Investigation of the effect of ultrasonic impact treatment modes on adhesive properties of AISI 321 steel surface

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Abstract. This paper provides the results of UIT modes influence on adhesive properties of the surface layer of AISI 321 austenitic stainless steel. The purpose of the study was to determine the adhesion force of the samples surface processed with a varying static load of an ultrasonic instrument and its relative travel velocity to the sample. The adhesion force was experimentally detected via atomic force microscopy from the force curves of the probe retraction. In this study it has been established that ultrasonic impact treatment of AISI 321 steel does not significantly affect the adhesive component of friction force.

1. Introduction

Ultrasonic impact treatment (UIT) is an effective method for increasing the wear resistance of austenitic stainless steels by the regular microrelief formation, surface layer nanocrystallization and residual compressive stresses generation. Numerous researchers note that UIT improves physical, mechanical and tribotechnical characteristics, as well as the fatigue strength of various friction surfaces, due to formation of a regular surface microrelief consisting of bulges and valleys with a large radius of the peaks rounding [1–11]. Application of ultrasonic impact treatment results in a decrease in the mechanical component of the friction force by the action of the ultrasonic tool on the working surface of parts; it ensures a decrease in roughness.

Relevance of the work is due to necessity for investigation of how the UIT impacts on adhesive component of the friction force. This is significant for further evaluation of tribological characteristics of the working surfaces of parts made of AISI 321 steel. Thus, the research goal is to establish the effect of ultrasonic impact treatment modes on the adhesive properties of AISI 321 surface layer. The objectives of the study are: 1) experimental determination of the adhesion force of AISI 321 steel samples subjected to UIT and 2) establishment of the UIT modes influence on adhesive properties of the samples preliminary processed by turning and grinding.

2. Molecular–mechanical states of friction theory

According to the molecular–mechanical theory of Bowden and Tabor, and appropriate approach of Kragelsky, the friction force is considered as the sum of two components: 1) the force component due to the molecular (adhesive) interaction of the surfaces, and 2) the force component arising from the surface deformation (mechanical component).

$$F = F_{adh} + F_{def} \tag{1}$$

here F_{adh} and F_{def} are the adhesive and deformational components of the friction force, acting on local contact areas.

In the modern theory of friction, the transition conditions from one type of friction bond to another (for mechanical interlocking) are formulated. The theoretical calculation methods based on the theory of elasticity and plasticity, taking into account the discreteness of interacting surfaces, have been developed for the force and friction coefficient estimation. The greatest difficulty in such calculations is the determination of the adhesive component of the friction force. In theoretical approaches to assessing the friction force, the adhesive component is estimated by empirical methods, and a general methodological approach to its determination has not been developed. The processes occurring in the contact area are not equilibrium, which leads to a variety of theories of external friction. The tribological interaction of solids is most fully revealed by the molecular–mechanical (adhesive–deformational) theory of friction, which is based on the concept of contact discreteness of the friction surface.

Due to the surfaces roughness, their contact occurs in tiny contact areas formed through the mutual intercalation of micro irregularities or their plastic crushing. The interaction of sliding surfaces in these areas is inherent in deformation–adhesive dualism. The deformational interaction is caused by multiple deformations of the surface layer's micro–volumes by means of intercalated irregularities. Resistance to this deformation is called the deformational component of the friction force Fdef. The adhesive interaction is associated with the formation of adhesive welding bridges in the contact areas. The resistance of these bridges to shear, as well as the formation of new bridges, leads to appearance of adhesive component of the friction force. Thus, the friction force as well as the friction coefficient, defined as the ratio of the friction force F to the normal load N ($\mu = F/N$), are characterized by deformational and adhesive factors.

The tribological interaction of surfaces subjected to turning or grinding is characterized by an insignificant amount of adhesive component, which is several percents of the deformational component, and does not make a significant contribution to the resulting friction force. However, it should be noted that, for relatively smooth surfaces, such as polished, the role of the adhesive component increases notably. One of the most obvious examples of the significant adhesive component contribution to the friction force is Johansson gauges (gauge blocks), the surface of which is polished to Ra = 0.02–0.01 μm. The surface roughness provided by UIT reaches Ra = 0.08–0.05 μm, comparable in order of magnitude with the roughness of polished surfaces, which makes it necessary to estimate the contribution of the adhesive component to the resulting friction force along with the deformational component.

