COMPUTER-AIDED DUCTILE IRON COOLING CURVE ANALYSIS

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Abstract: The structure and mechanical properties of cast alloys are closely related to the metallurgical and technological parameters of the production process. Mathematical models enabling the prediction of the structure and mechanical properties of cast alloys employ computer-aided analysis of the cooling curves scanned. The paper summarizes the results of research work aimed at obtaining data files recording the temperature waveform during the solidification of the specimens cast. The temperatures were recorded by means of type K thermocouples, and a DaqBook 100 analog to digital converter with the DBK 19 thermocouple card and DaqView 7.0 software were used to digitize the signal. The cooling curves obtained from experimental melts were analyzed in the Mathcad 7 Professional program environment, in which the modelling of the appearance of the primary (pouring) structure was also performed. In conclusion the structures predicted by mathematical models are compared with specimen structures evaluated by methods of stereometric metallography.

Keywords: computer-aided cooling curve analysis, ductile iron

1   INTRODUCTION

Computer-aided cooling curve analysis of recorded curves is employed to design and verify mathematical models of eutectic crystallization of ductile iron (DI) [1]. At this stage, emphasis is laid on optimizing the lay-out of the experiment in which the cooling curves and geometrical characteristics of the structure of the cast specimens are obtained. During the eutectic crystallization of ductile iron, verified mathematical models are applied to the temperature waveform obtained by numerical solution of sets of differential equations describing the solidification process of the casting.

2   MATHEMATICAL MODELLING OF DI CRYSTALLIZATION PROCESS

When modelling mathematically the kinetics of solidification, the most complicated problem consists in the calculation of the rate of nucleation, i.e. determining the number of stable nuclei. *Continuous nucleation models* are based on the assumption that nucleation is an on-going process, that the number of graphite particles, dN, appearing during the change in melt temperature depends on the variable undercooling with respect to the graphite liquidus, ΔT_L^g [2]:

$$dN = A_n \cdot \left(\Delta T_L^g\right)^{n-1} \cdot f_l \cdot d\left(\Delta T_L^g\right) \qquad \text{when} \qquad d\left(\Delta T_L^g\right) > 0 \tag{1}$$

n is a constant characterizing the efficiency of inoculation

A_n is a constant depending on the amount of inoculant

f_l is the volume fraction of remaining melt

The total number of nodules, *N,* appearing at time t in the whole volume is the sum of the number of nodules in individual time steps. By the above model, nucleation comes to an end when undercooling with respect to the extrapolated liquidus branch decreases, which is the case of recalescence occurring during eutectic crystallization [2]. It is obvious that continuous nucleation models assume nucleation continuing till the beginning of recalescence, which results in the prediction of continuous distribution of the size of eutectic cells.

Another possible approach can be seen in the *conception of instantaneous nucleation*, which assumes a simultaneous formation of all nuclei after reaching critical undercooling, ΔT . For the rate of nucleation it holds [1]:

$$I = \frac{\partial N}{\partial t} = (N_s - N)K_1 \exp\left(-\frac{K_2}{(\Delta T)^2}\right) \tag{2}$$

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N_s is the number of heterogeneous particles in a volume unit

K_1, K_2 are nucleation constants

In the literature, relations can further be found that have been obtained by regression analysis of experimental data, for example [3]:

$$N = 8171 + 20{,}82 \cdot \Delta T + 13{,}96 \cdot \Delta T^2 - 0{,}21 \cdot \Delta T^3 \tag{3}$$

When designing the mathematical models it is assumed that graphite particles of above-critical magnitude grow freely in the melt until they start being enveloped in austenite. Further growth of eutectic cells is controlled by carbon diffusion through the austenite shell towards graphite nodules [2], [4]. The rate of growth of eutectic graphite particles is given by the equation [3], [6]:

$$\frac{dR_G}{dt} = D_C^A \, \frac{r_A}{r_G} \, \frac{R_A}{R_G(R_A - R_G)} \, \frac{C^{L/A} - C^{G/A}}{C^G - C^{G/A}} \tag{4}$$

