EXTENDING THE FATIGUE LIFE OF AEROSPACE MATERIALS BY SURFACE ENGINEERING

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ABSTRACT

The effect of shot peening on the fatigue resistance of a 7150-T651 aluminium alloy was studied using an in situ four point bending fatigue machine under an optical microscope. The tests results showed that the fatigue lives for peened specimens are longer than those for unpeened specimens, over a wide range of applied stress. They also showed that the crack growth rate of the failure crack increased steadily in unpeened specimens while in peened specimens there was an initial decrease to a minimum, occurring when the crack length was equal to the peening depth. The potential of extending the life of fatigue damaged components was investigated by shot peening specimens which had been fatigue damaged to different degrees. The results indicated that cracks shorter than the peening depth were arrested by shot peening. However, little benefits are achieved in terms of life extension by shot peening specimens with fatigue cracks longer than the peening depth. The 7150 alloy is very sensitive to the shot peening conditions used. Inappropriate peening leads to early crack formation and shorter fatigue life. A fatigue crack model incorporating shot peening effects is used to predict fatigue life of peened specimens.

INTRODUCTION

Of the various types of structural failures, fatigue is considered to be the most important and crucial mechanism. One method used for preventing or delaying crack initiation and propagation is to introduced a compressive stress on the material by means of shot peening. The common belief is that this treatment introduces a residual compressive stress and that it is more difficult for fatigue cracks to initiate and propagate under these conditions [1 - 3].

Most of the work carried out up to date on the effects of shot peening on fatigue does not consider the important aspects of initiation and propagation of cracks. However, it is well known now that fatigue crack growth in the earlier stages is affected by the microstructure and by the mechanical and work-hardening state of the material [4 - 7]. Shot peening, besides inducing compressive residual stresses, severely distorts the crystalline structure, which there has a marked effect on crack initiation and propagation.

The major objective of this work is to determine the effect of shot peening on fatigue crack initiation and propagation in 7150-T651 aluminium alloy, which is a relatively new material widely used by the aerospace industry in the top wing skin of aircrafts. This will lead to a better understanding of the reasons behind the observed improvement in fatigue life, and to the optimisation of the shot peening process in terms of fatigue resistance.

EXPERIMENTAL PROCEDURE

Material

The material under investigation was a 7150-T651 aluminium alloy, with an elastic modulus in the range 71-75 GPa, a chemical composition of (%): Si - 0.12, Fe - 0.15, Cu - 1.9-2.5, Mn - 0.1, Mg - 2-2.7, Cr -0.04, Zn - 5.9-6.9, Ti - 0.06, remainder Al and mechanical properties as yield strength: 450 MPa, tensile strength: 530 MPa, elongation: 2.5% [8].

Specimen preparation

Aluminium 7150-T651 alloy in the form of 25 mm thick plate was used for the tests. Average sizes of the specimens were 6.5 mm thick, 4.6 mm wide and 80 mm long. Some specimens were shot peened using the process parameters given in Table 1.

TABLE 1
SHOT PEENING PARAMETERS

Almen intensity	Shot diameter, mm	Pressure, psi	Shot type	Time, s
14A	0.8	55	Cast steel	15

Metallography

Unpeened specimens

Because the 7150-T651 aluminium alloy was obtained in the form of rolled plate, the alloy had a preferred grain orientation. The average grain sizes were as follows: 28.5 μm in the longitudinal direction, 14.3 μm in the transverse direction, 9.3 μm in the short transverse direction.

Shot-peened specimens

The metallography revealed that the depth of the compressed layer was approximately 0.1-0.2 mm. This depth could be evaluated observing the short-transverse section of the specimen. The average grain size in the short-transverse direction was 7.8 μm, which is less than for the unpeened specimen.

Loading conditions

Fig. 1 shows the four point bend loading configuration used, where c = 21.8 mm and a = 22.1 mm. The four point bend facility was purposely designed for in-situ testing, using an optical fatigue damage viewing facility. It provides the possibility of continuously monitoring crack propagation during a fatigue test. It is a simple matter to stop the test, scan the specimen gauge surface to find points of interest and then, when a crack has formed, continuously monitor it up to failure or until the crack has reached the required length. A frequency of 15 Hz and a stress ratio of 0.1 were used in the tests.
The specimens loading conditions are listed in Table 2.