3. Experimental details

Investigation of the samples with cylindrical shape (diameter rollers of 25.5 mm), subjected to preliminary turning (Ra = 2.15 mμ) and grinding (Ra = 0.36 mμ), was carried out. The samples were made of corrosion–resistant, high–alloy austenitic AISI 321 steel with the chemical composition: C = 0.12%; Cr = 18.64%; Ni = 10.1%; Ti = 0.54%.

The samples were subjected to UIT by a spherical indenter (sphere radius of 3 mm) made of tungsten carbide (figure 1). To generate impacts on the sample surface, it was used the dynamic technological module DTM–07 constructed on the basis of PMS15A–18 magnetostrictive transducer. Processing modes were as follows: ultrasonic tool oscillation frequency f = 18 kHz, amplitude ξm = 50 μm, static load Pst = 10–50 N, the relative travel velocity of the ultrasonic tool and sample v = 1.28–8 m / min, longitudinal feed of the tool s = 0.05 mm/rev.

The morphology of the surfaces, subjected to preliminary processing by turning and grinding, as well as the adhesion forces after UIT were investigated via atomic force microscopy using an MFP – 3D SA microscope (Asylum Research, USA) in a semi–contact mode in the air atmosphere. The adhesion force was calculated from the force curves of the probe retraction from the sample. For each sample, ten measurements were made. The ambient temperature was 20° C with a relative humidity of 60%. The resulting scans (frames) were analyzed using the GWYDDION software module for image processing. The surface roughness of the samples was studied using a TR – 220 profilometer (TimeGroup).

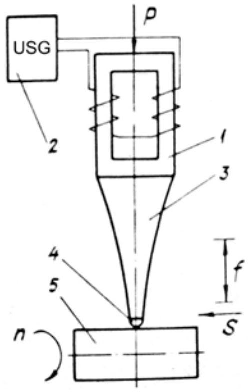


Figure 1. Schematic diagram of the UIT method: 1 – magnetostrictive transducer, 2 – ultrasonic generator, 3 – ultrasonic tool, 4 – hard alloy tip, 5 – workpiece.

4. Results and discussion

Figures 2 and 3 a demonstrated the surface morphology of AISI 321 steel samples depending on the UIT mode. It should be noted, that the surface morphology is a surface textured with micro–dimples. At the same time, there are no scratches remaining on the surface after turning or grinding, which is explained by the complete reforging of the surface layer by impacts of an ultrasonic tool. More details about the regular microrelief formation and the methods of its control can be found in [12–14].

