Influence of the cutting material on tool wear, surface roughness, and force components for different cutting speeds in face turning of CoCrFeNi high-entropy alloys

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Abstract. High-entropy alloys (HEAs) provide advanced properties like a high resistance to corrosion and wear. Concerning this and the elevated material costs wear protection layers are a possible field of application. Finish machining of these layers is necessary to achieve adequate surface properties. In the experimental investigations face turning of high-entropy alloy CoCrFeNi layers generated by spark plasma sintering is regarded. In this context, the influence of the cutting material and the cutting speed is analysed. For this, CBN tipped (two types), PCD tipped, CVD diamond tipped, and solid cemented carbide indexable inserts are used. Additionally, the influence of four different cutting speeds in the range between 100 m/min and 400 m/min is analysed. The feed and the depth of cut are kept constant with 0.05 mm and 0.1 mm, respectively. The geometrical surface properties are determined by tactile measurements and 3D laser scanning microscopy. The tool wear is analysed microscopically. Regarding the surface roughness, CBN tipped tools with a high content of boron nitride lead to the best results with the lowest roughness values irrespective of the cutting speed. The tool wear is also significantly reduced compared to the other cutting materials tested. The investigations represent the first results analysing the influence of the cutting material in machining of high-entropy alloys. Hence, this contributes to the enhancement of the field of application of HEAs.

1. Introduction
High-entropy alloys (HEAs) represent a relatively new material group with properties like a high resistance to corrosion and wear. They are characterised by a composition of at least four different elements with nearly equimolar proportions. Regarding the comparatively high costs of these materials, the application of HEAs as protection layers is reasonable. Especially in tribological applications finish machining becomes necessary. Processes with geometrically defined cutting edges provide a high geometrical flexibility. Next to the geometrical surface properties, an adaption of the physical properties of the surface layer (e.g. hardness, residual stresses) by these processes is possible. Machining is generally associated with tool wear. Hence, the tool geometry and resulting surface properties change. Accordingly, a low tool wear rate and long tool life, respectively are aspired. Next to the workpiece material, the tool wear is influenced by the cutting material and the machining parameters. Knowledge
of the relationships between machining parameters, tool wear, and resulting surface properties enables an adaption of the machining parameters depending on the state of tool wear. Additionally, the determination of an appropriate cutting material for machining of HEAs represents an important step for the application of HEA coatings in tribological systems.

Concerning the machining of high-entropy alloys only few results are published. In investigations of Clauß et al. [1] in turning of AlCoCrFeNiTi thermally sprayed HEA layers applied by atmospheric plasma spraying the influence of the cutting speed (100 m/min – 400 m/min) and the feed (0.05 mm, 0.1 mm) on the surface properties was analysed. The results showed a decrease of the surface roughness values with increasing cutting speed, as a consequence of the reduced proportion of pulled-out coating material. The minimum values for the surface roughness depth $R_z$, the reduced valley depth $R_{vk}$, and the valley void volume $V_{vv}$ of the machined surfaces were reached when using a cutting speed of 300 m/min. The small increase of the mentioned values for higher cutting speeds of up to 400 m/min was attributed to increasing tool wear. Additionally, the absolute values of the compressive residual stresses in the axial / feed direction decreased with increasing cutting speed.

Huang et al. [2] analysed the influence of the cutting material (CBN and diamond), the rotational speed (1,000 min$^{-1}$ – 2,500 min$^{-1}$), the feed (0.5 µm – 10 µm), and the depth of cut (0.5 µm – 20 µm) in face turning of Al80Li5Mg5Zn5Cu. Generally, the measured surface roughness depth was significantly higher in case of using CBN compared to using diamond tools. Increasing the rotational speed in the mentioned range led to slightly increased roughness values when using CBN tipped tools as a result of higher tool wear. For the use of diamond tools regardless of the cutting speed the measured roughness values correlated to the kinematic roughness. The use of CBN generally resulted in a higher tool wear and an increased thickness of the affected surface layer, as a consequence of the increasing friction between tool and workpiece compared to utilising diamond tools. Machining (rotational speed: 2,000 min$^{-1}$, feed: 5 µm, depth of cut: 8 µm) using CBN tipped tools led to a slight increase of the surface hardness (218 HV), whereas machining using diamond tools resulted in a decrease of the measured hardness (191 HV) compared to the raw material (211 HV).