The rate of growth of austenite shell in steady conditions is given by the equation [4], [6], [7]:

$$\frac{dR_A}{dt} = D_C^A \, \frac{r_L}{r_A} \, \frac{R_G}{R_A(R_A - R_G)} \, \frac{C^{L/A} - C^{G/A}}{C^{A/L} - C^{L/A}} \tag{5}$$

where D_C^A is the coefficient of carbon diffusion in austenite

R_G, R_A are the radii of graphite grain and austenite shell, respectively

$C^{G/A}$, $C^{L/A}$, $C^{A/L}$, C_G are carbon concentrations acc.to the Fe-C-Si phase diagram

r_A, r_G, r_L are the densities of austenite, graphite and melt, respectively

If the nucleation density and growth rate are known, the fraction of solid phase can be calculated with equation [1], [7]:

$$f_s = 1 - \exp\left(-(4/3)p.N.R_A^3\right) \tag{6}$$

3   COOLING CURVE RECORDING AND ANALYSIS

Determining the number of stable nuclei, N, requires the knowledge of undercooling obtained, ΔT. The set of the above differential equations can be solved numerically in the Mathcad 7 Professional program environment. Since the coefficient of carbon diffusion in austenite, the individual carbon concentrations and, to a lesser degree also the densities of individual phases are all functions of temperature, the solution of differential equations is dependent on the knowledge of temperature waveform during eutectic crystallization.

The cooling curves were recorded by type K (NiCr-Ni) thermocouple without protection tube. A DaqBook 100 analog to digital converter with the DBK 19 high-accuracy thermocouple card of the firm OMEGA was used to digitize the signal. The temperature values measured were currently saved in the data file on a PC disk by means of the DaqView 7.0 software. The calibration of the data acquisition system was performed by the comparative method with a secondary thermoelectric etalon in an accredited calibration laboratory; moreover, the data acquisition system was tested on 99.9% electroconducting copper. The position and length of thermocouples were also optimized. It was shown that the accuracy of cooling curve recording could be guaranteed with a thermocouple immersion depth of 100 mm, with solidification temperature deviations not exceeding 1.5 °C (Fig1).

