Technical Report

Thermal impact on HDG construction

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1. Introduction

For structures in fire, different material behaviors have to be taken into account. With elevated temperatures, material properties of carbon steel, like strength and deformation properties, have to be adjusted. Therefore the Eurocode DIN EN 1993-1-2 provides reduction factors for stress-strain relationships at corresponding steel temperature. For example, with increasing member temperatures a falling residual strength is accompanied. To adjust this disadvantage of steel construction, compared to a concrete solution, the state of the art is a passive fire protection with intumescent paint or a fire-resistant panel encasement around the steel element.

For this purpose, positive effects of hot-dip galvanization on the temperature development of steel members in the accidental situation of fire exposure are investigated to avoid additional passive fire protection for an R30 requirement.

2. Hot dip galvanization

Galvanizing is a corrosion protection process for steel, in which the steel is coated with, the electrochemically less noble metal, zinc to prevent it from rusting. According to DIN EN ISO 1461, hot dip galvanizing (HDG) is a discontinuous method to apply zinc coating on steel by dipping the prefabricated and previously treated members in molten zinc. The pretreatment of the steel pieces in galvanizing lines consists of degreasing, pickling, rinsing, fluxing and drying.

The material steel, the molten zinc and the intermetallic phases formed from both metals during the galvanizing process are responsible for the specific course of the iron-zinc reaction. This determines the properties of the zinc coatings, their adhesive strength, and layer thickness as well as the appearance and their corrosion resistance. In principle, all common structural steel grades can be hot dip galvanized, but the appearance and thickness of the coating can vary. The formation of the zinc coating depends on the galvanizing conditions (melting temperature, dipping time, etc.), the surface condition of the steel and to a decisive extent on the chemical composition, in particular, the silicon and phosphorous content of the steel.

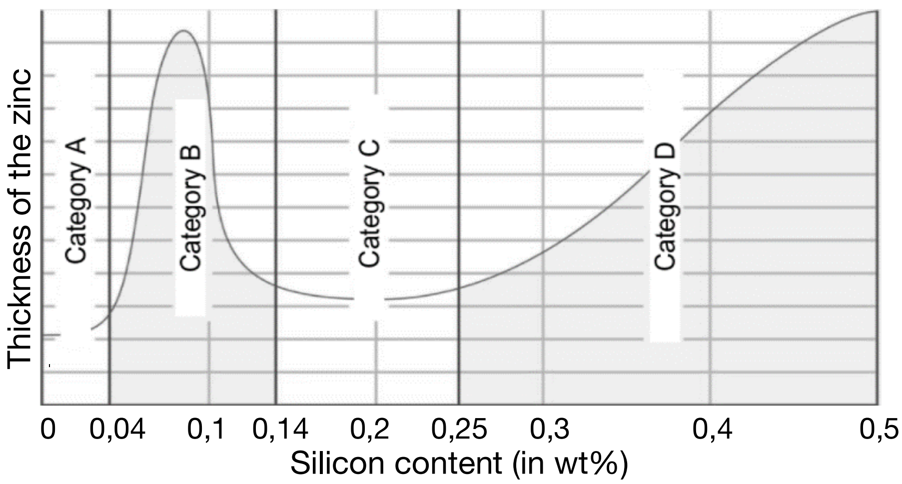


Fig. 1: Influence of the silicon content to the thickness of the zinc alloy layers

The common known galvanized surface appearance is smooth and shiny, but in certain concentrations, for example, silicon accelerate the zinc-iron reaction and a thicker zinc coating with a different alloy layer structure is formed. These zinc coatings usually have a rough surface with a matte or grey appearance.

3. Emissivity measurements of metals

At temperatures above absolute zero (-273.15 °C) all objects emit electromagnetic radiation. However, the amount of thermal radiation emitted into the environment for every wavelength or temperature depends on the emissivity of the object's surface.

