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SHOT PEENING AND VALVE FATIGUE

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ABSTRACT

Shot peening can be used as one of the finishing operations in manufacturing of compressor valves. During this process, a material deformation hardening on the surfaces is reached and the induced residual stresses are generally considered as beneficial with respect to the fatigue life. A study was made to evaluate the influence of the shot peening on the valve material fatigue. The fatigue data are presented in view of the surface and sub-surface residual stresses, their relaxation during dynamic loading and the resulting surface topography for two standard valve steels AISI 1095 (1 % C) and AISI 420 (0.38 % C, 13.5 % Cr, 1 % Mo). Some practical hints on the relevance of the shot peening treatment for high strength valve steels are given.

INTRODUCTION

The development efforts aiming at increased fatigue performance of compressor valves include besides design aspects such as modification of the valve lift, valve speed, improved cushion at guard or seat (1-4), also materials and valve treatment (5, 6). Shot peening is one of the well known finishing techniques applicated in cases when the machine component contains geometrical notches or other stress raisers. There is experimental and empirical evidence showing improvement in fatigue durability of components such as gears, shafts etc, fabricated from low strength or medium strength materials with UTS below 1400 MPa (200 ksi) (7). The effect of the shot peening on thin valves and reeds from high strength materials with UTS above 1800 MPa (260 ksi) is, however, more unclear particularly at high cycle fatigue above 10^6 loading cycles and high loading rates. Furthermore, there are also significant costs involved in valve finishing by peening technique. The aim of this work was to contribute to the basic understanding of the effect of shot peening of the fatigue behaviour of valve steels.

MATERIALS

Two standard steels, UHB 20C and UHB Stainless 716, strip thickness 0.38 mm (0.015 in) were used. Both materials were cold rolled, hardened and tempered. The material data are presented below:

Chemical composition (wt %)

| Grade UHB | C | Si | Mn | Cr | Mo |
|---------------|------|-----|------|------|-----|
| 20C | 1.0 | 0.3 | 0.4 | | |
| Stainless 716 | 0.38 | 0.5 | 0.45 | 13.5 | 1.0 |

Tensile strength and hardness

| Grade UHB | Tensile strength | | 0.2 % offset Yield strength | | HV 300 N |
|---------------|------------------|-----|-----------------------------|-----|----------|
| | MPa | ksi | MPa | ksi | |
| 20C | 1930 | 280 | 1770 | 257 | 550 |
| Stainless 716 | 1870 | 271 | 1580 | 229 | 560 |

The cantilever bending specimens, Fig 1, were used for the peening treatment. After blanking the samples were tumbled 48 hours and polished 45 min. The peening was made as a final operation.

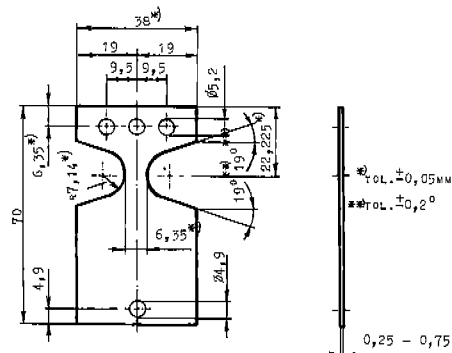


Fig. 1 Cantilever specimen used for bending fatigue test.

SHOT PEENING

In this process small hard particles, shots, are blasted on the surface with high velocity. This is the most versatile of the surface-stressing techniques, applicable to metals and machine components of various shape. The peening action results in a number of changes in the exposed surface and subsurface. Since the shot peening, like other mechanical working processes, involves localized plastic deformation, it is believed that the surrounding, unexposed elastic material forces the permanently deformed region back towards its original dimensions and thereby inducing a residual compressive stress in the surface layer.

Depending on the type of the shot, its size, velocity, duration of the peening process and the treated material properties, the maximum compressive stress can reach approx. 80 % of the material's yield strength. The beneficial effect produced by the residual compressive stresses is determined by their magnitude and depth in relation to the applied tensile stresses and the defects present in the surface and subsurface layer where the fatigue fracture starts. It is empirically known that shot peening is effective in components that contain a stress concentration or stress gradient. An unavoidable condition is that the compressive stresses are not relaxed due to the exposed external load or temperature.

