Fine Intergranular Surface Cracks in Bloom Casting*

By Manfred M. WOLF**

Synopsis

The occurrence of fine intergranular surface cracks is investigated for the case of bloom section 260 × 260 mm cast on a low head curved mold type four strand machine with 8 m radius, based on EAF steel supply. Crack incidence depends on residual elements primarily and can be reduced below critical levels by limiting the Cu content to max. 0.22 %, provided the application of optimized casting conditions.

The latter consist of a casting speed limit at about 1.0 m/min, connected with a minimum mold powder consumption of 0.3 kg/m². Furthermore, high stability of mold level control and pouring stream directed toward the meniscus as well as soft indirect secondary cooling below the mold are also important, and, at low casting speeds, an increased mold taper appears to be beneficial, too.

On the other hand, soft mold cooling by reduced water velocity and increased wall thickness as well as wall plating and also total spray cooling intensity do not show significant effects. Replacement of mold powder by oil lubrication indicates a lesser sensitivity to residual content but is not practical due to occurrence of large depressions. No effect of C-content becomes apparent but increasing Al-content seems to enhance crack susceptibility.

I. Introduction

In bloom casting, the requirements on surface quality are steeply increasing—particularly in view of the application of hot charging in order to save energy. Thus, it is necessary to avoid any surface defects on the as-cast blooms which can not be scaled-off in the reheating furnace.

Longitudinal face cracks and transverse (near-) corner cracks which are the prominent surface defects in slab casting, are of less frequent concern in bloom casting. However, there is one type of surface cracking still persistent which appears as network of fine intergranular cracks (Fig. 1), thus also termed “network” cracks. Such cracks have been described early in literature and originally attributed to copper pick-up from the mold wall2; consequently, mold plating was introduced as a countermeasure. The similarity in the formation mechanism of star cracks in slab casting is thus obvious.

Nevertheless, the cracks were also observed using newly plated molds—although to a lesser extent and, subsequently, attributed to the grain boundary infiltration of Cu and Sn at the surface after preferential oxidation of iron during scaling.3 In accordance with a similar crack mechanism during hot rolling,4,5 such cracks were also termed “hot shortness” cracks; other terms often used are “checking”, “crazing”, “hair”, or “shatter” cracks.

In a fundamental study involving laboratory simulation as well as plant trials6 the following cracking features had been clearly brought about:

i) crack areas show a considerable enrichment in Cu, Ni, Sn and Sb (e.g., Cu-rich phase of 85 % Cu, 5 % Sn, 4 % Ni, 5 % Fe and 1 % Sb);
ii) enhanced crack severity with increasing Cu- and Al-contents;
iii) cracking also increases at higher surface temperatures (e.g., 1 200 °C vs. 1 000 °C), and with increasing impingement density of spray cooling.

The above alloy effects on hot shortness are, of course, particularly relevant in case of EAF-steelmaking with high residual level from poor scrap quality. However, the cracking can also be observed in case of BOF-steel where rather an effect of mold powder behavior was found decisive,7,8 and crack frequency also reduced by mold EMS9; beside a reduction in spray cooling intensity.7-9 The change-over to the air/mist-type spray cooling gave significantly reduced cracking, too.10

The fact that such intergranular cracking can occur also in BOF-steel, i.e., without high residual levels, indicates close similarity with other fine surface cracks but more distinct orientation, i.e., either transverse11 or longitudinal.9,12 The general feature of such cracking is the coincidence with “depressed” surface areas—although sometimes hardly visible by eye and only detectable by a coarser subsurface microstructure. Thus, the beneficial effect of mold plating8 might equally well be explained by a reduced depression frequency owing to the higher wall temperature of plated molds. In this respect, the mold wall thickness may be a further factor, although the cracking has been reported even with plated block molds of 60 mm wall thickness when mold powder selection and strand cooling was not optimized.13

Fig. 1. Network of fine intergranular cracks.

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Research Article (351)
In the present case study, cracking problems became apparent only when a heavier section, i.e., 260×260 mm was introduced for the manufacture of seamless tubes. Thus, an investigation was started considering the factors of known influence as described above.

