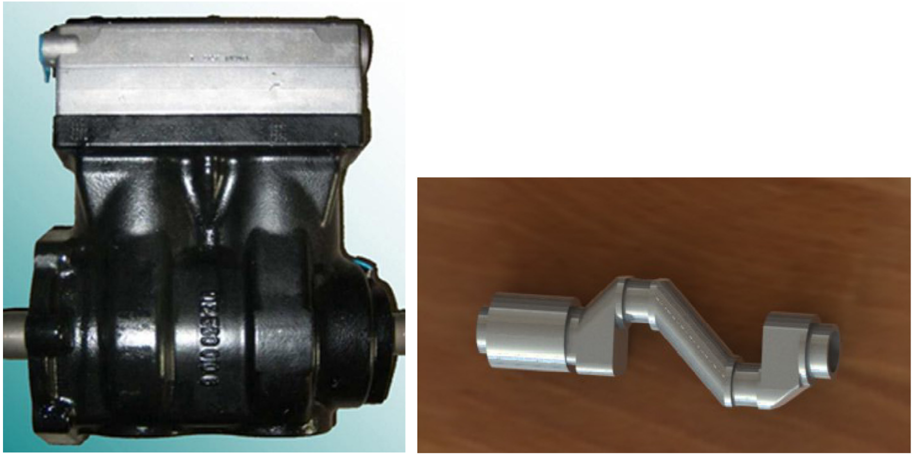
1. Introduction

The crankshaft is a structural component which converts the linear piston movement into rotary motion while the force connecting rod is transformed to torque. Several researchers have been studied on the failed shafts [1–4]. Recently, researchers indicate that mechanical fatigue produced by cyclic bending load on the fillets and steady torsion were probably the most common cause of crankshafts failure [5–10]. Zhang and Yin [11] have investigated a wind turbine main shaft and the results show that stress concentration on the shaft surface are the main reasons that result in fracture of the main shaft. Bugarin [12] has studied two shafts and found that a larger-size fillet can minimize stress concentration in the dangerous sections which shows that the fatigue life can be significantly increased with a simple change in the structural details. Because the fracture failure of the crankshaft can affect the normal work of the machine, the failure analysis of crankshaft have a very important theoretical and practical significance. This paper finds out the cause of the crankshaft fracture through the failure analysis of the crankshaft (Fig. 1), so as to guide the design and production, improve the fatigue strength and the work reliability of the crankshaft.

In this paper, the crankshaft is made of 42CrMo steel with forging, heat treatment and nitridation. The crankshaft occurred fracture failure after using a period of time. The fracture position and surface of the crankshaft is shown in Figs. 2 and 3. The region around the lubrication hole is rough by observing Fig. 3.

2. Investigation into the cause of main shaft fracture

In order to analyze the cause of crankshaft fracture thoroughly, three parts of study were carried out: (1) experimental analysis of the crankshaft, (2) analysis of macroscopic feature and microstructure of the crankshaft, and (3) theoretical calculations.



(a) the air compressor (b) the crankshaft

Fig. 1. Picture of the air compressor.