In this work a full scale experiment was applied at peening of fatigue samples. The aim was a uniform treatment on edges and surfaces. The air pressure monitored by a pressure generator is given instead of Almen intensity (7):

Processing parameters

| Peening pressure psi | Exposure time h |
|-------------------------|--------------------|
| 20 | 0.5 |
| 20 | 1.0 |
| 40 | 0.5 |
| 40 | 1.0 |

The cast steel shots according to SAE J444a, diameter 0.1-0.4 mm, hardness 50 HRC, were used.

The shot peening resulted in somewhat increased surface roughness compared to tumbled samples, see below:

| Grade UHB | Shot peening psi/h | Surface roughness μm | | | |
|---------------|-----------------------|------------------------------------|-----------|------|-----|
| | | R_a | R_{max} | CLA | MAX |
| 20C | tumbled | 0.08 | 1.5 | 3.1 | 60 |
| | 20/0.5 | 0.15 | 1.4 | 6.0 | 56 |
| | 20/1.0 | 0.13 | 1.5 | 5.1 | 60 |
| | 40/0.5 | 0.25 | 2.1 | 10.0 | 83 |
| | 40/1.0 | 0.29 | 2.6 | 10.4 | 102 |
| Stainless 716 | tumbled | 0.08 | 1.3 | 3.1 | 51 |
| | 20/0.5 | 0.16 | 2.0 | 6.3 | 79 |
| | 20/1.0 | 0.18 | 1.9 | 7.1 | 75 |
| | 40/0.5 | 0.24 | 2.0 | 9.4 | 79 |
| | 40/1.0 | 0.23 | 2.6 | 9.1 | 102 |

Fig 2 illustrates the surfaces as observed in scanning electron microscope. The visual appearance was similar to the tumbled treatment for both examined materials. At the highest peening pressure a tendency to shallow holes representing the shot prints into the surface was more pronounced.

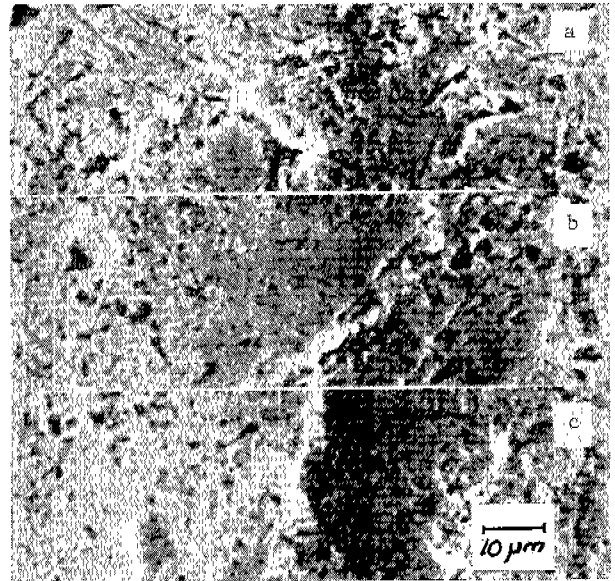


Fig. 2 a-Tumbled surface. b-Peened 20 psi/0.5h. c-Peened 40 psi/0.5h. Note the shallow shot prints.

RESIDUAL STRESS DISTRIBUTION

The residual stresses were determined by X-ray diffraction. For subsurface measurement the surface layer was removed by electrolytical polishing. To take into account the stress relief due to the surface removal the correction suggested by Moore and Evans was applied (8). A stress measurement was performed on the cantilever specimens, Fig 1, before and after fatigue testing. The measurement direction was identical with the principal stress orientation at the bending fatigue test, Fig 3.

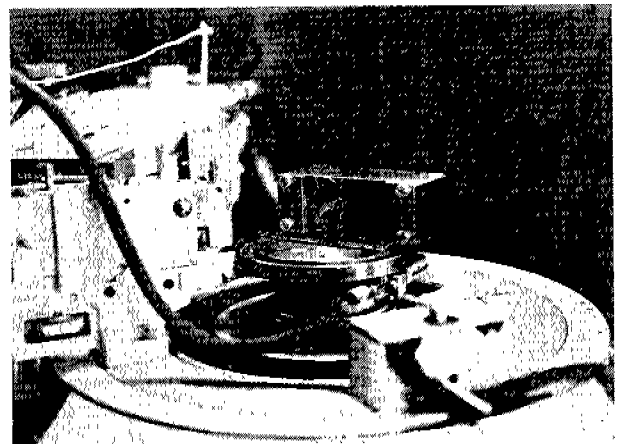


Fig. 3 X-ray stress measurement on a Siemens diffractometer.