II. Experimental Procedure

The main caster data are listed in Table 1. For all quality steels like seamless tubes, the submerged pouring technique is applied. Deviating from the smaller sections with chamfered corner geometry, the mold for the large size of 260×260 mm has a corner radius of 20 mm.

The range of casting speed for each size is given in Table 2, together with the spray cooling intensity in Zone I which is assumed to be most decisive for cracking. This figure does not include the cooling in the top zone (Zone IA) which is indirect only, by means of 300 mm long cooling plates of Cu (i.e., "multi stage mold" or, briefly, "MS-mold"). As shown in Fig. 2, these plates are cooled by spray nozzles form behind; no direct cooling of the strand with corner sprays is applied in case of 260×260 mm. In order to check whether cracking might be related to eventual copper pick-up from the plates, several casts were also made with direct spray cooling instead.

The tests comprised 21 heats. The tested parameters and their range are listed in Table 3. All the tests were carried out by casting 260×260 mm on one strand only, with smaller sections simultaneously cast on the other three strands.

Steel superheat in the tundish was maintained mostly between 25°C and 40°C. Regarding steel analysis, Fig. 3 shows that C-content ranged from 0.09 to 0.42 %, and Al-content was between 0.003 % and 0.016 %. The Cu-content went from 0.08 up to 0.48 %, with the corresponding levels of Sn and Ni as illustrated in Fig. 4 (the Sb-analysis was not available). Since intergranular cracking can be enhanced also by the precipitation of (Fe, Mn)–oxysulfides, the Mn/S-ratio is evaluated in both figures, too: they range from 17 to 116, with higher values in the Cu-containing steels.

Table 1. Main caster data.

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bloom caster type</td>
<td>CONCAST Model-S</td>
</tr>
<tr>
<td>Machine radius</td>
<td>8 m</td>
</tr>
<tr>
<td>Strand number</td>
<td>4</td>
</tr>
<tr>
<td>Start-up</td>
<td>1976</td>
</tr>
<tr>
<td>Steel making</td>
<td>EAF</td>
</tr>
<tr>
<td>Ladle</td>
<td>Capacity 120 t</td>
</tr>
<tr>
<td>Metallurgy</td>
<td>Cu-wire feeding</td>
</tr>
<tr>
<td>Rinsing</td>
<td>Lance type</td>
</tr>
<tr>
<td>Lining</td>
<td>Dolomite</td>
</tr>
<tr>
<td>Shroud</td>
<td>Tubular, mechanical</td>
</tr>
<tr>
<td>Tundish</td>
<td>Lining</td>
</tr>
<tr>
<td>Flow control</td>
<td>Metering or slide gate</td>
</tr>
<tr>
<td>Shroud</td>
<td>Open or pouring tube</td>
</tr>
<tr>
<td>Mold</td>
<td>Size 160, 200, 220, 260 mm</td>
</tr>
<tr>
<td>Length</td>
<td>800</td>
</tr>
<tr>
<td>Type</td>
<td>Tubular, tapered Cr-plated</td>
</tr>
<tr>
<td>Level control</td>
<td>Automatic (Co)</td>
</tr>
<tr>
<td>Strand guide</td>
<td>Support</td>
</tr>
<tr>
<td></td>
<td>Top zone cooling plate</td>
</tr>
<tr>
<td></td>
<td>(&quot;MS-mold&quot;)</td>
</tr>
<tr>
<td></td>
<td>Spray length 8.3 m</td>
</tr>
<tr>
<td></td>
<td>One-point</td>
</tr>
<tr>
<td>Dummy bar head</td>
<td>Permanent claw type</td>
</tr>
</tbody>
</table>

Table 2. Section sizes, casting speed and spray cooling intensity in Zone IB.