The set of differential equations (4), (5) was solved by the Euler method in the Mathcad 7 Professional program environment using the cooling curves recorded from experimental melts. The $C^{G/A}$, $C^{L/A}$, $C^{A/L}$ concentrations in the Fe-C-Si system were established using the THERMO-CALC software on the basis of thermodynamic data. First, the temperature of eutectic nucleation (TEN) and the temperature of end of eutectic solidification (TEE) were found on the cooling curve. The temperature and time of TEN correspond to the first point of inflexion on the cooling curve, i.e. the point of first minimum on the curve of the first derivative ($\partial^2 t / \partial t^2 = 0$). The temperature and time of TEE correspond to the second point of inflexion on the cooling curve, whose position is established in a similar way. The positions of significant points marked on the cooling curve, inclusive of the temperature of eutectic undercooling (TEU) and temperature of eutectic recalescence (TER) are established on equivalent lines fitted, with the aid of the Mathcad 7 Professional software, to the respective areas of the recorded curve (Fig.2). The number of stable nuclei was determined using relation (3). Part of the cooling curve recorded, namely from the beginning of eutectic crystallization till its end, and the waveform of solid state portion f_s calculated by equation (6) are shown in Fig.3. The growth of graphite grain and austenite envelope is evident from Fig.4.
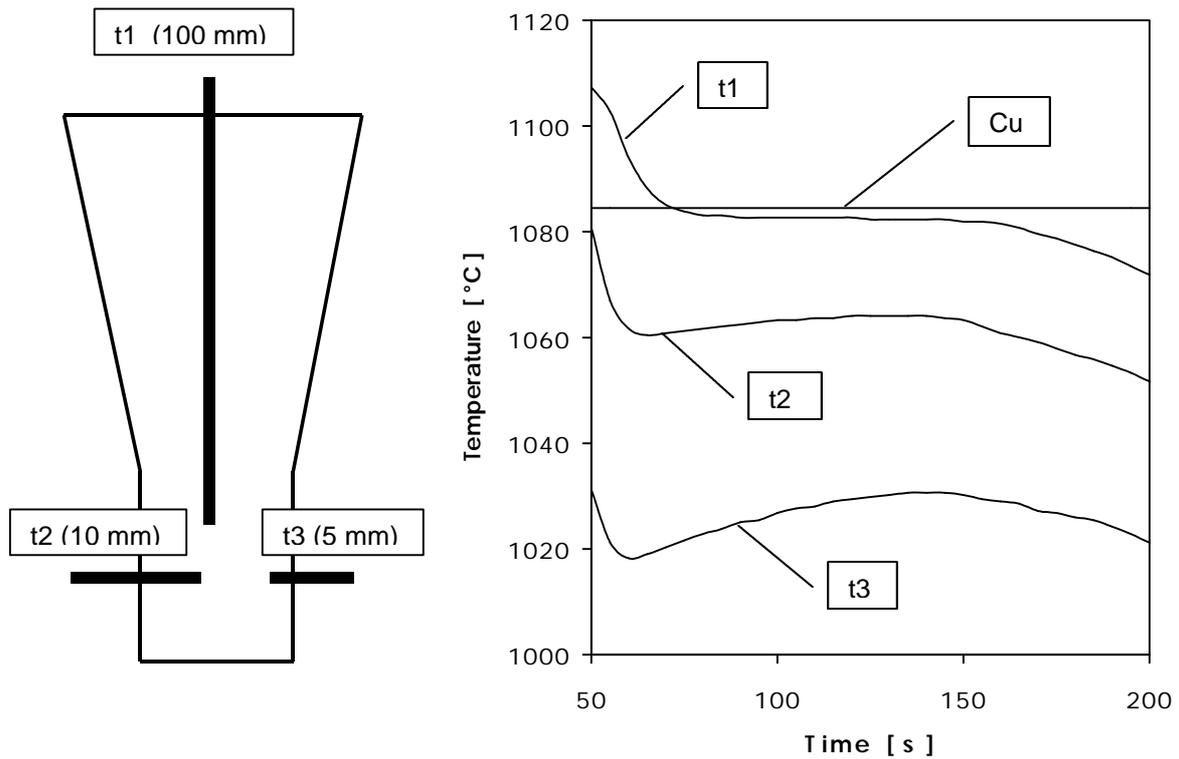
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Figure 1. Optimized lay-out of thermocouples in experimental casting.

The structure in the vicinity of thermocouple tip was evaluated on the OLYMPUS CUE-4 image analyzer, and geometrical characteristics of graphite were established that provide for a comparison of the calculated parameters with those established in the image analysis (Table 1).

Table 1 Geometrical characteristics of graphite

Specimen number	Specimen diameter	As calculated			Picture analysis		
		N	D_g	D_a	n	d_g	s
M21	30 mm	200,0	31,7	98,5	182,7	24,2	8,8
V21	40 mm	166,4	39,8	125,0	182,3	27,0	12,4
M23	30 mm	166,8	31,5	95,2	189,3	24,0	9,6
V23	40 mm	178,0	39,7	124,5	122,6	23,3	11,8
973	40 mm	129,6	34,4	108,2	175,4	31,2	9,8
974	40 mm	123,8	37,5	118,5	112,1	36,1	16,1

Note: n, N – number of graphitic nodules [mm^{-2}]

D_g, d_g – diameter of graphite nodules [mm]