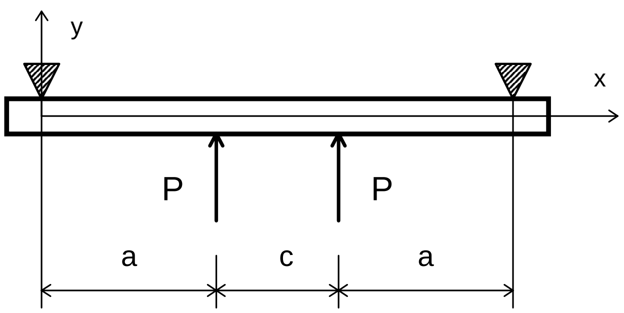


Figure 1. Specimen loading configuration.

TABLE 2

SPECIMENS LOADING CONDITIONS

Specimens	Maximum stress, MPa	Δσ, MPa
Unpeened	380-480	342-432
Peened	420-500	378-450

Crack detection and measurement

The method used for crack detection in this work was direct observation with the optical microscope. The image of the crack is captured by a video camera and displayed on the video unit of an image analysis system. Using a mouse, the crack is traced and its measurement is displayed on the computer screen.

RESULTS AND DISCUSSION

Observation of cracks in the optical microscope revealed that dominant cracks grow as surface cracks in unpeened specimens and as corner cracks in peened specimens. Initially they have a semi-elliptical shape with a ratio of crack depth to crack length of approximately 0.25 but then they assume approximately a semi-circle or quarter of a circle shape.

Crack length measurements were used to calculate crack growth rates using the secant method. The fatigue life test results are presented in Fig. 2 which shows how peening improves the fatigue resistance.

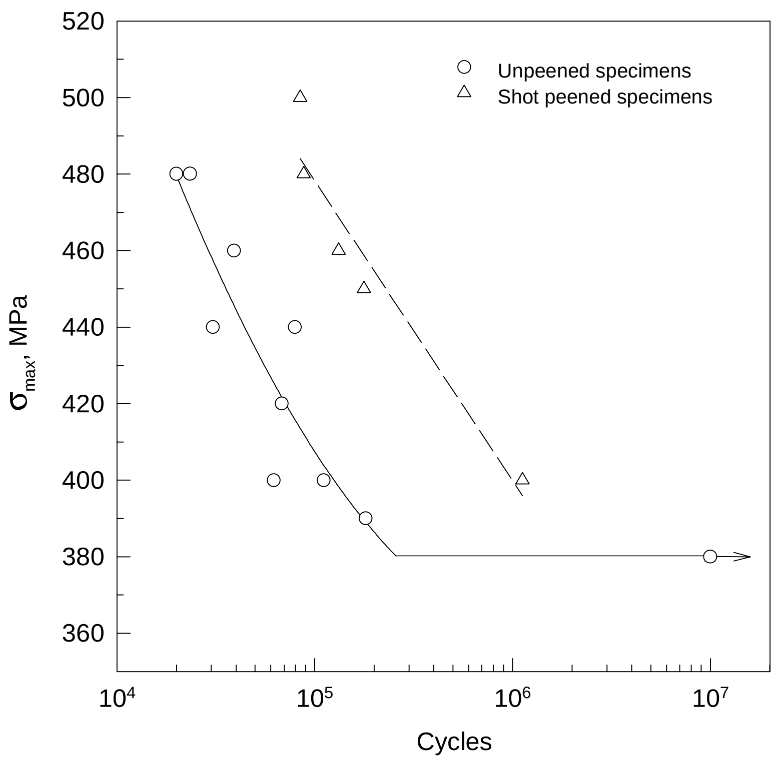


Figure 2. Experimental S-N curves for unpeened and peened specimens.

The improvement of fatigue resistance by shot peening is further illustrated in Figs 3 and 4, comparing crack growth data of unpeened and peened specimens tested at comparable stresses. These graphs show clearly that the beneficial effect of shot peening is greater in the earlier stages of crack development and growth. Shot peening increases substantially the time to crack initiation: for example, Fig. 3 shows that the number of cycles needed to form a crack detectable by the optical system, increased from 80 000 to 120 000 after shot peening, in spite of the peened specimen being tested at the higher stress of σ_{max}= 450 MPa, while the unpeened specimen was tested at the stress of σ_{max}= 400 MPa.

