Trends in the Application of High-Performance Steel in European Bridge Building

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Abstracts: This article summarizes the current state of the art in the production and application of high strength heavy steel plates for steel structures. By the thermo-mechanical rolling process steel plates with a yield strength of up to 500 MPa can be produced. These steel grades are also characterized by best fabrication properties and can therefore be efficiently used in bridge building. For special elements sometimes also high strength grades with a yield strength up to 690 MPa are used. They are produced by the quenching and tempering process. Typical application examples in bridge building will be given.

1. Introduction

Steel – in particular heavy plates – is the most important input material for heavy steel structures. Therefore it is obvious that the improvement of the efficiency of steel products in design, fabrication and service life of a steel structure is a key element to develop also the efficiency of the steel structure. One way of gaining a higher productivity is offered by the use of higher strength steel, which can be defined as a product with a yield strength exceeding 355 MPa. Under special constructional circumstances such higher strength steel enables the designer to reduce cross-sections, saving also considerable fabrication time and costs by smaller welds. Furthermore, also higher strength steels with a good structural safety in particular against brittle fracture and excellent fabrication properties (welding) already exist. However, the weak points of designing with higher strength steel such as fatigue or displacement restrictions will also be commented.

Higher strength plates can be produced by various production processes which also influence the final using and fabrication properties of the steel. Here, mostly the thermo-mechanical rolling process is applied as thereby also good fabrication and utilisation properties can be guaranteed. Such plates are today produced up to a yield strength of 500 MPa and have gained special attentiveness in large span landmark bridges. But also other fields of applications, such as industrial buildings or medium span bridges, can profit from these mate-

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rials. Beyond that, extra high strength steel with a yield strength up to 690 MPa is sometimes used for special structural elements in bridges and buildings. These steels are produced by a quenching and tempering process.

It can be seen that the production process of heavy plates has fundamental impact on the fabrication properties of a steel product. Therefore, the various production techniques which exist today for heavy plates will be described first. Secondly, it will be explained how this influences the fabrication properties, in particular welding of these steels.

However, some peculiarities concerning design have to be taken into account when constructing with high strength steel. Finally, it will be shown how these steels can successfully be applied for steel bridges.

2. Overview On Production Processes

Weldable structural steels are delivered in the conditions: normalized, quenched and tempered, and thermo-mechanical controlled rolled, schematically shown in Fig.1. Fig. 2 allows to compare typical microstructures for the above mentioned supply conditions.

For steel grades of moderate strength and toughness requirements a classical hot rolling and normalizing of the steel is sufficient to obtain the necessary mechanical values. By this process route weldable structural steels up to S460N are produced. Hot rolling is generally carried out at high temperatures above 950°C (process A in Fig. 1). By reheating the hot rolled plates to some 900°C followed by free cooling in air a refined microstructure of ferrite and pearlite (process B in Fig. 1) is obtained. However with this process, a higher strength of steel plates is mostly related to higher alloying contents, which influence weldability in a negative way.

By quenching and tempering, structural steels can reach a yield strength of up to 1,100 MPa. This heat treatment (process C in Fig. 1) applied subsequent to hot rolling, consists of an austenitisation, followed by quenching and finally tempering.

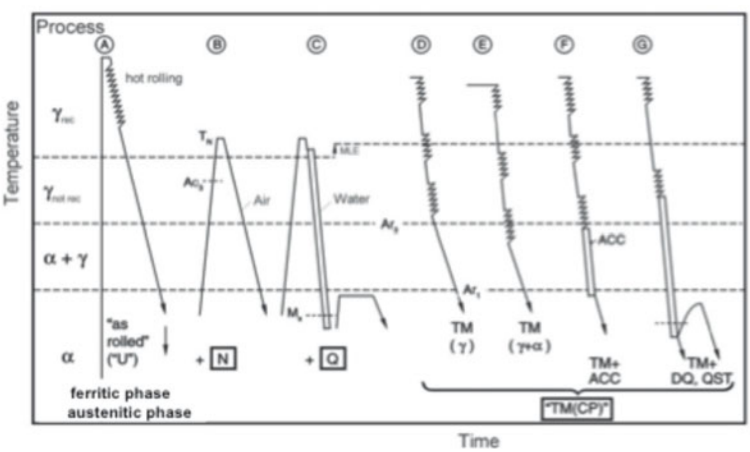

Figure 1: Schematic temperature-time-procedures used in plate production: normalized (process A+B), quenched and tempered (process A+C) and different TMCP processes (D – G)