D_a - diameter of austenite envelope [mm]

s – standard deviation

4   CONCLUSION

From a comparison of the geometrical characteristics of graphite in the specimens cast obtained by calculation and by picture analysis, it follows that the calculated size of graphitic nodules is larger than the mean value determined by picture analysis but it lies within an interval bounded by the double, in some cases triple value of standard deviation. The calculated number of graphitic nodules is for three specimens greater and for three specimens smaller in comparison with the results of picture analysis; in most cases, however, the differences are not significant. It has been found that the mathematical model based on solving a set of differential equations of the growth of graphite and austenite envelopes enables a prediction of the number and size of graphite grains and of eutectic cells if

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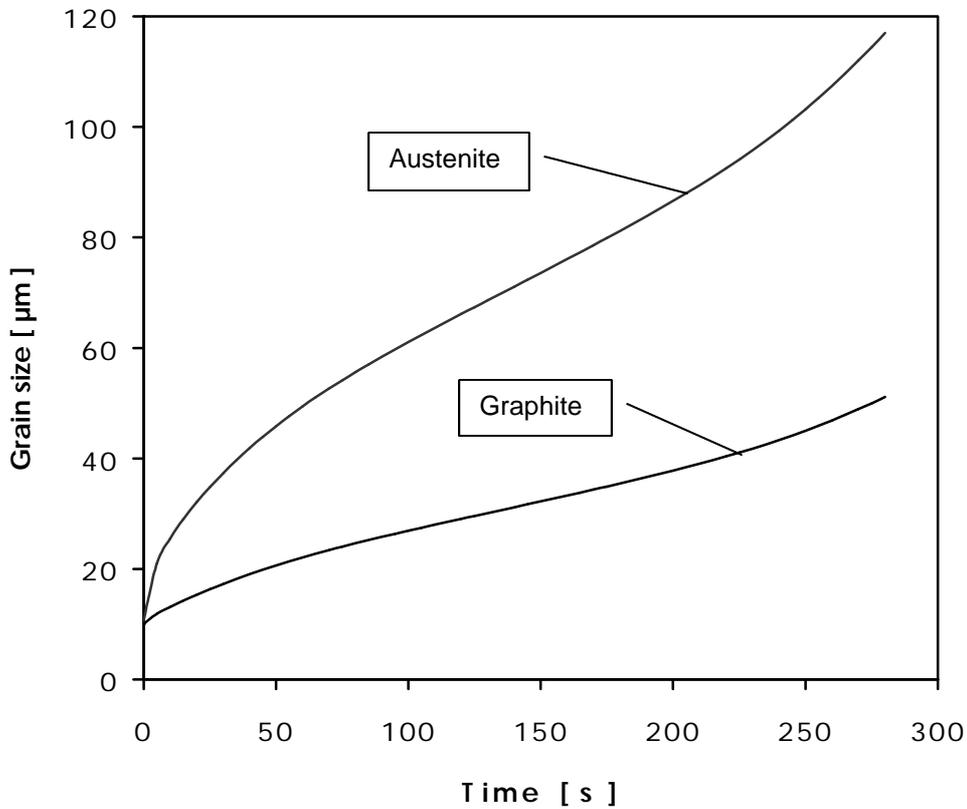Vienna, AUSTRIA, 2000, September 25-28

