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Tensile property of Al-Si closed-cell aluminum foam

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Abstract: Al-Si closed-cell aluminum foams of different densities were prepared by molten body transitional foaming process. The tensile behavior of Al-Si closed-cell aluminum foam was studied and the influence of relative densities on the tensile strength and elastic modulus was also researched. The results show that the fracture surfaces of Al-Si closed-cell aluminum foam display quasi-cleavage fracture consisting of brittle cleavages and ductile dimples. The tensile strength and elastic modulus are strictly affected by the relative density of Al-Si closed-cell aluminum foam. With increasing relative density, the tensile strength increases and the strain at which the peak strength is measured also increases; in addition, the elastic modulus increases with increasing relative density.

Key words: Al-Si; aluminum foam; closed-cell; tensile property

1 Introduction

The unique properties of metallic foams make them useful in a number of potential application fields including damping, electromagnetic shielding, heat exchange, sound insulation, sound absorption, and energy absorption[1−4]. The closed-cell aluminum foam as a kind of widely used metallic foam can be prepared by several techniques. In the Alcan process, gas is injected into a mixture of molten aluminum and ceramic particles (SiC or Al_2O_3). The injected air causes bubbles to rise to the surface of the melt, forming a liquid foam which is stabilized by the presence of ceramic particles. The liquid foam is then mechanically conveyed out of the surface of the melt and allowed to cool[1]. Closed-cell aluminum foam can also be made by powder metallurgy process and molten body direct foaming process. In the former process, aluminum foams are made by adding titanium hydride (TiH_2) powder to aluminum powder and then release hydrogen gas to form bubbles in the aluminum[5]. The schematic diagram of preparing Al-Si closed-cell aluminum foam by molten body transitional foaming process, which is improved from molten body direct foaming process, is shown in Fig.1. Owing to its low cost and proneness to industrial production, molten body transitional foaming process is used to prepare Al-Si closed-cell aluminum foam made by Northeastern University of China[6−8].

Compared with the traditional materials, the aluminum foam materials have advantages of low density, high stiffness, against impact, low thermal conductivity, low magnetic conductivity, and fine damping, so it has become one of the research fields in high technological materials all over the world. As a kind of new material, many studies are needed to characterize its properties. At present, many tests have been done on the compressive properties, which are of primary importance to aluminum foam[9−12], but there are no systematical studies on other important mechanical properties of aluminum foams owing to the difficulty to make large and uniform Al-Si closed-cell aluminum foam to avoid the ununiformity of density. It is of both academic and practical significance to study the tensile behavior of Al-Si closed-cell aluminum foam. However there has been no report on this aspect up to now. In this paper, the tensile and fracture behavior of Al-Si closed-cell aluminum foam were studied. The influence of relative density on tensile strength and elastic modulus was also researched, and the model of Gibson and Ashby was introduced to analyze the experimental results.

2 Experimental

Al-Si closed-cell aluminum foams were produced by molten body transitional foaming process prepared by

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Northeastern University of China[7]. The sketch map preparing Al-Si closed-cell aluminum foam is shown in Fig.1, which has five steps as follows: 1) melting alloy of aluminum-silicon and calcium (3%, mass fraction) in furnace at 850 ℃; 2) adding titanium hydride (45 μm; 1.5%, mass fraction) to the molten body at 680 ℃ and stirring at a speed of 2 000 r/min; 3) transferring the melt to the bubbly case; 4) pushing bubbly case to the furnace (650 ℃) and foaming in it for 6 min; 5) Al-Si closed-cell aluminum foam post processing[8].

For preparing the foams, two different metals and one kind of powder were employed: 99.9% high purity binary eutectic Al-Si alloy (Al-12.6Si from Fushun aluminum manufacture, China), high purity metal Ca (from Sichuan Jianzhong Corporation, China) and the powder of TiH_2 (with granularity of 47 μm from Fushun Aluminum Manufacture, China). The densities of the foams were calculated by weighing the machined specimens on a balance and measuring their dimensions by a digital caliper. Relative density could be calculated through the ratio of Al-Si closed-cell aluminum foam density to dense metal density. The cell and cell wall size for each cell were measured using the method of arithmetic average. Dimensions in detail of the specimens can be seen from Table 1 and Fig.2, and from which it can be concluded that the cells are uniform for specimens with large relative density, the specimens for all relative densities have no particular orientation.

