Fatigue Strength and Residual Stress Analysis of Deep Rolled Crankshafts

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Abstract

The endurance life of an engine crankshaft is closely related to its fatigue strength, in addition to other material properties and shape parameters. Deep rolling, moreover, enhances the fatigue limit by applying compressive residual stress within the fillet radius area as a major surface hardening technique. The objective of this paper is to maximize fatigue life of engine through crankshaft design optimization by quantifying fatigue strength for microalloyed steels versus Cr-Mo alloy steel, and to examine the effects of deep rolling load and rolled fillet geometry.

Fatigue tests have been made with standard rotary bending test samples from both bar and forged blanks. Rig tests for actual crankshafts have been made to show how the fatigue strength correlates with different sample types. A correlation of stress distribution with bending moment was demonstrated by applying a strain gauging technique on crankshaft specimens. Therefore, an analysis of combined stresses could be made by considering the effect of static residual stress in addition to the applied dynamic bending stress.

Optimum conditions for rolling load, fillet geometry and material were identified. Consequently, these results will be adapted to CAE analysis database to enable an optimization of safety factors.

Key Words: Deep rolled crankshaft, Fatigue strength, residual tresses, design and optimization.

1. Introduction

Preliminary performance prediction is the goal of all automotive designers. For the crankshaft this will be achieved by the quantification of material and the strengthening process. Deep rolling of the fillet area is a significant surface treatment of an engine crankshaft by which the fatigue life of a crankshaft is increased by developing a compressive residual compressive stress in the fillet area.

Two types of forged crankshaft were made by using medium carbon microalloyed steels and a Cr-Mo alloy steel. The quantification of deep rolling on cast iron and carbon steel has been widely studied so far. [1][2].

However, the effects of fillet rolling were determined mostly on standard test samples rather than on actual crankshafts. Needless to say, the quantification of rolling on crankshafts used in engines was greatly lacking. Although a former study [3] revealed the effects of fillet rolling by load control, it is still difficult to explain the correlation of stress and moment on the enhancement of the design. In this research, a correlation was made between stress and moment by utilizing moment control that could support the design. The database extracted from these tests could directly enhance the design and FE analysis. Crankshafts from a V6 engine application were selected for testing as shown in Fig.1.

The fatigue strength was investigated in terms of different materials and rolling load. Standard rotating bending fatigue specimens were prepared from the bar steel and forged crankshaft. Also, bending fatigue testing was conducted on crankshafts by a magnetic resonance system.

Fig. 1 Shape of V6 crankshaft

Attempts to apply a strain gauging technique to a production crankshaft have been successful. The correlation of stress distribution with the bending moment of a production crankshaft with a deep rolled area was demonstrated. An analysis of the effect of residual stress under normal conditions to bending stress at dynamic load was performed as well.

2 Experimental procedure

2.1 Material

Table 1 shows detailed chemical compositions of the steels used for the crankshaft study. Samples ‘A and B’ are microalloyed steels while sample ‘C’ represents a typical alloy steel that is quenched and tempered.

Table 1 . Chemical composition of crankshaft steels (wt%)

	C	Si	Mn	P	S	Cr	Mo	V
A	0.39	0.67	1.38	0.01	0.05	0.12	-	0.14
B	0.37	0.62	1.30	0.01	0.05	0.12	-	0.12
C	0.40	0.29	0.84	0.02	0.01	1.1	0.2	-

- A: Microalloyed steel – Only controlled cooling after forging

- B: Alloy steel - Quenched and tempered after forging

2.2 Rotating bending fatigue test

In this test, bending fatigue tests were conducted in order to determine how deep rolling could improve the fatigue strength of production crankshafts. Sections from actual forged crankshafts were extracted and used as test samples. Fig. 2 shows the method of specimen preparation from the forged part, (1) longitudinal (2) perpendicular to the direction of metal flow. The Ohno-type rotary bending fatigue test was used to determine the fatigue limit. .