The deformation hardening process is more evident in material with lower yield strength. At the same hardness and surface treatment UHB Stainless 716 shows somewhat higher compressive stresses than UHB 20C. The residual stress distribution in tumbled and shot peened fatigue samples is shown in Fig 4 and 5. For both finishing treatments the magnitude of the surface compressive stresses varies in a narrow range. The UHB 20C showed -600 to -700 MPa (-87 to -100 ksi) while UHB Stainless 716 gave -700 to -800 MPa (-100 to -115 ksi).

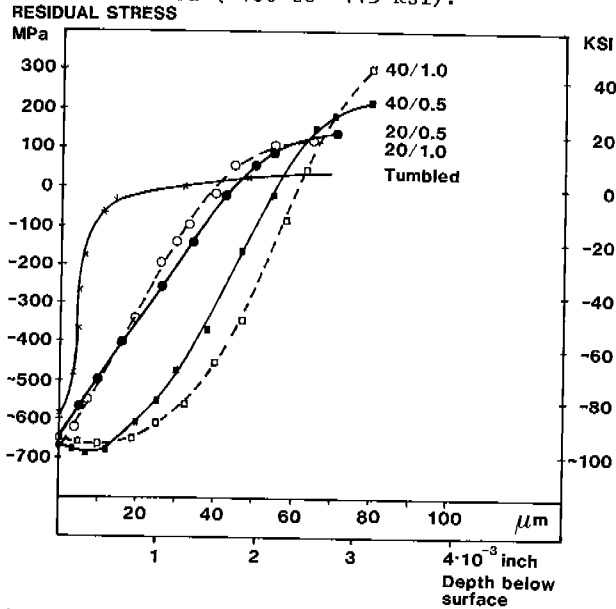


Fig. 4 Residual stress distribution after tumbling and shot peening (psi/h), UHB 20C, thickness 0.38 mm (0.015 in).

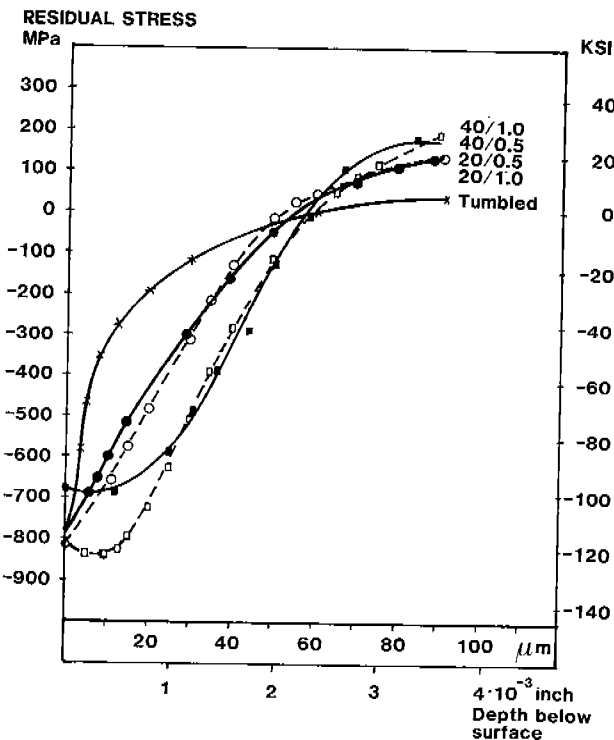


Fig. 5 Residual stress distribution after tumbling and shot peening (psi/h), UHB Stainless 716, thickness 0.38 mm (0.015 in).

The differences in the subsurface stress distribution are more significant. The tumbling treatment resulted in the compressive stresses being concentrated in a very thin surface layer. It is visible that the compressive stresses decrease sharply and in the depth of 10 μm reach very low values. It is clear that the main benefit of tumbling is to remove the notches and other stress raisers caused by blanking.