Emissivity is the ratio of the energy radiated from a material's surface to the energy radiated from a black body, under the same conditions, at the same temperature and wavelength. It is thus a value between zero and one.

A black body radiator itself is a body that absorbs all radiation on him, neither reflection nor transmission occurs ($\alpha = \varepsilon = 1$; α = absorption coefficient, ε = emissivity). A black body radiator emits the maximum possible energy at each wavelength with an angle-independent radiance, but this exists only in theory. In reality, a black body radiator can only be approximated, but this provides the basis for understanding the physics of non-contact temperature measurement and calibration of infrared thermometers.

Many surfaces have a constant emissivity over the wavelengths but emit less radiation than the black emitter. They are called gray emitter. A large number of non-metallic substances have a high and relatively constant emissivity, at least in the long-wave spectral range, regardless of their surface condition. Objects surfaces whose emissivity depend inter alia on temperature and wavelength, e.g. metallic surfaces, are called selective emitters.

As previously mentioned, all objects with a temperature above absolute zero radiate infrared energy. Infrared radiation is the portion of the electromagnetic spectrum, which refers to the intensity of a mixture of electromagnetic waves as a function of wavelength or frequency. The infrared spectral range, which is used to measure the temperature, occupies only a very narrow section in the spectrum of electromagnetic radiation. It ranges from the end of the visible spectral area of about 0.78 μm to wavelengths of 1000 μm, which is the beginning of radio waves range. However, the invisible part of the spectrum contains up to several thousand times more energy. This is why infrared measuring technology builds on this part of the spectrum.

Planck's law of radiation represents the most fundamental connection for non-contact temperature measurement. It describes the spectral specific emission $M_{\lambda s}$ (λ, T) of the blackbody as a function of its temperature T and the wavelength λ:

$$M_{\lambda s}(\lambda, T) = \frac{c_1}{\lambda^5 (e^{\frac{c_2}{\lambda T}} - 1)} \qquad (1)$$

The constants c_1 and c_2 can be traced back to fundamental constants of nature, including the speed of light c in the vacuum, the Planck constant h, and the Boltzmann constant k.