Dogbone shaped specimens for tensile testing were machined by electric discharge machining (EDM) to minimize the local cell wall damage. The length of the specimens was 235 mm, with a 130 mm gauge length; within the gauge length the cross section had a width (W) of 30 mm and a thickness (B) of 20 mm[13]. For convenience, the Al-Si closed-cell aluminum foams with relative densities of 0.12, 0.18, 0.22, and 0.32 are labeled Specimens 1, 2, 3, and 4, respectively. Two specimens were adopted for each density, and the tension result is the average outcome of two specimens. The tensile specimens were loaded at a rate of 1 mm/min and measured with a CMT4000 mechanical testing machine. Each test was stopped at the failure of specimen. The fracture surfaces of the tensile specimens were observed with an SSX-550 scanning electron microscope.

3 Results and discussion

3.1 Uniaxial tensile test

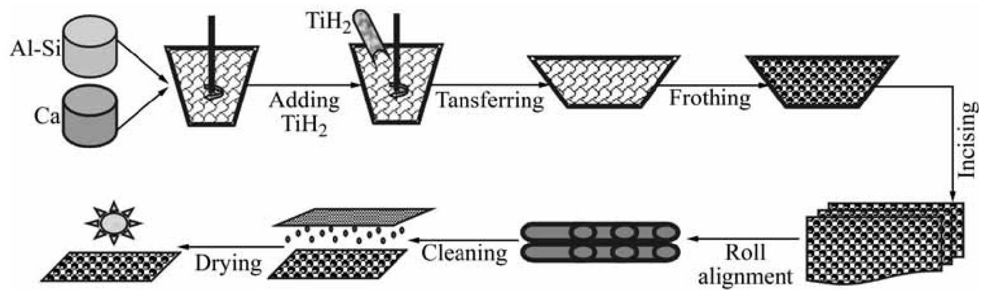

Fig.1 Schematic diagram of preparing Al-Si closed-cell aluminum foam by molten body transitional foaming process

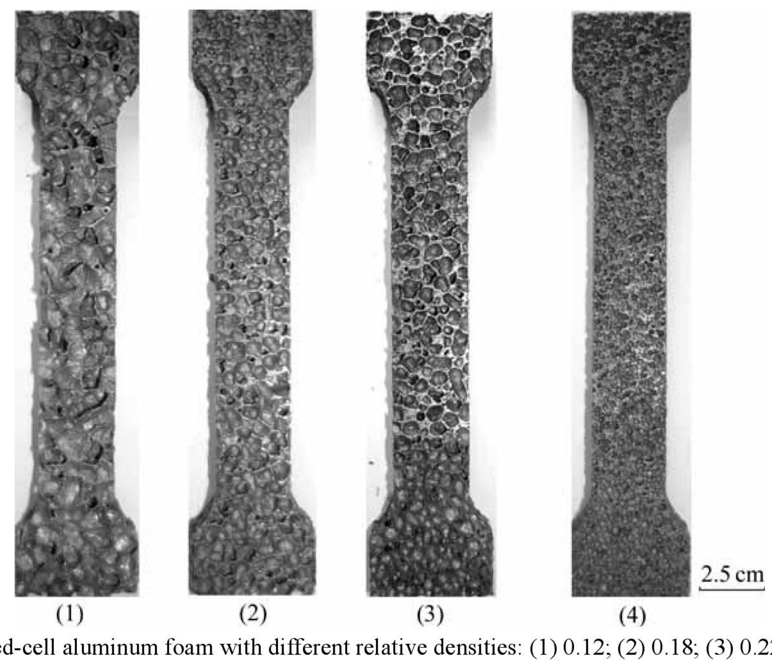

Fig.2 Photo of Al-Si closed-cell aluminum foam with different relative densities: (1) 0.12; (2) 0.18; (3) 0.22; (4) 0.32

Table 1 Parameters of Al-Si closed-cell aluminum foam

Specimen	Relative density	Porosity/ %	Main cell diameter/mm	Cell wall thickness/mm
1	0.12	87.8	11	0.42
2	0.18	81.4	5	0.44
3	0.22	78.5	6	0.5
4	0.32	67.7	2	0.6

Typical uniaxial tensile stress versus strain curves of Al-Si closed-cell aluminum foams of different relative densities are shown in Fig.3. Each curve of the four foams shows linear elastic behavior at small strains, and the tensile strength reaches the highest value when the linear elastic behavior ends, followed by sudden drop. The part of the linear elastic behavior on the curve denotes linear-elastic elongation behavior, the slope of the straight line is the nominal elastic modulus and the ending point of the line is the tensile strength of foams. The whole specimen fractures when the stress reaches the tensile strength of foams.