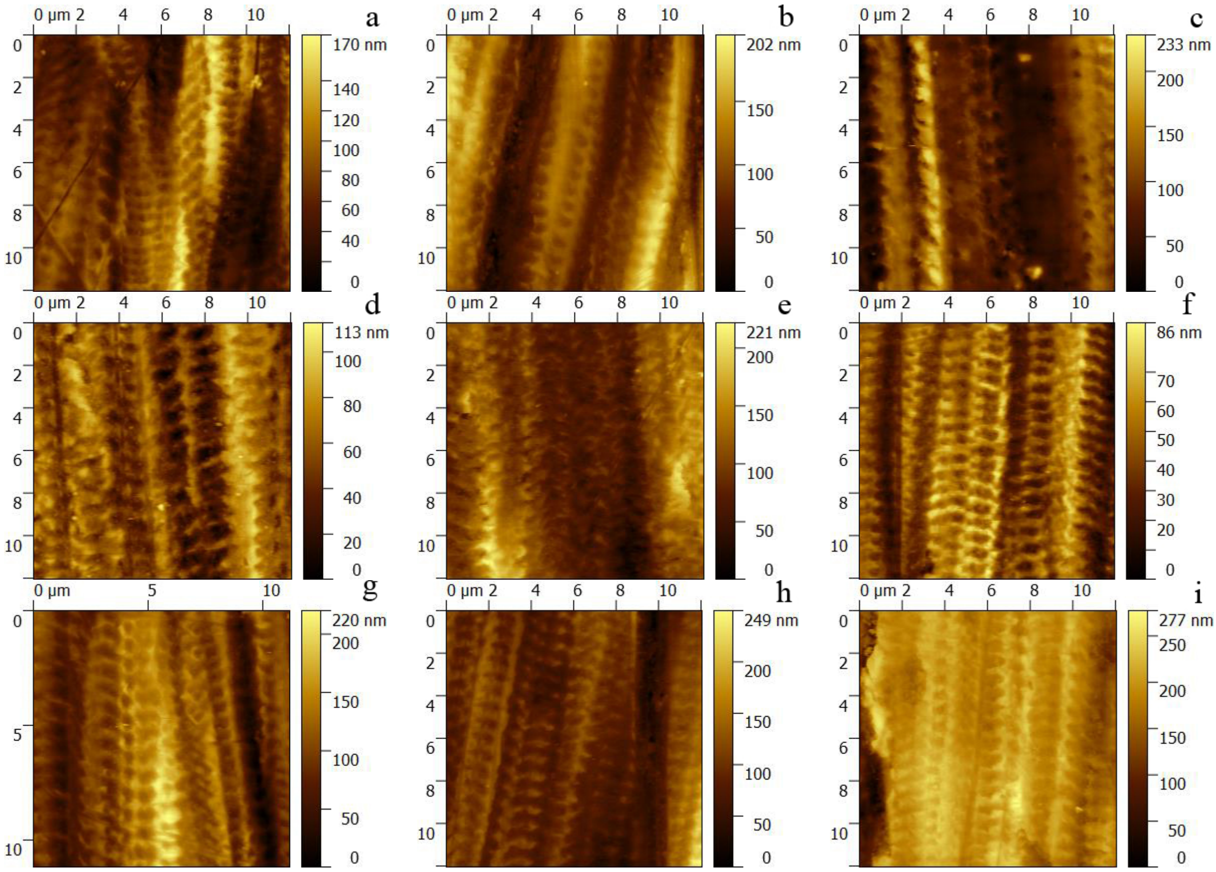


Figure 2. Effect of the static load force of the ultrasonic tool (Pst) on the surface morphology of AISI 321 samples processed by UIT, AFM: a – 9.8 N, b – 14.7 N, c – 19.6 N, d – 29.4 N, e – 34.3 N, f – 39.2 N, g – 49 N, h – 14.7 N, and i – 19.6 N. Samples h and i had an initial roughness Ra = 0.36 µm, the rest samples had an initial roughness Ra = 2.15 µm.

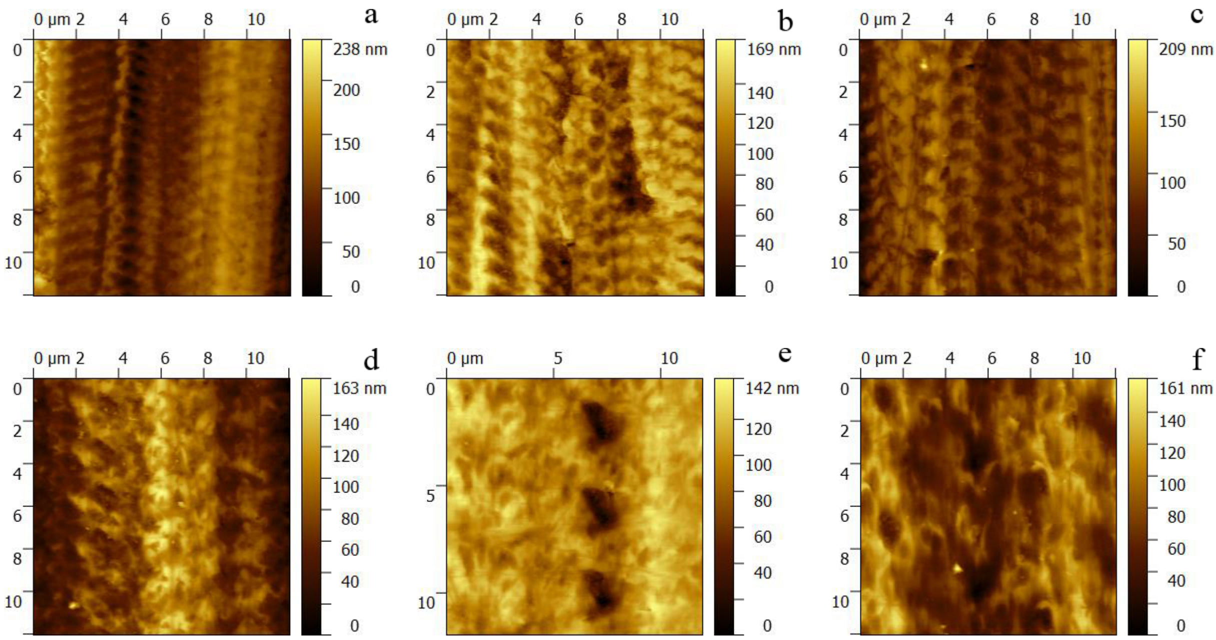
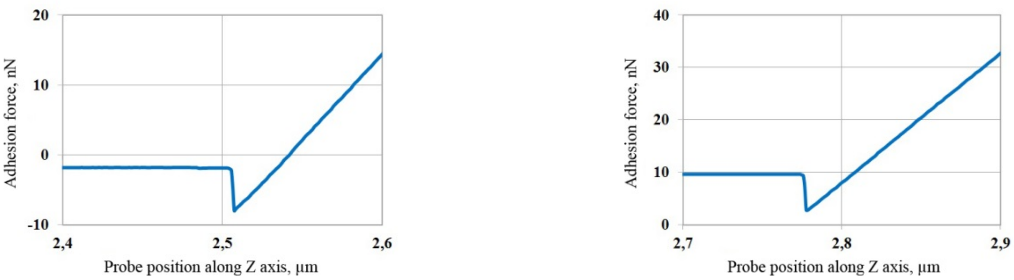


