

Low alloy steel versus ADI – differences and similarities

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Summary

The results of comparison between the microstructure of selected bainitic low alloy steel and austempered ductile iron ADI are presented. The aim of the comparison was to find out differences and similarities existing in these iron carbon commercial alloys. In this paper our own results on ADI structure and literature data were used. It follows from discussion presented here that both microstructure and properties of ADI are very close that which are observed in low alloy carbon steel. Moreover, we suggest that there is no so doubt to treat ADI mechanical properties as steel containing nodular inclusions of graphite.

Key words: ADI; Low alloy steel; Structure; Difference; Similarities.

1. Introduction

There is no doubt for the foundryman that austempered ductile iron (ADI) is probably one of the most outstanding achievements in iron-carbon metallurgy. In last years, it has been tremendous interest in processing and development of ADI [1-4]. The excellent combination of strength, wear resistance and toughness make ADI concurrent material for wide variety of applications in automotive, rail and heavy engineering industries [5-7]. Although it will take some time before designers accept this relative new structural material but commercial use of different grades ADI is continually increasing. The unique mechanical properties of ADI resulted from its specific microstructure consisting of carbon stabilized retained austenite and bainitic ferrite. This microstructure, called often ausferrite, during specific two step heat treatment including austenitization [8] followed by isothermal quenching at selected temperature. Temperature of

austenitization controlling the carbon concentration in austenite is about 850 – 950°C while temperature of isothermal quenching lies in a range 250 – 450°C. After quenching which, depending on temperature, takes 1 to 3 hours, the castings are cooled to room temperature. The choice of the austempering time for given temperature is critical, because the process should stop within so called “*processing window*”[4,8,9] to allow bainitic ferrite to maximize but before the carbides start to form. Except mixture of bainitic ferrite and retained carbon supersaturated austenite some amount of martensite forms. It appears mainly in low temperature austempered, high strength ductile iron where high wear resistance is needed and where its relative small amount can be tolerated. There is one thing we forget and which for sure should be taken into account. We must remember that isothermal quenching is from many years applied to steel. This isothermal heat treatment lead to formation of bainite, which “*is a eutectoid transformation product of ferrite and a fine dispersion of carbide*”

generally formed below 450 to 500°C (840 to 930°F). Upper bainite is an aggregate that contains parallel lath-shape units of ferrite, produces the so-called “feathery” appearance in optical microscopy, and is formed above approximately 350°C (660°F). Lower bainite, which has an acicular appearance similar to tempered martensite, is formed below approximately 350°C (660°F)” [10]. It should be added that in upper bainite fine dispersed carbides are located at the ferrite grain boundaries while in lower bainite these fine dispersed carbides occupy interior of bainitic ferrite. This “definition” of bainite was given to underline that it is two-phase microstructure resulted by means of very short distance diffusion of carbon in metal matrix. More and more frequently we meet the term bainite used for description of ADI microstructure¹ resulted during isothermal quenching of ductile iron. As was stated above ADI matrix is a mixture of ferrite and carbon supersaturated austenite.

Recently isothermal quenching is used also to low alloy steel with higher silicon content to produce carbide free bainite [10]. These steels denoted as TRIP because of Transformation Induced Plasticity effect during loading are more and more frequently used in automotive industry [11, 12]. The microstructure of TRIP steel consists of bainitic ferrite and some amount of retained austenite and is very similar to ADI matrix microstructure [13]. The quenching procedure is also very similar. So it would be very interesting to compare both microstructures to see the similarities or differences between them.

2. Experimental procedure

For comparison of ADI matrix microstructure with “bainitic” steel microstructure the low alloy steel described in paper of Caballero and all [11], devoted to design of advanced bainitic steel was selected. In their paper two middle carbon (0.29-0.31%C) low alloy steel were studied. The relative high Si concentration was used to prevent cementite precipitation during bainite formation. Moreover some amount of Ni, V and Cr was used for hardenability and 0.25%Mo to prevent temper embrittlement and Mo. The temperature of isothermal quenching for these steels was approximately 500°C. Details of experiment are given in [11]. It should be mentioned however, that as other high strength exhibiting TRIP effect steels, steel used for comparison was thermo-mechanically treated to produce fine grain microstructure.