Guo et al. [3] analysed the influence of different processes for finishing (EDM, electro and chemical polishing, grinding, milling, and process combinations) of CoCrFeMnNi high-entropy alloy specimens, produced by selective laser melting. The initial surface roughness ($R_a$ about 30 µm) could be reduced significantly by finishing. Grinding led to an arithmetic mean surface roughness $R_a$ of 4 µm. For EDM values of 3 µm were reached. However, milling allowed for the lowest surface roughness values represented by $R_a$ of 1 µm. Mechanical polishing offered the possibility to significantly reduce the surface roughness $R_a$ down to 0.003 µm. Additionally, grinding led to a surface hardness of about 350 HV0.2, EDM to about 400 HV0.2 and milling to about 450 HV0.2. As a result of the high forces and the plastic deformation, milling (about -700 MPa) and grinding (about -400 MPa) entailed strong compressive residual stresses after machining. It could be observed that after grinding and milling, respectively the microstructure was deformed in the cutting direction. Causing the higher cutting forces in milling compared to grinding, this disorientation was more severe in the case of machining with geometrically defined cutting edges.

The cutting material strongly influences the tool wear rate and the resulting surface properties after machining. This influence depends on the workpiece material. Additionally, the wear mechanisms of cutting tools are affected by the shear zone temperature. Depending on the cutting tool and the workpiece material composition softening of the cutting material as well as diffusion or adherence effects are possible. Concerning the few research studies and results in machining of high-entropy alloys, experimental investigations regarding the influence of the cutting tool material are necessary for upcoming tests analysing the effects of the machining parameters and the tool geometry. The material properties of the high-entropy alloy CoCrFeNi were properly analysed in numerous scientific material investigations. Accordingly, this alloy is appropriate for machinability investigations.
2. Experiments

2.1. Specimens
In the experimental investigations circular disc specimens of the high-entropy alloy CoCrFeNi were machined by face turning. To reduce the material consumption, substrates of the steel 1.4404 (AISI 316L) were utilised. These substrate discs exhibit a diameter of 40 mm and a thickness of 10 mm. The surface of these steel discs was roughened by grit blasting in order to achieve a good adhesion of the sintered coatings. On one face of the discs the high-entropy alloy layer was applied using spark plasma sintering (SPS). In this process, the HEA powder with a grain size of 20 µm to 50 µm was sintered using a constant pressure of 50 MPa. After a heating time of 10 min, a sintering temperature of 1050 °C was maintained for 5 min. The resulting thickness of the layers was about 3.5 mm. The substrates were used for clamping the specimens during the machining experiments. Hardness measurements at the unmachined specimens were conducted on the sintered surface. The values average out at 259 HV0.5.

2.2. Tools
For analysing the influence of the cutting material, five different grades were used applying indexable inserts of the type CCGW 09T304. The tools were characterised by a nominal rake angle of 0°. In connection with the tool holder used the cutting edge angle of the minor cutting edge was 5°.

Referring to the first published results for machining of thermally sprayed high-entropy alloys [1], a cutting tool with a CBN tipping characterised by about 90% – 95% boron nitride, a grain size of 1 µm, and a cobalt-based (metallic) binder was used (CBN 90). This cutting material is mostly used for machining grey cast iron. Additionally, a CBN tipped indexable insert with a proportion of about 50% boron nitride, 1 µm grain size and a ceramic binder was utilised (CBN 50). The cutting material with the equal proportion of boron nitride and binder is generally used for machining of hardened steels. Furthermore, indexable inserts with tips consisting of Polycrystalline diamond (PCD) and CVD diamond (CVD) were tested in the experimental investigations. Additionally, a cemented carbide (Carbide) indexable insert, characterised by a grain size of the WC particles less than 1 µm and a mass proportion of cobalt (binder) of about 6% was used.

