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Micro-scratching tests of a rolled aluminium alloy AA2024-T351 thick plate using a diamond micro-blade

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Abstract. The present research work is focused on investigating the apparent coefficient of abrasive friction of a rolled thick plate of an AA2024-T351 aluminium alloy, using micro-scratch tests. For this study, specific materials specimens and a particular UMT Micro-Scratch Equipment were used. The test involved the generation of a scratch process at a local scale using a diamond stylus (micro-blade defined by a radius of 0.8 μm) moving along a specified path under a constant normal force (10 N) and with a constant speed (0.2 mm/s). For the characterization of the surface quality, two orthogonal directions were considered: the longitudinal one, along the rolling direction, and the corresponding transversal one. Given the fractal nature of the surface, an investigation was done in order to assess its influence on the coefficient of abrasive friction. The fractal dimension D_f , one of the most important parameters in a fractal surface analysis, was used to determine this influence in the global friction and abrasion phenomena. The abrasion factor was calculated using the Zum Gahr method for the data obtained with a specialized Mitutoyo SJ-301 surface tester. Measurements were made at the beginning, middle and at the end of the scratch channel. The obtained value for the abrasion factor was slightly less than zero. Other influences of anisotropic material features on global abrasion effects were also analyzed via comparisons of the coefficients of abrasive friction for both static and kinematic conditions.

1. Introduction

The scratch test is an established procedure commonly used as a technique for studying mechanical properties of materials near their surface. This procedure is of great interest to both academic and industrial communities [1, 2]. The micro-scratching test is one of the most widely used methods to obtain an effective and fast assessment of the critical loads related to adhesion properties of coating. There are two types of scratch tests that can be done: the scratch hardness test (scratch with constant normal load on a specimen and on a reference material using a stylus) and the scratch adhesion test where a progressive or a constant load is applied [3].

The scratch hardness and the materials surface deformation mechanisms depend mainly on the material's rheological behavior, on the indenter geometry and on the friction at the interfaces [2].



2. Experimental setup

2.1 Material properties

For the micro-scratch tests a rolled aluminium alloy AA2024-T351 was used, which is one of the most popular high-strength aluminium alloys, having a good behavior at high temperatures and a low corrosion resistance. The composition of the 2000 aluminium alloy series has as a distinctive feature a copper content of approximately 4% and almost unnoticeable small impurities of iron. The mechanical proprieties are shown in table 1, from the technical literature and from the previous work concerning anisotropic rheology of AA2024 rolled thick sheets, conducted at National Institute of Applied Sciences of Rennes (INSA Rennes) [4].

Table 1. General mechanical proprieties of rolled AA2024-T351 aluminium alloy.

| Propriety | AA2024-T351 |
|----------------|----------------------------------|
| Strength | $> 420 \text{ N/mm}^2$, |
| Yield strength | $0.2\% > 260 \text{ N/mm}^2$ |
| HD harshness | 120 Kgf/mm^2 |
| Young modulus | $71000\text{-}74000 \text{ MPa}$ |
| Poisson ratio | 0.33 |

2.2 Micro-scratch apparatus

For this study it was used an UMT Micro-Scratch Equipment (figures 1, 2) from the Machine Elements and Tribology Department (OMTR) – University Politehnica of Bucharest (UPB). The equipment can provide rotational, translational or reciprocating motions with speeds starting from $0.1 \mu\text{m/s}$ up to 10 m/s . A constant or a progressive load between 0.05 N and 1000 N can be applied on the sample by the carriage. This normal force F_z is controlled by a close-loop feed-back procedure. The tangential force (F_x), normal load (F_n), penetration depth and the coefficient of friction, or of abrasive friction, can be measured and recorded at a total sampling rate of 20 kHz [5].

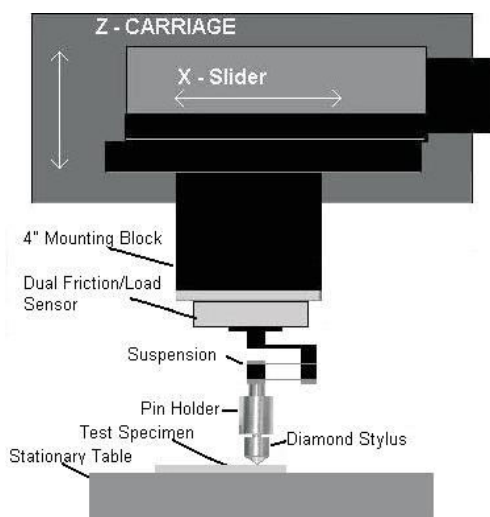


Figure 1. UMT Micro-Scratch configuration.



