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Prevention of HS-type Crack in Welding under Pulsating Loads[†]

You Chul KIM*, Izumi IMOTO**, Yasumasa NAKANISHI** and Kohsuke HORIKAWA***

Abstract

Repair and reinforcement works by the welding on the steel structures in service condition are often done under the pulsating loads. The hot crack, which was classified into that in solid-liquid state (solidification crack) and that in solid one (called as the HS-type crack) initiating at high temperature, sometimes occurred in the welding under the pulsating loads. This study examined the preventive condition of the HS-type crack by using the results of the weld hot cracking test under the pulsating loads. Then, prevention of the hot crack (including the solidification crack) was synthetically investigated in mechanics.

The equation which describes the initiation of the HS-type crack produced in the welding under the pulsating loads was derived. Based on it, a practical equation to decide the initiation of the HS-type crack was shown, in which relative root gap opening displacement, $\Delta\delta$, that can be easily measured before the welding was used as a measure for the crack initiation. Applying it to the results of the hot cracking test, the validity of the practical equation proposed in this study was concretely shown. The critical strain for the hot crack of the weld metal used in this study was shown. Concerning the solidification crack initiation, the main factor was the product of $\Delta\delta$ by the external loads and repeated number. The main factor for HS-type crack initiation was the maximum strain rate (the root gap opening rate) by the external loads in a cycle. The procedure to apply the evaluating expression for the prevention of the hot crack produced in the welding under the pulsating loads, that is the solidification crack and the HS-type one, was shown. So far as the equation proposed in this study is used, the critical strain is not necessary to be obtained from a series of the weld hot cracking test in the whole frequency range.

KEY WORDS: (Hot Crack) (HS-type Crack) (Solidification Crack) (Measure for Hot Crack Initiation) (Critical Strain for Hot Crack) (Critical Root Gap Opening Displacement for Hot Crack) (Prevention of Hot Crack) (Pulsating Load)

1. Introduction

Repair, reinforcement or reconstruction works by the welding on the steel structures in service condition are often done under the pulsating loads.

The weld cracking test had carried out under the pulsating loads¹⁾. Based on the test results, it was shown that the hot crack, which was classified into that in solid-liquid state (solidification crack) and that in solid one initiating at comparatively high temperature (called as the HS-type crack), sometimes occurred²⁾. Then, the measure deciding the solidification crack initiation under pulsating loads has been proposed and the practical equation for the crack prevention was derived³⁾.

This study examines the procedure for the prevention of the HS-type crack produced in the welding under the

pulsating loads and synthetically investigates the prevention of the hot crack (including the solidification crack) under the pulsating loads in mechanics.

2. Evaluating expression for the Hot Crack Prevention

Figure 1 shows the specimen using the weld hot cracking test under the pulsating loads. Figure 2 shows the weld cracking test results under the pulsating loads obtained in the previous paper³⁾ (the dotted line shows the critical root gap opening displacement, $\Delta\delta_{cr}$, for the solidification crack). In the cases that the frequency, f , of the root gap opening displacement, $\Delta\delta$, before the welding is low and that it is high, the tendency of the different crack initiation can be seen in Fig.2.

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* Associate professor

** Ishikawajima-Harima Heavy Industries Co., Ltd.

*** Professor

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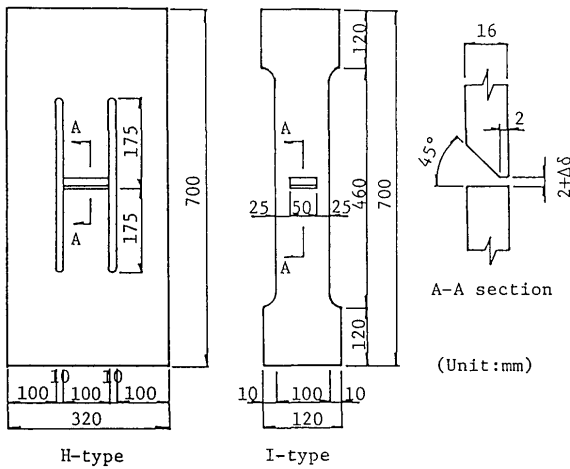


Fig. 1 Specimen for the hot cracking test in the welding under the pulsating loads.