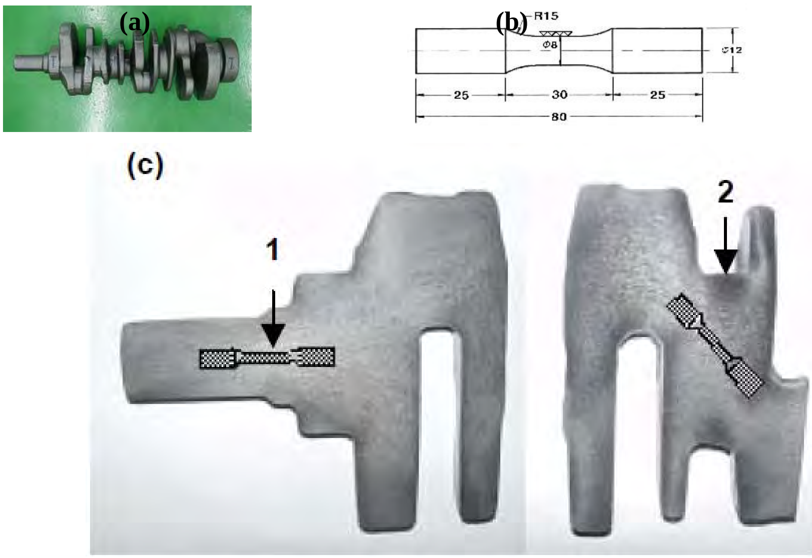


Fig. 2 Specimen preparation for actual crankshaft

(a) Forged crankshaft (b) Standard bending fatigue specimen (c) A schematic of the machined area (hatched) in mm

2.3 Crankshaft fatigue test method

Actual crankshafts were prepared from the various steels to compare the bending fatigue limit which is defined by a bending moment. Fig. 3 shows the crankshaft magnetic resonance bending fatigue test rig. Specimens of each material were deep rolled at an optimized condition that was determined empirically. For the rig test, a half-cut of the crankshaft was used as a specimen. A bending moment was applied to the round area between crank pin and journal, the maximum stress was concentrated at the fillet radius(R) location. The mean stress was set to zero while an alternating moment was applied to simulate an engine load of compressive and tensile conditions.

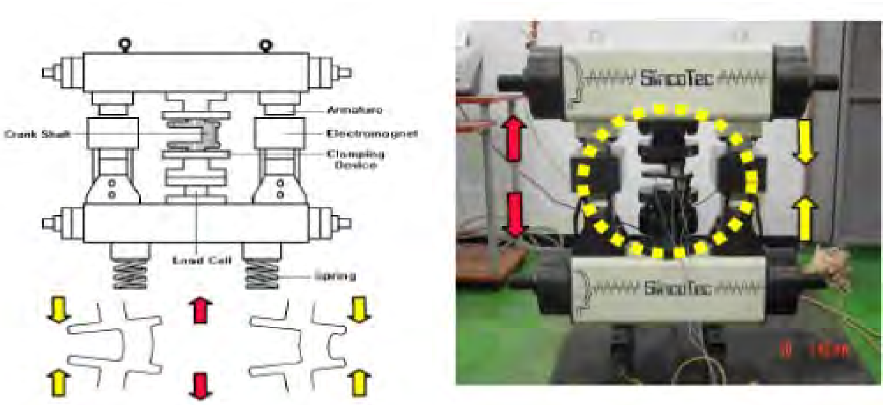


Fig.3 Schematic diagram of magnetic resonance bending fatigue tester.

2.4 Stress measurement method

The analysis of surface stress was conducted using strain gauges. As shown in Fig. 4, four gauges were used to acquire the strain signal of amplitude and mean strain.

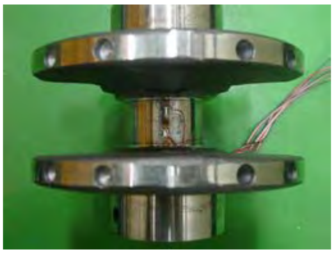


Fig. 4 Machined crank specimen used for fatigue rig test and strain gauging location.

3 Results and discussion

3.1 Rotating bending fatigue strength

3.1.1 Effect of metal flow and hardness

Fig. 5 shows a difference in fatigue strength of coupon samples machined from the front-end and web of crankshaft. The fatigue strength of the front-end sample is 10 % higher than that of web sample. The front end sample has a metal flow parallel to the machined surface while the web sample has a metal flow perpendicular to the surface as shown in Fig. 6. In addition, the front end sample has higher hardness of HB 25 on average than the web sample due to a faster cooling rate. It is an indication that the geometry of metal flow is a predominant parameter to enhancing the fatigue limit along with hardness. Therefore, it should be noted that the design of the crankshaft should be optimized to accommodate the parallel metal flow especially in the fillet radius area where crack formation can be initiated. The safety factor should also be considered on the basis of the actual mechanical properties of the fillet radius area.