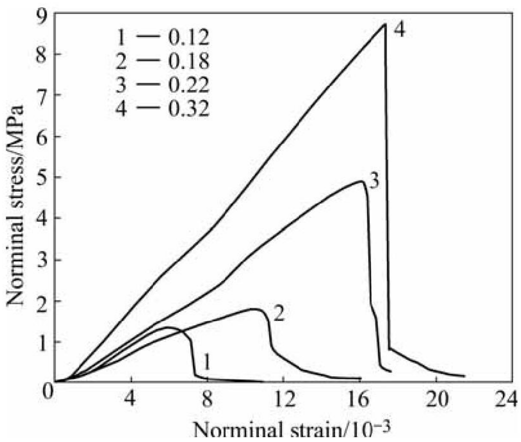

Fig.3 Uniaxial tensile stress versus strain curves for Al-Si closed-cell aluminum foams with different relative densities

Typical fracture surfaces of Al-Si closed-cell aluminum foam are shown in Fig.4. It can be seen from Fig.4(a) that there exist many cleavage surfaces on the fracture surface and steps between cleavage surfaces of different height, and these are basic micro features of cleavage fracture. Fig.4(b) shows the dimples and tear fractures-transitions from cleavage to dimple fracture surface. The mixed fracture consisting of brittle cleavage and ductile dimple is called quasi-cleavage fracture[14]. This indicates that the fracture behavior of Al-Si closed-cell aluminum foam is not pure brittle fracture, some plastic yield must occur.

The major reason for quasi-cleavage fracture of Al-Si closed-cell aluminum foam is the influence of second-phase and foreign particles. The existence of brittle second-phase silicon: $CaAl_2Si_2$ and $Al_{3.21}Si_{0.47}$ (Figs.5(a), (b) and Fig.7) and oxide particles Al_2O_3

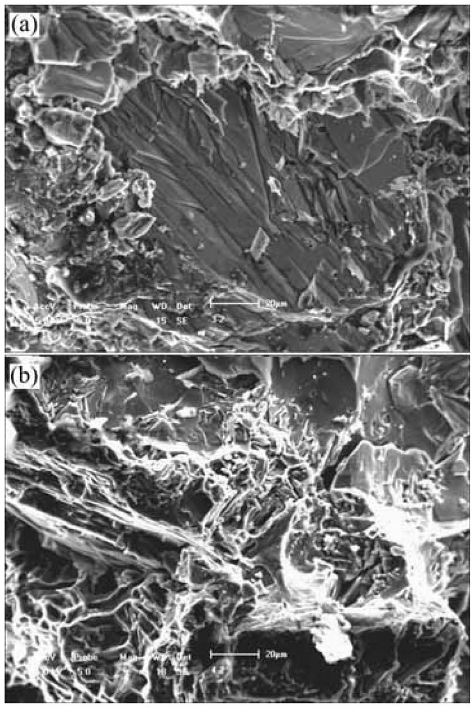

Fig.4 Typical tensile fracture patterns of Al-Si closed-cell aluminum foam: (a) Cleavage surfaces; (b) Dimples and tear fractures-transitions from cleavage to dimple fracture

