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Casting simulation of cast steel joint based on Pro-CAST

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Abstract. The casting process is usually divided into five steps of melting, molding, casting, heat treatment and testing. This paper focuses on the two stages of casting and quality inspection of a casting process for a cast steel joint in actual engineering. Studies have shown that the sharp change or improper arrangement of the sections of cast steel joints will make certain areas more likely to produce defects than other areas, and these areas are often complex stress locations when they are in service, which leads to “risk-on-risk”. So both structural design and process design should pay attention to these issues. The analysis results show that ultrasonic flaw detection can detect casting defects but cannot be quasi-deterministic. The setting of riser and cold iron plays a key role in casting quality. The design of riser has a great influence on the generation and distribution of casting defects.

1. Introduction

With the development of the spatial structure, the span of the structure is getting larger and larger, and the form is correspondingly increased. The continuous emergence of new structural systems has made the connection between the components and the components in the structure increasingly complicated. Traditional joints such as welded ball joints and steel pipe joints have been unable to adapt to the development of modern steel structures. In foreign countries, especially in developed countries such as Japan and Germany, cast steel joints have been very widely adopted. In China, the cast steel node has gradually gained recognition and understanding from the domestic engineering community and triggered a boom in engineering applications. However, due to the large volume of the cast steel joints, there are inevitable casting defects such as porosity, shrinkage, slag inclusion, cracks, etc., which affect the quality of the cast steel joints and may seriously threaten the structural safety. The choice of production process plays a decisive role in casting quality.

2. Introduction to experimental materials

The castings uses cast steel joints produced by Yongyi Cast Pipes Company. The material composition table is shown in Table 1. The modeling parameters are shown in Figure 1.

Table 1. Chemical composition of Gs-20Mn5V cast steel joint:

| element (%) | C | Mn | Si | S | P | Ni |
|-------------|-----------|-----------|-------|--------|--------|-------|
| require | 0.17~0.23 | 1.00~1.60 | ≤0.60 | ≤0.020 | ≤0.020 | ≤0.80 |



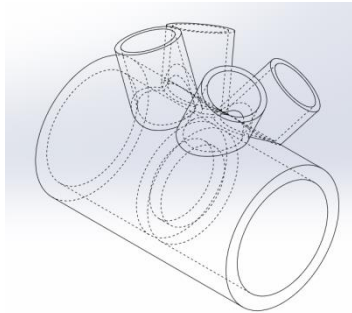


Figure 1. Cast steel joint shape

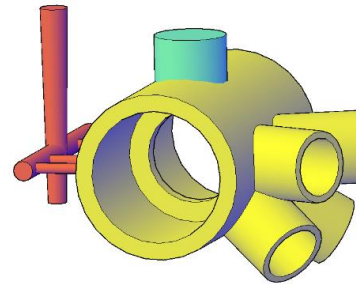


Figure 2. The pouring system

3. Numerical simulation of solidification process^[1]

3.1. Boundary conditions and parameter settings

The casting method, casting speed and pouring time are determined by the actual casting process. The cast steel material uses Pro-CAST's own material database. The Scheil–Gulliver model is used to calculate the thermal property parameters of the alloy through software^[2]. The casting temperature is set to 1560°C, the casting speed is 40 kg/s, the heat transfer coefficient of the casting and the silica sand type is set to 500 W/(m²·K), the heat exchange coefficient of the casting and the cold iron is 2000 W/(m²·K), the heat exchange coefficient of the sand type and the air is 10 W/(m²·K), and the cooling method is by air cooling. The casting method is sand gravity casting, and the riser adopts a 120mm high cylindrical riser.

3.2. Simulation results and analysis^[3]

The casting molding process includes the casting filling process and the casting solidification process. The filling process is a process in which a high-temperature fluid gradually fills a casting cavity through a gate, and the solidification process of the casting is essentially a heat exchange process between heats. Heat exchange mainly includes three processes, heat conduction, heat convection and heat radiation. The simulation of the solidification process includes the heat transfer of the casting and the flask, the thermal convection of the casting and the air, and the thermal radiation of the liquid in the casting^[4]. As shown in the figure, the temperature field changes during the solidification of the steel casting.