The aim of thermo-mechanical rolling (TM or TMCP) is to create an extremely fine grained microstructure by a skilled combination of rolling steps at particular temperatures and a close temperature control. The gain in strength obtained by this grain refinement allows reducing effectively the carbon and alloying content of the TM-steel compared to normalized steel of the same grade. The improved weldability that results from this leaner steel composition is a major advantage of TM-plates. Depending on the chemical composition, the desired strength, the toughness requirements as well as the plate thickness the "rolling schedule" is individually designed. Some typical TM-processes are shown in Fig. 1. Especially for thick plates an accelerated cooling after the final rolling pass is beneficial for the achievement of the most suitable microstructure as it forces the transformation of the elongated austenite grains before recrystallization can happen. For very thick plates and higher yield strength grades an additional tempering process can be used after the accelerated cooling.

TM-rolled plates with minimum yield strength values of 500 MPa were supplied up to 100 mm for hydropower, offshore platforms and special ships [Schütz & Schröter 2005]. Even higher yield strength classes up to 690 MPa are feasible by the TM-process, however, in a more limited thickness.

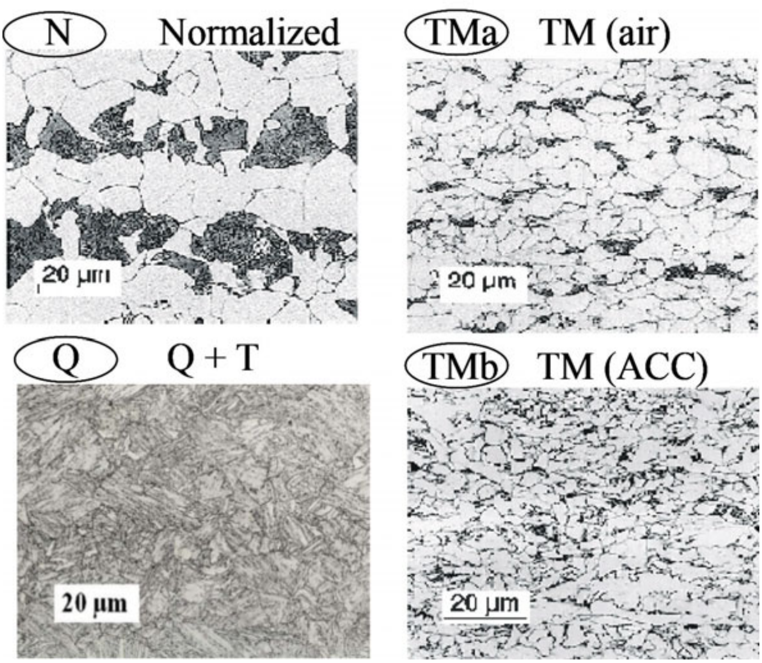

Figure 2: Microstructure of conventional normalized steel (process B of Fig. 1) compared to TMCP (process D), TMCP+ACC (process F) and Q+T steel (process C)

3. Availables Grades and Construction Rules

According to the various production processes described above, higher strength steel plates for construction purposes with yield strength higher than 355 MPa are defined in three European standards:

- EN 10 025-3: Normalized fine grain steel: S420N, S420NL, S460N, S460NL
- EN 10 025-4: Thermo-mechanical rolled fine grain steel: S420M, S420ML, S460M, S460ML
- EN 10 025-6: Quenched and tempered fine grain steel: S460Q, S460QL, S460QL1, S500Q, S500QL, S500QL1, S550Q, S550QL, S550QL1, S620Q, S620QL, S620QL1, S690Q, S690QL, S690QL1, S890Q, S890QL, S890QL1, S960Q, S960QL

In the above steel grade designation, the figure indicates the minimum yield strength of the product at the lowest available thickness. The following code is an abbreviation for the production process and the Charpy-V impact energy tested. Thus, the abbreviation N or M corresponds to a minimum toughness of 40 J at –20°C (longitudinal), whereas NL- or ML- grades are characterized as low-temperature grades with more than 27 J at –50°C. For quenched and tempered grades the following is valid:

- Q: 30 J at –20°C (long.)
- QL: 30 J at –40°C (long.)
- QL1: 30 J at –60°C (long.)