Crack propagation rates in the earlier stages of crack development were also substantially slower in the peened samples , as shown in Fig. 4. This comparison of crack propagation rates gives an insight into the effect of shot peening on fatigue resistance. While there is an almost monotonic increase in the crack propagation rate in unpeened specimens, peened specimens showed an initial decrease to a minimum. This minimum, achieved when the crack was between 200-300 μm, coincides with the shot peening depth, which was estimated from microhardness measurements. Two effects of shot peening are responsible for these results. Firstly; the compressive residual stress acts as a closure stress on the crack, thereby increasing the resistance to crack opening and; secondly, the distortion of the crystalline structure, as manifested by strain hardening over the peened depth, increases the resistance to the development of crack tip plasticity. These two factors are known to decrease crack propagation rate and in some instances, as will discussed later, to arrest cracks.

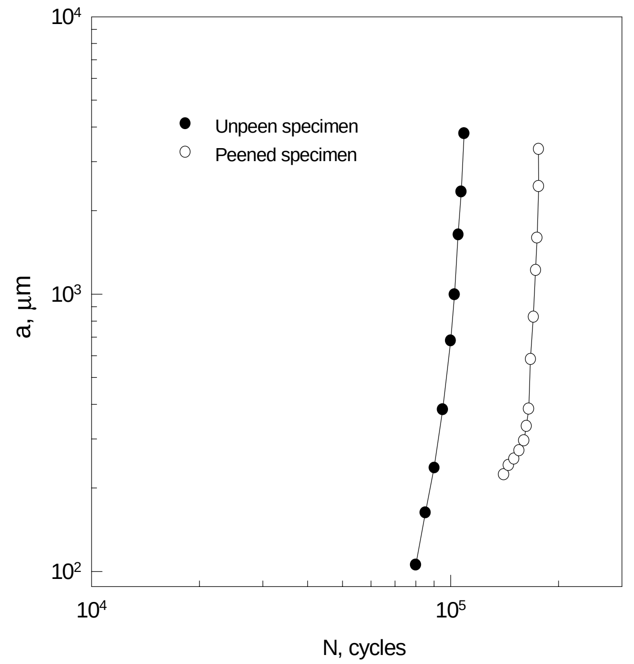


Figure 3. Experimental crack growth data of peened (σ_{max}= 450 MPa) and unpeened (σ_{max}= 400 MPa) specimens.

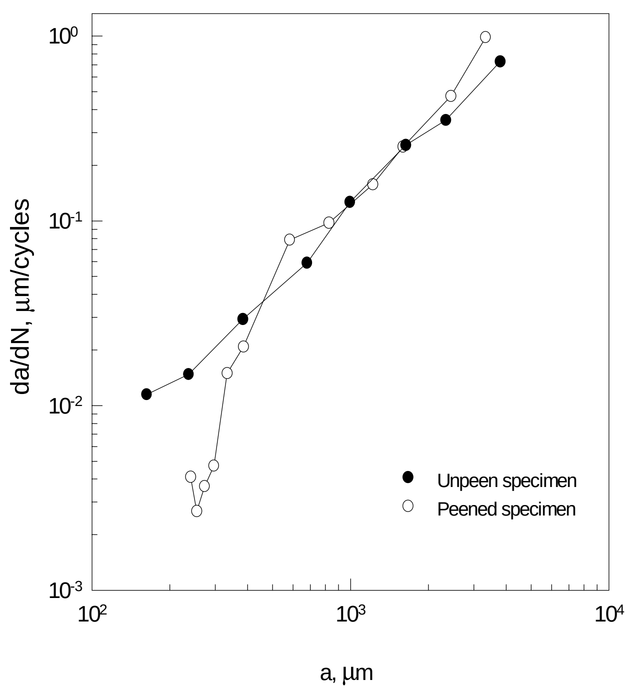


Figure 4. Comparison of crack propagation rate between peened (σ_{max}= 450 MPa) and unpeened (σ_{max}= 400 MPa) specimens.