<table>
<thead>
<tr>
<th>Section (mm)</th>
<th>Casting speed (m/min)</th>
<th>(I_\text{v}^*) (10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>maximum</td>
</tr>
<tr>
<td>160×160</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>200×200</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>220×220</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>260×260</td>
<td>0.85</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(I_\text{v}^* = W/(P \cdot L \cdot V_\text{c}) = L = 1.3 \text{ m}\)

Table 3. Range of test conditions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casting speed (m/min)</td>
<td>0.8~1.4</td>
</tr>
<tr>
<td>Mold powder (--)</td>
<td>6 types</td>
</tr>
<tr>
<td>Pouring tube (--)</td>
<td>Straight; four hole</td>
</tr>
<tr>
<td>Oscillation frequency (rpm)</td>
<td>60; 120</td>
</tr>
<tr>
<td>Oscillation stroke (mm)</td>
<td>12; 6</td>
</tr>
<tr>
<td>Mold water velocity (m/s)</td>
<td>5.5; 3.4; 2.5</td>
</tr>
<tr>
<td>Mold wall thickness (mm)</td>
<td>18; 27</td>
</tr>
<tr>
<td>Cr-plating thickness (mm)</td>
<td>0.1; 0.6; 0.9</td>
</tr>
<tr>
<td>Top zone cooling (--)</td>
<td>Plates; sprays</td>
</tr>
<tr>
<td>Total spray cooling (l/kg)</td>
<td>0.2~1.2</td>
</tr>
</tbody>
</table>

Fig. 2 Sketch of mold and top zone cooling plates ("MS-mold").
values for the medium carbon steels around 0.2 % C (Fig. 3). There is also a tendency to lower values with increasing Cu-content (Fig. 4) but the scatter too wide for a meaningful correlation.

For the evaluation of crack severity, a sample slice was cut from each bloom (bloom length about 5 m) and etched in 20 % hydrochloric acid in order to remove scale and reveal eventual intergranular cracking. The severity was rated based on standard samples with the grades from 0 to 4 (0 = no cracks, 4 = strong network of cracks up to 2 mm deep). This was performed for all four faces of every slice independently. Furthermore, also the defect location, i.e., corner, off-corner and mid-face was monitored.

Despite the substantial amount of defect readings (N ~ 400) a proper multiple regression analysis could not be performed in view of the many variables involved. Thus, the evaluation had to be based rather on mean value comparison which yields not more than a "trend analysis" and semi-quantitative correlations at the most.

III. Test Results

In the first test casts, efforts concentrated on the optimization of secondary cooling. Then, further attention was focused on the mold area. In both respects, alloy effects were given due consideration.

1. Effects of Secondary Cooling

In the first tests, direct spray cooling was applied in Zone IA instead of the cooling plates in order to check whether copper pick-up from this support system would be a factor. Thus, only 0.1 l/kg was applied in the top zone to match the soft intensity of the indirect plate cooling, and 0.3 l/kg for the total secondary cooling. As indicated by the results in Fig. 5, the average crack indices of 1.30 and 1.33 for plates and sprays respectively are virtually identical.

During these tests, differences in the preferred defect position could be observed. Table 4 shows the relative frequency of defect location, i.e., how frequently defects were observed at corner, off-corner and mid-face location for the slices checked. As can be seen, the mid-face location is distinctly less plagued by defects in case of the cooling plates, thus, copper pick-up might be ruled out. Rather the corner and off-corner regions are the preferred crack locations for both cases, in case of direct cooling.

![Fig. 3](image3.png)

**Fig. 3.** Range of C- and total Al-contents as well as Mn/S ratio for the test heats.

![Fig. 4](image4.png)

**Fig. 4.** Range of Cu-, Sn- and Ni-contents as well as Mn/S ratio for the test heats.

![Fig. 5](image5.png)

**Fig. 5.** Crack index vs. mode of top zone cooling.

<table>
<thead>
<tr>
<th>Cracks</th>
<th>Corner</th>
<th>Off-corner</th>
<th>Mid-face</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plates</td>
<td>84</td>
<td>84</td>
<td>42</td>
</tr>
<tr>
<td>Sprays</td>
<td>73</td>
<td>79</td>
<td>78</td>
</tr>
</tbody>
</table>
equally the mid-face position. The reasons are not immediately evident but the coincidence of cracking with surface depressions was clear in many instances.