Figure 3. Effect of the relative travel velocity of the ultrasonic tool and the sample on surface morphology of AISI 321 steel samples processed by UIT, AFM: a – 0.98 m / min, b – 1.28 m / min, c – 2 m / min, d – 2.84 m / min, e – 5.04 m / min, f – 8 m / min.

Figures 4–6 show the force curves of the probe retraction from the sample both for the initial surfaces (after preliminary turning and grinding) and for the surfaces subjected to UIT. For each of the samples, ten force curves were obtained, from which ten values of adhesion force were calculated. Next, the arithmetic mean adhesion force was calculated for each sample, the results are summarized in tables 1–3.



(a) (b)

Figure 4. Effect of the initial surface preparing method on the adhesion force of AISI 321 steel samples: a – turning (Ra = 2.15 µm), b – grinding (Ra = 0.36 µm).

Table 1. Effect of preparation quality of the initial surface on the adhesion force.

Preparation quality of the initial surface	The minimum value of F_{adh}, nN	The maximum value of F_{adh}, nN	The mean value of F_{adh}, nN
Turning (Ra=2.15 µm)	5.10	7.53	6.41
Grinding (Ra=0.36 µm)	5.57	7.30	6.61

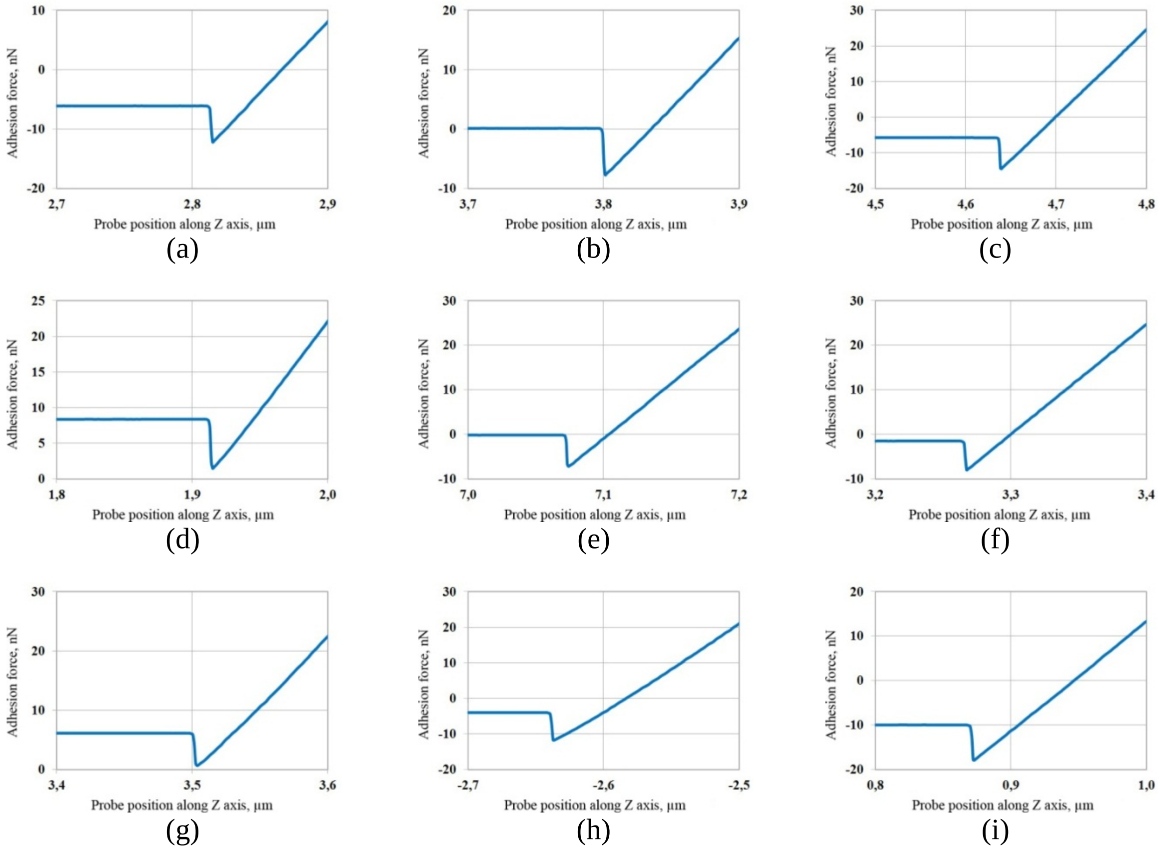


Figure 5. The force curves of the probe retraction from the samples subjected to UIT. The curves are represented the effect of the static load force of the ultrasonic tool (Pst) on the adhesion force of AISI 321 steel surface: a – 9.8 N, b – 14.7 N, c – 19.6 N, d – 29.4 N, e – 34.3 N, f – 39.2 N, g – 49 N, h – 14.7 N, and i – 19.6 N. Samples h and i had an initial roughness Ra = 0.36 µm, the rest samples had an initial roughness Ra = 2.15 µm.

Table 2. Effect of the static load force of the ultrasonic tool (Pst) on the adhesion force.

Quality of the initial surface / UIT mode	Ra, µm	The minimum value of F_{adh}, *nN*	The maximum value of F_{adh}, *nN*	The mean value of F_{adh}, *nN*
Turning (Ra=2.15 µm) / Pst = 9.8 N	0.085	5.02	7.81	6.27
Turning (Ra=2.15 µm) / Pst = 14.7 N	0.107	5.53	8.55	7.12
Turning (Ra=2.15 µm) / Pst = 19.6 N	0.098	7.56	15.22	11.53
Turning (Ra=2.15 µm) / Pst = 29.4 N	0.097	6.33	11.8	8.51
Turning (Ra=2.15 µm) / Pst = 34.3 N	0.099	5.73	10.8	8.67
Turning (Ra=2.15 µm) / Pst = 39.2 N	0.108	4.20	10.4	7.42
Turning (Ra=2.15 µm) / Pst = 49 N	0.072	3.08	6.13	4.54
Grinding (Ra=0.36 µm) / Pst = 14.7 N	0.066	3.68	8.14	5.78
Grinding (Ra=0.36 µm) / Pst = 19.6 N	0.081	4.74	9.31	6.94