The use of shot peening to healing fatigue damage

As shown above, shot peening improves the fatigue properties of new components, but it may also heal components which already have fatigue damage. In order to investigate this aspect, four unpeened specimens were tested in the following way: The maximum stress level was 420 MPa, R = 0.1 and the frequency 20 Hz. The tests were stopped after the appearance of surface initial cracks with sizes between 270 μm and 1500 μm. Specimens were then shot peened (intensity 15 A) and the fatigue test resumed. The results of these tests are shown in table 3.

TABLE 3

LISTING CYCLES AND CRACK LENGTH BEFORE PEENING, CYCLES AFTER PEENING AND CYCLES TO FAILURE

Specimen N	Initial crack length, μm	N_{ini}, cycles	N, cycles	N_f, cycles
1*sp	1500	70000	5735	75735
3*sp	970	40000	7480	47480
4*sp	500	58700	15570	74270
2*sp	270	45000	71100	116100

Comparing the results listed in table 3 with those shown in Fig. 2, shot peening specimens with initial cracks did not increase the fatigue life beyond that of unpeened specimens. These results seem to contradict those obtained using the 2024-T351 alloy [9], where it was found that for specimens with initial short cracks (between 200-300 μm) shot peening healed totally the prior fatigue damage. This was manifested in the endurance results of the damaged specimens with short cracks, which after shot peening, coincided with the peened data for undamaged specimens. The situation for the 7150-T651 is that, as with 2024-T351, shot peening arrested the initial crack (270 μm crack), but within a short time of resuming the test after shot peening, new corner cracks were formed due to the roughness introduced by the shot peening on the edge of the specimens. This seems to indicate that the peening conditions used (see table 1) were not the optimum for the 7150 alloy. It is expected that the optimisation of the shot peening process in terms of fatigue resistance, presently being carried out, will establish the most suitable combination of peening variables (shot size, coverage, intensity, etc.) for optimum fatigue life improvement in aerospace materials.

Modelling shot peening effects on fatigue crack growth

The key factor for fatigue life enhancement seems to be the development of a compressive residual stress. However, shot peening also introduces additional surface effects, which include work hardening, grain refinement and phase transformations of the material. Because shot peening alters the microstructure and properties of the peened layer, the characterisation of fatigue damage needs to be done in terms of short crack behaviour. In the present work, the modelling developed by Navarro-Rios [10, 11], is extended to incorporate the effects of shot peening. The important aspects of this fatigue crack growth model as applied to surface engineered surfaces are:

The effect of shot peening is separated into two parts, 1) residual stresses and 2) work hardening. The residual stress is incorporated as a closure stress (σ_1) acting on the crack flanks, which is obtained by integrating the function describing the residual stress over the length of the crack. The work hardening is incorporated as an increase on the yield stress of the plastic zone. Similarly to the residual stress, the function describing the work hardening is integrated over the length of the plastic zone to calculate the peening enhanced yield stress (σ_2). Crack propagation rate is made proportional to crack tip open displacement (CTOD). Then, by means of a Paris type equation:

$$\frac{da}{dN} = A_2\, CTOD^{m_2}\,. \quad (1)$$

To obtain the coefficient A_2 and exponent m_2, long crack propagation data for 7150 T651 is used. This is so because the short - long crack propagation prediction, based on CTOD, should coincide with the long crack propagation data when the crack is long (no effect of microstructure or surface treatments). Because the cracks observed during the tests were corner or semielliptical cracks, the stress intensity calibrations by Newman were used to calculate ΔK [12]. For a given crack length, a ΔK according to Newman was calculated and the corresponding da/dN read from the long crack fatigue data. This procedure is repeated for various crack lengths within the straight line section of the da/dN vs ΔK curve. Using the same crack lengths, corresponding CTOD values are obtained using the Navarro-Rios model. Assuming that these calculated CTODs produce the same da/dNs as their equivalent ΔKs then, fitting the CTODs to the da/dN's, the coefficient A_2 and exponent m_2 of expression (1) are obtained. These A_2 and m_2 values incorporate the 3D and constraint factors of a corner or semielliptical crack. It is now possible to include the compressive residual stress and the work hardening due to shot peening into the determination of CTOD.