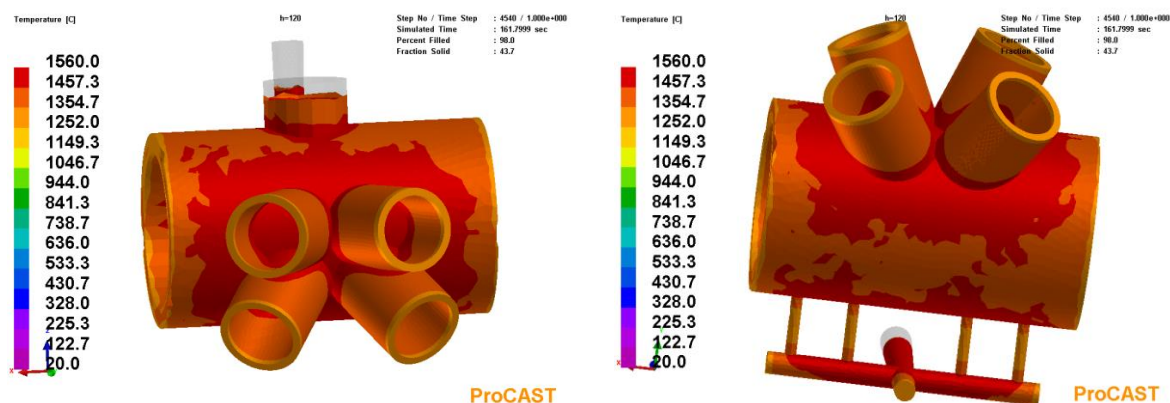
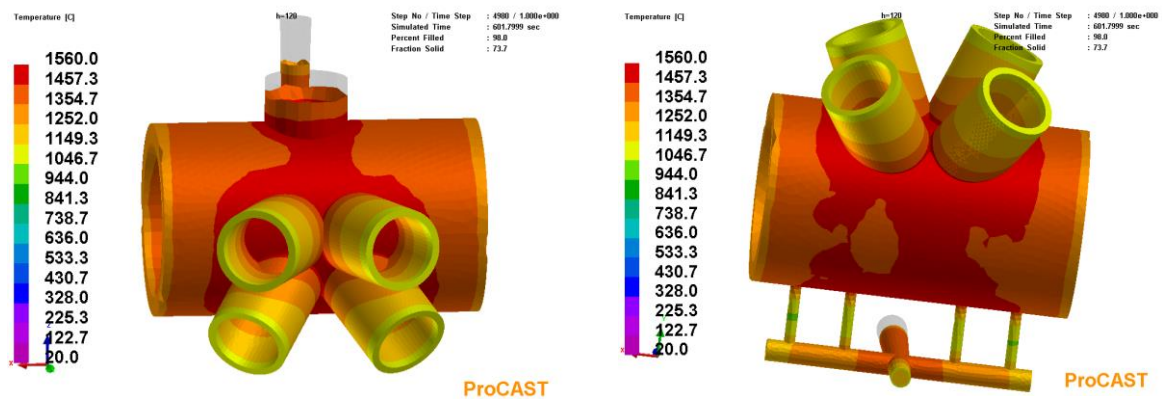
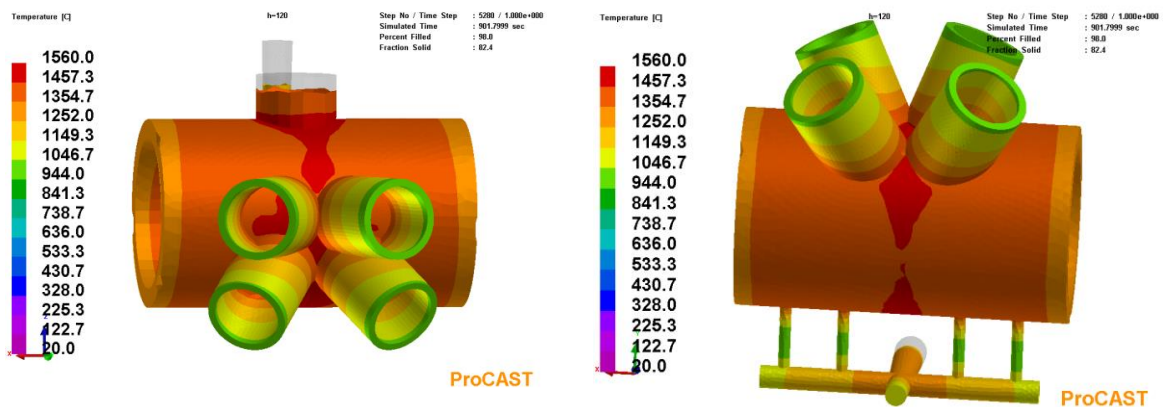
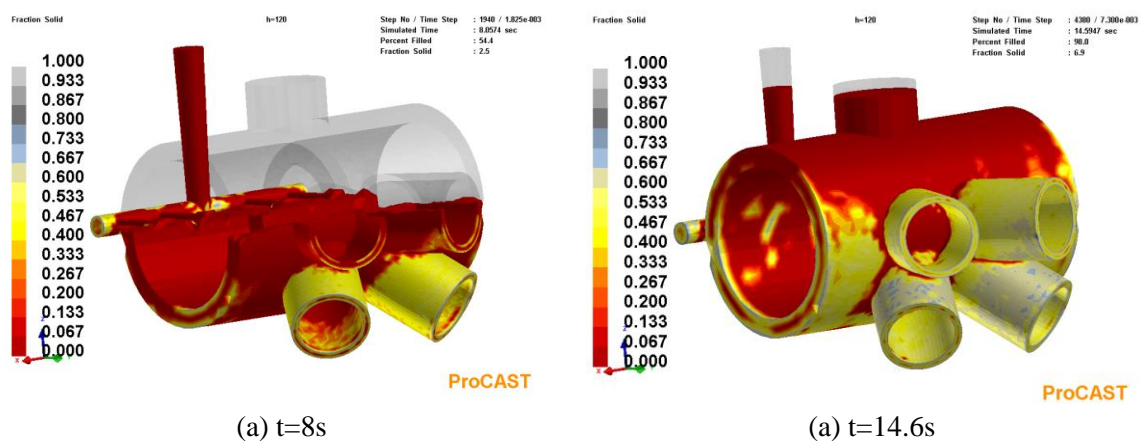