For comparison the authors results obtained for ADI in last years were used. In those studies commercial 500-07 grade ductile iron was solution heat treated 1h at 900°C and then isothermally quenched. The temperature and time of quenching were different, depending on the microstructure of ADI we would like to produce. Because we decided to compare steel with ADI mostly from point o view of their structure, light metallography, scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were employed. Details concerning the preparation of the specimen for metallography and TEM observations were given elsewhere [14, 15].

¹ Similar inconsequence appear in other cases, eg. eutectic grain, although in physical metallurgy the grain denote one-phase region.

2. Results

2.1. Metallography

Fig.1 illustrate example of typical microstructure ductile iron after 90 minutes isothermal quenching at the temperature 350°C.

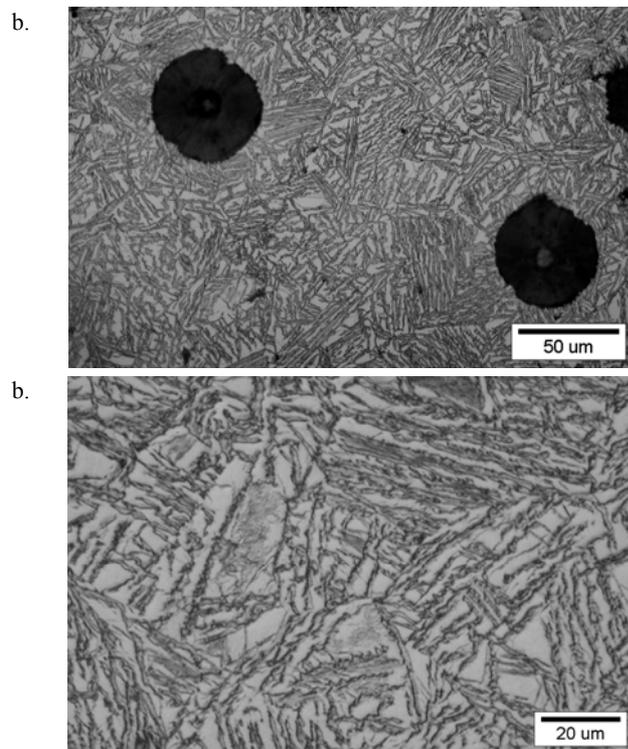


Fig.1. The microstructure of ductile iron 90 min. isothermally quenched at temperature 350°C: a – x500, b – x1500 [16]

It is very easy to see that the matrix consists of mixture of bainitic ferrite and carbon stabilized austenite. In micrograph the gray needles of ferrite are embedded in white austenite matrix. The needles of ferrite often form specific agglomerates (blocks) where they are parallel to each other. The relative high austempering temperature prevents formation of martensite which usually is one of phases formed when the low temperature austempering is applied. No other phases, like carbides are visible in micrograph even at magnification x1500 (fig.1b). The authors [13] did not presented the microstructure of low alloy steel observed using conventional light microscopy so we have no occasion to compare metallography ADI with austempered low alloy steel. Nevertheless they presented SEM metallography which results are comparable with light microscopy. These are given in next section.

2.2. SEM observations

In fig.2 the SEM micrograph illustrating metallography of ADI is presented. Despite much higher magnification no carbides are visible.

