric data should be sought before material selection is finalised.

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Long Sub-sea Rail Tunnels

Data on the suitability and performance of materials and conditions in long sub-sea rail tunnels is limited as few exist. The oldest is the 53.9 km (23.3 km sub-sea) Seikan Tunnel which links the Japanese islands of Honshu and Hokkaido. It is currently being upgraded to accommodate the Shinkansen high speed train.

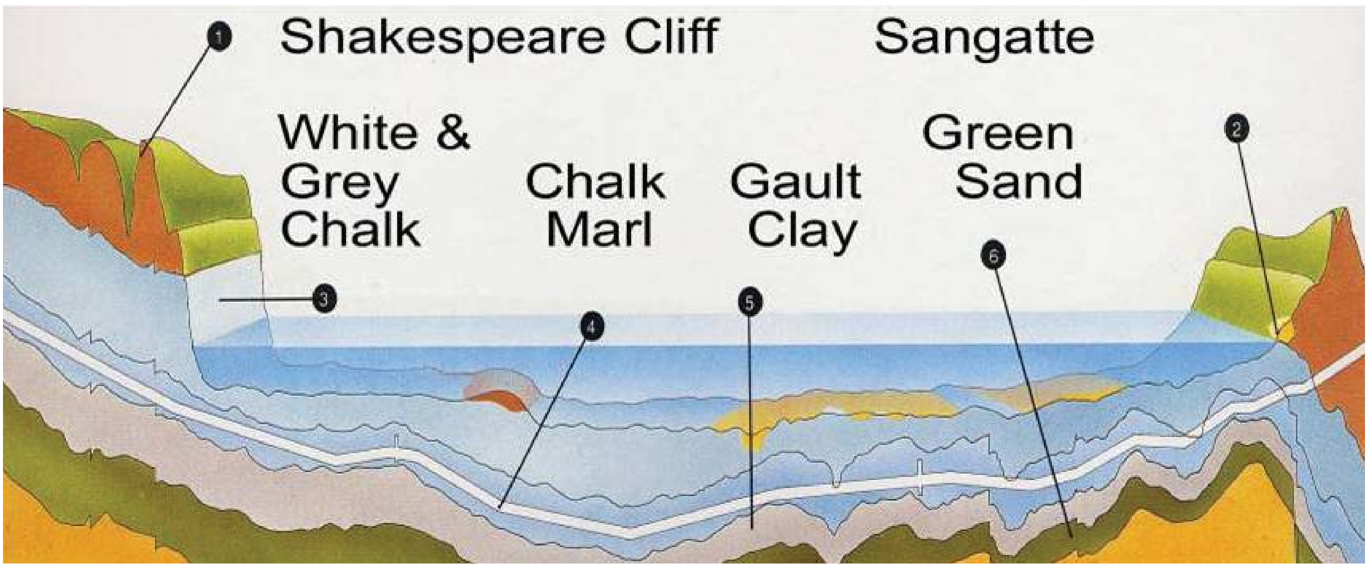
Case Study: Stainless steel performs in materials tests in the Channel Tunnel

While materials performance data is not available for the Seikan Tunnel, some experience has been gained from the Channel Tunnel (49.2 km long, 37.5 km sub-sea) which links England and France. Tests on stainless steels and other materials have been conducted at different points throughout the tunnel to gauge their performance in this unique environment.

The first test was instigated by the Nickel Development Institute (now Nickel Institute) in 1994 to assess material performance in the Channel Tunnel. French and British stainless steel producers created test coupons from different grades of stainless steel. In conjunction with the operator Eurotunnel, the coupons were installed at various positions in both the running and service tunnels.

Nickel bearing grades required

In 1994, existing knowledge indicated that nickel bearing austenitic stainless steel grade EN 1.4401/AISI 316 would probably be suitable for many of the components within the tunnel. It met the requirements for good corrosion and fire resistance, and low maintenance demanded by many of the key tunnel applications. Electrical splitter boxes for example, of which there are 17,000



The Channel Tunnel passes through a variety of soil and rock types on its journey from the UK (left) to France (right)

Stainless Steel in Railway and Sub-sea Tunnels

View inside one of the running tunnels

throughout the Tunnel, must remain fully functional at a temperature of 1,000°C. Using grade EN 1.4401/AISI 316 for their construction ensured they achieved this target in compliance fire tests.

Extended materials testing

The initial test programme to evaluate different grades of stainless steel was subsequently extended by Eurotunnel to include a broader range of materials. Test coupons were installed in racks positioned at various points throughout the tunnel as conditions differ from one part of the tunnel to the next.

A near-constant temperature, ranging between 20 and 25°C, is maintained by twin 400 mm diameter water-filled pipes which run the complete length of the tunnel. However, humidity varies from 45 to 76% depending on location and the saline content of the atmosphere.

Atmospheric cocktail

Passenger and freight trains which use the tunnel are electric-powered, but the maintenance train is diesel powered. The atmosphere therefore contains small quantities of sulphur dioxide from the exhaust fumes. Tests have shown that the atmosphere contains cement dust from the tunnel lining and iron particles resulting from the contact between train wheels and track. Chloride ions are also present as a result of the marine atmosphere.

Combined with high humidity, the atmospheric cocktail can be severely corrosive if left on surfaces. The potential for corrosion is enhanced due to the buffer of wind created as trains pass through the tunnel at speeds of up to 140 km/hour. This has two effects:

1. Damp dust particles can adhere to some surfaces, particularly those facing the direction of travel and those at 90 degrees to the buffer forces.
2. The combination of wind speed, concrete dust and iron particles can erode protective coatings as they are under constant bombardment from the abrasive medium.