$$c_1 = 2\pi c^2 h = 3.741 * 10^{-16}\ Wm^2 \quad (2)$$

$$c_2 = \frac{ch}{k} = 1.438 * 10^{-2}\ mK \quad (3)$$

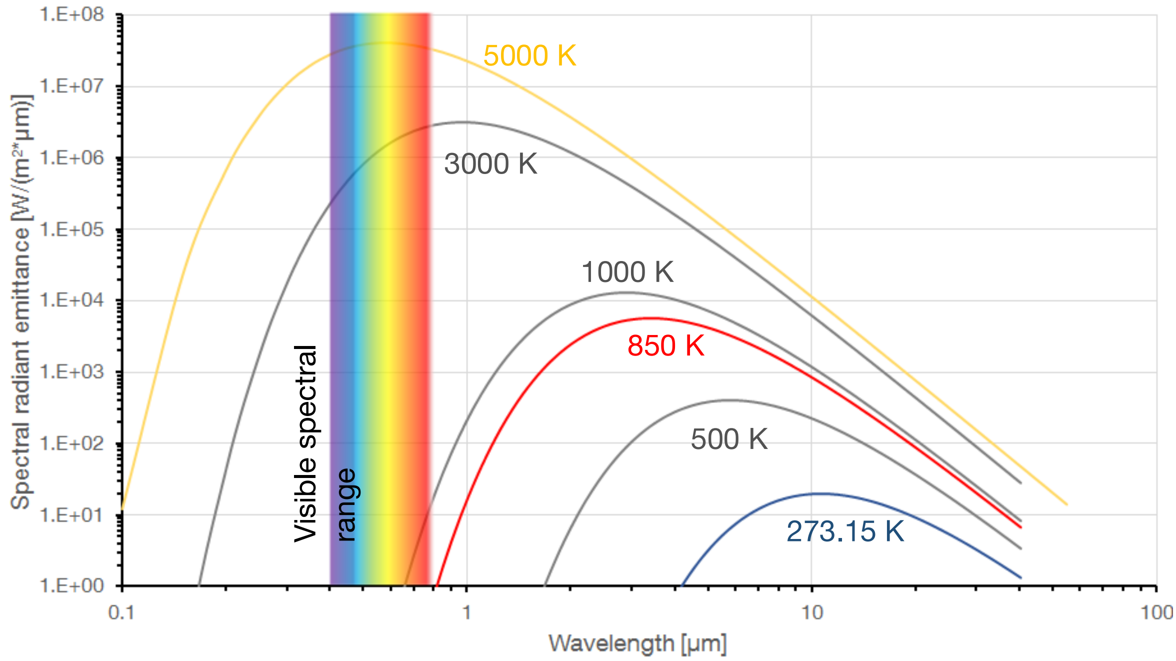


Fig. 2: Planck's black body spectrum at different temperatures

In Fig. 2 the spectral radiant emittance $M_{\lambda s}$ (λ, T) of a blackbody at various temperatures is plotted in a logarithmic scale, including the range of visible light. As indicated, bodies at high temperatures, in addition, emit an amount of visible radiation. Starting from the so-called Draper point at 798 K (525 °C) heated bodies get slowly visible to the human eye as a dark red object.

It can be seen that the radiation maximum of a matter increases and moves towards the shorter wavelengths as the target temperature rises. In addition, the isotherms do not cross each other at different temperatures.

By integrating the spectral intensity of radiation over all wavelengths from zero to infinity, one obtains the value for the entire radiation M_s (T) emitted from the body. The value increases with the 4th power of the temperature. This relationship is called the Stefan-Boltzmann law. Starting from the equation (1) a rather simple one follows:

$$M_s(T) = \sigma T^4 \quad (4)$$

with the Stefan-Boltzmann constant:

$$\sigma = \frac{c_1 \pi^4}{15 c_2^4} = \frac{2\pi^5 k^4}{15 c^2 h^3} = 5.6704 * 10^{-8}\ \frac{W}{m^2 K^4} \quad (5)$$

For the infrared temperature measurement, only the wavelength range from 0.7 to 14 µm is suitable for measuring temperatures. Above this wavelength, the energy levels are too low for IR-detectors.

Due to the spectral transmissivity (highlighted in blue in Fig. 3) of air, two pyrometers measure in two different atmospheric windows in this approach. One at the wavelength of about 2.3 µm and the other one at the range of 8-14 µm.