To ensure comparable machining conditions, all indexable inserts provide a sharp cutting edge with a rounding of less than 10 µm. For a more detailed analysis, the cutting edges were recorded using a 3D laser scanning microscope Keyence type VK-9700. For the evaluation of the data the software MountainsMap® was used. In Table 1 the cutting edge radius for the different tools is shown. Although there were small differences regarding the cutting edge rounding, the change of the effective rake angle in relation to the parameters in the machining experiments was acceptable.

| Tool          | CBN 90 | CBN 50 | CVD  | PCD  | Carbide |
|---------------|--------|--------|------|------|---------|
| Cutting edge  | 2.8    | 7.6    | 3.6  | 3.7  | 5.7     |
| rounding (µm) |        |        |      |      |         |

2.3. Experimental investigations
The experimental investigations were carried out on a precision lathe SPINNER type PD 32. The specimens were clamped on the outer diameter of the substrate using a chuck. In the experimental investigations face turning was realised. To guarantee a constant cutting speed while machining, an increase of the rotational speed with decreasing radius of the tool engagement point was necessary. Concerning the limited rotational speed of the lathe and the acceleration of the rotational and the translational axes, machining the whole face with a constant cutting speed was not possible. Therefore the specimens were premachined by boring and internal turning. Afterwards, the specimens were characterised by an inner diameter of 25 mm and an outer diameter of 40 mm. The specimen geometry is shown in Figure 1.
Figure 1. Geometry of the specimens used: before (left) and after premachining (right).

The machining experiments were carried out at the ring-shaped surface between the inner and outer diameter which was characterised by a resulting width of 7.5 mm. This area was premachined in several steps to ensure similar starting conditions and to reduce the initial roughness using tools of the type CBN 90. Premachining and finish machining were done dry using a constant depth of cut of 0.1 mm and a feed of 0.05 mm. For premachining the cutting speed amounted to 200 m/min. The influence of the cutting material and the cutting speed was analysed according to the experimental design represented in Table 2.

Table 2. Experimental design.

| Experiment number | Cutting material | Cutting speed (m/min) |
|-------------------|------------------|-----------------------|
| 1 – 4             | CBN 90           | 100 200 300 400       |
| 5 – 8             | CBN 50           |                       |
| 9 – 12            | CVD              |                       |
| 13 – 16           | PCD              |                       |
| 17 – 20           | Carbide          |                       |

For each cutting material used the influence of four different cutting speeds was analysed. Thereby it was possible to influence the temperature in the shear zone. Hence, it was possible to define appropriate, but also not suitable ranges of cutting speed and temperature for the respective cutting materials regarding the tool wear and the resulting geometrical surface properties. Generally, the shear zone temperature increases with increasing cutting speed (see [4]). For every combination of cutting material and cutting speed the specimens were machined three times (three cutting steps). The tool was not changed between these experimental investigations. Tool wear and geometrical surface properties were analysed after one and after three cutting steps. In the experimental investigations the components of the resultant force were measured by a three-axis dynamometer Kistler type 9257A on which the tool was mounted.

2.4. Analysis of the tools and the specimens

After machining the influence of the cutting material and the cutting speed on the tool wear was evaluated. The tool wear was analysed using a 3D microscope Keyence type VHX-100, an optical microscope Nikon type MM-400, and a 3D laser scanning microscope Keyence type VK-9700. The tool
wear was evaluated qualitatively regarding the type of tool wear and also quantitatively by measuring the flank wear land width.

The geometrical surface properties of all specimens machined were analysed using a stylus instrument Mahr type LD 120. The stylus was characterised by a radius of 2 µm and an included angle of 90°. The measuring was done between the inner and outer diameter in the feed / radial direction. The measuring length was 4 mm. The filtering of the profile was done in accordance to ISO 11562. For a validation of the roughness values, each specimen was measured at five different positions. Additionally, the specimens were measured using a 3D laser scanning microscope Keyence type VK-9700. The size of the analysed area was 1 mm × 1 mm.

3. Results and discussion

3.1. Tool wear

After machining the tool wear was detected. As quantitative evaluation criterion the flank wear land width \( VB \) was analysed. Additionally, qualitative criterions like built-up edge formation or material adherence were regarded. The tool wear was detected after one and three machining steps. Generally, the relationship between cutting speed and tool wear depends on two simultaneously acting mechanisms. Increasing the cutting speed leads to an increased shear zone temperature resulting in a reduction of the strength of the cutting material or its binder. Additionally, increasing the cutting speed causes a quadratic increase of the kinetic energy of the workpiece material included hard phases like carbides.