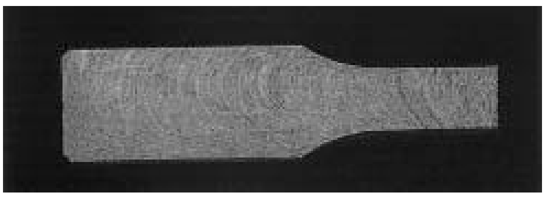


Fig.5 Fatigue strength of Cr-Mo steel vs. microalloyed steels for 3.3L forged crankshaft

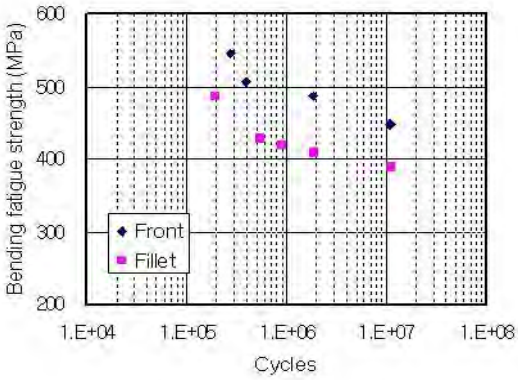


Fig. 6 Metal flow of specimen from fillet radius area.

3.1.2 Microalloyed steel vs. alloy steel

Fig. 7 illustrates the fatigue strength data of the micro-alloy steels and that of the quenched and tempered (Q-T) alloy steel. Microalloy steels show a fatigue strength ranging from 370 to 390 MPa whereas the Q-T alloy steel exhibits a fatigue strength of 410 MPa. This data is in good agreement with Richards et al.[2]. The fatigue strengths in this study are within 5~10% of those steels. It should be noted the microalloy steels have different fatigue strengths presumably due to differences in vanadium content. The average vanadium content of microalloy steel A is 0.14% whereas that of B is 0.12%. The minor increase in the vanadium content of steel A compared to steel B could achieve a 5% increase in fatigue strength due to an increase in tensile strength resulting from the higher vanadium content. When it comes to the development of a better alloy design for microalloy steels, the goal is to achieve an equivalent level of fatigue strength with a Q-T alloy steel. Thus, it is proposed that the chemistry be modified such that the vanadium content is more than 0.15% when substituting microalloy steels for Q-T alloy steels.

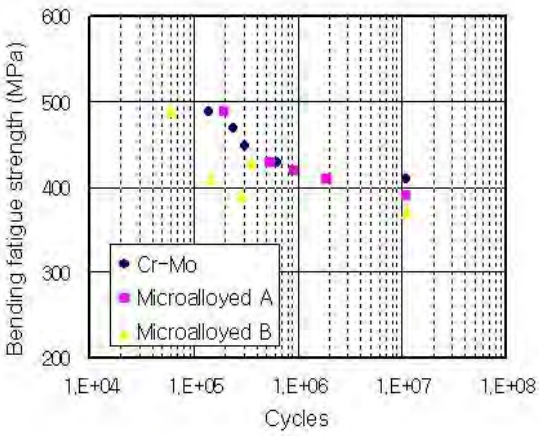


Fig. 7 Fatigue strength of standard sample from forged steel crankshaft variations

3.2 Crankshaft rig test results

A crankshaft is a component on which a torsional bending mode or so called combined stress is exerted. Yet, the bending stress significantly exceeds the torsion stress. In fact, most of the crankshafts that failed in fatigue were due to bending fatigue. In this test, the primary focus was on bending fatigue using bending moment control.

3.2.1Bending moment of microalloyed steel vs. alloy steel

The bending fatigue limit obtained for the crankshafts is shown in Fig. 8. This figure shows that the bending fatigue limit of microalloyed steel is 1100~1150N.m and bending fatigue limit of alloy steel is 1200N.m. These results follow the same trend as the results obtained from rotating bend testing which are shown in Fig. 7. These results demonstrate that the effect of fatigue stress can be evaluated by a dynamic bending moment test.