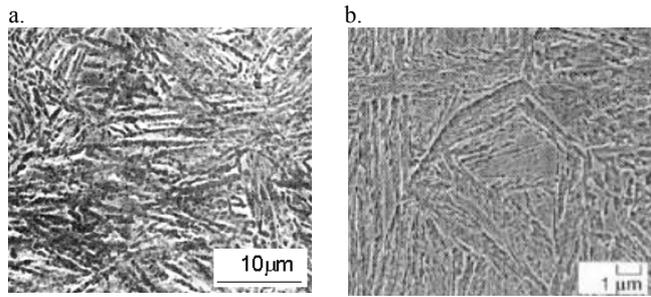


Fig.2. The microstructure of: a - ADI austempered at temperature 310°C [17], b - low alloy steel austempered at 400°C [10]

In next photo (fig.3) the morphology of fracture surface was shown. The characteristic dimples, typical for ductile mode of fracture [18] are clearly visible on the left side of micrograph. The depth of dimples reflects ductility of material. It can be suggested that this ductile mode of fracture is caused by austenite which has FCC lattice.

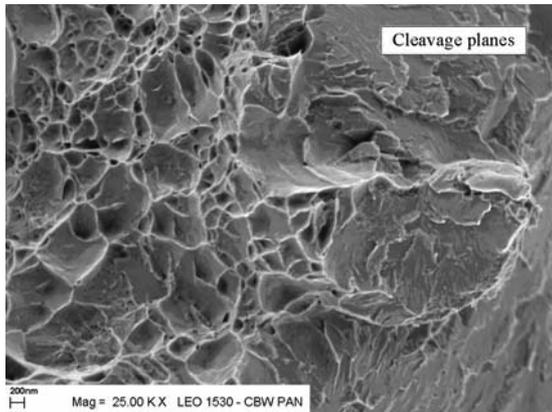


Fig. 3. The fracture surface of ductile iron 90 min. isothermally quenched at temperature 350°C (x25.000) [15]

The right side of photo is quite different. It is characterized with rather flat surfaces usually assisting {100} cleavage plane in ferrite. This mode of fracture surface morphology (fig.3) confirms the complex microstructure of ADI which consists of ductile FCC lattice austenite and less ductile BCC ferrite. More or less similar morphology of fracture surface could be expected in case of carbide less, bainitic low alloy steel. On the other hand the aim of low alloy steel heat treatment including isothermal quenching is microstructure consisting mostly of bainitic ferrite, relative small amount of austenite and some martensite. As follows from quantitative evaluation carried out by Caballero et al. [11], the relative volume of bainitic ferrite V_B , carbon stabilized austenite V_γ and martensite V_M is in range: 75 – 88%, 3 - 10% and 3 – 20% respectively. It would mean that at relative small proportion of FCC phase (austenite) the fracture morphology could differ a little from that in fig.3, although the tensile elongation of this steel reached 18%.

2.3. TEM observations

Here we decided to start with results of TEM observations obtained by Caballero and coworkers [11] for isothermally quenched low alloy steel.