In further tests with direct cooling by spray nozzles, total spray cooling intensity was varied within a relative wide range (Fig. 6). Nevertheless, the defect index does not indicate any clear trend under the test conditions applied: while the curve for powder C reflects the expected trend, the one for powder B would just give the inverse dependence. Thus, other factors must be more important to defect formation. Nevertheless, spray cooling intensity in Zone IB and II was maintained at a low level down to 0.2 l/kg in total, to realize a high strand surface temperature up to 1030 °C at straightening. This also provided adequate safety against transverse crack formation. In this context, the crack index was evaluated independently for each face in order to find out whether the straightening action would enhance the cracking incidence. As can be seen from Table 5, the outer radial side (fixed side) shows the lowest average crack index which may be due to the compressive surface stresses during straightening, although the effect does not appear to be very significant.

From these comparative trials, the beneficial effects of cooling plates on strand containment became clearly apparent (Table 6). Allowing up to 5 mm side bulging—which is at least permissible for lower carbon steels to prevent interdendritic cracks—, the critical casting speed is nearly 1.3 m/min for the plates whereas for sprays the limit is 1.0 m/min for lower and 1.1 m/min for higher cooling intensity. Of course, the best strand support is provided by a rigid roller apron but, necessarily, also more expensive. Consequently, the cooling plates have been maintained on all further test conditions.

2. Mold Effects

In earlier tests, deep oscillation marks have led to a preferentially transverse course of cracking which was aggravated particularly in case of low carbon contents, i.e., around 0.1% C. Such cracking largely disappeared when the oscillation frequency was increased to the maximum of 120 cpm.

The main attention was devoted to the selection of mold powders, and also to the uniformity in (manual) distribution. Mold powder consumption was monitored, too. Mold powder performance was mainly judged by the appearance in general. In this respect, powder A gave consistently the most favorable results—at least up to a casting speed of about 1.0 m/min which coincides with a minimum permissible powder consumption in the order of 0.3 kg/m² (Fig. 7). The data for powder A bring about also a quite a clear relationship between crack index and Cu-content as shown in Fig. 8. Powder A has a viscosity of 7.5 poise at 1300 °C and the
typical composition of 29 % CaO, 33 % SiO₂, 16 %
Al₂O₃, 6 % F and 5 % Na₂O.

Several control tests performed with oil instead of
slag lubrication gave quite low defect incidences,
particularly the ones performed with a thick wall
tubular mold (Fig. 9). However, at the same time
several deep transverse face depressions were ob-
served which present a potential hazard to breakout
safety. Thus, oil lubrication is not a practical solu-
tion for large blooms—even when applying a gas
shroud for maintaining high steel cleanness. The
tests with reduced mold water velocity (Fig. 10)
gave no clear trend. Also the tests with increased
thickness of the Cr-plating (Fig. 11) did not show
any significant improvement.

Some rather adverse results in the latter test, even
with low Cu-content of only 0.15 %, were found at-
tributable to the rare occurrence of rhombic bloom
deformation with 3.4 and 4.5 % (Fig. 12) whereas
the usual conditions being only 0.6 % in the average,
and 1.0 % for sprays respectively 0.9 % for plates
as maximum values. On the rhombic blooms, the
main defect occurrence was found indeed on the
obtuse corners which points to the important effect
of local cooling rate as function of strand/mold-contact
intensity. The latter context may also explain the
beneficial effect of mold taper (Fig. 13) although any
change in bloom geometry was not obvious at the
standard conditions, already characterized by low
values of rhomboidity as well as side bulging (Table 6).

The final tests of this investigation were devoted
to optimized pouring stream configuration in re-
placing the straight tube by one with lateral orifices.

This measure resulted in substantial improvement as
illustrated by Fig. 14.

3. Effects of Steel Composition

The effect of C-content is evaluated in Fig. 15,
with no apparent influence. On the other hand, the
Al-content in Fig. 16 shows some increase in cracking
incidence at higher levels.