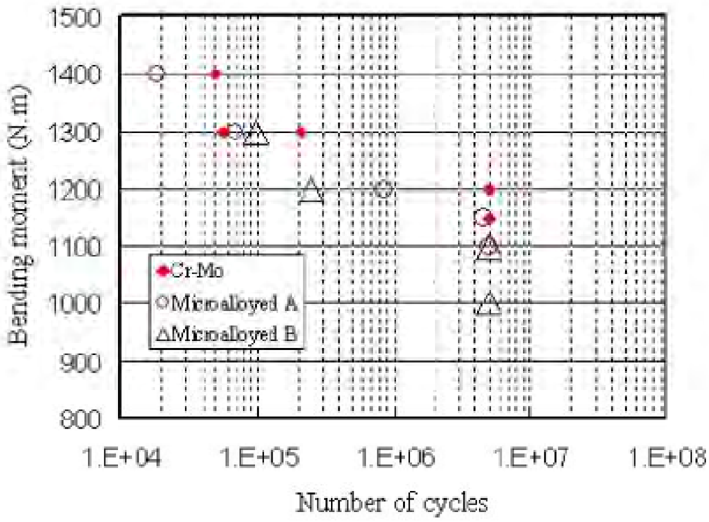
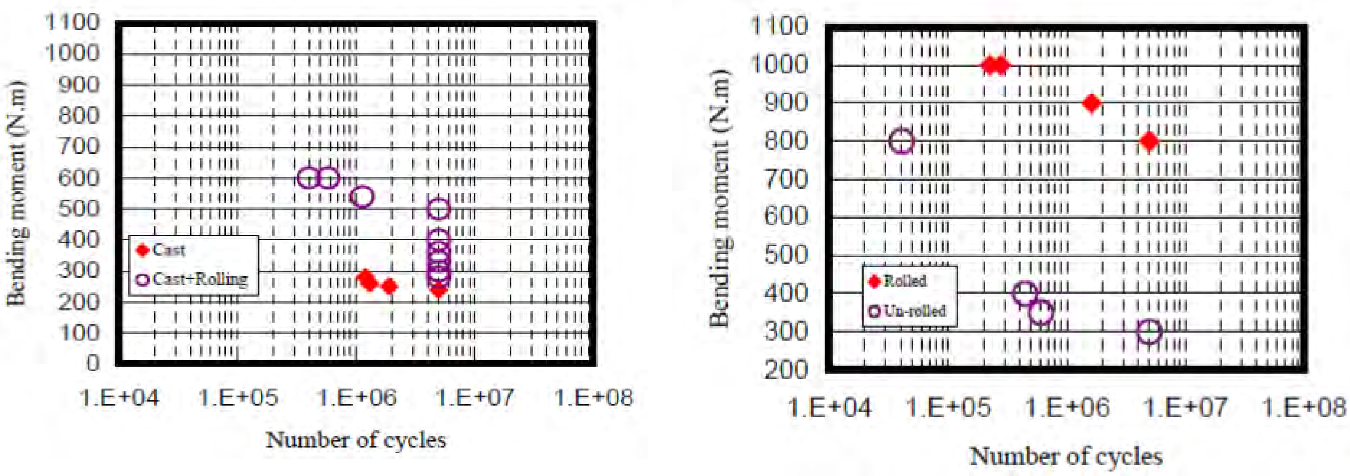


Fig.8 bending moment of a 3.3L crankshaft

3.2.2 Effect of deep rolling

Fig. 9(a) shows the difference in results between deep rolled and un-rolled crankshafts for a 1L engine. The bending fatigue limit for the deep rolled crankshaft was 500N.m whereas the bending fatigue limit for the groove machined crankshaft was 240N.m. Hence, the deep rolled crankshaft's bending fatigue limit was enhanced by 108% compared to that of the groove machined crankshaft. Fig. 9(b) depicts the results from the deep rolled and un-rolled crankshafts for a 2.5L engine application. Here, the bending fatigue limit for the rolled crankshaft was 800N.m whereas the bending fatigue limit for the un- rolled crankshaft was 300N.m. Thus, the deep rolled crankshaft showed a 166% improvement as compared to that of the un-rolled version. The rolling loads of crankshafts are 4.5kN and 7.0kN, respectively. Improvement of the bending fatigue limit for deep rolling indicates that surface strengthening is a major portion of the fatigue limit for crankshaft.