the waveform of temperature in eutectic crystallization is known (recorded or PC-simulated cooling curve).
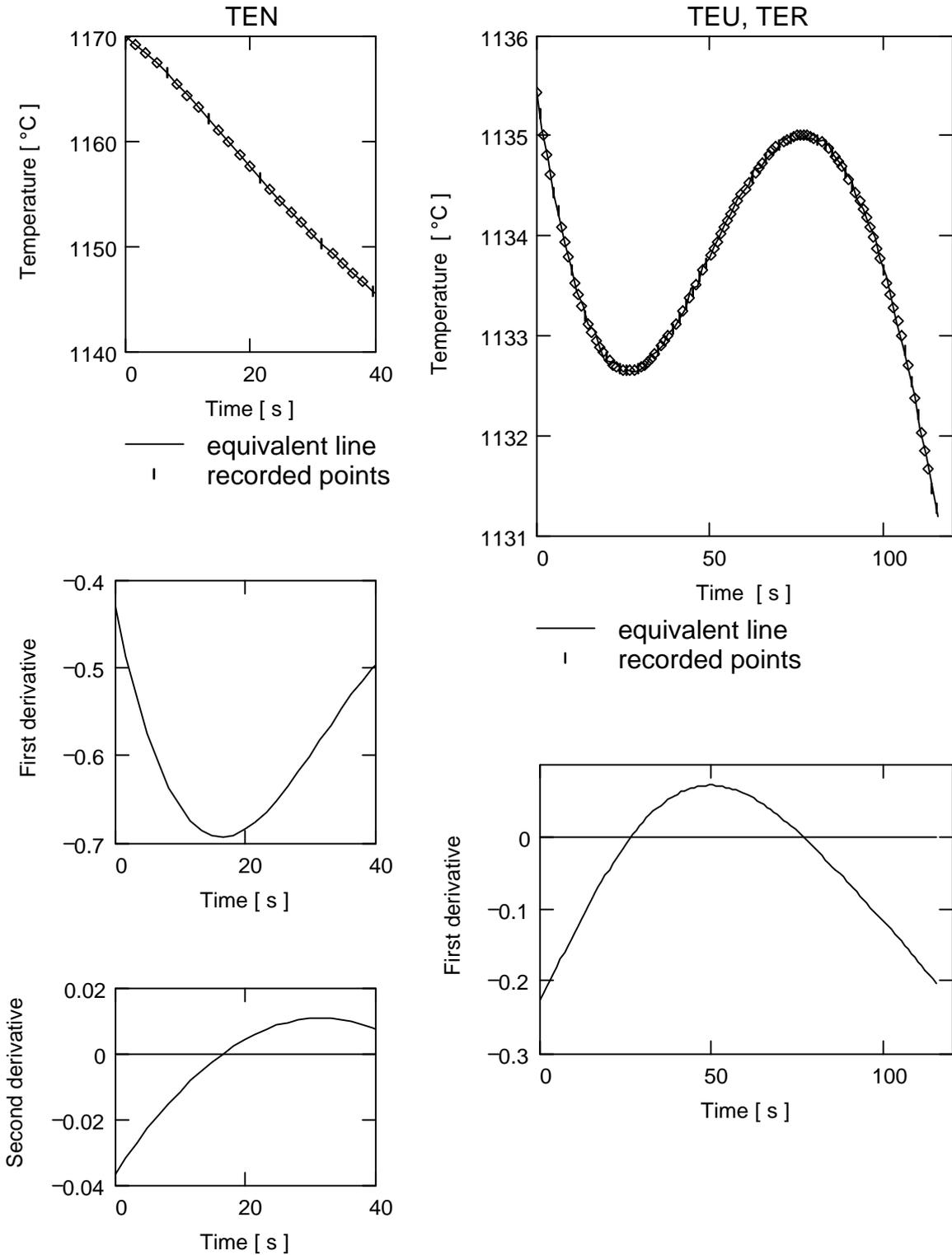
Figure 2. Establishing some significant points marked on the cooling curve
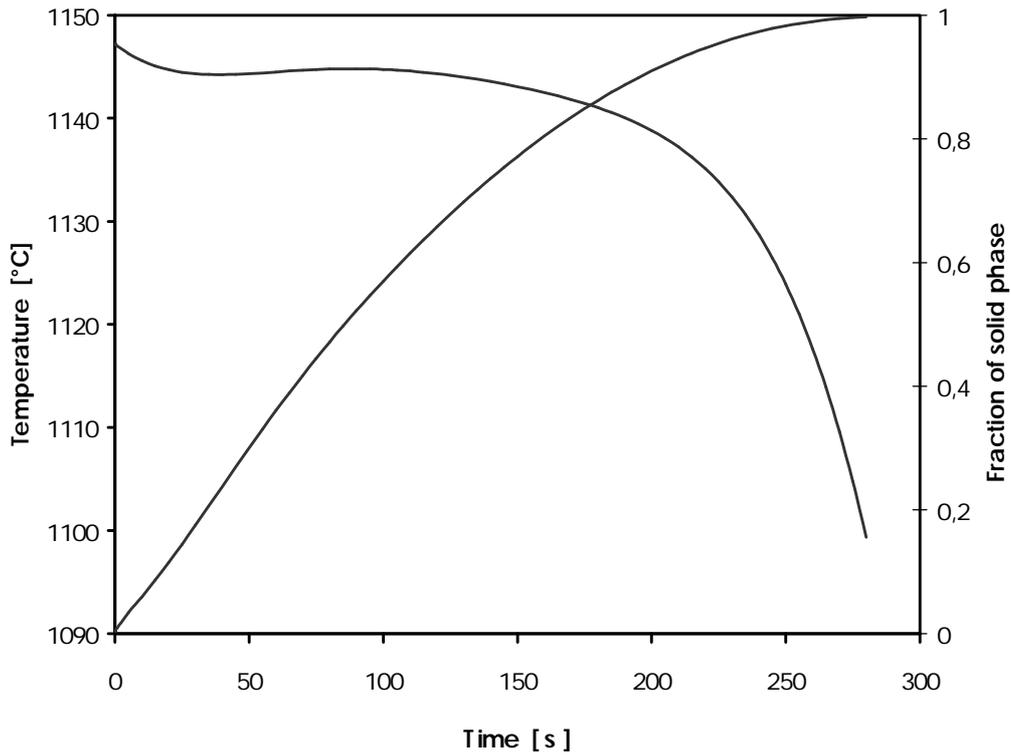
Figure 3. Temperature and fraction of solid phase in the course of eutectic crystallization of specimen # 974