As indicated in Fig. 3 already, the higher Al-
content applies more to steels with higher C-content
which, therefore, should render the latter more crack
sensitive. However, this steel group is, on the other
hand, characterized by a lower Cu-content and also
a higher Mn/S-ratio which both may compensate
the unfavorable effect of the increased Al-content,
although the effect of Mn/S-ratio does not appear to
be very significant when comparing the crack indices
for the second and third range of C-content in Fig.
15 under the largely identical conditions of Cu- and
Al-content as listed in Table 7. But, at least the
inverse correlation of Cu- and Al-content can provide
a valid explanation why no effect of C-content is
apparent in the present case.

IV. Discussion

Owing to the preferred crack location in depressed
surface regions, this aspect will be discussed first.

1. Shell Contraction and Depression Formation

Depression formation of the strand shell in the
mold is a very complex phenomenon. Basically the

Fig. 9. Crack index as function of Cu-content
for oil lubrication and two different
wall thicknesses of the tubular mold.

Fig. 11. Crack index as function of mold
water velocity for two mold powders.

Fig. 12. Crack index and rhombic
deforation.

Fig. 13. Crack index , mold taper.

Fig. 14. Crack index vs. pouring tube
gometry.
strand shell contracts in more or less regular intervals whenever the compounded effect of shell thickness and shell strength has reached an extent where the shell is able to detach from the mold wall against the action of the ferrostatic pressure. Consequently, "soft" mold cooling with controlled heat flux is necessary in particular for shrinkage-sensitive steel grades to avoid this very undesirable "buckling" effect. Therefore, it is important to reduce initial shell growth. For instance, in static casting experiments a $K$-factor of about 12 mm/min°5 was derived as a critical threshold. Assuming the order of 25 mm as typical buckling distance, the section 260 X 260 mm would indicate a shell thickness exceeding 1.6 mm as being critical since depressions and cracking were observed even on the blooms cast at 1.4 m/min.

In order to reduce the initial shell thickness in favor of greater growth uniformity and avoidance of depressions, the optimized casting conditions are listed in Table 8. Regarding the comparatively enhanced crack incidence on 260 X 260 mm as compared to the smaller sizes, the higher casting speed appears to be the most prominent factor in favor of the latter ones.

As cracking is most frequently observed in the corner region, this must be attributed to enhanced contraction at the large corner radius of 20 mm in case of 260 x 260 mm whereas the smaller sections being cast with a chamfered corner. Thus, a change to the latter configuration should be contemplated, too, since its positive effect on shell growth uniformity has been empirically established from the experience of several other casters.

Table 7. Average Cu- and total Al-contents as well as Mn/S-ratio for three groups of C-content in case of heats cast with powder A and cooling plates at max. 1.0 m/min.

<table>
<thead>
<tr>
<th>C-content (%)</th>
<th>0.08~0.12</th>
<th>0.13~0.25</th>
<th>over 0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-content (%)</td>
<td>0.26</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>Al-content (%)</td>
<td>0.006</td>
<td>0.010</td>
<td>0.012</td>
</tr>
<tr>
<td>Mn/S-ratio (--)</td>
<td>40</td>
<td>78</td>
<td>17</td>
</tr>
<tr>
<td>($\lambda$) (--)</td>
<td>(6)</td>
<td>(4)</td>
<td>(1)</td>
</tr>
</tbody>
</table>

Table 8. Optimized casting conditions for 260 x 260 mm to reduce intergranular crack occurrence.

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Steel superheat</td>
<td>25~40 (°C)</td>
</tr>
<tr>
<td>2) Casting speed</td>
<td>max. 1.0 (m/min)</td>
</tr>
<tr>
<td>3) Mold level stability</td>
<td>+/− 5 (mm)</td>
</tr>
<tr>
<td>4) Mold powder consumption*</td>
<td>min. 0.3 (kg/m²)</td>
</tr>
<tr>
<td>5) Pouring tube</td>
<td>four hole (−)</td>
</tr>
<tr>
<td>6) Mold taper</td>
<td>1.15 (%/m)</td>
</tr>
<tr>
<td>7) Strand cooling below mold</td>
<td>&quot;MS-mold&quot; without corner sprays (−)</td>
</tr>
<tr>
<td>8) Cooling intensity Zone 1B</td>
<td>0.2 (l/kg)</td>
</tr>
<tr>
<td>9) Strand surface temperature**</td>
<td>min. 950 (°C)</td>
</tr>
</tbody>
</table>