(a) Deep rolled and un-rolled crankshafts for the 1L engine (b) Deep rolled and un-rolled crankshafts for the 2.5L engine

Fig.9 Results of dynamic bending moment test

3.2.3 Correlation of bending moment and stress

In line with the fatigue moment strength obtained from the above rig test, the following test was conducted in order to quantify the fatigue strength. Stress measurements were made with different applied moments by bonding the strain gauges to the main locations: fillet radius and the centre of pin journal. The signal produced from the strain gauge is shown in Fig. 10(a). In addition, the amplitude, the mean stress of the fillet radius and the pin surface are defined in Fig. 10(b). The stress measurements from the dynamic bending test were nearly identical regardless of the types of steel that were used and when the design of the crankshafts stayed the same. The area of interest is the amplitude stress on the fillet radius.

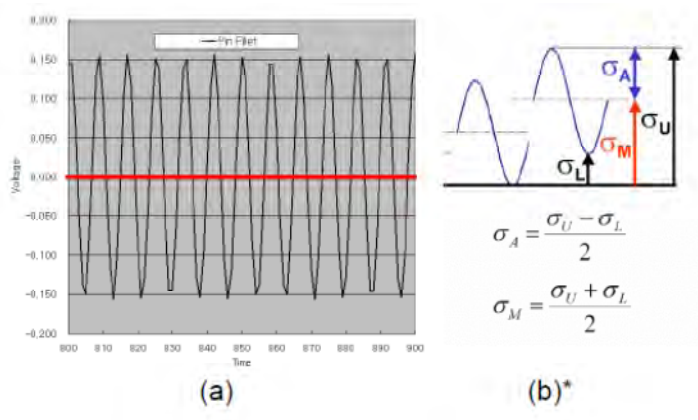
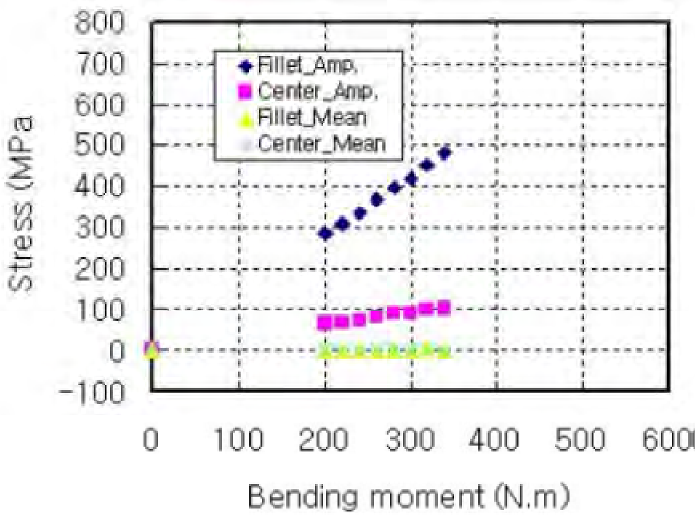


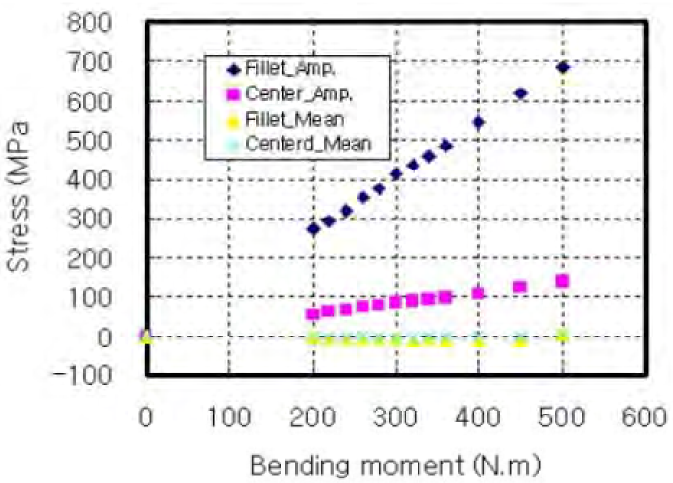
Fig. 10 Stress measurement method by strain gauging