Figure 2. UMT Micro-Scratch.

The micro-scratch process is performed by moving a diamond stylus along a specified trajectory, maintaining a constant normal force and a uniform speed (figure 3). The thick plate specimen of 10 mm thickness has been prepared and machining by Mechanical Common Center (CCM) of INSA Rennes. The experimental tests were made at OMTR – UPB using the operating parameters shown in table 2.

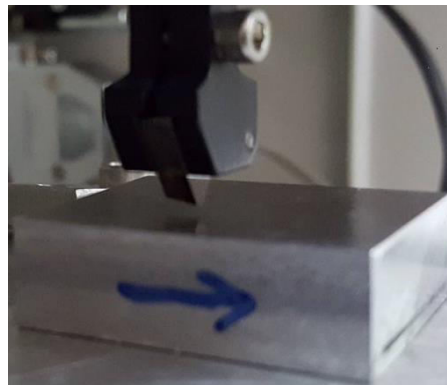


Figure 3. Micro-blade (with a radius of 0.8 μm) and the AA2024-T351 specimen used for the scratch tests.

Table 2. Micro-scratch parameters.

| | |
|------------------|---|
| Load type | constant |
| Load value | 10 N |
| Scratching speed | 0.2 mm/s |
| Scratch Length | 5 mm |
| Indenter | micro-blade, radius= 0.8 μm |

In order to analyze the quality of the material surfaces there were made scratch tests in two perpendicular directions. Five scratch tests along the rolling longitudinal direction – LD and other five scratch tests in the transversal direction – TD (figure 4).



Figure 4. Schematic illustration of longitudinal and transversal orientation of scratch.

3. Experimental results

In figure 5 the variations in time of the tangential forces and of the apparent coefficient of abrasive friction are presented. In figure 6 it is plotted the time variation of the penetration depth. In these figures the results for both scratch directions (LD – rolling longitudinal direction and TD – transversal direction) are shown as a statistic mean of the five measurements done for each case.

Abrasive friction is considered to be one of the main causes of mechanical energy loss. It is known that two forms of friction exist, corresponding to static and kinetic conditions. Static friction represents the frictional force acting between two surfaces which are attempting to move relative to each other, but sliding has not occurred yet, whereas the kinetic friction is the frictional force acting between the two surfaces which are in motion relative to each other.

Starting from the above described scratching tests, an apparent coefficient of abrasive friction can be defined as the ratio between the measured tangential force and the normal one:

$$\mu_s = F_s / F_n \quad \mu_k = F_k / F_n \quad (1)$$

where: F_s , F_k - static and kinetic abrasive tangential force; F_n - normal force.