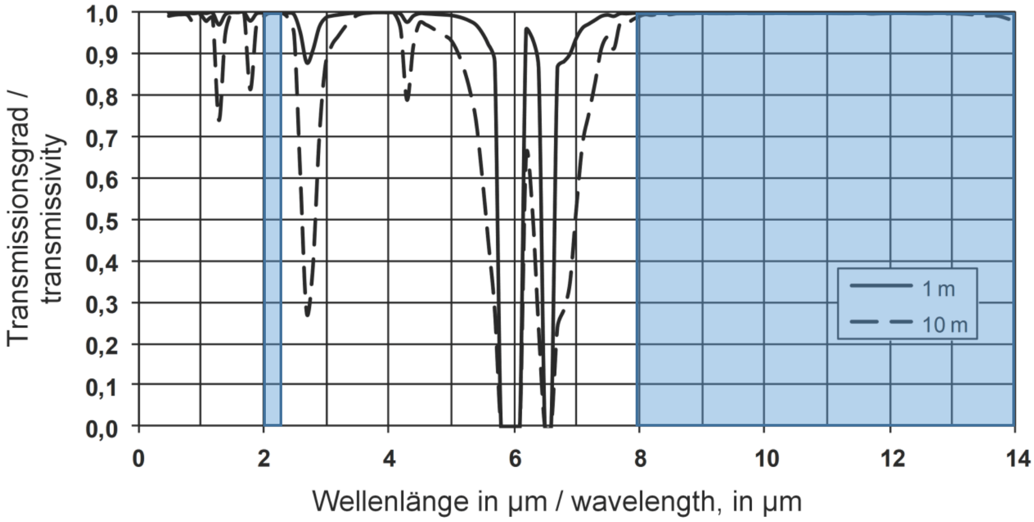


Fig. 3: Spectral transmissivity of air at 25 °C, 1 bar pressure, 98 % relative air humidity and 0.03 % CO_2 content for 1 m and 10 m air paths [1].

4. Emissivity measurements of HDG steel members at elevated temperatures

Test specimens

The test samples (d=50 mm; t=10 mm) for this research have two types of steel categories: category A, the lower silicon content range (≤ 0,04% Si), and category D, with a higher silicon content range (> 0,25% Si) as shown in Fig. 4. The resulting thickness of the different zinc layers are given in the following *Table 1*.The measured values coincide with the different layer structures and agree with the known iron-zinc layers in literature [2]:

Table 1: Thickness of the zinc coating of different specimen

Specimen Category	Average Thickness [µm]
A	88.0
D	179.3

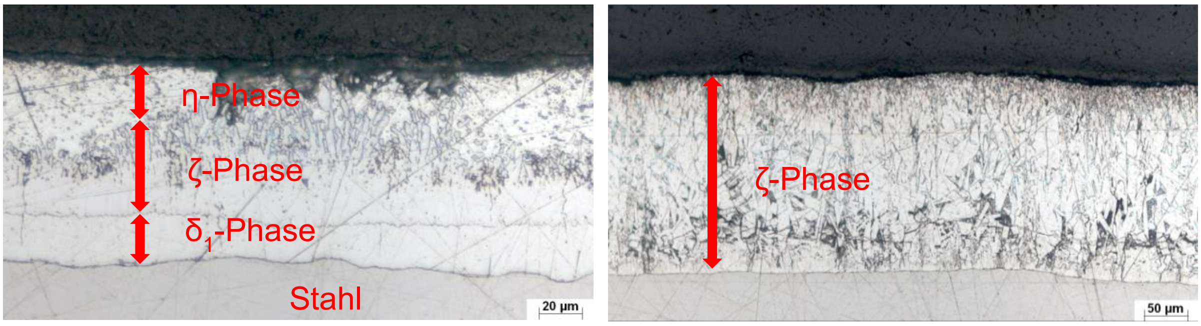


Fig. 4: Micrographs of HDG alloy layers. Left: Category A; Right: Category D

Research tests

Huge amounts of emissivity tables are provided by different companies, but values for metal surfaces depend for example on surface texture, temperature, and viewing angle. To determine the temperature dependent emissivity, one method is to compare the temperature of the specimen, measured with thermocouples (TC), with the measured temperature by the pyrometer and simultaneously adjusting its emissivity.

In this research, to simulate an R30 fire exposure according to the standard temperature-time curve, the behavior of HDG-steel at a temperature range of 20°C (room temperature) till 850°C was observed. The exact setup of the so-called “small-scale tests” is described in [3], [4] and can be seen in Fig. 5.