Concerning the solidification crack, the previous report has already discussed in detail³⁾. Here, for the HS-type crack initiating in the range where the frequency is low, the condition of crack initiation is examined and the practical equation for the crack prevention is derived.

2.1 Condition of the hot crack initiation

According to the Trans-Varestraint test results of the filler material (D4316), the HS-type crack initiated in the temperature range where it was from 1200°C to 700°C. In this temperature range, the weld metal is considered to be in the solid state, where it is more cooled from the

solid-liquid state. As the HS-type crack is the one initiating in the solid state, if the crack occurs once, it remains as the crack after cooling to the room temperature. Therefore, considering the initiation condition of the HS-type crack in mechanics, the HS-type crack initiates only when the strain by the external loads, ϵ , exceeds the critical strain for the crack of the weld metal, ϵ_{cr} , even if the strain affects on the weld metal once or repeatedly. That is, the condition of the HS-type crack initiation is as follows in mechanics.

$$\epsilon \geq \epsilon_{cr} \tag{1}$$

where,

ϵ : the strain applied at the weld metal by the external loads

ϵ_{cr} : the critical strain for the HS-type crack (the metallurgical property of the weld metal).

2.2 Practical equation for the hot crack prevention

The relative root gap opening displacement, $\Delta\delta$, which can be easily measured before the welding was used as the practical measure for evaluating the behavior which the weld metal would be affected by the pulsating external loads³⁾.

Here, the relation between $\Delta\delta$ and the applied strain ϵ by the external loads is investigated. Then, based on the Eq.(1), the practical equation judging the HS-type crack initiation is derived, in which $\Delta\delta$ is the practical measure.

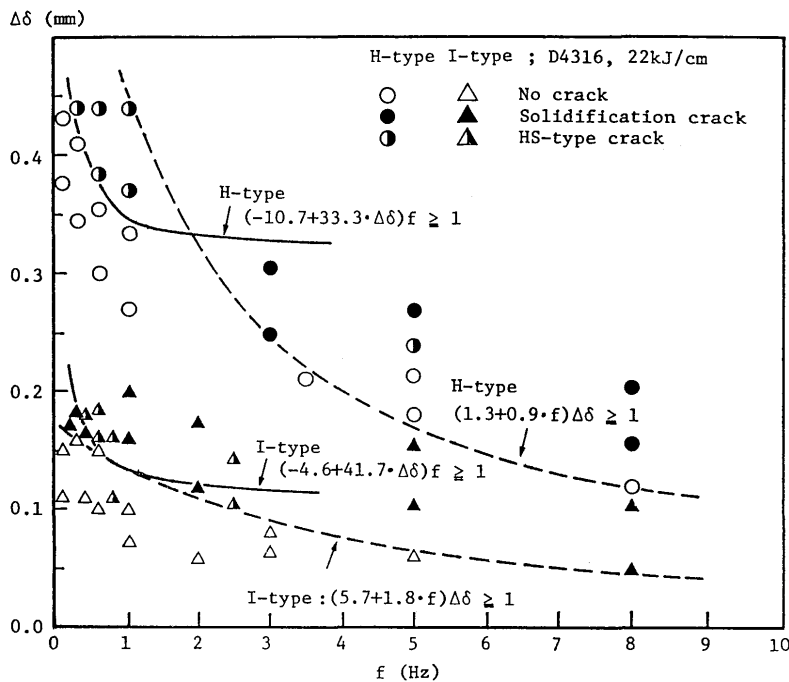


Fig. 2 Results of the hot cracking experiment in the welding under the pulsating loads.

2.2.1 In the case without external loads

In the case that no external loads affects to the weld metal, ϵ becomes the strain, ϵ_w , which is produced when the free shrinkage of the weld metal is restricted by the base metal. ϵ_w is the constant which is obtained by the welding condition and the stiffness of the weld joint. In this case, the condition of the HS-type crack initiation becomes as follows.

$$\epsilon = \epsilon_w \geq \epsilon_{cr} \quad (2)$$

where,

ϵ_w : the strain which is produced when the free shrinkage of the weld metal is restricted by the base metal.