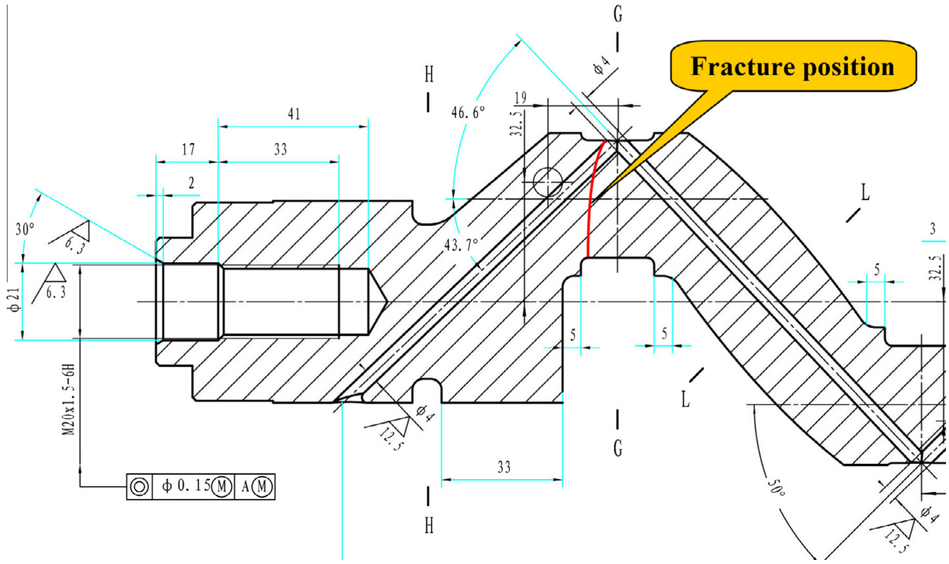


Fig. 2. The fracture position of the crankshaft.

2.1. Experimental analysis of the crankshaft

2.1.1. Chemical composition detection

The chemical element analysis is to accurately determine the elements content of the crankshaft material and compared it with the standard values, then determines whether the crankshaft material is suitable.

Chemical analysis of the fractured crankshaft material was carried out using a spectrometer. Examination of chemical composition of the samples taken at the point of fracture was carried out. Table 1 gives the chemical composition of the crankshaft and the standard composition of 42CrMo.

As shown in Table 1, obviously, the chemical composition of the main shaft is in accordance with the requirements of 42CrMo steel.

2.1.2. Mechanical properties test

The test results of mechanical properties including σ_b (Tensile strength), δ (Reduction of area) and hardness shown in Table 2.

(a) The front side

(b) The back side

(c) The crank of the shaft

Fig. 3. The fracture surface of the crankshaft.

Table 1
Chemical compositions (%).

Element	Specification	Actual
C	0.38–0.45	0.41
Cr	0.90–1.20	0.95
Mo	0.15–0.25	0.15

Table 2
Mechanical properties.

Test items	σ_b (N/mm^2)	δ (%)	Hardness(HRC)
Standard value	$\geqslant$900	$\geqslant$12	27–32
Measured value	915	14.5	31

2.2. Macroscopic analysis

The fracture surface shown in Fig. 4 can be divided into three regions: (1) fatigue crack initiation region, (2) fatigue expansion region and (3) static fracture region.

The catastrophic fracture which shows the fatigue crack growth rate is high seems to be a consequence of a high bending according to the Fig. 4. The reasons why the bending loading is too high is that the misalignment of main journals and the small fillet of the lubrication hole. Under the above two cases which can generate high bending stress concentration, the fatigue crack initiated on the edge of the lubrication hole and finally fractured.

The presence of beach marks with semi-elliptical shape surrounding fatigue crack initiation region indicates its expansion. These beach marks, also named progression marks were extremely important to describe fatigue fractured surfaces,