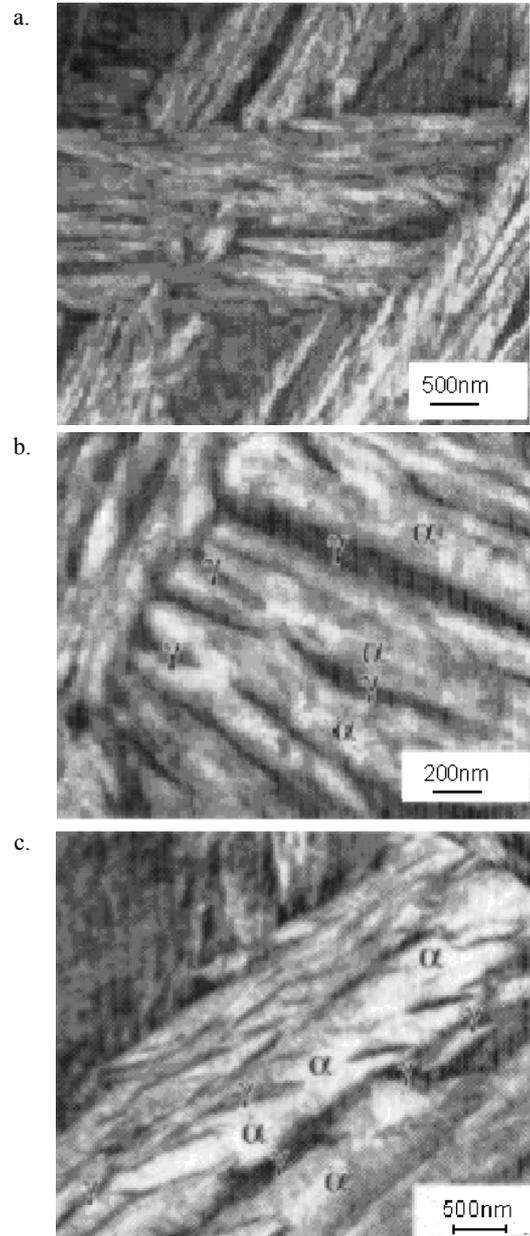


Fig.4. TEM micrograph of low alloy steel structure after cooling from different temperatures: a - 550°C, b and c - 500°C; where: α - bainitic ferrite, γ - retained austenite

Although the quality of the micrograph is rather poor because these were scanned from original paper (fig.2 in [11]) it is evident that structure consists mostly of mixture plate - like or acicular ferrite (α) and some amount of austenite (γ).

Below a few examples of ADI structure obtained for different parameter austempering are shown (fig.5). In all micrographs, except fig.5d, characteristic acicular or plate-like matrix microstructure is visible. In first of them (fig.5a) corresponding very short time low temperature quenching some martensite appears. In fig.5b, taken at relative small magnification (x10.500), distribution of ferrite lath mixed with austenite is visible. Next photo (fig.5c) illustrates ferrite plates containing high density of

dislocations. The next micrograph (fig.5d) represents ADI structure after the same heat treatment as shown in fig.5c.

In this picture relative large austenite grain exhibiting specific diffraction contrast is depicted. This specific contrast may result either from microtwins or stacking faults [19]. Apart from these defects numerous dislocation and dislocation loops can be identified. Fig.5e shows a set almost parallel ferrite laths with many dislocations where retained austenite is located as a very thin ribbon along these laths.