2.2.2 In the case with external loads once or repeatedly applied

When the external loads apply to the weld metal once or repeatedly, the strain by the external loads, $\Delta\epsilon_L$, is added to ϵ_w due to the free shrinkage of the weld metal as mentioned above. In this case, the condition of the HS-type crack initiation becomes as follows.

$$\epsilon = \epsilon_w + \Delta\epsilon_L \geq \epsilon_{cr} \quad (3)$$

where,

$\Delta\epsilon_L$: the strain due to the external loads.

It can be considered that the strain affecting at the weld metal by the external loads, $\Delta\epsilon_L$, is proportional to the relative root gap opening displacement, $\Delta\delta$, of before the welding by the external loads³⁾. That is,

$$\Delta\epsilon_L = a \cdot \Delta\delta$$

where,

a: proportional constant

$\Delta\delta$: the relative root gap opening displacement.

Therefore, Eq.(3) can be rewritten as follows.

$$\epsilon = \epsilon_w + \Delta\epsilon_L = \epsilon_w + a \cdot \Delta\delta \geq \epsilon_{cr} \quad (4)$$

Equation (4) is the expression dominating the HS-type crack initiation in the welding under the external pulsating loads in mechanics.

2.3 Critical strain for HS-type crack

As mentioned above, the HS-type crack initiated in the solid state. By the way, considering the welding process, the weld metal is sequentially laid and solidifies, that is, it continuously changes from the liquid state to the solid one. So, the position which has the possibility of the HS-type crack initiation is on the welding line where the change to the solid state just occurs. This time, t , is regarded as $t=0(s)$. Then, considering the severest state in mechanics, it is the case which strain ϵ by the pulsating external loads applies to the weld metal cooling from liquid state to the solid one as it opens the root gap. Specially, the state which applied strain ϵ begins to affect as it opens the root gap at $t=0(s)$ and

becomes gradually larger is the severest one in mechanics. From this, in order to grasp the tendency of the critical root gap opening displacement, $\Delta\delta_{cr}$, (In critical strain, ϵ_{cr} , it shows the same tendency) for the HS-type crack, the experimental result (Fig.2) for the H-type slit specimen (Fig.1) is shown in Fig.3 using the applying time, t , of the external loads instead of frequency, f , that is $t=1/2f$. Naturally, the positions where the HS-type crack initiates are different on the weld line owing to the difference of the frequency affecting the external loads because time t is considered to be relative time.

According to Fig.3, it is found that ϵ_{cr} can be divided into two ranges with the time passing (temperature cooling process) and that it is expressed with two different lines in the filler material (D4316) used in the experiment. The reason is considered below.

The weld metal cools down sequentially from the liquid state to the solid-liquid one and to the solid one. In such a cooling process, the external loads are applied. In the solid-liquid state, the transient range where the liquid state remains a little exists, although most of it becomes solid one. Therefore, ϵ_{cr} is different between in the cases that the external loads are applied in this transient range and that they are applied in the solid state. And even in the solid state, ϵ_{cr} for the HS-type crack becomes a function of time (temperature). That is, ϵ_{cr} has a tendency that it becomes larger with the time passing. In all cases, although the broken line and the solid line in Fig.3 express critical strain ϵ_{cr} for the hot crack, the range shown in the solid line expresses ϵ_{cr} for the HS-type crack. (The generality is not lost even if it

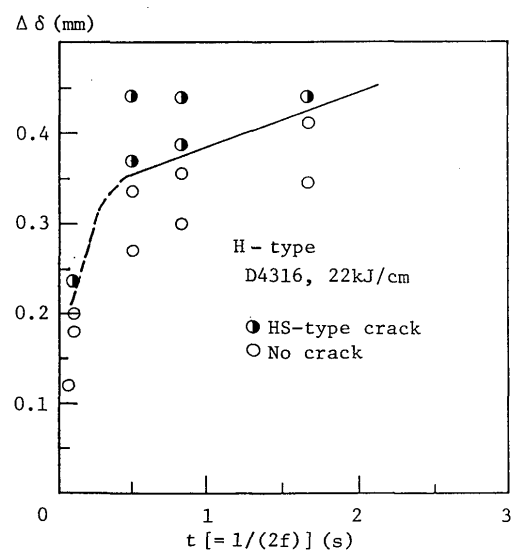


Fig.3 Critical root gap opening displacement for the HS-type crack with the H-type slit specimen (In the critical strain, it has the same tendency.).

is not a straight line.) If this range is converted by the frequency, it is below 1Hz.