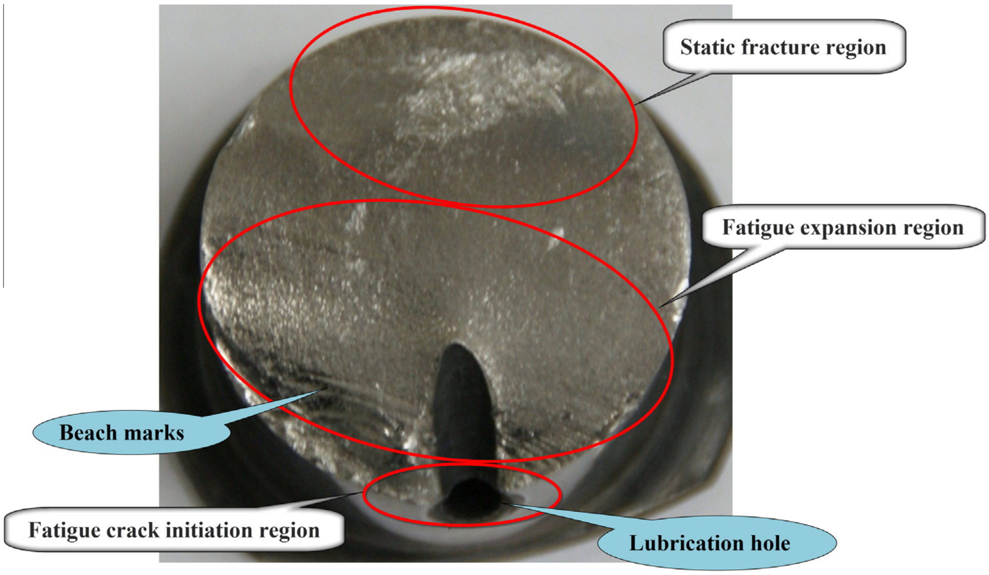


Fig. 4. Macro-photograph of the fracture surface.

but the beach marks are only the characteristics of the fatigue fracture and some fatigue fracture did not have obvious beach marks. The beach marks are a consequence of small overloads as a result of starting or stopping of compressor. The beach marks are really important to determine the fatigue crack growth rate and also to determine where the focus of the semi-ellipses (the crack initiation site) exists.

In the fatigue expansion region, the beach marks observed in the beginning of the expansion region resulted of the starting or stopping of the compressor operation.

The static fracture region is the portion of the structure where the final catastrophic failure occurs.

According to the above analysis, the crankshaft fracture process is as follows:

In a certain rotating cycle after a period time of normal work, micro cracks due to high bending stress concentration appeared on the fillet of lubrication hole, but the crankshaft can still close to normal working condition. As the lengthening of working time, the crankshaft began to appear obvious fluctuation with the fatigue crack extending gradually to static fracture region and then fractured completely. At the moment of fracture, friction collision happened between the two fracture surfaces, which lead to a certain degree of damage on the surfaces.

From the macroscopic analysis: The fatigue zone was formed by gradual extension of the crack source.

2.3. Microscopic analysis

The microscopic observation of the fracture surface was carried out using Scanning Electron Microscopy (SEM) due to its high resolution and high magnifications. By the microscopic observation and analysis, we can accurately confirm the fracture type and the initiation of crack source region, its propagation and the cause of possible fracture.

The observation points numbered 1–9 are shown in Fig. 5. However, only display of those critical observation points are shown in Fig. 6, numbered 1, 2, 4, 5, 6 and 9.

Point 1 is located on the edge of the fracture surface which is shown in Fig. 6(a).The display of the rough surface which means the point 1 is located in the static fracture region.

Point 2 is located at the static fracture region. The picture shows clearly the typical morphology of fast fracture.

Point 4 is located on the surface of the lubrication hole. The relatively smooth surface shown in Fig. 6(c) means there is no stress concentration.

Point 5 is on beside of the lubrication hole. The obvious beach marks distributed in Fig. 6(d) meaning that this is a typical fatigue expansion region.

Point 6 is located on the edge of the lubrication hole. There are three pictures in different magnification to understand the morphology of the point 6 clearly. Fig. 6(e) shows a smooth surface and we can make sure the point 6 is on the fatigue source region. We can also find out the fatigue crack initiation site by tracing back the beach marks.

Point 9 is located at the fatigue expansion region and the morphology of point 9 seems to show an occasional beach mark.

According to the above analysis, a preliminary conclusion can be drawn that the crack on the edge of the lubrication hole is the cause of the fracture of the crankshaft.

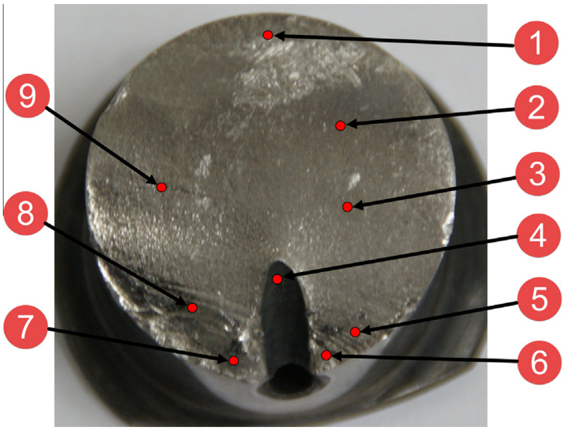


Fig. 5. Observation points of the fracture surface under SEM.