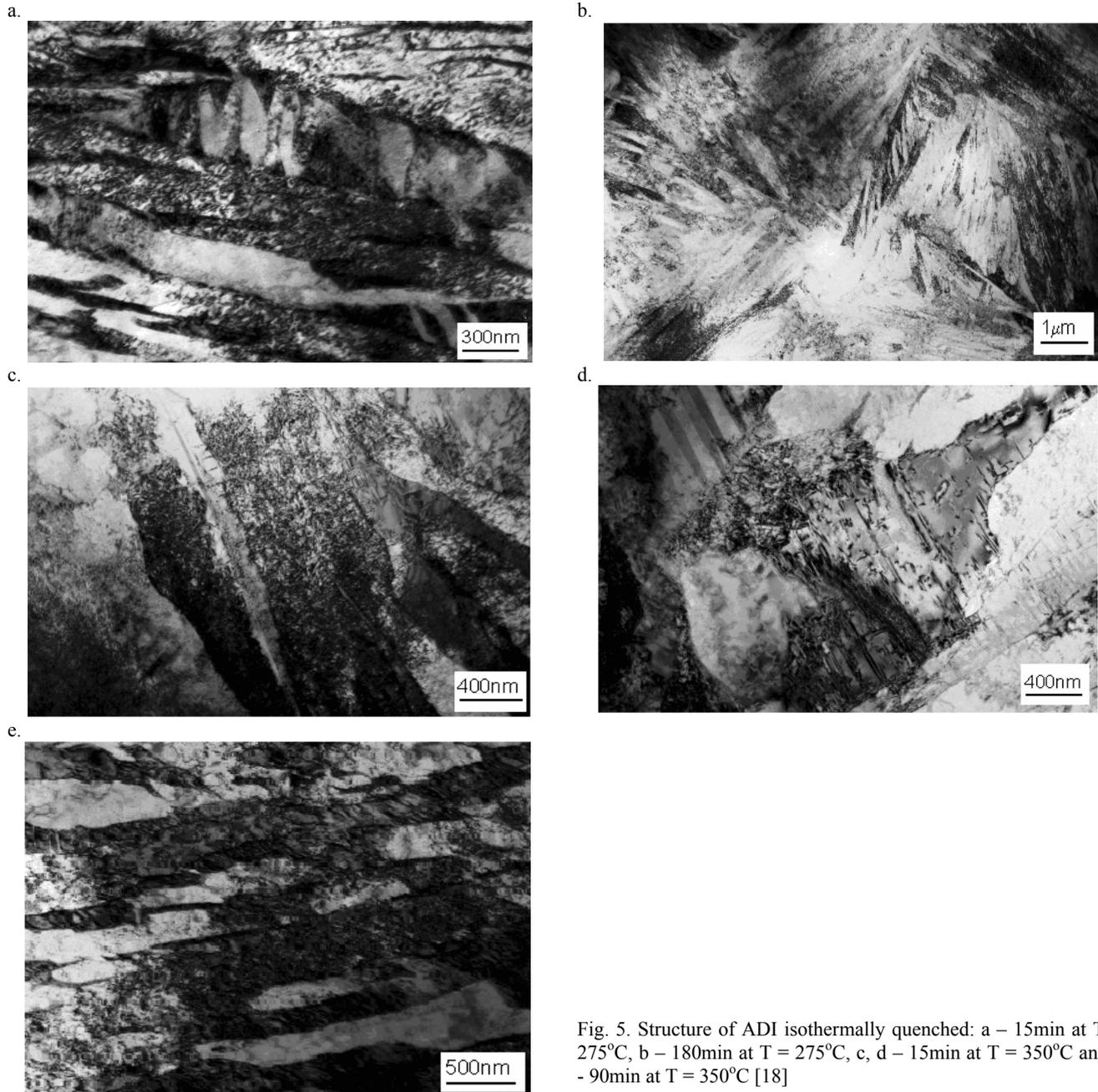


Fig. 5. Structure of ADI isothermally quenched: a – 15min at T = 275°C, b – 180min at T = 275°C, c, d – 15min at T = 350°C and e - 90min at T = 350°C [18]

3. Discussion

As we stated at the very beginning the aim of this paper is to compare low alloy steel and ADI in term of their structure obtained after austempering, although the parameters of heat treatment, especially temperature and time of isothermal quenching were different.

First of all it can be assumed that mechanism undercooled austenite decomposition is generally very similar although the temperature of bainitic quenching of steel and ADI are different.

As we see from the micrograph showed above the structure of austempered low alloy steel and ADI are qualitatively similar. In both materials characteristic plate- and needle - like microstructure is observed. Both steel and ADI matrix consists of mixture ferrite plus carbon stabilized austenite, however size of bainitic ferrite is much less than in ADI. It looks that the dispersion of ferrite is at least 5 or even more times that in ADI (see fig.2). The higher dispersion of bainitic ferrite in steel results from thermo-mechanical treatment leading to finer austenite grains before isothermal quenching.

The next difference is contribution each component is these materials. As was said before, the austenite content in low alloy steel quenched at the temperature 500-550°C lie between 3-10%. In case of ADI the amount of austenite austempered at temperature 350 - 400°C is usually much higher and reached even 30 - 40%. The next difference is 3-20% martensite content in steel while in "high - ductile" ADI martensite is not allowable in all. Martensite appears in high strength grade ADI only but usually in very small proportion.

As follows from literature, in isothermally quenched steel carbon concentration in retained austenite reaches approximately 1% [11]. On the other hand, in ADI the saturation austenite with carbon was evaluated close to 2% [20].