Below 1Hz, the HS-type crack initiates. Over 1Hz, the solidification crack initiates or transits to be the HS-type crack. So, this range is considered to be a transient one. Then, Section 3 describes the treatment of ϵ_{cr} in this transient range. The $\Delta\delta_{cr}$ for the HS-type crack is obtained from the solid line in Fig.3 as follows.

$$\Delta\delta_{cr} = b' \cdot t + c' \quad (5)$$

where,

b' : proportional constant

c' : constant.

By the way, assuming it is considered that ϵ is proportional to the root gap opening displacement, $\Delta\delta$, ϵ_{cr} becomes the following equation rewriting t by f .

$$\epsilon_{cr} = b / f + c \quad (6)$$

where,

$b = d \cdot b' / 2$

$c = d \cdot c'$

d : proportional constant.

Equation (6) becomes ϵ_{cr} of the HS-type crack initiation for the filler material D4316.

2.4 Validity of proposed equation for the hot crack initiation

Substituting Eq.(6) for the right part of Eq.(4) for the HS-type crack initiation under the external loads, Eq.(4) becomes as follows.

$$\epsilon = \epsilon_w + a \cdot \Delta\delta \geq b / f + c \quad (7)$$

Equation (7) is the evaluating expression for the HS-type crack initiation in the welding under the pulsating external loads. Equation (7) can be rewritten by non-dimensional representation as follows.

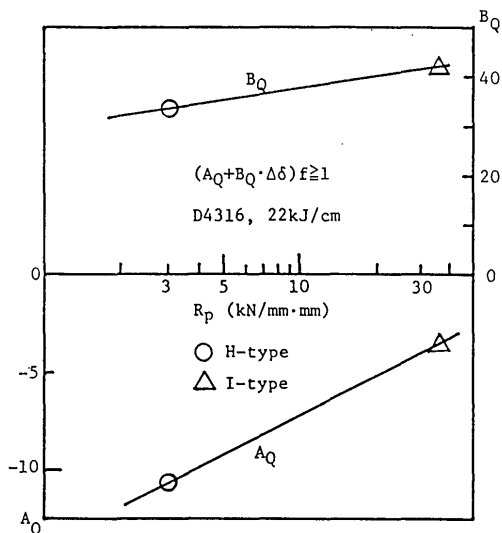


Fig. 4 Relation between A_Q , B_Q and in-plane stiffness (the restraint intensity, R_p).

$$(A_Q + B_Q \cdot \Delta\delta) \cdot f \geq 1 \quad (8)$$

where,

$$A_Q = (\epsilon_w - c) / b$$

$$B_Q = a / b.$$

A_Q and B_Q are the value which can be decided by the welding condition, the chemical composition of the weld metal, the in-plane stiffness of the weld joint and so on.

The weld cracking test in which the frequency and the magnitude of the external loads are variously changed was carried out. So, Fig.2 shows the experimental results by the symbol which are arranged by the frequency f and the root gap opening displacement, $\Delta\delta$, measured before the welding. Because the HS-type crack initiates below 1Hz, deciding the constants A_Q and B_Q by using $\Delta\delta_{cr}$ at $f=0.2$ and 0.6 (Hz) in Fig.2, the following equation can be obtained.

H-type slit specimen:

$$(-10.7 + 33.3 \cdot \Delta\delta) \cdot f \geq 1 \quad (9)$$

I-type slit specimen:

$$(-4.6 + 41.7 \cdot \Delta\delta) \cdot f \geq 1 \quad (10)$$

The relation between f and $\Delta\delta$ obtained from Eqs.(9) and (10) is expressed by the solid line in Fig.2. According to this, not only for H-type slit specimen but also for I-type one, it is found that the possibility of the HS-type crack initiation below 1Hz can be accurately evaluated. So, it is elucidated that the equation for the HS-type crack initiation under pulsating external loads proposed in this paper provides the valid results.