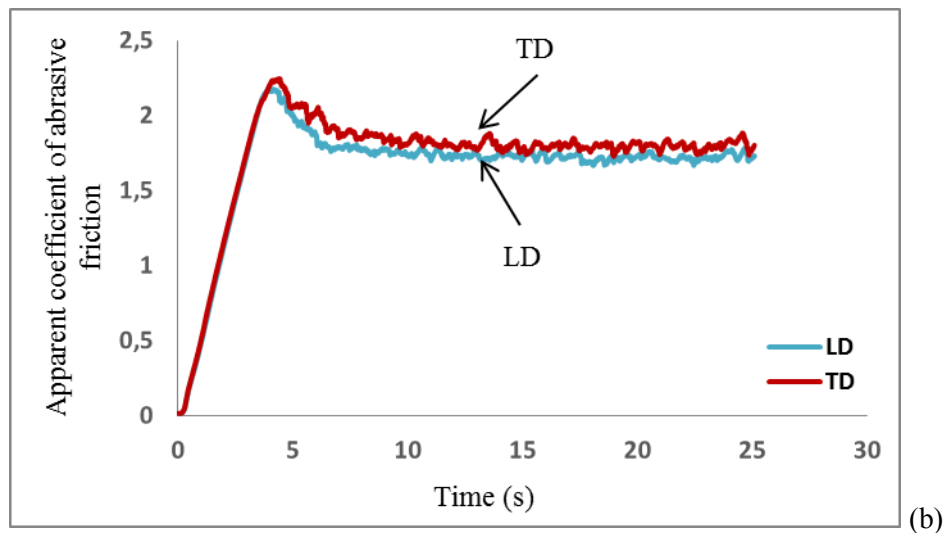
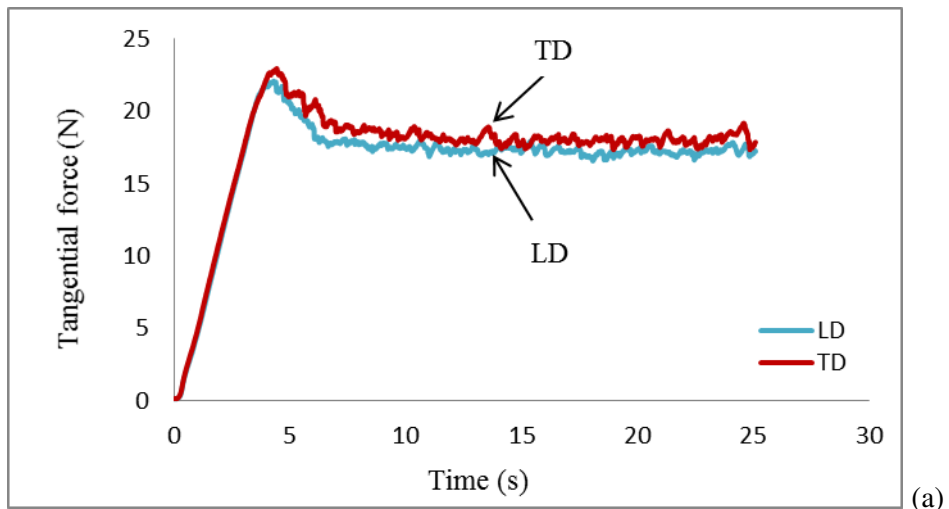


Figure 5. (a) The time variation of the tangential force, (b) The time variation of the apparent coefficient of abrasive friction.

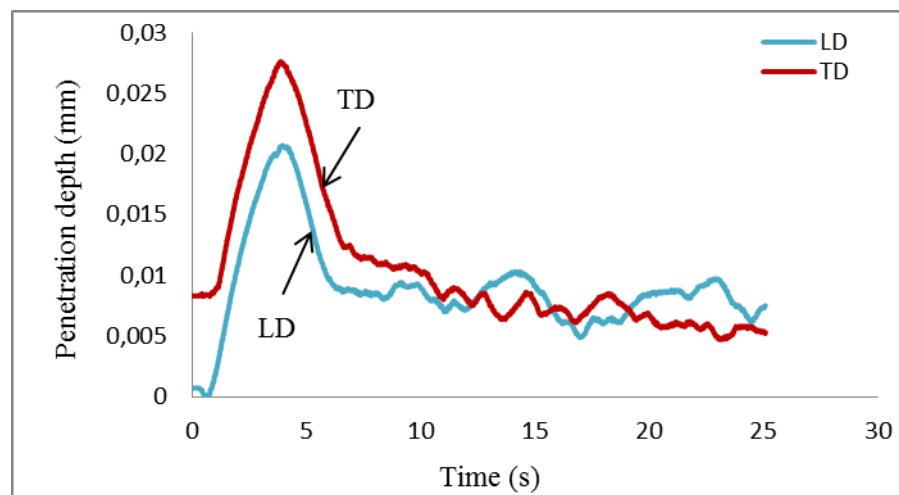


Figure 6. The time variation of the penetration depth.

From figure 5 it can be observed an apparent coefficient of static-abrasive friction in the interval 0-4 s and a kinetic one after 4s. Considering that the surfaces have a fractal behavior up to $1.1 \mu\text{m}$, it had to be determined if there is any possible influence of this characteristic upon the coefficient of abrasive friction. The fractal dimension D_f was used to describe the fractal quality of the surface [6]. The values of this parameter were obtained for each scratch direction in [6]: along the longitudinal direction $D_f = 1.216$ and along the transversal direction $D_f = 1.113$.