For instance, Tab. 1 and 2 summarize the mechanical properties of high strength TMCP rolled material according to EN 10025-4.

Table 1: Mechanical properties of higher strength TMCP steel according to EN 10 025-4

	Yield Strength [MPa] at thickness t [mm]						**Charpy-V [J] at T [°C]**
	t ≤ 16	t≤ 40	t≤ 63	t≤ 80	t≤ 100	t≤ 120	
S420M	420	400	390	380	370	365	40 J at –20°C
S420ML							27 J at –50°C
S460M	460	440	430	410	400	385	40 J at –20°C
S460ML							27 J at –50°C

Table 2: Mechanical properties of higher strength TMCP steel according to EN 10 025-4

	Ultimate Strength [MPa] at thickness t [mm]				
	t≤ 40	t≤ 63	t≤ 80	t≤ 100	t≤ 120
S420M	520-680	500-660	480-650	470-630	460-620
S420ML					
S460M	540-720	530-710	510-690	500-680	490-660
S460ML					

According to the basic Eurocode EN 1993-1-1 steel grades up to a yield strength of S460 can be used for steel structures either in the normalized, the thermo-mechanically rolled or the quenched and tempered condition.

Furthermore, a new part of the Eurocode EN 1993-1 was been published, which defines rules for the application of steels up to a yield strength of S690. Here, also some requirements on steel products have been adapted. Thus, for instance a tensile to yield strength ratio fu/fy of 1.05 is sufficient.

4. TMCP-rolled steel

The most significant advantage of TM-plates compared to conventional steel grades of the same thickness is their outstanding suitability for welding characterized by two main features: on the one hand, preheating of thicker TM-plates can be considerably reduced or omitted completely, which allows significant savings in fabrication time and costs. On the other hand, TM-plates exhibit high toughness values and low hardening tendency in the heat affected zone (HAZ) after welding [Schröter 2004].

These effects are due to the very low alloying contents (in particular carbon contents) which can be reached by this special rolling process. Thus, Tab. 3 compares the typical alloying content of a conventional S355J2+N with that of a TM-steel of the same yield strength S355ML.

Table 3: Comparison of chemical compositions (according to the relevant standard and common production values for 50 mm plate thickness) between a normalized S355J2+N and a TMCP rolled S355ML

	S 355 J2+N		**S 355 ML**	
	acc. EN 10025-2	typ. analysis	acc. EN 10025-4	typ. analysis
C	≤ 0,22	0,17	≤ 0,14	0,08
Si	≤ 0,55	0,45	≤ 0,50	0,35
Mn	≤ 1,60	1,50	≤ 1,60	1,53
P	≤ 0,025	0,018	≤ 0,025	0,012
S	≤ 0,025	0,015	≤ 0,020	0,005
Nb	-	-	≤ 0,05	0,02
V	-	-	≤ 0,10	-
Mo	-	-	≤ 0,10	-
Ni	-	-	≤ 0,50	-
CE	≤ 0,47	0,42	≤ 0,40	0,34
Pcm		0,26		0,17
CET		0,32		0,24

The table also indicates the values for the mostly used carbon equivalents, formulas which are used to judge the influence of the alloying elements on weldabilty. It can be seen that TMCP rolled steel shows much smaller carbon equivalents than normalized steel grades of the same yield strength.

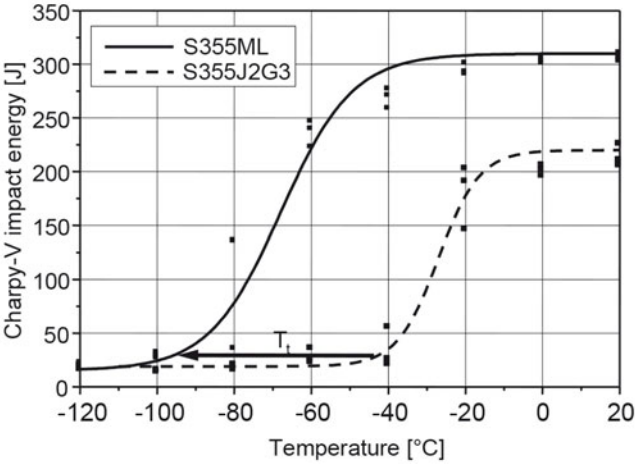

Figure 3: Comparison of the Charpy-V-temperature transition curve for a conventional normalized steel S355J2+N and a TMCP rolled steel S355ML