(a) Signal of strain gauge (b) Definition of amplitude and mean stress, * A: amplitude, M: mean, U: upper, L: lower

Figure 11 plots applied stress against the bending moment for the 1L crankshaft. Figs. 11(a) and (b) show the 1L crankshaft with 4.5kN rolling load. The mean stress is nearly zero, that is, R=-1 and the amplitude stress is significantly higher at the fillet radius than at centre of the pin surface. This figure shows the linear relationship of stress and moment. The applied stress for fillet radius area was compared to quantify the effect of deep rolling. The evaluation revealed that applied stress of the unrolled crank was 332MPa at a bending moment fatigue limit of 240N.m whereas the nominal stress of the rolled crank was 688MPa at the bending moment fatigue limit of 500N.m. It was found that the surface nominal stress is increased 107% as the bending moment fatigue limit is increased up to 500N.m.

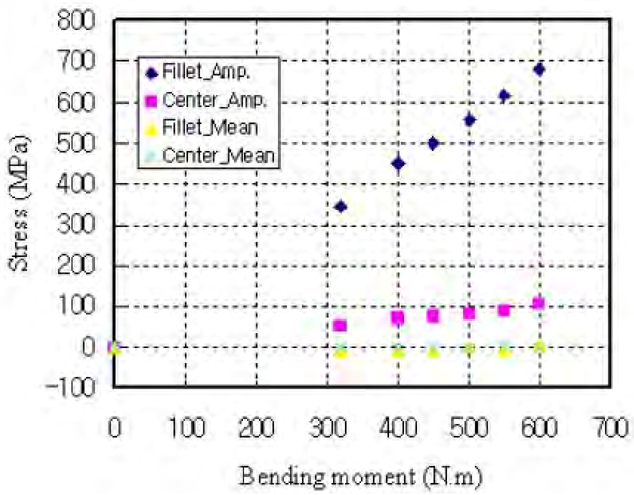


(a) Stress analysis of un-rolled for 1L engine



(b) Stress analysis of deep rolled 1L engine

Figure 11(c) also shows the result of stress vs. moment for 3.3L type crankshaft with 7.0kN rolling load. The bending moment fatigue limit of this crankshaft was 1100~1200N.m as shown in Fig.8. Since the strain gauge can be used only up to 600N.m, a linear regression was made to obtain the nominal stress at 1100N.m~1200N.m. The nominal stresses are in the range of 1239MPa~1352MPa. By applying the fatigue strength of the former results, 370MPa and 410MPa for microalloyed and alloy steel, it is estimated that the surface nominal stress of the fatigue limit increased up to 230%~235%.



(c) Stress analysis of deep rolled 3.3L engine

Fig.11 Correlation of applied moment and stress

3.2.4 Effect of residual stress

It should be noted that the increase of fatigue limit referenced in this paper is considerably higher than the results from Richards et al.[3] where fatigue limit increases 51~63% after deep rolling. Our results are from an actual crankshaft sample test where the nominal stress represents only the crack initiated area in the subsurface while the fatigue strength of standard sample [3] is calculated from the cross section area of specimen.

Considering the distribution of residual stress after deep rolling, the subsurface area has the maximum compressive stress which contributes to the fatigue strength increase at the crank-web area. Therefore, there is a good agreement between rig test and standard sample fatigue results. Besides, it is found that one should recognize the real applied stress value at the tip of fillet radius surface to optimize crankshaft design.

A detailed map is under development of the fillet radius area in terms of the hardness distribution to confirm the effect of residual stress at different locations.

4 Conclusions

The conclusions obtained in this work are as follows.

1. Correlation of bending moment and stress has been evaluated to quantify the effect of deep rolling. It was

demonstrated that the bending moment of deep rolled and unrolled crankshaft vs. applied stress of the fillet radius area. The design safety factor can now be calculated directly by quantifying the stress.

2. The optimal chemistry for the microalloyed steel, which provides the same level of fatigue strength as the alloy steel, was established. The fatigue strength varied accordingly with the different chemistry.

3. It was demonstrated that the geometry of metal flow is a predominant parameter to enhance the fatigue limit along with hardness. Therefore, the design of the crankshaft should be optimized to accommodate the parallel metal flow in the fillet radius area.

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