Figure 3. Temperature field distribution of casting during solidification at t=160s

Figure 4. Temperature field distribution of casting during solidification at $t=600s$ Figure 5. Temperature field distribution of casting during solidification at $t=900s$ (a) $t=8s$ (a) $t=14.6s$

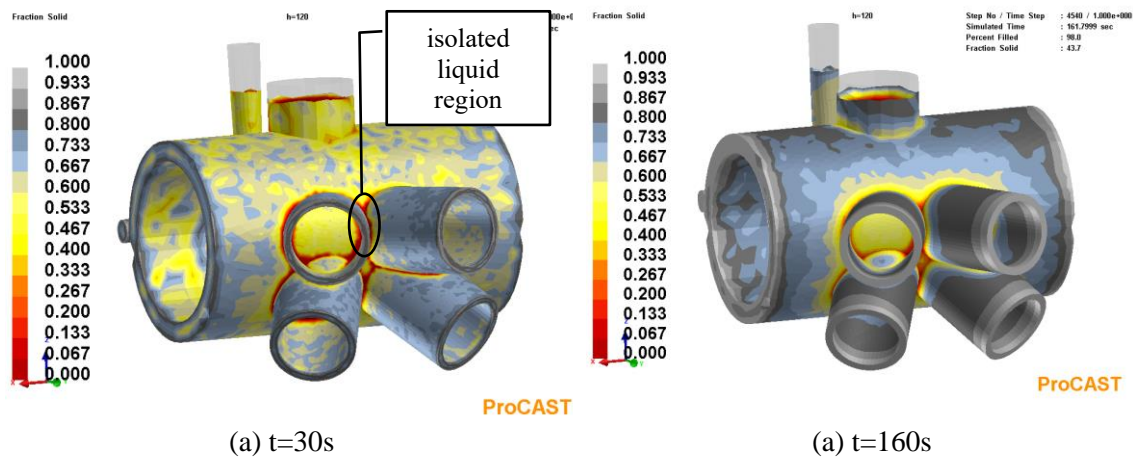


Figure 6. Casting solid phase rate change diagram (t=8/14.6/30/160s)

Figure 7 shows the time distribution of various parts filled with molten metal. At the beginning, the molten metal fills the bottom of the casting cavity under gravity, so the slowest cooling is also the part. In engineering practice, we can actually at the bottom. To add a few pieces of internal cold iron to speed up the cooling of the bottom, because this part of the cooling is difficult to shrink and it is easy to produce shrinkage defects. It has also been found through casting simulation that a liquid phase closed zone is easily formed at the intersection of the branch pipes, and defects are easily generated.