According to the results synthesized in figure 7, it can be noticed, that there is little influence on the coefficients of abrasive friction, both in the static and in the kinetic case, by the fractal surface behavior. It is observed that the loading direction (longitudinal direction or transversal direction) has a small influence of 3% on the apparent coefficient of abrasive friction.

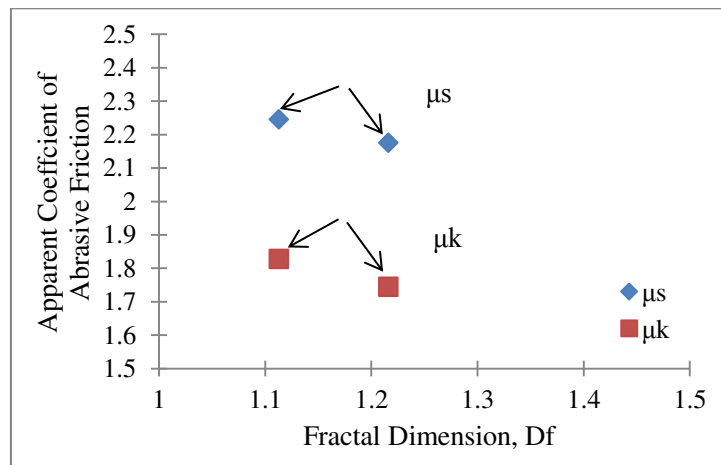


Figure 7. The variation of global static and kinetic apparent coefficients of abrasive friction with the fractal dimension D_f .

These results must be interpreted taken into account that the determined coefficient of abrasive friction is only an apparent one and not on a Coulomb friction coefficient. The latter can be estimated only if the measured tangential force is close to a real sliding friction force, where its component generating the plastic deformation during the scratching is reduced to a minimum. Generally this condition can be obtained if the applied contact pressure is smaller than one third of the Vickers hardness of material. Further tests along the diagonal direction DD must be added in the future in order to conclude on the influence of the anisotropy and of the fractal dimension.

4. The abrasion factor

The abrasion factor is defined as the ratio between the material volume that was moved in the wear process and the wear volume. For ductile materials, the abrasion factor can be estimated using the following formula [7]:

$$f_{ab} = 1 - (A_1 + A_2) / A_v \quad (2)$$

where A_1 and A_2 are the structured surfaces areas situated above the initial axis of the undistorted surface and A_v is the area of the deformed surface structure under the initial axis [8].

The principle of Zum Gahr's formalism of a cross-sectional cut it is shown in the following figure [9].

To compute the abrasion factor, the surface profile of each scratch channel was measured with a specialized Mitutoyo SJ-301 surface tester (figure 9). The measurements were made at the beginning, middle and at the end of the scratch channel.

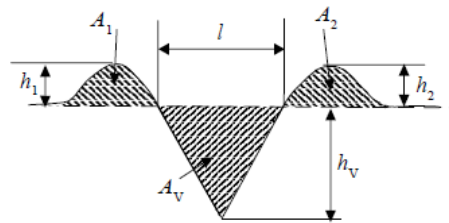


Figure 8. The principle of Zum Gahr of a cross-sectional cut.



Figure 9. Mitutoyo SJ-301 surface tester [8].

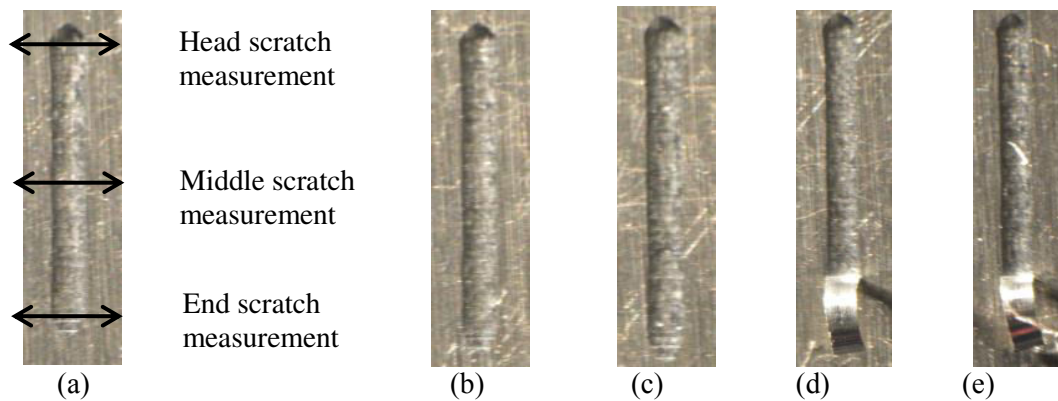


Figure 10. Microscopic images of the five micro-scratch tests for LD (rolling longitudinal direction).