Furthermore, TMCP rolled steel has excellent toughness behaviour. Fig. 3 illustrates that the transition temperature between brittle and tough fracture behaviour, which is often defined by the temperature, where a Charpy-V impact energy of 27 J is attained, can be significantly reduced by TMCP rolling in comparison to a conventional steel grade S355J2+N.

Thus, a reserve is given in order to ensure also outstanding toughness properties in the heat affected zone of the weld. As an example Fig. 4 shows the Charpy-V-temperature transition curve of an S355ML measured in the heat affected zone in distance of 2 mm to the fusion line. It can be seen that even at –50°C a good toughness level can be reached resulting in a high safety of the welded joint against brittle fracture. Furthermore, good toughness levels in the heat affected zone are a prerequisite for the application of welding processes with high heat input. Thus, also the efficiency of the welding process can be increased by using TMCP rolled material.

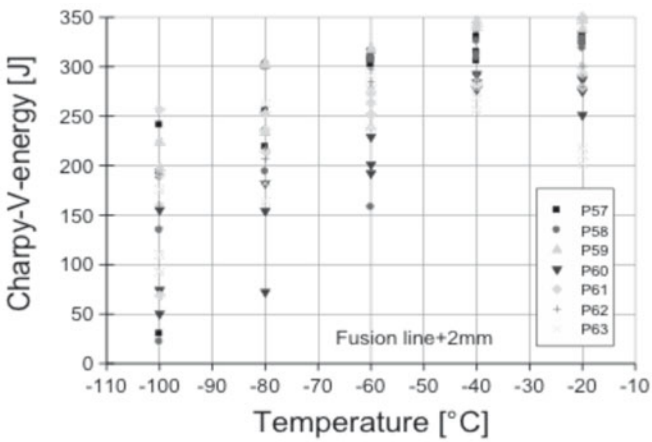

Figure 4: Charpy-V-temperature transition curve in the heat affected zone of a S355ML after welding with submerged arc welding (3.0 kJ/mm)

Due to the higher carbon content and the risk of hydrogen induced cracking a conventional S355J2+N in thicknesses above 30 mm is normally preheated prior to welding. Due to its low alloying content, TM-steel S355M is normally not preheated if EN 1011-2 is applied for the calculation of preheating temperatures.

The economic benefit of avoiding preheating is clear. A time and money consuming step in the fabrication process of steel structures can be avoided and the production efficiency of the workshop increased [Hever & Schröter 2003].

One big advantage of TMCP rolling technique is that even higher strength grades can be produced by an appropriate heat treatment without considerably increasing the alloying content. Thus Fig. 5 shows the mechanical properties of two steel plates of the same chemical compositions but with different treatments after rolling. By applying an especially harsh cooling – the so-called heavy accelerated cooling – the yield and ultimate strength of the steel plates can be increased without any change of the chemical composition.

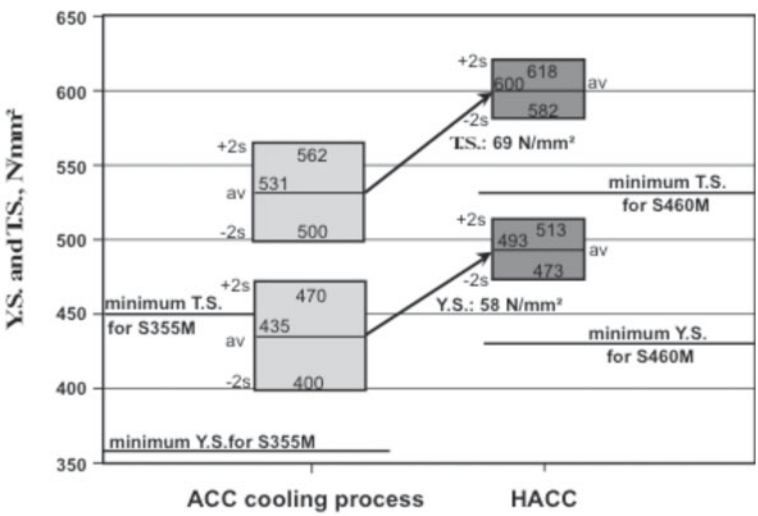

Figure 5: Tensile strength and yield strength of two TMCP-rolled steel plates with the same chemical compositions but with different cooling speed after rolling