For a better understanding of temperature and solid-phase rate volume fraction near the branch pipe during solidification, three points are selected along the axial direction on the branch pipe. Point A is taken from pipe mouth, point B is taken from the middle of tube, point C is taken from tube root.

The temperature and solid-phase rate volume fraction are obtained by post-processing module. The curves have shown in Fig. 7-8.

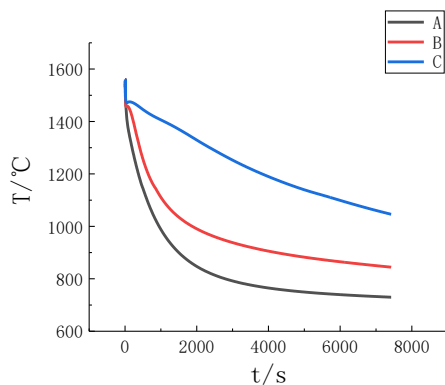


Figure 7. Temperature versus time

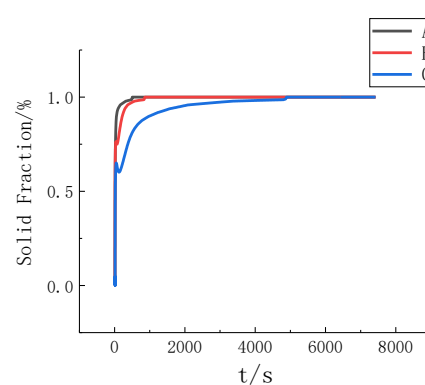


Figure 8. Solid phase rate versus time

The data in the figure shows that the initial stage of solidification is very fast, the solidification rate becomes slower and slower with time, and finally solidifies completely. However, the temperature drop rate in the root region of the branch pipe is slow, and the solidification speed is also slow, and various defects may occur in this portion. As the temperature decreases, the strength and stiffness of the earlier portion of the cooling gradually increase. As the temperature decreases, the part near the root of the slower branching tube begins to produce large deformation and shrinkage. At this time, the part of the earlier cooling part has greater strength and rigidity, and the deformation and contraction near the intersection line is more resistant. It is possible to form a large stress and form a crack^[5]. The castings are detected by magnetic particle inspection at the root of the branch pipe, which is in agreement with the actual situation.

3.3. Niyama criterion for castings

The flow of metal liquid, casting system and other factors will have an impact on the defects of castings. However, due to the full consideration of all factors, the simulation process is complicated, the efficiency is low, and the heat transfer phenomenon is the main cause of shrinkage. Therefore, researchers from various countries have proposed several effective prediction criteria from the perspective of heat transfer, which are mainly based on time, temperature, solid phase rate and flow. There are temperature gradient method, solid phase rate gradient method, Niyama criterion method, etc.^[6] The Niyama criterion is also generally used for the prediction of cast steel defects. Niyama's research shows that the ratio of the temperature gradient G at the end of solidification of the casting to the quadratic root of the cooling rate R is a function that best reflects the internal shrinkage and shrinkage distribution of the casting. When the value is less than a certain critical value, shrinkage cavities and shrinkage defects are generated in the region, and the critical value is independent of the alloy composition and the shape and size of the casting^[6]. According to the Niyama criterion formula:

$$\frac{G}{\sqrt{R}} \leq C_{Niyama} (^{\circ}\text{C}^{0.5} \text{min}^{0.5} \text{cm}^{-1})$$

For the Niyama criterion of steel castings, the value is generally 0.8-1.