2.4. Theoretical calculation

According to the force condition of the crankshaft when it is working, the dangerous sections are the surface of the lubrication hole and the transition fillet of journal.

2.4.1. Fatigue strength checking on lubrication hole

Mechanical part theoretically able to bear force must be greater than its actual force, and the ratio of the limit stress and the allowable stress is called safety factor. In the fatigue strength design, we use fatigue limit replace the limit stress and the safety factor is determined according to design experience.

The calculation of the safety factor on the lubrication hole is obtained, as follows [13]:

$$S_{ca} = \frac{\sigma_{-1}\varepsilon_\sigma}{K_\sigma \eta \sigma_a + K_\tau \eta_\tau \tau_a + \psi_\sigma(\eta\sigma_m + \eta_\tau \tau_m)} \tag{1.1}$$

In order to calculate the safety factor, the meanings of the parameters in above calculation must be known and the calculations to obtain the parameters is as follows:

$$\begin{cases} K_\sigma = \frac{K_{t\sigma}}{0.88+AQ^b} \\ K_\tau = \frac{K_{t\tau}}{0.88+AQ^b} \\ Q = \frac{4.6}{d} \end{cases} \tag{1.2}$$

Here, K_σ and K_τ are the effect coefficients of lubrication hole under bending and torsion, $K_{t\sigma}$ and $K_{t\tau}$ are the theoretical stress concentration factors under bending and torsion, Q is relative stress gradient, d is diameter of crankshaft pin, A and b are constants related to the heat treatment where $A = 0.290$, $b = 0.152$, η and η_τ are relative stress strength factors, ε_σ and ε_τ are size factors, ψ_σ and ψ_τ are stress convert factors, σ_a and σ_m are working stress of the crankshaft under bending, τ_a and τ_m are working stress of the crankshaft under torsion, S_{ca} is safety factor.

We can get the following parameters, $K_{t\sigma}$, $K_{t\tau}$, η and η_τ according to the Standard Hand book of Machine Design, and then obtain the curve of theoretical stress concentration factor and the curve of the relative stress strength factor on lubrication hole through MATLAB simulation which is shown in Figs. 7 and 8.