It quickly became evident that accumulations of dirt could not be tolerated and a routine washing regime was implemented by Eurotunnel. The smooth surface of stainless steel also helps to prevent a build-up of

Table 2: Chloride and humidity levels at test points

Reference	Chloride (mg/m²/day)	Humidity*
PK1511	**74**	**< 10 H/A**
PK2102	**400**	**2500 < 5500 H/A**
PK3574	**142**	**< 10 H/A**
PK3575	**80**	**< 10 H/A**
PK5052	**228**	**3 < 30 H/A**
PK5877	**75**	**3 < 30 H/A**

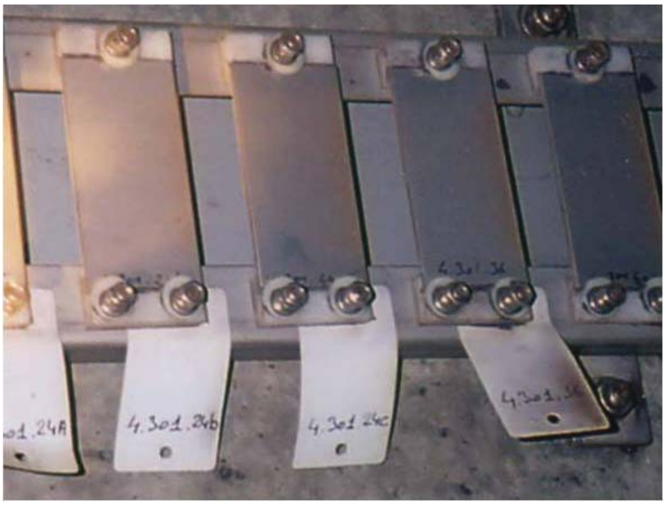
**Hours/annum [condensate measure]*

Stainless Steel in Sub-sea Tunnels

corrosive dirt on the surface and makes washing and cleaning easy.

While much of the Channel Tunnel is reasonably dry, the coupon tests showed that conditions did vary significantly. The carbon steel coupon was included in the test for comparative purposes.

A summary of the chloride and humidity levels at each location is shown in Table 2. At all locations, sulphur dioxide levels were less than 10 mg/m^2/day, a level considered to be insignificant.



Test coupons in position inside the Channel Tunnel

Table 3: Weight loss in g/m^2/annum

Reference	EN 1.4306/AISI 304L	EN 1.4318/AISI 301LN	EN 1.4404/AISI 316L	Carbon steel
PK1511	0.01	0.04	0.00	10.39
PK2102	2.00	8.49	7.34	276.26
PK3574	0.01	0.06	0.00	10.10
PK3575	0.03	0.02	0.02	7.94
PK5052	0.07	0.15	0.05	27.79
PK5877	0.03	0.07	0.01	40.16

Note: The high rate of weight loss of grade EN 1.4404/AISI 316L at PK2102 was due to a water leak that directly affected some (but not all) of the coupons at that site. The carbon steel coupon was not affected.

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Stainless steel is widely used in the Channel Tunnel for applications such as ventilation (left) and electrical splitter boxes (below)

Conclusions

Tunnels vary considerably in length, location and purpose. They are constructed to reduce journey times and to reduce congestion, therefore heavy demands are placed on the materials used in their construction to minimise maintenance and repair. They represent a significant outlay for governments and operators and must perform for many trouble-free decades in order to recoup that investment.

These requirements make stainless steel the ideal material for tunnel construction and the operating equipment inside. Stainless steel:

- Does not emit toxic fumes at elevated temperatures
- Retains a high proportion of its strength at temperatures in excess of 900^{o}C.
- Requires no added surface protection to resist corrosion
- Is available in a range of grades and forms which provide a long and durable life with little or no maintenance.

Stainless steels are already widely deployed in tunnel construction and vital operating equipment throughout the world. For tunnel designers and operators, stainless steel is a key material to provide safety, low maintenance costs and the long term operation of vital equipment and the tunnel itself.

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Appendix A: Further Guidance

Guidance on materials for use in tunnels is available from your local statutory authority, or construction and fixing associations in individual countries. The following references provide some examples.

Germany

ZTV-ING Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (English: Additional technical specifications and guidelines for civil engineering). Latest edition: April 2010.

The document provides guidelines for road tunnels which are constructed using either the closed or open-cut method. Specific stainless steel grades are required in some tunnel applications.

Italy

ANAS is the national road agency in Italy and sets directives for safety in traffic tunnels. For street tunnels, ANAS stipulates that any exposed material in the tunnel must be non-toxic, fireproof, and must not be able to generate smoke.

Equipment such as fans and parts of the lighting system must be able to resist temperatures of up to 400°C for a minimum of 90 minutes. Stainless steel's ability to retain its strength at temperatures in excess of 900°C have been proven in real-life fire tests; a temperature that far exceeds the capacity of aluminium.

Switzerland

The Swiss Society of Engineers and Architects (SIA) can provide advice and links for tunnel builders and operators. Their website (also partially in English) can be accessed at www.sia.ch.

United Kingdom

The UK Department of Main Roads maintains a comprehensive online Design Manual for Roads and Bridges (DMRB). Information on tunnels is provided in Volume 2: Highway Structures: Design (Substructures & Special Substructures), Materials. For more information go to: www.dft.gov.uk/ha/standards/dmrb/

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For more information on stainless steel and its alloying elements, please consult the websites of the following organisations:

- www.icdacr.com
- www.imoa.info
- www.nickelinstitute.org
- www.worldstainless.org

This brochure is also available in Chinese, Japanese and Korean.

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