The influence of the cutting material and the cutting speed on the flank wear land width is summarised in Table 3. Additionally, an indexable insert (CBN 90) before and after machining with the highest cutting speed is shown in Figure 2.

| Cutting material | Tool wear \( VB \) (µm) depending on the cutting speed |
|------------------|--------------------------------------------------|
|                  | 100 m/min | 200 m/min | 300 m/min | 400 m/min |
| CBN 90           | 30        | 40        | 50        | 65        |
| CBN 50           | 45        | 50        | 45        | 55        |
| CVD              | 110       | 65        | 110       | Cutting edge breakage |
| PCD              | 60        | 40–60     | 50        | 60        |
| Carbide          | 65–85     | 70        | 100       | 200       |

Figure 2. Indexable insert (CBN 90) detected by 3D laserscanning microscopy before machining (left) and by optical microscopy at the flank face after machining three specimens with a cutting speed of 400 m/min (right).

Generally, a continuous tool wear leads to an increase of the \( VB \)-values. The increase of the flank wear land width depends on the properties of the specimens, the tools, the process parameters, and the machined length. Regarding the predictability of this tool flank wear, the tool life time and the impact on the properties of the machined surfaces are also assessable.
The lowest tool wear was achieved by using the CBN tipped tools with the high proportion of boron nitride (CBN 90). The state of wear was characterised by flank wear. Nearly no chipping of the cutting edge occurred. The flank wear land width increased with increasing cutting speed. This was a result of the raising shear zone temperature and the subsequently decreasing strength of the cutting material binder. The decreasing strength and hardness with increasing temperature for cobalt and cobalt-based alloys was shown in [5] and [6]. Independent of the CBN properties (grain size, proportion of binder) there was a continuous decrease of hardness with increasing temperature (see [7]). Additionally, the increased kinetic energy of the workpiece material results in an easier separation of the BN grains from the binder. In [8] tools characterised by similar cutting material were used. In the experimental investigations a decrease of hardness and transverse rupture strength with increasing temperature was shown. In the analysed range of cutting speed the maximum flank wear land width was reached after three machining steps with the highest cutting speed \((VB = 65 \, \mu m)\). Additionally, it should be mentioned that after the first cutting step the flank wear land width of the tools was naturally lower (up to 30 \, \mu m). For cutting speeds of 100 m/min and 200 m/min nearly no tool wear could be detected after the first cutting step. Additionally, in the case of using CBN 90 independent of the cutting speed no built-up edge occurred after machining.

When using CBN with the lower proportion of boron nitride (CBN 50), for all cutting speeds similar values concerning the flank wear land width could be detected. The largest value was reached after machining with the highest cutting speed \((VB = 55 \, \mu m)\). All tools were characterised by severe cutting edge chipping after three machining steps. But the number and size of the microcracks increased with raising cutting speed and subsequently increasing shear zone temperature. This was caused by the reduced hardness and strength of the cutting material binder with increasing shear zone temperature. The effect of reducing the hardness with increasing temperature was shown for different ceramics in [9]. The ceramic binder of the CBN led to a less reduced transverse rupture strength with increasing temperatures compared to cutting materials with a cobalt-based binder. This was shown for similar tools in [8]. The transverse rupture strength for CBN with 85 % to 90 % boron nitride bounded by a metallic binder was about 140 kg/mm² at room temperature and decrease to 55 kg/mm² at 1000 °C. For CBN characterised by a proportion of 50 % - 55 % boron nitride and a ceramic binder, the transverse rupture strength (105 kg/mm² – 110 kg/mm²) was constant in the same temperature range. This effect results in the similar values for the flank wear land width depending on the cutting speed in machining of CoCrFeNi. Additionally, there was a higher proportion of binder in the cutting material. The strength between the boron nitride and the binder was lower when using a ceramic binder compared to the also utilised cobalt binder. Hence, the increased occurrence of cutting edge chipping could be explained. Additionally, no diffusion effects between the cutting material binder and the workpiece material were expected in the case of using CBN characterised by a ceramic binder. The results conform to experimental investigations with similar cutting materials [10], in which a more strongly increasing tool wear rate with increasing cutting speed in the case of using CBN with a high content of boron nitride and metallic binder compared to CBN with a lower content of boron nitride and a ceramic binder was also visible. This was caused by a more intensive diffusion between the metallic binder and the specimen material with increasing cutting speed. Additionally, changes in the thermal conductivity, defect density within the grains of the tool, and tribo-chemical effects have to be taken into consideration.