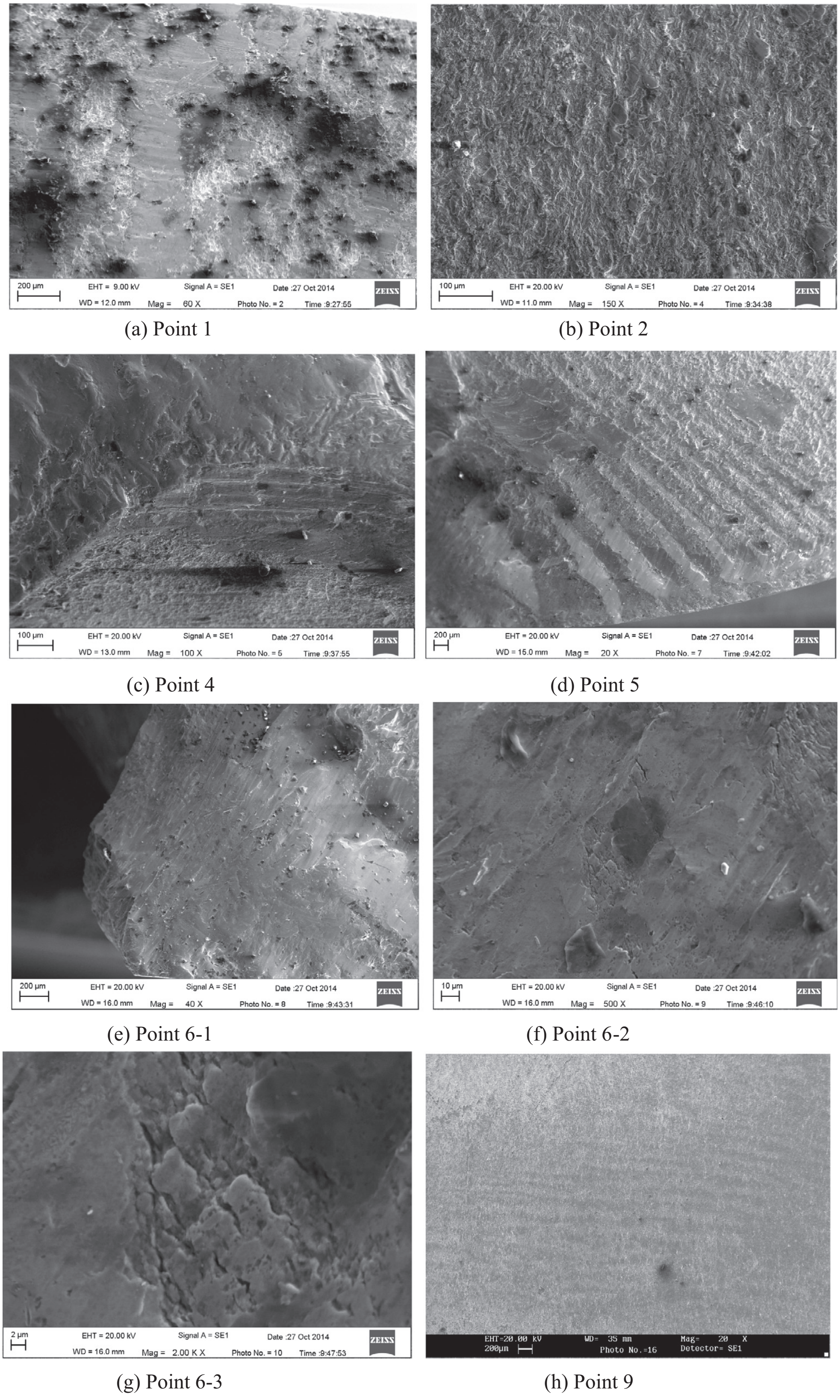
According to the known parameters of the crankshaft, the relationship between the safety factor and the diameter of lubrication hole after fillet has been obtained, which is shown in Fig. 9. The parameter a represents diameter of the lubrication hole after fillet in Fig. 9.

According to the part drawing where $a = \varphi 5$ mm, $d = \varphi 32$ mm, the safety factor $S_{ca} = 2.477$ has been got from Fig. 9, and then we know that the fatigue strength on the lubrication hole is in allowable range which is $[S_{ca}] = 2.0–3.0$.

2.4.2. Fatigue strength checking on the transition fillet of the journal

The calculation of the safety factor on transition fillet of the journal is as follows:

$$\begin{cases} S_\sigma = \frac{\sigma_{-1}\varepsilon_\sigma}{\frac{K_\sigma \beta \sigma_a}{\beta_1} + \psi_\sigma \beta \sigma_m} \\ S_\tau = \frac{\tau_{-1}\varepsilon_\tau}{\frac{K_\tau \beta_\tau \tau_a}{\beta_1} + \psi_\tau \beta_\tau \tau_m} \\ S_{ca} = \frac{S_\sigma S_\tau}{\sqrt{S_\sigma^2 + S_\tau^2}} \end{cases} \tag{2.1}$$



(a) Point 1 (b) Point 2

(c) Point 4 (d) Point 5

(e) Point 6-1 (f) Point 6-2

(g) Point 6-3 (h) Point 9

Fig. 6. Microstructure of the fracture surface.

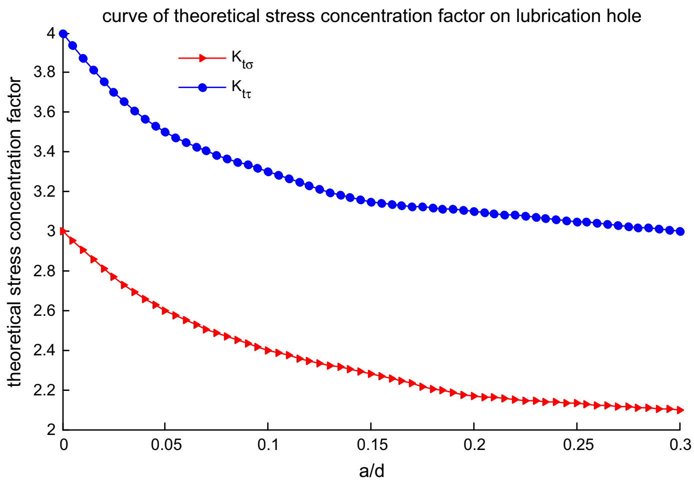


Fig. 7. Curve of theoretical stress concentration factor on lubrication hole.