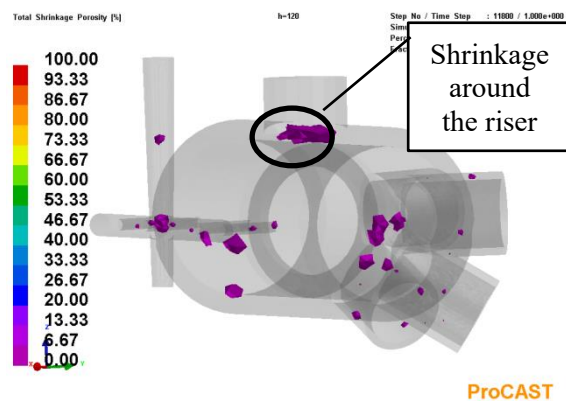


Figure 9. Shrinkage prediction

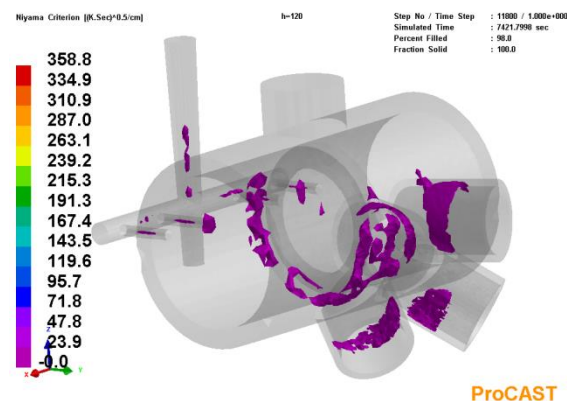


Figure 10. Niyama Shrinkage prediction

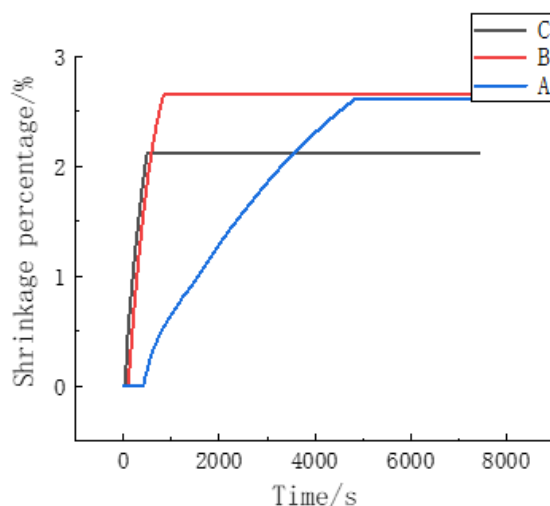


Figure 11. Shrinkage rate versus time

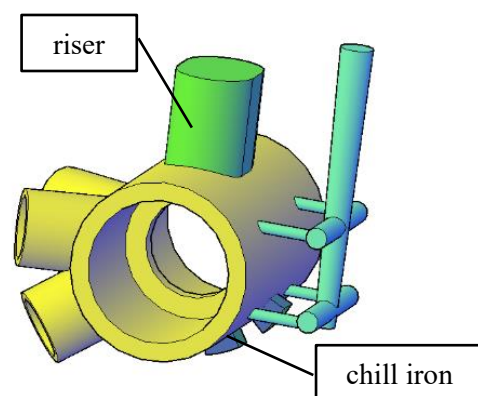


Figure 12. Improved casting process

The critical value of the Niyama criterion is affected by the number of grids, the shape of the casting, and the type of alloy. The critical value needs to be determined according to actual tests. It can be seen

from Figure 10 that the shrinkage cavity, shrinkage porosity obtained by the Niyama criterion are concentrated at the center of the casting, while ignoring the existence of shrinkage cavities and shrinkage defects at other positions (the center of the riser and the root), so it has certain limitations^[7]. It can be seen from the casting simulation results that the riser of the cast steel node is seriously insufficient, and the riser shrinkage is generated, and the branch pipes has a higher probability of shrinkage.

4. Non-destructive inspection of castings

Non-destructive testing of castings includes ultrasonic testing, magnetic particle testing, and penetrant testing^[8]. The main applications of marine steel castings and cast steel joints are ultrasonic testing and magnetic particle testing. The cast steel mill will carry out zone inspection of the cast steel joint according to the requirements of the design institute. For example, sometimes the cast steel joint branch will be required to carry out ultrasonic flaw detection near the weld affected zone and other parts will be magnetically powdered. Ultrasonic testing was performed on the cast steel joints with more casting defects. The flaw detection instrument uses the PXUT-320C digital ultrasonic flaw detector. The probe uses a longitudinal wave dual crystal probe with a frequency of 2.5Hz. The standard of flaw detection used is GB/T7233.1-2009.