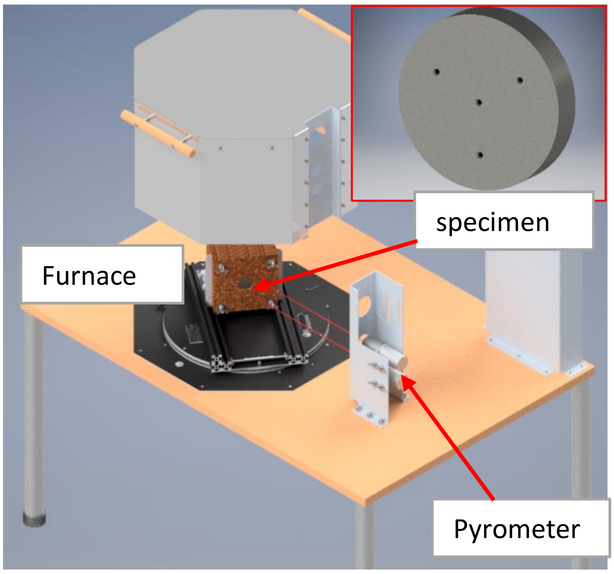


Fig. 5: Experimental setup

As mentioned before emissivity depends on several surface characteristics and thereby to a decisive extent on the surface texture, the chemical composition and as well on the degree of oxidization. All these factors had to be considered to make reliable statements about hot-dip galvanized steel specimen under the impact of high temperatures. For this purpose different sample with, for example, various weathering conditions have been tested to gain an optimized statement of realistic values of the emissivity.

By calculating the radiative emittance of the specimen for every different elevated temperature step, with the given formula (1), and comparing it with the radiative emittance gained through retroactive calculation of energy values out of the pyrometers measurements at a specifically adjusted emissivity, the real emissivity of the surface is obtained. This is done for every single temperature step at defined test settings for both pyrometers.

Shortwave pyrometers reduce the measurement errors considerably if the emissivity is set incorrectly. For this reason, the following analysis shows a detailed view of the results of the 2.3 µm pyrometer.

As shown in figures below (Fig. 6 & Fig. 7), the zinc-iron alloy layers at the surfaces have a big influence on the emissivity value. Looking at Fig. 6 one can see, that the curve starts at lower levels (≈ 0.35) and increases two times, first at the stage of round about 419°C (resistance level of the η-phase / melting point of the pure zinc) and second at about 530°C (resistance level of the ζ-phase) with an ending average value of 0.65. The exact emissivity values at the different temperature stages depend on the surface texture. The specimens, who have been stored outside exhibit about 5-10% higher values than samples stored inside. Nevertheless every single emissivity value from ambient room temperature till 750°C of the steel sample is better than $\varepsilon_{EC} = 0.7$, given by the Eurocode [5].