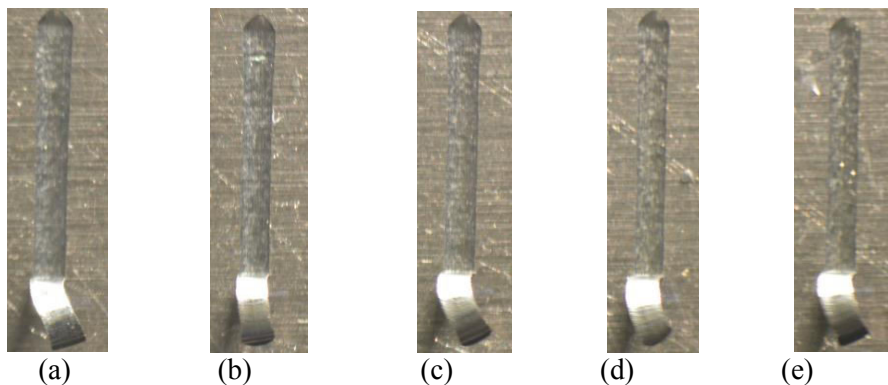


Figure 11. Microscopic images of the five micro-scratch tests for TD (transversal direction).

Microscopic images of the scratch channels for all five micro-scratch tests (for longitudinal direction and transversal direction) are presented in figure 10 and figure 11. The profilograms for the first scratch test (longitudinal direction) are shown in figure 12.