Ultrasonic non-destructive testing technology is used to obtain the ultrasonic image of internal defects of a typical quadrilateral cast steel joint, and try to judge the defect type according to the waveform diagram. It is found that the defects of the cast steel joint are serious, and a serious large-area shrinkage defect occurs near the riser. Cracks appear in the intersection of the main pipe and the branch pipe, and shrinkage defects appear below the stiffener. Ultrasonic flaw detection is highly dependent on the experience of flaw detection, and subjectivity is relatively large, but the results of the simulation are basically verified. Cracks were also found on the main pipe at the root of the branch pipe.

5. Improved scheme and simulation results

The results of the casting simulation show that the old cylindrical riser has insufficient shrinkage capability, and the process is improved. The height of riser is changed to 285mm, and the inner cold iron is added to the lower part of the casting. The improved scheme is shown in Fig. 12. The shrinkage prediction is shown in Fig. 13-14.

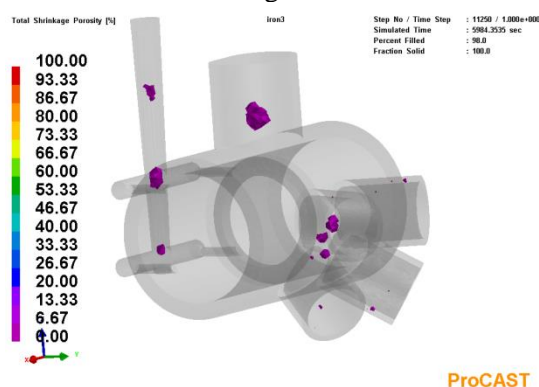


Figure 13. Shrinkage prediction

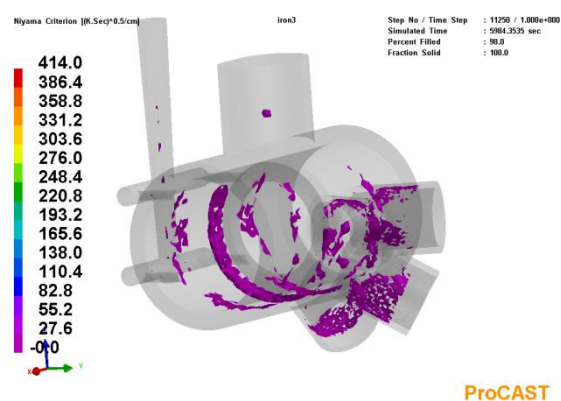


Figure 14. Niyama Shrinkage prediction

Through the improvement process, it can be found that the shrinkage defect of the riser has been greatly reduced, the shrinkage near the riser has been transferred to the inside of the riser, and the shrinkage defect at the bottom is also reduced, and the defect of the branch pipe still exists. Through the casting simulation, it can be found that although the casting defects are random but not completely unacceptable, the Pro-CAST casting simulation software can reflect the actual situation of the casting quality and the distribution of the defects to some extent through the comparison between the casting simulation and the actual flaw detection. As far as the cast steel joint is concerned, there are many defects near the intersecting line and at the branch pipe, which should be the focus area.

6. Conclusion

The Pro-CAST software is used to simulate casting of a quadruple cast steel joint. The conclusions obtained are as follows:

1. Through the casting simulation, it is found that the casting process has a great influence on the quality of the cast steel parts, but the casting quality is sensitive to the setting of the cold iron and the riser, so the correct setting of the riser and the cold iron is very important. The riser is a relatively solidified area in the entire system and can serve as a complement to the casting. The setting of the riser plays a key role in the casting effect, and the design of the riser has a greater impact on the generation and distribution of defects.

2. The problem of casting defects is mainly to face shrinkage and hot and cracks, if the casting process can reduce these two problems, the quality of castings can be guaranteed. The design of the cast steel joint is actually unreasonable, and the branch pipe is very dense and unreasonable, which makes it easy to produce casting defects in this part of the intersecting area.

3. The results of the casting simulation can be matched to the actual situation to a certain extent, and the casting simulation software can be used to guide the casting production.

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