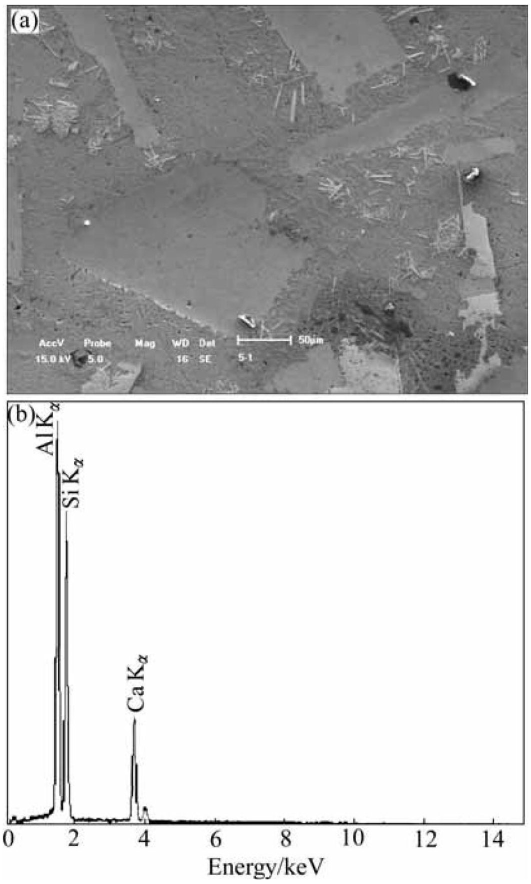

Fig.5 Patterns and composition analysis of second-phase in Al-Si closed-cell aluminum foam: (a) SEM patterns of second-phase; (b) EDX analysis of second-phase

(Figs.6(a), (b) and Fig.7) in Al-Si closed-cell aluminum foam can introduce non-uniformity of microscopic structure. According to the Smith theory[15], under stress, the hardness of second-phase substance and foreign particles existing in the material are higher than that of metallic matrix, so their elastic and plastic deformation properties are different from that of metallic matrix. When the metallic matrix is subjected to stress, the plastic yield occurs whereas the second-phase and foreign particles are still in elastic deformation state [14, 15]. When the uncoordinated deformation runs up to a certain extent, the second-phase substance separates from metallic matrix and becomes cleavage surface. Dimples in Fig.4(b) can be partly attributed to the separation of foreign particles from metallic matrix and the formation of micro hollow spaces. However, there may be other mechanisms, which need further investigation in the future. Observing the Al-Si closed-cell aluminum foams with the scanning electron microscope, cracks and micropores exist in the material (Fig.8), which cause fracture. In order to study the fracture behavior of Al-Si closed-cell aluminum foam in detail, Griffith crackle theory is introduced[15] as well as the energy balance theory, which indicates that the existence of cracks can decrease the elastic energy in the system. The way to

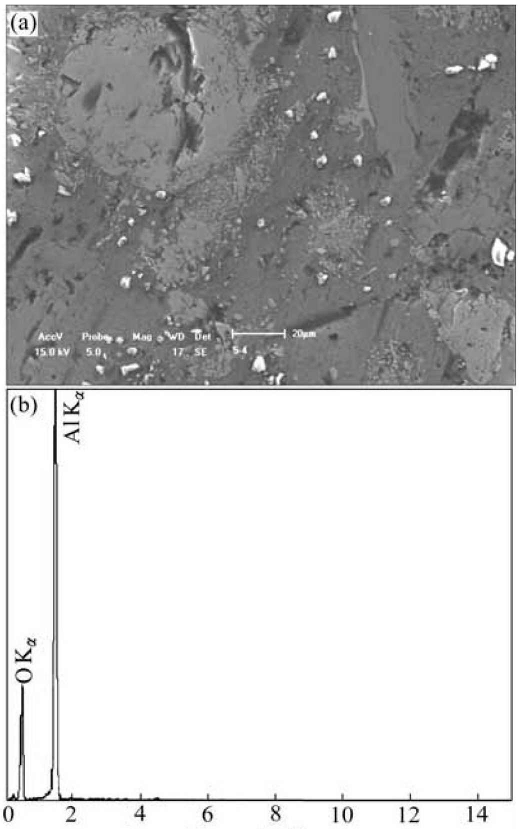

Fig.6 Patterns and composition analysis of foreign particles in Al-Si closed-cell aluminum foam: (a) SEM patterns of foreign particles; (b) EDX analysis of foreign particles