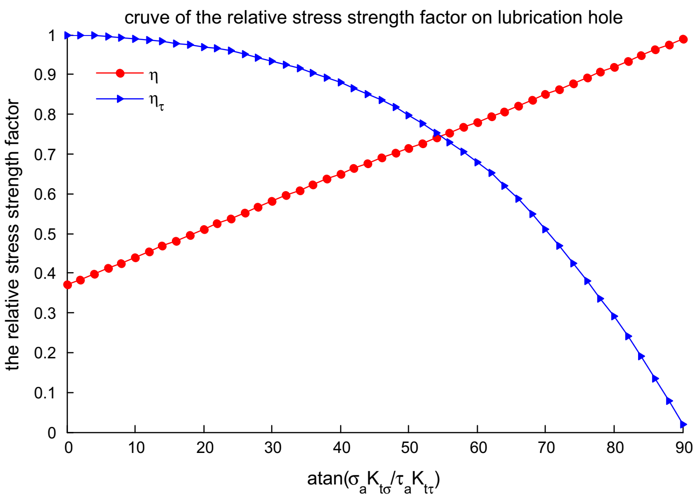


Fig. 8. Curve of the relative stress strength factor on lubrication hole.

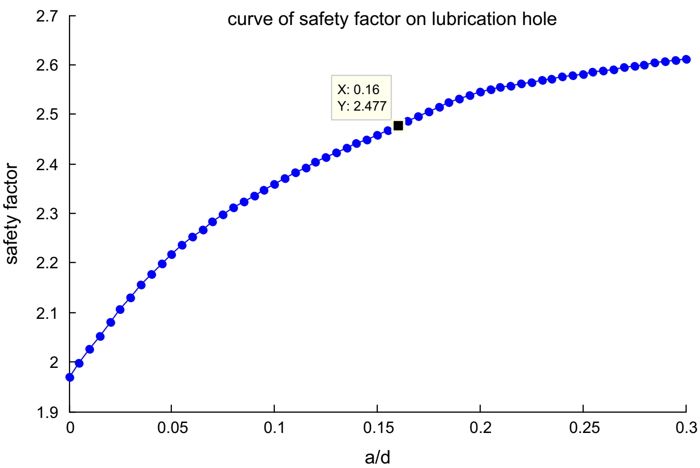


Fig. 9. Curve of safety factor on lubrication hole.

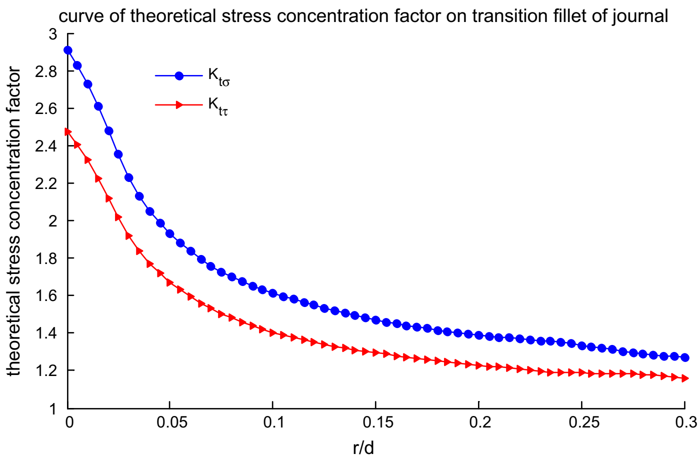


Fig. 10. Curve of theoretical stress concentration factor on transition fillet of journal.