Figure 4. Waveforms of the growth of graphite grain and austenite envelope in specimen # 974

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REFERENCES

[1] Stefanescu, D.M., Upadhya,G., Bandyopadhyay,D.: Heat Transfer-Solidification Kinetics Modeling of Solidification of Castings. Metallurgical Transactions A, volume 21A, 1990, pp 997 - 1005

[2] Lacaze,J., Lesoult,G.: Modelling the Formation of Microstructures: the Example of Spheroidal Graphite Cast Iron, in: *COST 504 Conference "Advanced Casting and Solidification Technology 1994".*Espoo 1994, pp 5 - 34

[3] Banerjee, D.K., Stefanescu, D.M.: Structural Transitions and Solidification Kinetics of SG Cast Iron During Directional Solidification Experiments. AFS Transactions, 1991, pp 747 - 759

[4] Upadhya, G., Paul, A.J. : Comprehensive Casting Analysis Model Using a Geometry-Based Technique Followed by Fully Coupled, 3-D Fluid Flow, Heat Transfer and Solidification Kinetics Calculations. *AFS Transactions*, 1992, pp 925 - 933

[5] Frost, J.M., Stefanescu, D.M.: Melt Quality Assessment of SG Iron Through Computer-Aided Cooling Curve Analysis. *AFS Transactions*, 1992, pp 189 - 200

[6] Wenzhen,L., Baicheng, L.: Microstructure Simulation and Property Prediction of Spheroidal Graphite Iron Castings, in:*62nd World Foundry Congress*. Philadelphia 1996, paper # 6

[7] Chang, S., Shangguan, D., Stefanescu, D.M. : Prediction of Microstructural Evolution in SG Cast Iron from Solidification to Room Temperature. *AFS Transactions*, 1991, pp 531 - 541

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