Published residual stress data for 7150 was used in the modelling [1, 13, 14]. The distribution of the residual stress is described by equation (2) [13].

$$Y = Ae^{\left[\frac{-2(x-x_d)^2}{W^2}\right]} + B \qquad (2)$$

where Y - residual stress, x - depth below the surface, A+B - maximum residual stress, B - pre-set residual stress level, W - a measure of the width of the residual stress curve, x_d - depth to maximum residual stress

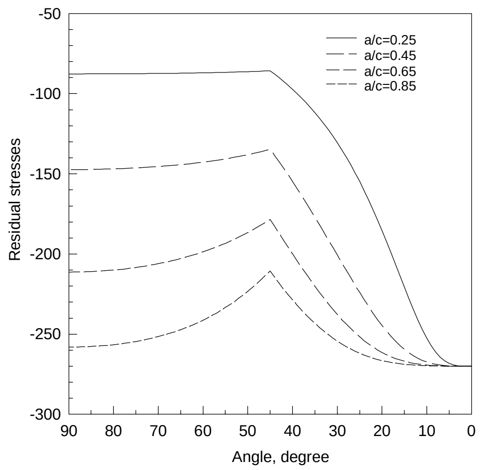
The calculation of the residual stress by means of equation (2), along various directions from the corner of the specimen (crack initiation point), for cracks of different shape and lengths, is given in Fig. 5. These values of residual stresses are used as closure stresses in the crack propagation model to predict fatigue life.

As indicated earlier, the work hardening due to shot peening is incorporated within the model as an increase on the flow stress of the plastic zone. This flow stress distribution is determined by taken microhardness measurements within the peening depth. and subsequently determining the relationship between microhardness and flow stress.

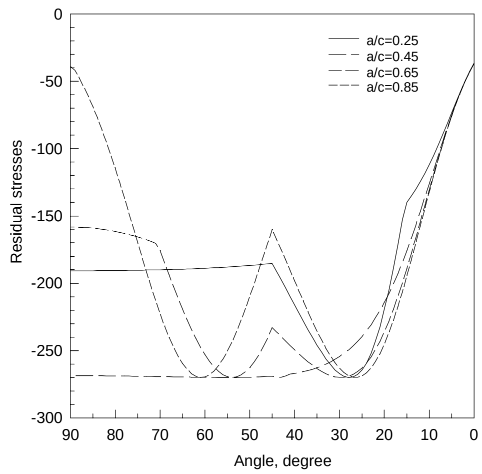
Finally, fatigue life is calculated by integrating the equation for crack growth rate (equation (1)) in each grain and then the individual partial lives added to compute total life. The integration in each grain is made by using limits a_s (initial crack length in each grain interval) and a_c (final crack length in each grain interval). Therefore, the number of cycles (N) to failure is:

$$N = \frac{1}{A_2} \sum_{i=1}^{i_c} \int_{a_s}^{a_c} \frac{da}{CTOD^{m_2}} \qquad (3)$$

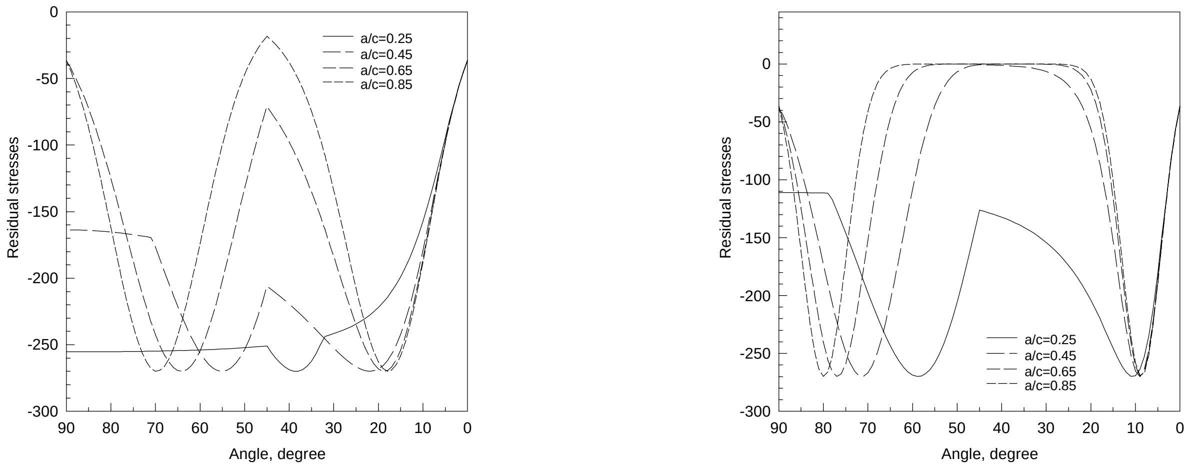
Following this procedure, the calculated S-N curves for peened and unpeened specimens are given on Fig. 6.