* Powder A
** At unbending point

2. Structural Effects and Crack Mechanism

As a consequence of depression formation, the solidification structure undergoes local coarsening, which leads to enhanced crack sensitivity as already outlined in previous work. Furthermore, a coarse solidification structure also increases grain size of the subsequent transformation structure (Fig. 17). Upon enrichment of residuals during scaling, local concentration reaches critical levels earlier if grain boundary extension is reduced by coarse grain diameter. Thus, the necessary precondition for crack formation is—under given conditions of residual content and other casting parameters—a certain critical grain diameter.

Of course, the real defect formation is more complex since also the extent of scaling being of influence. For instance, scale formation is found to be about three-times as high for a 0.1% C-steel when compared with a 0.7% C-steel; on the other hand, a maximum of network cracking at 0.25% C was reported in the same work. This was explained with the critical surface temperature of around 1 100 °C at mold exit for the latter steel group whereas lower C-steels (with close to 1 200 °C) would give less residual concentration owing to more rapid diffusion along grain boundaries. Diffusion rate is thus important for critical residual enrichment, and the critical temperature range generally found to be between 950 °C and 1 150 °C. From the above, one might conclude that a soft
spray cooling intensity leading to high strand surface temperatures could be deleterious—as also shown by laboratory simulation. However, strong cooling raises the thermal stress level and also may, at a given surface temperature, enhance total scaling by continually removing newly formed scale.

A further negative effect of strong secondary cooling, particularly observed in case of BOF-steels with low residual content can be the additional embrittlement due to precipitation formed by microalloys (Al, Nb, V, B) in connection with reduced surface temperature as well as strong thermal cycling. This probably may lead to a combined effect of region II- and III-embrittlement for network cracking—as illustrated in Fig. 18, and with the following consequences to the formation of surface cracks in general:

(1) Region I mostly concerns steels with strong segregation tendency (high C-steels and fully austenitic stainless grades in the first place), and crack formation of intergranular nature (rather than interdendritic) since microsegregation being highest at locations of mismatch in dendrite orientation, although this effect can be blurred by subsequent grain boundary migration away from its original position during cooling.27,28

(2) Region II is either caused by Cu/Sn/Sb-enrichment or (Fe, Mn) S-0 precipitated along grain boundaries whereby a critical minimum grain diameter is required, usually resulting as a consequence of coarse primary structure.

(3) Region III results from precipitations of microalloys (AlN, Nb(C, N), BN) enhanced by proeutectoid ferrite formation where solubility of precipitates is distinctively lower in ferrite, and also by coarse austenite grain size. Consequently, longitudinal cracks may form either in region I or II, depending on steel type which deviates from the generally assumed preference for region I.12,29 Star and network cracks are predominantly forming in region II, and transverse cracks in region III but mutual overlapping into regions II and III appears to be also possible. However, it is not excluded that the very initiation of microcracks would coincide with region I for all types of surface cracks—in connection with coarse solidification structure and enhanced microsegregation formed in depressed surface areas.

V. Conclusion

(1) The formation of fine intergranular surface cracks in bloom casting is strongly affected by the residual content but, like in case of star cracks, not a necessary precondition.

(2) Rather, the main precondition for crack formation appears to be a coarse microstructure leading to critical concentrations of segregated solutes and/or precipitates along austenite grain boundaries.

(3) Consequently, in order to assure best surface quality, the aim of a fine solidification structure is of highest priority, achievable by maximum uniformity in the initial shell growth and avoidance of depression formation. All other measures, in particular a soft spray cooling intensity, are of secondary importance only.

Nomenclature

I_s: relative spray cooling intensity (10^-3)
I_w: specific spray water consumption (l/kg)
L: length of spray cooling (m)
P: width of spray cooling (m)
Q: mold powder consumption (kg/m²)
V_c: casting speed (m/min)
V_w: mold water velocity (m/s)
W: spray water flow rate (m³/min)

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