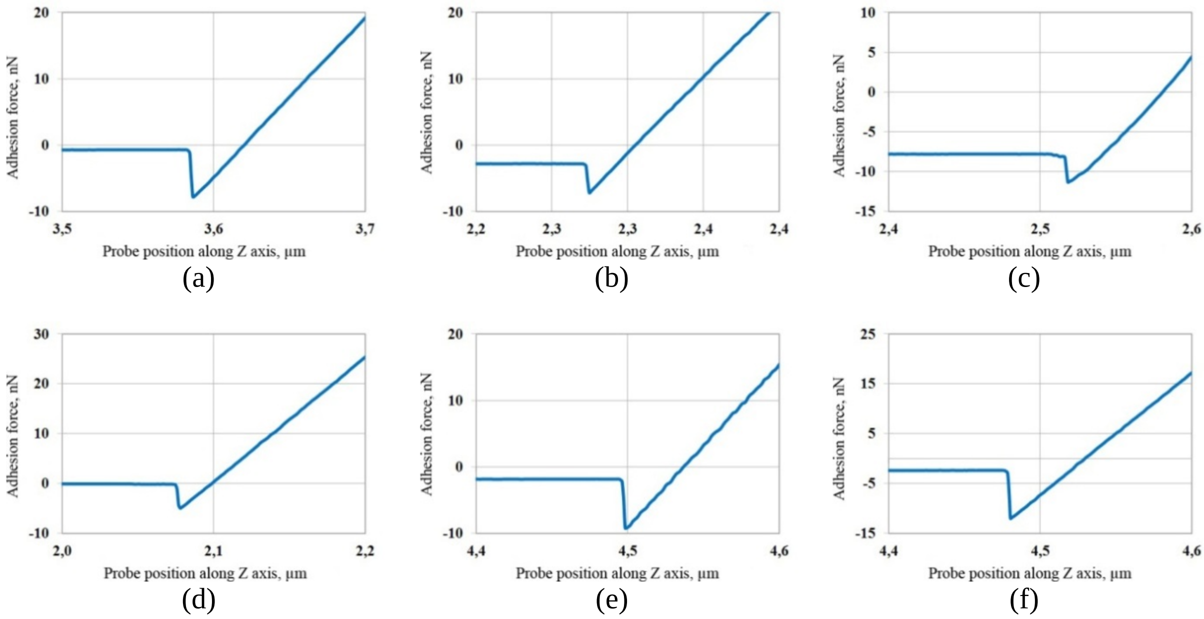


Figure 6. The force curves of the probe retraction from the samples. The curves are represented the effect of the relative travel velocity of the ultrasonic tool and the sample on the adhesion force of AISI 321 steel surface: a – 0.98 m / min, b – 1.28 m / min, c – 2 m / min, d – 2.84 m / min, e – 5.04 m / min, f – 8 m / min

Table 3. Effect of the relative travel velocity of the ultrasonic tool and the sample on the adhesion force of AISI 321 steel surface.

Preparation quality of the initial surface / UIT mode	**Ra, µm**	**The minimum value of F_{adh}, nN**	**The maximum value of F_{adh}, nN**	**The mean value of F_{adh}, nN**
Turning (Ra=2.15 µm) / v = 0.98 m/min	0.083	6.88	7.29	7.08
Turning (Ra=2.15 µm) / v = 1.28 m/min	0.059	3.05	5.25	4.03
Turning (Ra=2.15 µm) / v = 2 m/min	0.095	2.55	4.36	3.28
Turning (Ra=2.15 µm) / v = 2.84 m/min	0.058	3.24	8.63	5.03
Turning (Ra=2.15 µm) / v = 5.04 m/min	0.066	6.25	8.61	7.16
Turning (Ra=2.15 µm) / v = 8 m/min	0.056	7.56	10.1	8.94

Based on the data from table 1, it can be concluded that the method of preliminary surface preparation has practically no effect the adhesion force of the samples; however, for the ground surfaces the adhesion force, on average takes large values. An analysis of the data from Table 2 leads to the conclusion that Pst during UIT does not significantly affect the adhesion force of samples, which varied from 4.54 to 11.53 nN.

5. Conclusion

In this study, it has been established a direct correlation between the preliminary surface preparation method, its roughness after the UIT, the UIT mode and the adhesion force: the minimum roughness and the greatest static load force of the ultrasonic tool correspond to the lowest maximum, minimum and average values of the adhesion force for both samples subjected to turning and for samples with preliminary ground surface. The relative travel velocity of the ultrasonic tool (at a constant static load force) and the samples subjected to preliminary turning is not linearly related to the roughness and adhesion force after UIT: 1) the minimum average adhesion force (F_{adh} = 3.28 nN) and the maximum roughness (Ra = 0.095 μm) are obtained at v = 2 m / min; 2) the minimum roughness (Ra = 0.056 μm) corresponds to the highest average value of the adhesion force (F_{adh} = 8.94 nN) at v = 8 m / min.

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