The shot peening treatment resulted in much deeper residual stresses than the tumbling finishing. The peening pressure seems to control the depth and the size of the residual stresses while the influence of the exposure time is less evident. The peening pressure of 20 psi gave in all cases more or less linearly decreased stresses into the depth of 40-50 μm . The treatment with 40 psi resulted in distinctly deeper stresses, Fig 4 and 5. The compression in the surface and subsurface layer is balanced by tension in the depth above 50 μm . The detected stresses correspond to previously reported data for valve steel (6).

FATIGUE TESTING

The tumbled and shot peened specimens were fatigue tested in a SONNTAG SF-2-U machine. The series of cantilever specimens were exposed to a reversed bending stress, stress ratio $R_s = \sigma_{\text{min}} / \sigma_{\text{max}} = -1$, and the fatigue limits were detected for $2 \cdot 10^6$ loading cycles. More details on the testing procedure and the data evaluation can be found elsewhere (5).

The calculated fatigue limits defined as the stress at which 50 % of the samples failed within $2 \cdot 10^6$ loading cycles are shown in Fig 6. It should be noticed that the shot peening resulted in very small changes of the fatigue strength. The detected variations in the fatigue limits are less than 5 % and are comparable to the standard deviation at fatigue testing. The variations in fatigue strength is roughly comparable with endurance limit improvement noted by Wollatt in fatigue test machine (9). There is a modest increase which culminates at 20 psi/1 h for UHB 20C and at 40 psi/0.5 h for UHB Stainless 716.

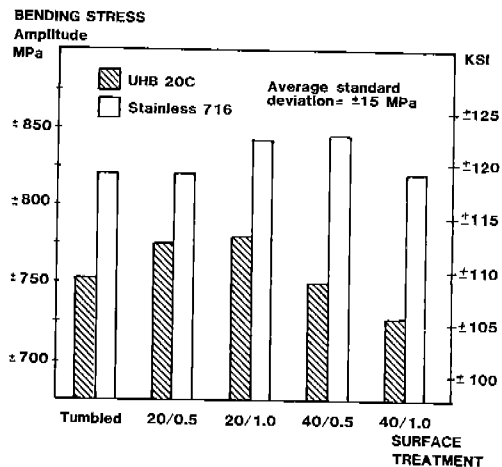


Fig. 6 Bending fatigue strength for tumbled and shot peened (psi/h) valve steels. Reversed bending, stress ratio $R_s = -1$, $2 \cdot 10^6$ loading cycles.

The "optimum" peening pressure for used shots is probably between 20 to 40 psi. The declining tendency noted for both materials can probably be explained due to the surface deterioration caused by the peening treatment which is favoured by the high peening pressure and by the extended exposure time. Note that UHB Stainless 716 showed consistently higher fatigue strength than UHB 20C.

It is believed that the compressive stresses induced in the surface and subsurface are reducing the superimposed tensile stresses generated at reversed bending. This is, however, under condition that the initially induced stresses from the mechanical working processes are not changed due to the temperature or external load. Furthermore, the depth of the "non-relaxed" residual stresses should be higher than the depth of the defects considered as potential crack starters at actual fatigue loads.

Based on the experimental results it can be stated that the documented fatigue data showed no improvement of practical significance. The probable explanation is indicated below.

STRESS RELAXATION

The small variations in fatigue strength gave reason to check the residual stresses after fatigue testing. The surface and subsurface stress measurements were performed on the fatigued specimens under the same conditions as on the peened samples.

The results are shown in Fig 7. It is visible that surface and subsurface stresses are drastically relieved from the initial level of -700 MPa (-100 ksi) down to -50 MPa (7 ksi) to -200 MPa (-30 ksi) in both materials.

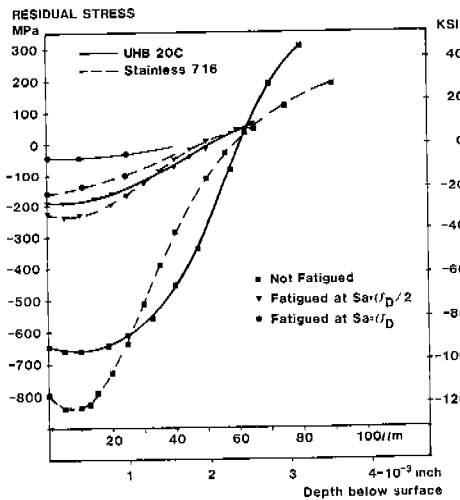


Fig. 7 Residual stress distribution after shot-peening (40 psi/1h) and stress relaxation due to dynamic loading, reversed bending, stress ratio $R_s = -1$, $2 \cdot 10^6$ loading cycles. The fatigue limit $\sigma_D = 730$ MPa (106 ksi) for UHB 20C and $\sigma_D = 820$ MPa (119 ksi) for UHB Stainless 716.