Comparing constants A_Q and B_Q in Eqs.(9) and Eq.(10), A_Q and B_Q of I-type specimen are larger than those of H-type one nevertheless the same welding condition and filler materials. It can be considered that this is owing to the difference of the in-plane stiffness of the weld joint. So, the restraint intensity R_p for the uniform loads is used as a measure expressing the in-plane stiffness of the weld joint⁴). Figure 4 shows the R_p and constants A_Q and B_Q corresponding to the each specimen. From this, it is known that the difference of the in-plane stiffness largely influences the HS-type crack initiation in the welding under the pulsating loads.

3. Hot Crack Prevention: Consideration

The hot crack initiated in the welding under the pulsating loads is synthetically investigated including the solidification crack³) and the HS-type one.

3.1 General discussion of the critical strain for the hot crack initiation

In the welding under the pulsating loads, the external loads are applied in the wide temperature range, that is, from the range where the weld metal is in the liquid state

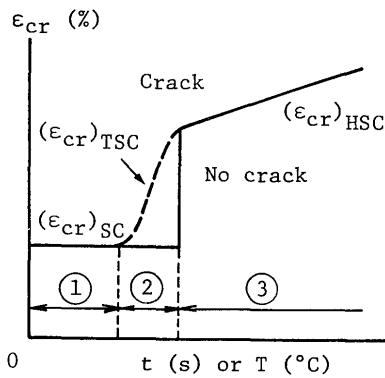


Fig. 5 Treatment of the critical strain for the hot crack in the welding under the pulsating loads.

to the range where it is in the solid state at room temperature. So, it is found that $(\epsilon_{cr})_{HSC}$ (the metallurgical property) does not become the constant irrelevant to temperature but becomes the function of it.

Figure 5 schematically shows the relation between the critical strain for the hot crack initiation and time passing (temperature change) in regard to the temperature range initiating the solidification crack and the HS-type one. As in Fig.5, ϵ_{cr} is different in the three ranges. In range ①, $(\epsilon_{cr})_{SC}$ is the critical strain in solid-liquid state, that is ϵ_{cr} for the solidification crack. In range ②, $(\epsilon_{cr})_{TSC}$ is the critical strain in the transient state from solid-liquid one to the solid one (Fig.3). In range ③, $(\epsilon_{cr})_{HSC}$ is the critical strain in the solid state, that is ϵ_{cr} for the HS-type crack.

By the way, as the treatment of the transient range (range ②) is complicated, ϵ_{cr} in this range is regarded $(\epsilon_{cr})_{SC}$ for the solidification crack as it is extending range ①. That is, ϵ_{cr} for the hot crack is expressed by the solid line in Fig.5. Using this ϵ_{cr} , the dotted line and the solid line in Fig.2 are the lines evaluating whether the solidification crack and the HS-type one initiate or not. It is found that the valid results are obtained including the transient range.

3.2 Hot crack initiation and applied strain

According to the combination of the magnitude of the applied strain ϵ by the external loads and its cycle (the frequency), it is decided whether the solidification crack initiating in the solid-liquid state, the HS-type crack initiating in the solid state, and both of them initiate or not. Figure 6 shows the characteristic pattern.

First, Fig.6(a) and (b) show the case when the cycle of the applied strain ϵ is short (that is, the frequency is high). Only the solidification crack occurs when the frequency is high and when ϵ does not exceed $(\epsilon_{cr})_{HSC}$

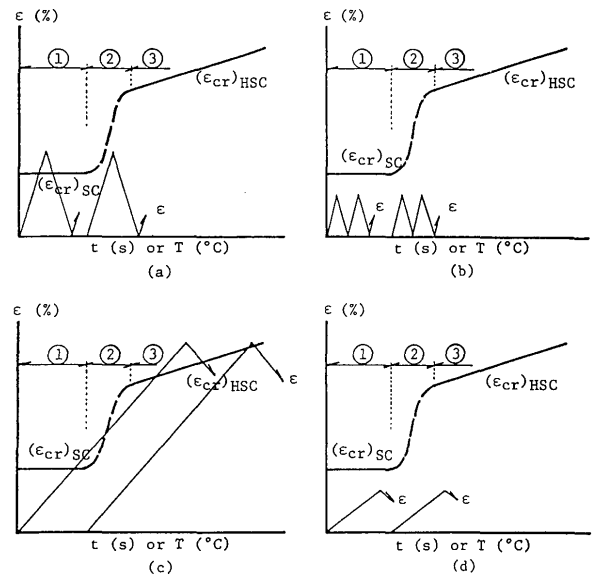


Fig. 6 Critical strain for the hot crack and pattern of strain applying at the weld metal by the external loads.