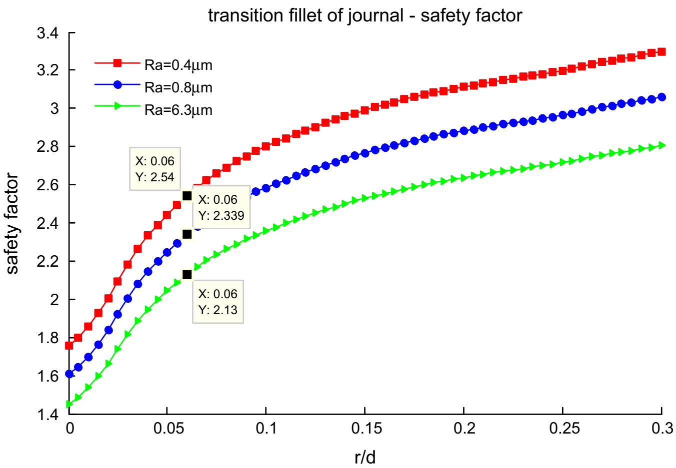


Fig. 11. Curve of safety factor on transition fillet of journal.

Table 3
Safety factor and surface roughness.

r (mm)	R_a (μm)	S_{ca}
2	0.4	2.540
2	0.8	2.339
2	6.3	2.130

Here, β_1 is surface quality factor, β and β_τ are uneven stress distribution factors, S_σ and S_τ are Safety factors under bending and torsion.

At first, the curve of theoretical stress concentration factor on the transition fillet of the journal through MATLAB simulation has been got which is shown in Fig. 10. The parameter r represents transition fillet radius of journal in Fig. 10.

Then the relationship between the safety factor, transition fillet of journal and surface roughness is found out and the curve is shown in Fig. 11 where R_a is surface roughness.

According to Table 3, the method to improve safety factor when the transition fillet has been large enough is found out which is reducing the surface roughness. The safety factor and surface roughness have been obtained where $S_{ca} = 2.540$, $R_a = 0.4$ μm which is shown in part drawing, and the conclusion that fatigue strength on transition fillet of journal is in allowable range which is $[S_{ca}] = 1.5–2.0$ can be drawn.

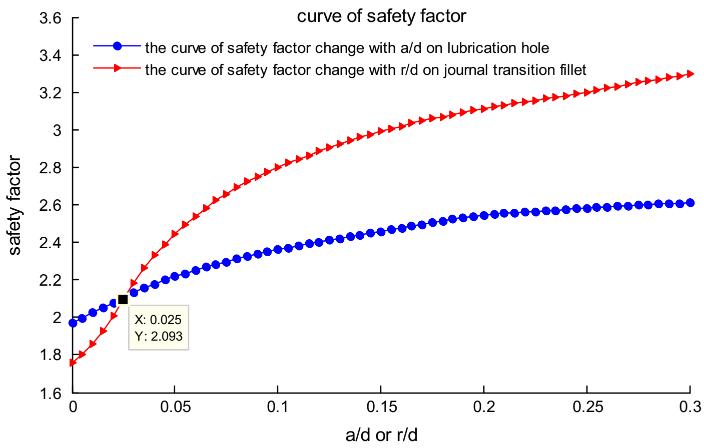


Fig. 12. Curve of safety factory.

2.4.3. Fatigue strength analysis of the whole crankshaft

Based on the above safety factor calculation, the safety factors of the two dangerous sections have been compared where 2.477 < 2.540. The result means that the dangerous section is on the surface of the lubrication hole on which the crack initially generated.

Then a comprehensive consideration of safety factor on surface of the lubrication hole and the transition fillet of journal has been taken into which is shown in Fig. 12.

The abscissa value 0.025 is a critical point from Fig. 12. When the abscissa value is greater than 0.025, the safety factor of transition fillet of journal is greater than the one on the lubrication hole and the dangerous section is on the surface of the lubrication hole. Through calculation we obtain that the critical radius is $r = 1$ mm and the critical lubrication hole diameter is $d = 1$ mm.