The magnitude of the stress relaxation and the final low stress level is hard to explain with respect to the fatigue stress level and the high yield strength of the tested materials. However, if the yield strength of the surface layer, where the relaxation primarily takes place is lower, then the phenomenon is easier to understand.

In order to determine the yield strength in the surface, the tensile tests were performed on samples of different thickness. The thickness reduction was made by electrolytic polishing. Furthermore, the simultaneous measurement of the stress/strain was made by x-ray and strain gage in order to detect the difference between the outmost surface layer and the bulk material yielding. The tensile load was applied by a special device assembled in the x-ray diffractometer.

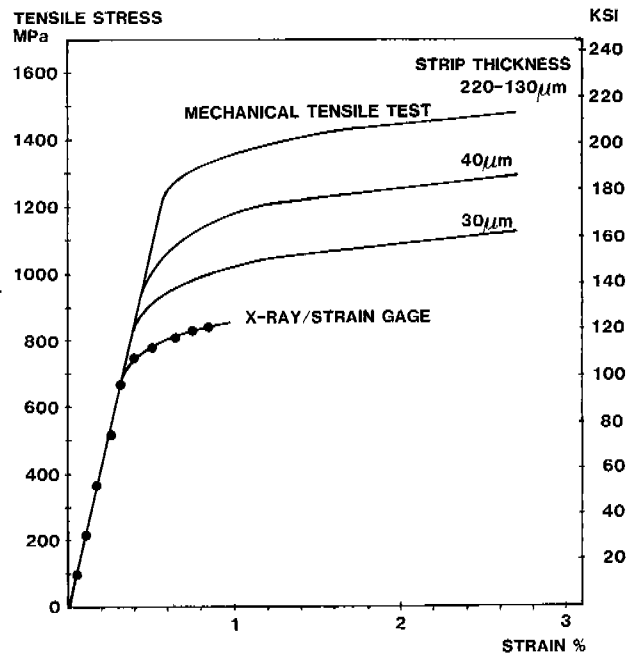


Fig. 8 Uniaxial tensile tests on samples with different thickness, UHB 20C, initial strip thickness 0.22 mm (0.009 in), UTS 1500 MPa (218 ksi).

As can be seen in Fig 8, a smaller thickness gives a decreased yield strength. The yield strength of the surface layer was estimated to 60% of the bulk yield strength. The similar results were found for UHB Stainless 716, UTS 1950 MPa (285 ksi), Fig 9, and for soft steels (10, 11).

It was shown, that the yielding starts in the surface earlier than in the bulk material. This phenomenon is associated with the constraint effect created by the material elements, grains, which are supported by surrounding grains. This support is absent at the outmost surface layer which therefore is far more sensitive to the plastic deformation.

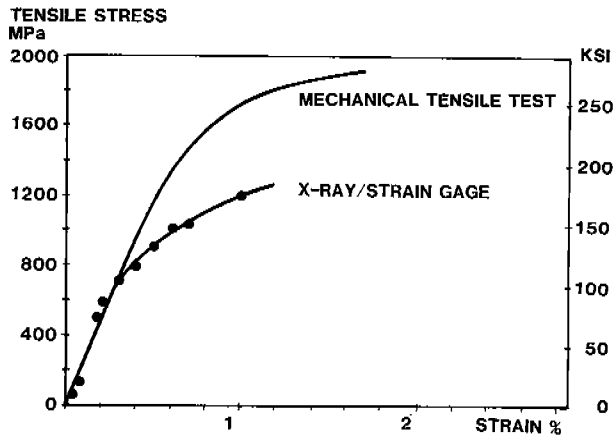


Fig. 9 Detection of the difference between the bulk and surface yielding at uniaxial tension, UHB Stainless 716, strip thickness 0.2 mm (0.008 in), UTS 1950 MPa (285 ksi).