Diffusion effects between the iron within the high-entropy alloy and the cutting material were expected to be an essential wear mechanism when using CVD diamond or PCD tipped tools. The HEA used consists of about 25 at.% iron. This value is significantly lower than in iron-based alloys. For machining of iron-based alloys the use of diamond tools is not common. Concerning other HEAs with a higher number of different elements, the proportion of iron is minor and it is expected, that the diffusion effect and subsequently the tool wear could be reduced. For a raising cutting speed, the increasing tool wear, for example the size and proportion of microcracks or the cutting edge chipping, could be explained by the higher temperatures in the shear zone. The increased temperatures accelerated the diffusion mechanisms. Additionally, when using PCD, there was again a softening of the cutting material binder. After machining, the CVD and PCD indexable inserts were characterised by material
adherence (built-up edge). In case of machining with the highest cutting speed, the CVD tool broke at the cutting edge.

The cemented carbide tools showed the highest flank wear land width after machining. After three machining steps with a cutting speed of 400 m/min the highest flank wear land width occurred \((V_B = 200 \, \mu m)\). This was twice the flank wear land width compared to machining with a cutting speed of 300 m/min. The cutting material consisting of tungsten carbide particles bound by cobalt is typically not used in this range of cutting speeds. Cemented carbides do not belong to the super-hard cutting materials, like the others used in the experiments. Concerning this, the high tool wear and especially the differences between machining with cutting speeds of up to 300 m/min and 400 m/min were caused by the increased thermal softening of the cutting material. For all cutting speeds the formation of a built-up edge was visible after machining.

3.2. Components of the resultant force

The components of the resultant force were measured while machining. In Figure 3 the influence of the cutting material on the cutting force \((F_c)\), the passive force \((F_p)\), and the feed force \((F_f)\) is shown. The mean values were calculated from the average values of the components of the resultant force disregarding the different cutting speeds. For the experiments, the respective mean values were calculated in the range of a theoretically constant cross-section of the undeformed chip. The first contact and subsequent raising of the cross-section of the undeformed chip as well as the decreasing cross-section of the undeformed chip at the end of the cutting process were omitted. The averaging for different cutting speeds was possible, because there was only a small difference between the mean values of the components of the resultant force for the different cutting speeds. This difference was smaller than the variation of the values during machining of the single specimens. The scattering bars shown in the diagram represent the highest and the lowest mean value out of the four single experiments.

**Figure 3.** Influence of the cutting material on the components of the resultant force \((f = 0.05 \, \text{mm}, a_p = 0.1 \, \text{mm})\).

For every cutting material used the cutting force represented the largest component of the resultant force followed by the passive and the feed force. Regarding the super-hard cutting materials, a slight increase of the average force components for the third cut compared to the first cut was visible. This resulted as a consequence of the progressing tool wear. In case of using cemented carbide tools, the average components of the resultant force slightly decreased with a higher number of machining steps. This
could be explained by the increasing tool wear as well. Regarding the comparatively high tool wear rates, the tool wear resulted in an offset of the cutting edge leading to a decreased cross-section of the undeformed chip. For all cutting materials the respective components of the resultant force were in a similar range, which can be explained by the constant cross-section of the undeformed chip. Although changes in friction between tool and specimen as well as the plastic deformation in the shear zone were expected (in particular comparing CBN and diamond) no tendencies were visible, especially regarding the spread of the values.

3.3. Geometrical surface properties

The geometrical surface properties of the machined specimens were determined by tactile measurements. Figure 4 shows the influence of the cutting material on the arithmetic mean surface roughness $Ra$ and the surface roughness depth $Rz$. Regarding the relatively high number of different cutting conditions (cutting material, cutting speed, number of cutting steps), only the results of the cutting experiments performed with a cutting speed of 300 m/min are represented in the diagram. There were also small differences concerning the cutting speed detectable, but the influence of the cutting material was more dominant. The respective surface parameters were determined after machining one and three cuts to analyse the influence of the tool wear on the geometrical surface properties. The scattering bars shown represent the respective minimum and maximum of the five single measurements.