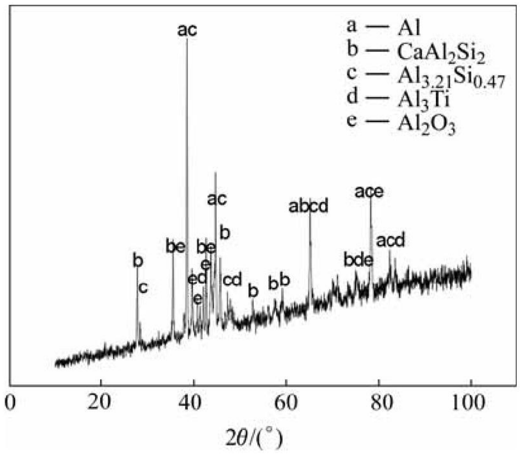

Fig.7 XRD patterns of Al-Si closed-cell aluminum foam

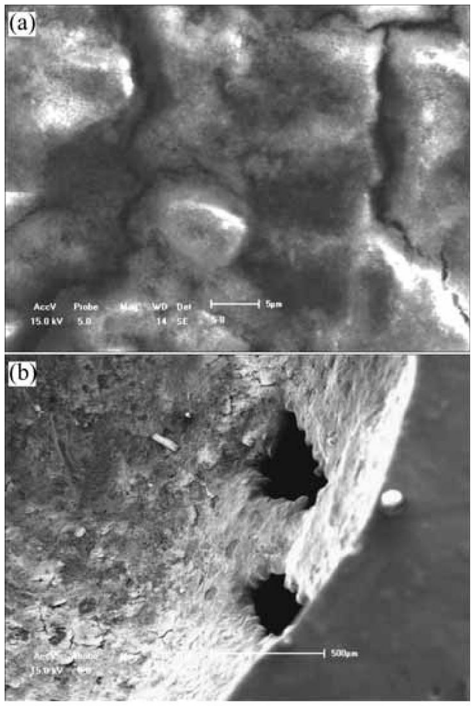

Fig.8 Cell wall faults of Al-Si closed-cell aluminum foam: (a) Cracks; (b) Micro-pores

keep total energy in the system constant is to make sure that the elastic energy released by cracks must balance the increased surface energy caused by the existence of cracks. If the decrease of elastic energy suffices for the increase of surface energy, the extension of cracks becomes the course of decrease of energy in the system, thus cracks will extend spontaneously resulting in brittle failure. Based on the energy balance theory, Griffith figured out the self-extending stress value of crack-strength of body containing cracks. Comparing the stress value of crack with the theoretical fracture strength, the following equation can be obtained:

$$\frac{\sigma_m}{\sigma_c} = \left(\frac{a}{a_0}\right)^{1/2} \tag{1}$$

where σ_m is the theoretical fracture strength; σ_c is the critical stress when crack presents; α_0 is the space between cleavage surfaces when tensile failure occurs for theoretical crystal; α is half-length of the crack (Griffith cracks). The equation indicates when crack with length of 2×10^{-4}cm (micron order) is present in Al-Si closed-cell aluminum foams, the practical strength will be reduced to 1/100 of the theoretical strength. So the stress concentration of the cusps of cracks or local area of micro-pores reaches a very high value; once material yields, the cracks or micro-pores will extend quickly and result in brittle fracture.

According to the criterion of cleavage fracture put forward by KELLY, TYSON and COTTRELL, the primary reason for the occurrence of a little plastic yield during the cleavage course is that the shear yield strength is not much smaller than the tensile fracture strength, so the plastic yield occurs when the stress reaches shear yield strength, and the brittle fracture occurs when the stress reaches tensile fracture strength.

3.2 Influence of relative density

The mechanical properties of foams can be modeled by considering the mechanisms by which the cells deform and fail[16]. Under uniaxial tensile stress, the tensile fracture strength (σ^*_{pl}), and elastic modulus (E^*) of metallic foams depend upon the relative density of foam by[17]

$$\frac{\sigma^*_{pl}}{\sigma_y}=C_1\left(\frac{\rho^*}{\rho_s}\right) \quad (2)$$

$$\frac{E^*}{E_s}=C_2\left(\frac{\rho^*}{\rho_s}\right)^n \quad (3)$$

where ρ^*, E^* and σ^*_{pl} are the density, elastic modulus and strength of the foam; ρ_s, E_s, σ_y are the density, elastic modulus and strength of the metal matrix. C_1 and C_2 are constants related to the cell geometry. Eqns.(2) and (3) are the simplified versions of the property relations proposed by GIBSON and ASHBY. The mechanism of deformation during uniaxial tensile stress can be described by a simple adaptation of Eqns.(2) and (3)[17].