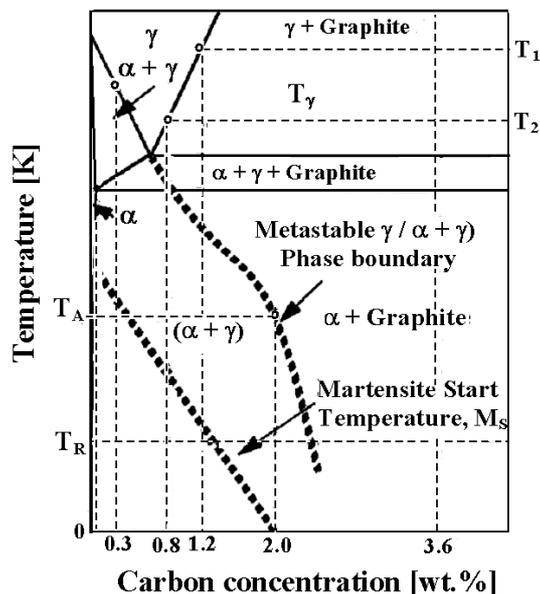


Fig. 6. Schematic phase diagram illustrating the M_s temperature, and its change with carbon concentration [21]

Now let us start with the graph proposed by Rundman [21] showed in fig.6². In this schema part of Fe-Graphite diagram is depicted, where metastable $\gamma / \alpha + \gamma$ phase boundary and start temperature of martensitic transformation M_s is show. It is easy to see drop of M_s temperature with austenite carbon content. If temperature of austenitization equals 900°C then concentration of carbon in austenite will depend on its maximum concentration in given Fe-C alloy. In case of low alloy steel considered in Caballero and coworkers paper [11], the amount of carbon was at the level 0.3%. In commercial ductile cast iron used for ADI manufacturing where typical carbon concentration lee between 3.6 – 3.8 wt. % the maximum austenite saturation with carbon is dictated by cross-section of horizontal line representing austenitizing temperature with curve of solubility carbon γ solid solution. The higher austenitization temperature the more carbon can dissolve in austenite³. Although graph in fig.6 represent Fe-Graphite (stable) phase diagram still can be used to show that M_s temperature for steel is distinctly higher than for ductile iron. This is why the isothermal quenching of steel proceeds at distinctly higher temperature than ADI.

From analysis of literature dealing with low- or middle carbon low alloy steel dedicated to automobile industry one more very interesting thing concerning austenite in AFI arise. As we said before in those steel so called transformation induced plasticity effect is observed. The question is, if this effect appears in ADI matrix austenite during loading? It is well known that transformation austenite into martensite can be induced by rapid cooling or shear loading. TRIP effect is caused just by shearing while loading. It looks very probable that this mechanism can be responsible for strengthening, especially in low strength ADI with high carbon stabilized austenite content [22]. This suggestion however needs verification, so the authors star with the experiment directed to explore this problem.

4. Conclusions

On the basis of the comparison of experimental data taken from literature own results and short discussion given above, following conclusion can be proposed:

Similarities:

- The mechanism of undercooled austenite transformation into bainitic ferrite + carbon stabilized austenite is qualitatively very similar. In both steel and ADI transformation start with nucleation of ferrite. Ferrite growth enriches austenite with carbon atoms stabilizing it to room temperature or much more below 0°C.
- The matrix microstructures steel and ADI are similar at least in this that in both are mixture ferrite and carbon stabilized austenite without carbides, although the relative amount of

² This scheme should be treated as rough approximation only because modification of Fe-graphite diagram caused by silicon was not included

³ The concentration of carbon in austenite depends also on time of austenitization.

austenite in steel is much smaller than in high temperature isothermally quenched ADI.

Differences:

- a. Size of ferrite grains in steel is much less than in ADI which results from much dispersed austenite before isothermal heat treatment.
- b. The relative amount of austenite in ADI is much higher than in low alloy steel.
- c. Carbon concentration in retained austenite is distinctly less in steel than in ADI where its concentration reaches up to 2 wt. %.
- d. The nucleation sites of ferrite in super-cooled austenite are different in steel and ADI. In steel nucleation of ferrite starts at austenite grain boundaries while in ADI at graphite nodules.
- e. The temperature of isothermal cooling of steel has to be higher than in ADI. This results from dependence of martensite start temperature M_s on austenite carbon content which is higher in case of ADI than in steel.

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