Thus, even steel with minimum yield strength of 460 MPa can be produced with acceptable carbon equivalents for best weldability. For instance, an S460M steel shows a carbon equivalent of 0.40 – 0.42 % which may be lower than that of a conventional S355J2+N.

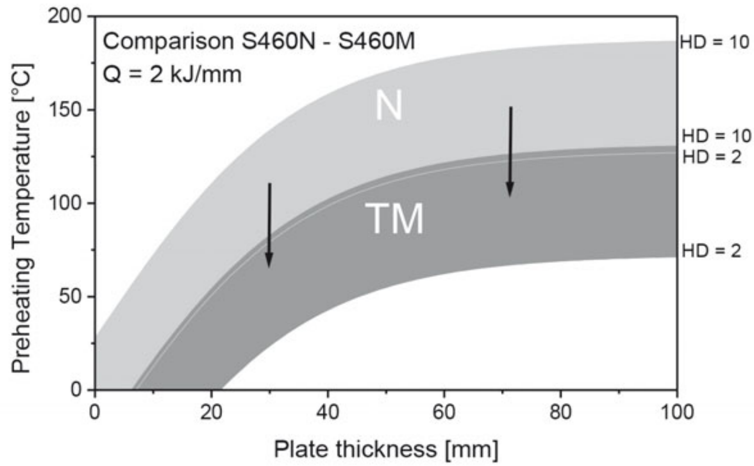

Figure 6: Comparison of preheating temperatures according to EN 1011 between normalized steel S460N and higher strength steel S460M

Thus, S460M enables the reduction of preheating temperatures in comparison to a conventional S460N. Furthermore, in most cases even for this higher strength steel grade preheating can be omitted completely if special conditions on the welding process are fulfilled, as in particular the usage of low hydrogen consumables (hydrogen content: HD) such as thoroughly dried basic electrodes. Fig. 6 compares the necessary preheating temperatures for a S460M and S460N steel.

In order to reduce the danger of embrittlement in the heat affected zone, steels unsusceptible to ageing are needed. The insusceptibility for ageing is shown on the material by notch impact tests on cold formed and artificially aged material. Fig. 7 shows that the notch impact temperature transition curve moves towards higher temperatures when the steel is being aged, but relatively low transition temperatures can still be found even under this hard test conditions.

Further fabrication properties of TMCP-rolled steel are given in [Schröter 2004, Hanus & Hubo 1999].

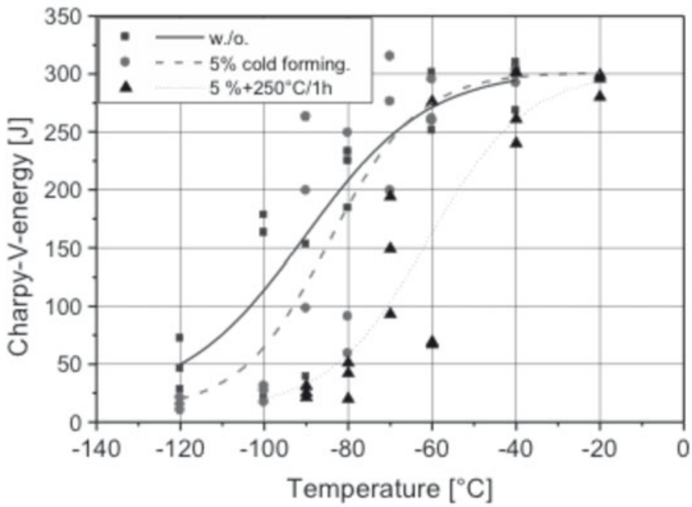

Figure 7: Charpy-V temperature transition curves for an S500M steel without cold forming, with additional cold forming and cold forming with additional artificial ageing

5. Quenched and Tempered Plates

Steels of 690 MPa yield strength became commercial about three decades ago. They were – like today – essentially produced by water quenching and tempering (QT). Nowadays QT-plates with a yield strength over 1,100 MPa are commercially available.