For all cutting speeds and cutting materials tested a kinematic roughness surface profile was visible. This was characterised by valleys and peaks representing the corner radius of the tool. The distance between these valleys and peaks corresponded to the feed of 0.05 mm. Generally, the roughness values were higher than the calculated kinematic roughness ($Rz_{\text{kin}} = 0.78 \, \mu m$). The lowest values for one machining step were reached in the case of using the CBN with the high proportion of boron nitride (CBN 90) as cutting material. The mean values for $Ra$ and $Rz$ were only slightly higher in the case of utilising CBN with the higher proportion of binder (CBN 50) after the first machining step. Regarding that both cutting materials led to the best results concerning the geometrical surface properties and the tool wear resistance, the results depending on the cutting speed are discussed more in detail. Only concerning each firstly machined specimen the use of cemented carbide resulted in similar values like
CBN 50. Utilising indexable inserts with PCD or CVD diamond tips led to the highest values of the analysed surface roughness parameters.

Machining using CBN as cutting material led to slightly higher friction between tool and specimen resulting in a slight smoothing of the surface and a small compensation of the higher surface roughness due to the cutting edge chipping. Utilising PCD or CVD diamond resulted in a more defined cutting at the cutting edge, less friction between tool and specimen, and subsequently a higher surface roughness following to the cutting edge chipping. This chipping was higher in the case of using diamond tipped tools (PCD and CVD) compared to CBN tipped tools as a result of the increased tool wear. For all cutting material used, the surface roughness values were higher after three machining steps compared to the first step. The increasing tool wear and cutting edge chipping resulted in raising mean values for $Ra$, $Rz$, and $Sa$.

Concerning the geometrical surface properties and the tool wear CBN seemed to be the cutting material to prefer in the analysed range of the cutting speed. Hence, the influence of the cutting speed on the surface roughness depth $Rz$, the arithmetic mean surface roughness $Ra$, and the areal parameter $Sa$ for using tools with tips from different types of CBN (CBN 50 and CBN 90) was analysed in detail (Figure 5). The diagram shows the highest and the lowest values of five tactile measurements and the results of the measurements using the 3D laser scanning microscope.

![Figure 5](image.png)

**Figure 5.** Influence of the cutting speed and the cutting material on the arithmetic mean surface roughness $Ra$, the average roughness $Sa$, and the surface roughness depth $Rz$ ($f = 0.05$ mm, $a_p = 0.1$ mm, values after first machining step).

In the case of using CBN 90 similar mean values were detected irrespective of the cutting speed. However, higher surface roughness values were measured after machining with a cutting speed of 100 m/min, while a slight tendency of decreasing mean values with increasing cutting speed was apparent. This could be a result of the increased temperature in the shear zone and a subsequent softening of the specimen material. In the case of using indexable inserts with CBN 50 as cutting material, generally higher surface roughness values were measured. However, after machining with a cutting speed of 300 m/min similar surface roughness values compared to using CBN 90 were measured. For the three other cutting speeds regarded, significantly higher mean values for $Ra$, $Rz$, and $Sa$ occurred when using CBN 50. These qualitative differences between machining with a cutting speed of 300 m/min and the other cutting speeds were also visible after three machining steps. The second highest
cutting speed regarded represented a suitable range of the cutting speed for machining these high-entropy alloys with CBN 50. Additionally, the tool wear was the lowest after machining with this cutting speed when using CBN 50. The cutting edge chipping was also minor after machining with a cutting speed of 300 m/min resulting in decreasing roughness values.

4. Conclusions and outlook
The investigations and results represent the first experiments analysing the influence of the cutting material and the cutting speed when machining spark plasma sintered high-entropy alloys consisting of the elements cobalt, chrome, iron, and nickel. In the experimental investigations, comparable mean values of the resultant force could be detected while face turning the HEA specimens with different parameters. The lowest surface roughness values could be achieved when using CBN tipped tools characterised by a high proportion of boron nitride. This was possible in the full range of cutting speeds applied. Additionally, these tools showed the lowest wear. Summarising, for face turning of the HEA CoCrFeNi indexable inserts with CBN tips exhibiting a high content of boron nitride should be preferred. Additionally, the determination of the surface layer properties, like residual stresses, grain size, grain orientation, and hardness contributed to a deeper understanding in machining of HEAs with different cutting materials.

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