The size of the stress relaxation is a direct consequence of the low surface yielding and exposed fatigue stress. The detected relaxed stresses are governed by the difference between the surface yield strength and applied stress amplitude. The stress relaxation takes place at an early stage. When the shot peened material reaches the relaxed stress level -50 MPa (-7 ksi) to -200 MPa (-30 ksi) the positive effect of the residual stresses created by shot peening can hardly be more favourable than the residual stresses introduced by a conventional finishing such as tumbling. The detected fatigue data support this conclusion.

VALVE FATIGUE AND BENEFIT OF SHOT PEENING

The fatigue process consists of three stages. The initial fatigue damage leads to the crack initiation. Thereafter the stable crack grows until the remaining uncracked cross section is unable to carry the imposed loads and the final sudden fracture. It is known that a fatigue crack is generated by tensile stresses. There is experimental evidence that the crack growth is relatively insensitive to the compressive loading (12).

The effect of the residual compressive stresses is to cause the defect or crack to remain closed until the externally applied tensile stress can overcome their action. This is the case when the superimposed stresses are higher than the threshold stress intensity necessary for the fatigue crack initiation and subsequent crack growth. According to Willenborg et al (12) the effective stress intensity factor range, ΔK_{eff} , is defined as a sum

of the applied ΔK_{app} and the residual stress intensity factor ΔK_{res} :

$$\Delta K_{eff} = \Delta K_{app} + \Delta K_{res}$$

In high strength materials the crack initiation is completely dominant from fatigue point of view (5, 13) and accounts for more than 99% of the total

fatigue life. Considering that the requirements on the total valve fatigue life are often in the range of 10^{10} - 10^{12} and the relaxation of the compressive stresses is completed within 10^5 - 10^6 loading cycles it seems to be understandable that an expected improvement from shot peening can hardly be correlated to the initial size of the residual stresses.

One can state that the bending stress levels used in this experiment were too high and notified relaxation is a result of that. Beside that the shape of the used specimens makes, that at bending loading the layer where the compressive stresses are concentrated will be loaded as the surface.

In practice, the peening is applied when an improved fatigue strength is desirable at valve fracture or when the safety margin is insufficient at higher valve lift, valve speed etc. Such cases are, however, often characterized by severe overloading and there is no doubt that the exposed stresses can often be higher than the fatigue strength of the unnotched materials. Despite far more complicated loading modes experienced by the valves, the relaxation process in the material is expected to be similar to that observed in laboratory. The shape of the compressor valve is relatively simple and no obvious stress raisers due to the design appear. However, at practical tests a certain increase in fatigue life on shot peened valves can be observed. This is probably determined by the time necessary for accomplishment of the relaxation process at a given load spectrum exposed to the valve.

There is a well defined volume of the material exposed to the maximum stressing at a given load mode and number of cycles at laboratory fatigue tests. However, in compressor the valve is exposed to the stressing randomly and at a certain number of loading cycles the comparable material volume is not experiencing the same stressing as the fatigue sample. The result is the delayed relaxation process and probably also increased number of cycles prior to the final fracture. This has a limited significance for fatigue life considered for valve components. If possible, the safety margin should be evaluated with respect to the stress amplitude experienced by the valve and material's fatigue limit at stipulated probability of fracture.

The presented fatigue results indicate that in case of insufficient fatigue strength exhibited by plain carbon steel the application of tumbled valves made from martensitic stainless valve steel is the most favourable solution from valve treatment and material point of view.

CONCLUSIONS

- The residual compressive stresses created by shot peening are induced to a higher depth than the stresses induced by conventional tumbling.
- The size of the residual stresses is controlled rather by the shot's velocity than by exposure time.

- The deformation hardening at peening treatment is more efficient in martensitic stainless steel.
- Concerning the fatigue strength no improvement of engineering significance was detected in both plain carbon steel, UHB 20C and martensitic stainless steel UHB Stainless 716 at laboratory test. The explanation can be found in the stress relaxation process which takes place at an early stage at dynamic loading.
- Martensitic stainless steel is recommended for compressor valve applications where the carbon steel gives insufficient fatigue performance.

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