The aim of quenching and tempering is to produce a microstructure consisting mainly of tempered martensite. Some amounts of lower bainite are also acceptable. Quenching of high strength steels is performed after austenising at temperatures of 900-960°C. In order to suppress the formation of softer microstructure, essentially ferrite, during cooling an accelerated cooling process is necessary. The fastest cooling is obtained by exposing the plate surfaces to a rapid water stream. By such an operation the very surface is cooled to a temperature below 300 °C within a few seconds. In the core of the plate cooling is considerably slower and the cooling rate decreases with increasing plate thickness. Therefore the alloying concept of thicker quenched and tempered plates has to be adapted to ensure sufficient hardening in the plate core.

If we consider the mechanical properties in the as quenched condition, the strength is considerably higher than required but the material is too brittle for most structural applications. A suitable tempering of the martensitic microstructure is necessary in order to get a satisfactory combination of tensile strength and toughness properties. By tempering the martensite, the super saturation of carbon in the matrix is reduced by the precipitation of carbides leading to a relaxation in the atomistic scale. At the same heat treatment the high dislocation density associated with martensite formation is reduced. Both effects improve the toughness of the material. A 60 mm thick S890QL (EN 10025-6) is chosen as an example, that shows the influence of tempering on the properties. Fig. 8 illustrates how the tensile properties are lowered with increasing temper parameter, as well as the improvement of impact toughness.

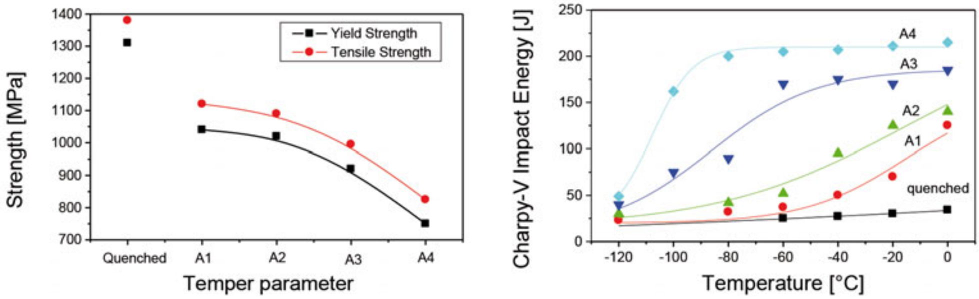

Figure 8: Influence of increasing tempering temperatures on the tensile properties and on the Charpy impact temperature transition of S890QL steel in 60 mm thickness [Hanus et al. 2002]

The tempering conditions must be adapted to the particular chemical composition of the steel. The higher the toughness and strength requirements the closer gets the permitted range for the tempering conditions.

It has already been mentioned that the alloying compositions of quenched and tempered steel in-creases with growing plate thickness in order to ensure a sufficient hardening of the plate in the core region. Therefore, it is obvious that the carbon equivalent of a quenched and tempered steel in-creases with the plate thickness. An example is given by Tab. 4.

Table 4: Typical carbon equivalents of S690QL steel

Thickness	CE	CET	Pcm
mm	%	%	%
≤ 20	0.42	0.30	0.26
> 20; ≤ 50	0.59	0.37	0.31
> 50; ≤ 80	0.66	0.39	0.32
> 80; ≤ 110	0.72	0.41	0.34
> 110; ≤ 150	0.79	0.44	0.35

Due to higher strength and carbon equivalents quenched and tempered steel grades with a yield strength of 690 MPa and above show a more sophisticated fabrication behaviour than thermo-mechanically rolled steel grades. Here especially the weldability should be examined in detail.

The temperature time cycles during welding have a significant effect on the mechanical properties of a welded joint. Generally the cooling time from 800°C to 500°C (t8/5) is chosen to characterize the cooling conditions of an individual weld pass for the weld metal and the corresponding heat affected zone for higher strength steel. Increasing heat input and interpass temperature leads to slower cooling and, hence, longer cooling times t8/5. Knowing the welding parameters (like heat input and preheating temperature) and geometry t8/5 can be calculated according to standard EN 1011-2.

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