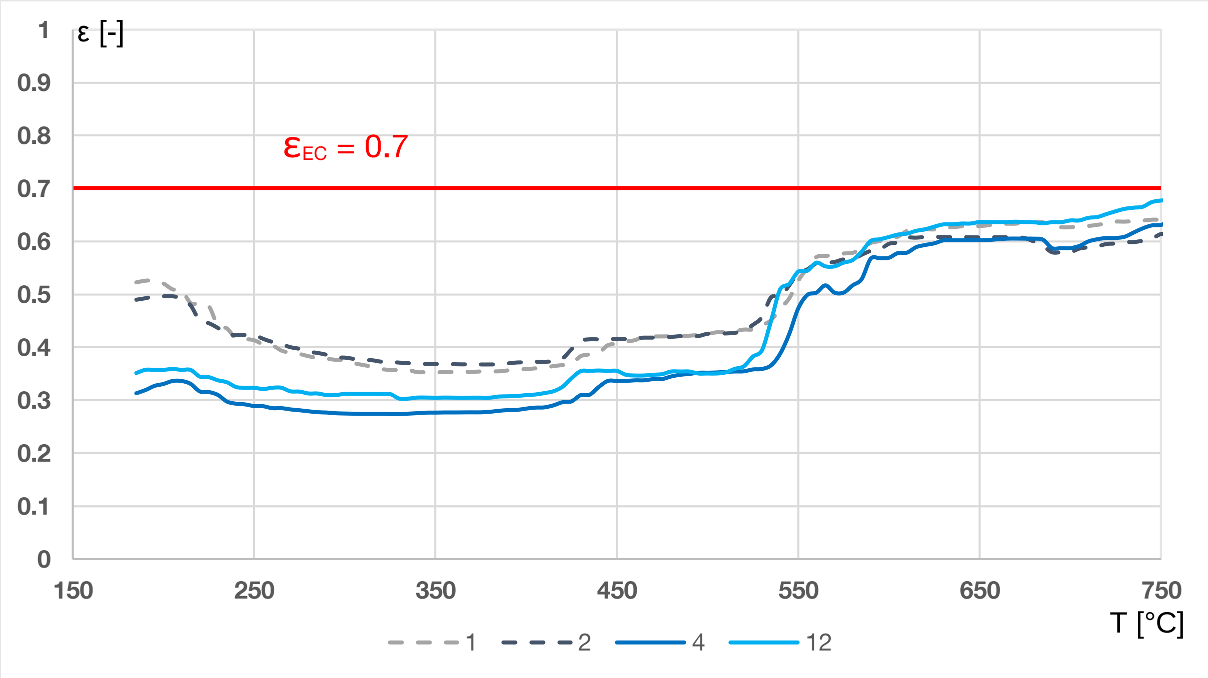


Fig. 6: Emissivity curves – Category A (grey-dashed: stored outside; blue: stored inside)

Comparing these curves of category A specimen (Fig. 6) with category D curves (Fig. 7) it's obvious that the behavior of the latter is worse but still better than the given emissivity of 0.7. Due to the difference in the alloy layers, the behavior of the curves differ.

Nevertheless same effects occur: again, at about 530°C, the resistance level of the ζ-Phase can be recognized.

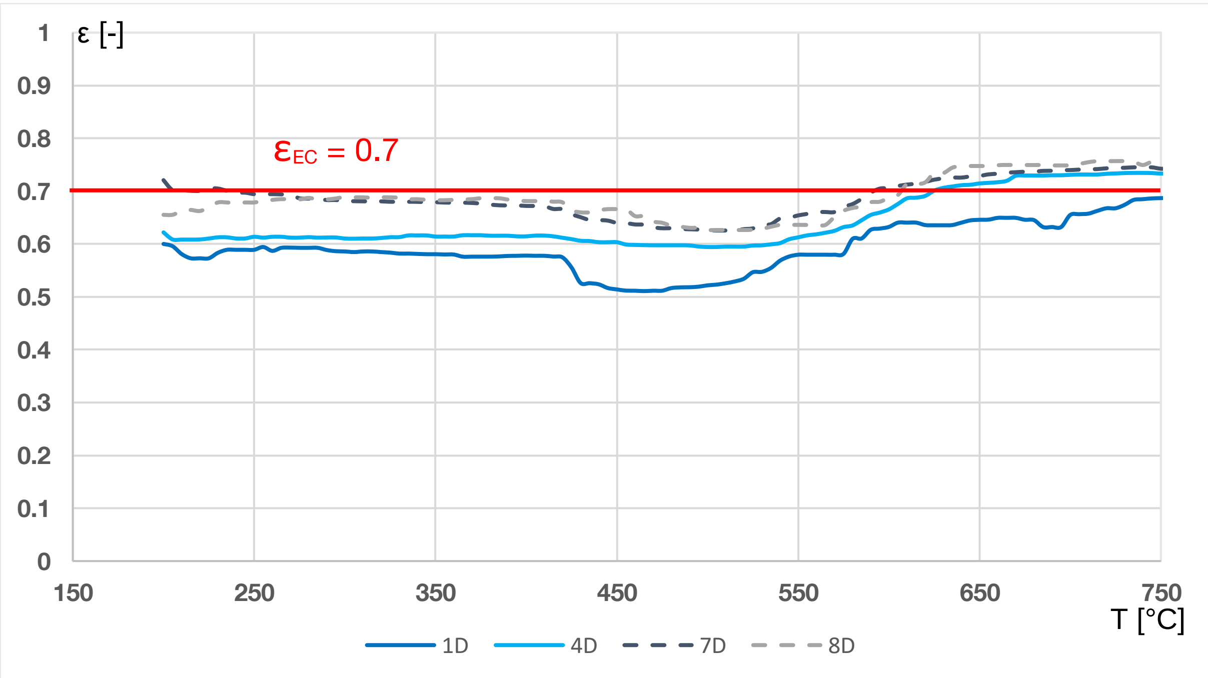
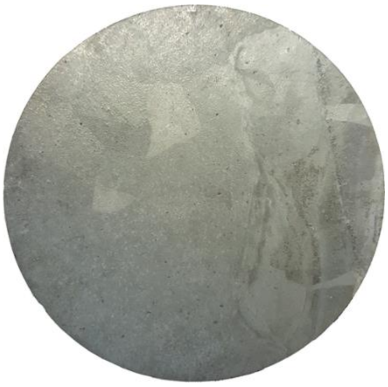