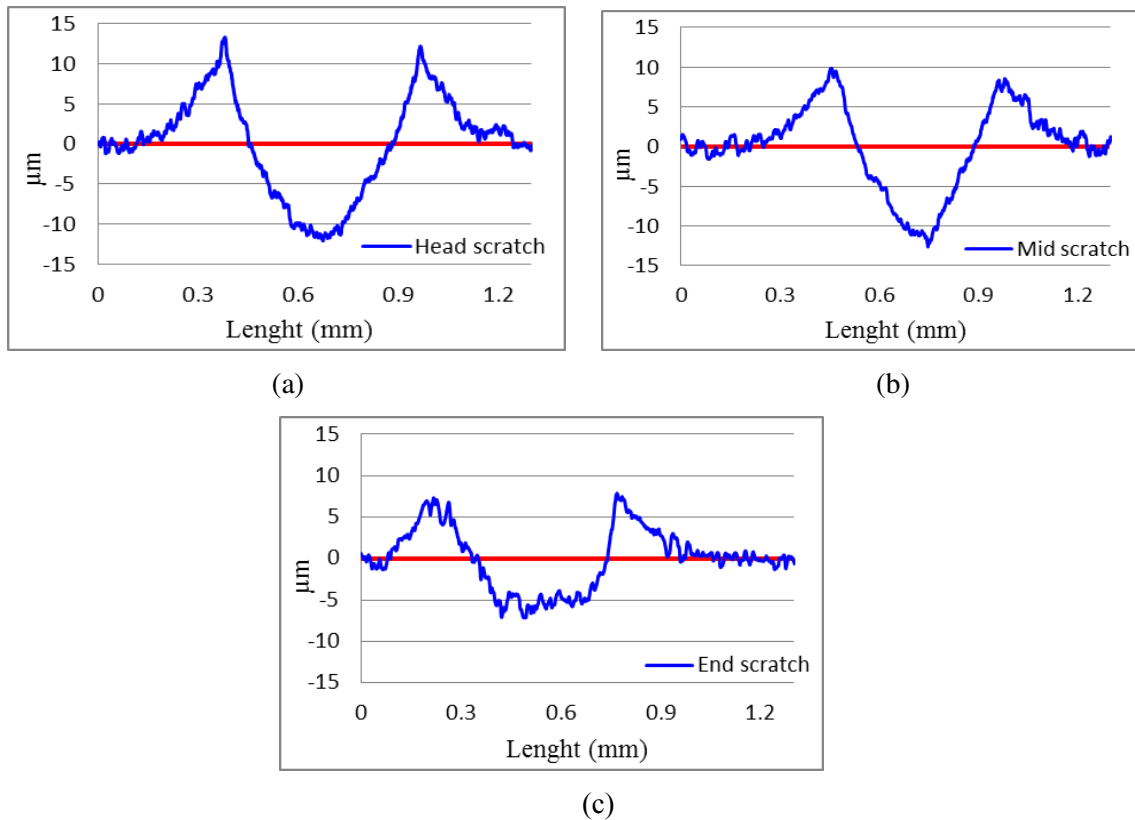


Figure 12. Profilograms for the first scratch test (longitudinal direction) at the beginning, middle and the end of the scratch channel.

The abrasion factor was calculated at the beginning, middle and the end of the scratch, using the principle of Zum Gahr. The calculated abrasion factors, for all tests, and their average are presented in table 3 and table 4.

The obtained values show a relatively important influence of the material anisotropy, especially regarding the ratio factor that has a variation from 4% to 30%.

Table 3. Abrasion factors for rolling longitudinal direction (LD).

| Scratch test | Head scratch | Middle scratch | End scratch | Ratio |
|--------------|--------------|----------------|-------------|--------|
| 1 | -0.41892 | -0.11949 | -0.11898 | -0.219 |
| 2 | -0.22165 | -0.42426 | -0.15980 | -0.269 |
| 3 | -0.32195 | -0.60129 | -0.19630 | -0.242 |
| 4 | -0.36294 | -0.41496 | -0.31339 | -0.364 |
| 5 | -0.41745 | -0.38424 | -0.25190 | -0.351 |

Table 4. Abrasion factors for transversal direction (TD).

| Scratch test | Head scratch | Middle scratch | End scratch | Ratio |
|--------------|--------------|----------------|-------------|--------|
| 1 | -0.34102 | -0.12499 | -0.16630 | -0.211 |
| 2 | -0.21360 | -0.43523 | -0.35275 | -0.334 |
| 3 | -0.32153 | -0.44334 | -0.30773 | -0.358 |
| 4 | -0.29634 | -0.37073 | -0.40975 | -0.359 |
| 5 | -0.47566 | -0.48230 | -0.36008 | -0.439 |

5. Conclusions

The aim of this paper was to determine whether there is a possible influence of the fractal nature of the surface on the apparent coefficient of abrasive friction. The samples used were plates of 10mm thickness, made of rolled aluminium alloy – AA2024-T351. The scratch tests were performed along two directions: a longitudinal one, corresponding to the rolling direction of the sample, and a transversal one. The impact of the anisotropic character of the material, due to the manufacturing process, was thus taken into account along with the desired parameters.

The micro-scratch tests were realized by moving a diamond stylus (micro-blade defined by a radius of 0.8 μm) along a specified trajectory (5mm length), maintaining a constant normal force (10N) and a uniform speed (0.2 mm/s). It can be observed an apparent coefficient of static-abrasive friction in the interval 0-4 s and a kinetic one after 4s.

Starting from a previous work, it was considered that the surfaces have a fractal behavior up to 1.1 μm and it was determined if there is any possible influence of this characteristic upon the coefficient of abrasive friction. It can be noticed that there is small influence of 3% on the coefficients of abrasive friction, both in the static and in the kinetic case, by the fractal surface behavior.

The results must be interpreted taken into account that the determined coefficient of abrasive friction is only an apparent one and not on a Coulomb friction coefficient. In a future work, to estimate the variation of Coulomb friction, smallest normal forces that 10 N will be considered.

Further tests along the diagonal direction DD must be added in the future in order to conclude on the influence of the anisotropy and of the fractal dimension.

The abrasion factor was calculated using the principle of Zum Gahr method. Measurements were made at the beginning, middle and at the end of the scratch channel. The obtained value for the abrasion factor was slightly less than zero, which confirms the good ductility of the aluminium alloy AA2024-T351 even for a micro-plastic process.

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