The uniaxial tensile stress versus strain curves is shown in Fig.3 for Al-Si closed-cell aluminum foams with different relative densities. Each curve of the figure signifies linear-elastic elongation behavior at small strains; the tensile strength and the elastic modulus slope

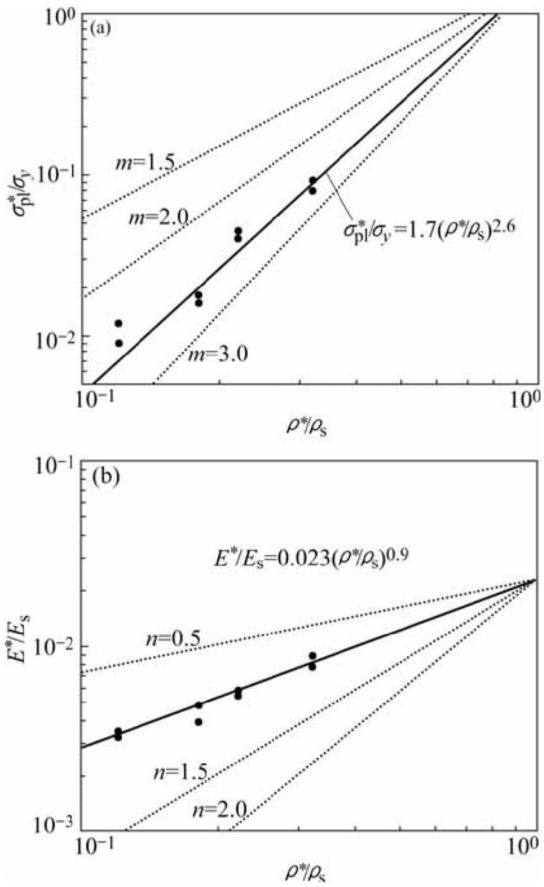

Fig.9 Tensile strength and elastic modulus of Al-Si closed-cell aluminum foams with different relative densities: (a) Relation between tensile strength and relative density; (b) Relation between elastic modulus and relative density, with dotted lines representing predictions of Eqns.(2) and (3), full line as best fit for experimental results

strength of Al-Si closed-cell aluminum foams can be approximately fitted by Eqn.(2) with the parameters C_1=1.7 and m=2.6. With increasing relative density, the tensile strength increases and the strain at which the peak strength is measured increases, which is different from the results obtained by LU and ONG[3]. For example, Specimen 1 with relative density of 0.12 reaches its peak strength at a strain of 0.6%, whereas Specimen 4 has a higher relative density of 0.32 peaks at a strain of about 1.7%. The difference between experimental values and fitted line is because the model of Gibson and Ashby is based on cube, but the cells of Al-Si cell aluminum foam are not regular. It can also be seen that the elastic modulus of Al-Si closed-cell aluminum foams are well fitted by Eqn.(3) with the parameters C_2=0.023 and thickness and the cell size of Al-Si closed-cell aluminum foams. Decreasing the cell size and increasing the cell wall thickness both can increase the relative density; so Al-Si closed-cell aluminum foams of high relative density must be either small in cell size or thick in cell wall. In this experiment, the relative density of Al-Si closed-cell aluminum foams are mainly controlled by the size of cell, and small cell size indicates high relative density. So Al-Si closed-cell aluminum foams with high relative density and with small cell can obtain high stability.

4 Conclusions

1) The deformation behaviors of Al-Si closed-cell aluminum foams subjected to uniaxial tension were studied, as well as the influence of relative density on mechanical property. The tensile strength and elastic modulus obtained from experiment can be approximately fitted by Gibson-Ashby model.

2) The fracture of Al-Si closed-cell aluminum foams can be considered as quasi-cleavage fracture, the main reasons for which are the second-phase substance and foreign particles in the material, which dissever the metallic matrix and thus result in the decrease of strength and ductility.

3) The fault in Al-Si closed-cell aluminum foams, such as micro-cracks and micro-pores, can also cause fracture. The tensile strength and elastic modulus increase with increasing relative density of foams.

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