Fig. 7: Emissivity curves– Category D (grey-dashed: stored outside; blue: stored inside)

Surface change during the tests

During rising temperatures, the influence of the thermal exposure can be seen on the surface structure. This ongoing process during the test transforms the different layers. The outer layer of category A (pure zinc layer) for example coalesce with the surrounding oxygen and builds zinc oxide. With increasing temperatures, further processes like diffusion as well as exchanges on molecular level take place in between the different alloy layers. A new layer structure is formed with a differential appearance and a distinct higher roughness on the surface. This fits the measured emissivity curves above – with an increasing roughness an increasing emissivity is accompanied.

Table 2: Thermal impact on HDG-steel specimen

Category	Before thermal impact	After thermal impact
A		
D		

5. Conclusion

Results of recent tests at the Technical University of Munich show a much better behavior of structural steel elements that has been hot-dip galvanized according to EN ISO 1461 in comparison to the given emissivity value of ε_{EC} = 0.7 for carbon steel in the Eurocode EN 1993-1-2 [5]. The better behavior especially appears for temperatures up to 530 – 550°C in fire exposure of a steel element itself. With a steel composition according to category A of EN ISO 14713-2, a new emissivity course can be provided as given in subsequent table:

Table 3: Following values of the emissivity related to the steel surface may be taken

Typ of steel	ε_m (≤ 530°C)	ε_m (> 530°C)
carbon steel	0,7	
stainless steel	0,4	
HDG steel[1]	0,35	0,65
[1]) Steel that has been hot-dip galvanized according to EN ISO 1461 and with steel composition according to category A of EN ISO 14713-2		

This favorable effect influences the fire resistance positively and, depending on the steel section, an R30 fire resistance requirement could be reached without additional passive fire protection.

References

[1] VDI - Verein Deutscher Ingenieure, "VDI/VDE 3511 Blatt 4.5:2015-06; Technische Temperaturmessung - Strahlungsthermometrie - Praktische Anwendung von Strahlungsthermometern," 2015-06, VDI/VDE 3511 Blatt 4.5:2015-06.

[2] W.-D. Schulz and M. Thiele, *Feuerverzinken von Stückgut*: *Werkstoffe - Technologien - Schichtbildung - Eigenschaften - Fehler*, Leuze, Bad Saulgau, 2012.

[3] C. Gaigl and M. Mensinger, "Hot dip galvanized steel constructions under fire exposure," in *IFireSS 2017,* E. Nigro and A. Bilotta, Eds., pp. 557–564, Doppiavoce, Napoli, 2017.

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[5] DIN Deutsches Institut für Normung e. V., "DIN EN 1993-1-2:2010-12; Eurocode 3: Bemessung und Konstruktion von Stahlbauten – Teil 1-2: Allgemeine Regeln – Tragwerksbemessung für den Brandfall Deutsche Fassung EN 1993-1-2:2005 + AC:2009," 2010-12, DIN EN 1993-1-2:2010-12.