(a)



(b)



(c) (d)

Figure 5. The distribution of residual stresses at a corner crack with different crack lengths (a) - 150 μm; (b) - 350 μm; (c) - 500 μm; (d) - 1000 μm

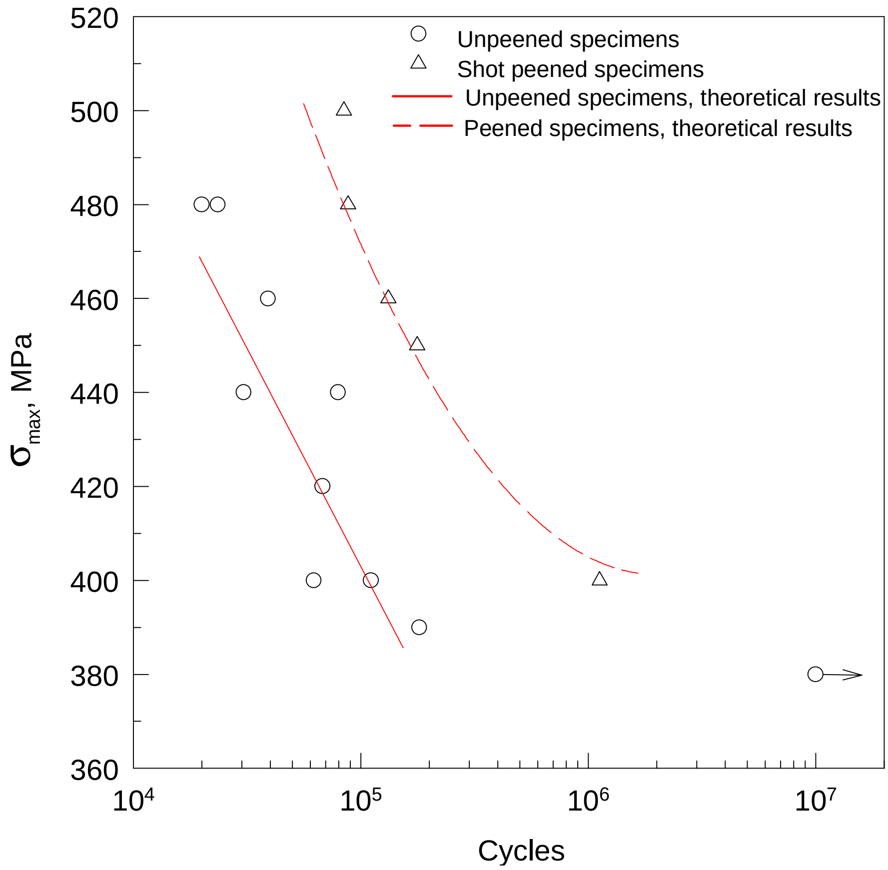


Figure 6. S-N curves, prediction results.

CONCLUSIONS

Shot peening increases the fatigue life of aluminium alloy 7150-T651 over a wide range of stress levels. It was observed that crack growth rate in peened specimens was at a minimum when the crack length was between 200-300 μm, which corresponds with the depth of maximum residual stress. Peening increases the hardness of the surface distorted layer above that of the unpeened material, thereby increasing the local yield or flow stress

The Navarro - de los Rios microstructural fracture mechanics model was used to predict the fatigue life of peened and unpeened specimens. The predicted difference in fatigue life between peened and unpeened conditions, results from the introduction of the residual stress, as a resistance to crack opening, and of the peen hardening as a resistance to the formation of crack tip plasticity.

Shot peening may be use for healing fatigue damage. However, when the initial damage is large (cracks longer than 300 μm), the "healing effect" is very small. Short cracks (less than 300 μm) are arrested after shot peening. Nevertheless, on resuming the tests new corner cracks are formed immediately due to the roughness left by the peening process. Therefore, the healing ability of Al 7150-T651 is very sensitive to the choice of shot peening process variables.

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