(Fig.6(a)) although t exceeds $(\epsilon_{cr})_{SC}$. However, only the solidification crack may occur when ϵ does not exceed $(\epsilon_{cr})_{SC}$ and $(\epsilon_{cr})_{HSC}$ (Fig.6(b)) as it is small. That is, it is the case³⁾ when the integrated value of applied strain history exceeds $(\epsilon_{cr})_{SC}$. Next, Fig.6(c) and (d) show the case when the cycle of the applied strain ϵ is long (that is, the frequency is low). The solidification crack and the HS-type crack occur at the same time when the large ϵ applies and exceeds $(\epsilon_{cr})_{SC}$ and $(\epsilon_{cr})_{HSC}$. And only the HS-type crack occurs when ϵ exceeds $(\epsilon_{cr})_{HSC}$ (Fig.6(c)). However, neither the solidification crack nor the HS-type crack occur when the small ϵ applies (Fig.6(d)).

As mentioned above, it is found that the hot crack in the welding under the pulsating loads largely depends on the magnitude of the applied strain and the frequency.

3.3 Main factor of the hot crack initiation

The equation in order to evaluate the solidification crack initiation³⁾ and the HS-type crack one (Eq.(8) in this paper) is rewritten. Then, the main factor for each crack initiation is discussed in mechanics and how to apply the each equation is mentioned.

(1) For the solidification crack³⁾

$$(A_S + B_S \cdot f) \Delta \delta \geq 1 \quad (11)$$

(2) For the HS-type crack

$$(A_Q + B_Q \cdot \Delta \delta) f \geq 1 \quad (12)$$

where,

$$A_S, B_S : \text{constant.}$$

The main factor for the solidification crack initiation is the product of the root gap opening displacement, $\Delta \delta$,

by the external loads and repeated number when the frequency is high and is the magnitude of $\Delta\delta$ when the frequency is low.

On the other hand, concerning the HS-type crack initiation, the main factor is the ratio of the maximum value of the applied strain, ε ($\Delta\delta$ is same) to the time, t , when ε ($\Delta\delta$) in the each cycle becomes the maximum (In Eq.(12), t is expressed by f). That is, the strain rate (the root gap opening rate) is the main factor in mechanics.

Next, how to use the Eqs.(11) and (12) are explained.

The constants, A_S , B_S and A_Q , B_Q , should be obtained to carry out a series of the weld hot cracking test changing the magnitude of $\Delta\delta$ under the pulsating loads selecting two points among any frequency as mentioned in Section 2.4. So, if the constants are decided, from Eqs.(11) and (12), it is possible to evaluate whether the hot crack occurs in the whole frequency range or not. So, as long as Eqs.(11) and (12) are used, it is not necessary to obtain the critical strain in the whole frequency range.

4. Conclusions

This study examined the prevention of the HS-type crack by using the results of the hot cracking test in the welding under the pulsating loads and synthetically considered the hot crack prevention in mechanics. The main results are as follows.

- (1) The equation which describes the initiation of the HS-type crack under the pulsating loads was derived. Based on it, the equation to evaluate the initiation of the HS-type crack was shown, in which relative root gap opening displacement, $\Delta\delta$, that can be easily

measured before the welding was used as a practical measure.

- (2) The practical equation for the HS-type crack prevention was shown in non-dimensional form. Moreover, applying it to the results of the hot cracking test for the case that the uniform pulsating loads are applied, its validity was shown.
- (3) The critical strain for the hot crack initiation of the filler material used in this study was obtained.
- (4) Concerning the solidification crack initiation, the main factor was the product of $\Delta\delta$ by the external loads and repeated number. The main factor for HS-type crack initiation was the maximum strain rate (the maximum root gap opening rate) by the external loads in a cycle.
- (5) The procedure to apply the evaluating equation for the hot crack prevention, that is the solidification crack and the HS-type one, was shown. So far as the equation proposed in this study is used, the critical strain is not necessary to be obtained from a series of the weld hot cracking experiment in the whole frequency range.

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