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Evaluation of the Strengthening Effect of Different Surface Treatment Techniques in Steel Crankshaft Manufacturing Industry

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At present, electromagnetic induction quenching and nitriding are two commonly used surface strengthening approaches applied in improving the strength of the steel parts. In this paper, a comparative study was proposed to research the strengthening influence of these two techniques on the fatigue property of two types of steel crankshafts. First a modified statistical analysis approach was proposed to obtain the distribution property of the fatigue limit load. Then two types of steel crankshafts were selected to be the object of research and treated by these two techniques. Finally the standard T and F hypothesis testing methods were conducted in evaluation the strengthening effect. The main conclusion of the research is that the strengthening effect of the electromagnetic induction approach in this condition is obviously higher than that of the nitriding, which makes the former technique more suitable to be applied in steel crankshaft manufacturing industry.

Keywords: crankshaft, nitriding, electromagnetic induction, high cycle fatigue damage

1 Introduction

Nomenclature:

A_{st}… The strengthening factor of a given surface treatment approach,

M_t…The median value of the fatigue limit load of the crankshaft after the surface treatment, N·m,

M_u… The median value of the fatigue limit load of the crankshaft before the surface treatment, N·m.

Nowadays, crankshaft has been widely applied in internal combustion engine to transfer the power and motion from the piston [1]. As a result of this, corresponding static and dynamic load will apply on the part during the working period until the final fracture happens. Thus, correct strength design of this part becomes important during the design stage [2].

In order to solve this problem, a number of excellent works have been conducted in recent years. For example, Gomes carried out the failure analysis on a V12 diesel engine crankshaft, as well as modified the geometric shape according to the selected Soderberg criterion. In this way the fatigue strength of the part has been enhanced obviously [3]. Xu and Yu also analysed a failure diesel engine crankshaft and pointed out that the stress concentration phenomenon at the fillet was the primary reason for the fracture [4]. Khameneh and Azadi compared the S-N curves of the material from different sources and discovered that the specimen from the broken crankshaft can provide more reasonable results [5]. Leitner et al. investigated the gas engine crankshafts under the multi-axial load conditions and found that the Spangnoli model can accurately evaluate the fatigue strength of the part, as well as predict the crack angle [6]. Jiao et al. conducted several standard tests and experiments on the diesel engine crankshaft and pointed out that the overload is the main reason for the final failure [7]. Sun et al. applied the critical distance approach in researching the steel crankshaft bending fatigue property and proposed several modified models to improve the accuracy of the predictions [8-10].

In recent years, the turbo charging system has been widely applied on the engines to provide higher power output, which requires more critical strength demands for the parts and corresponding surface treatment techniques. At present, the steel crankshafts are usually treated by nitriding or electromagnetic induction [11-12]. According to previous research, these two techniques can improve the strength of metal parts in two ways: producing the compressive residual stress at the stress concentration area and creating layer on the surface. The improvement in the strength property of these two techniques can be defined as [13-14]:

$$A_{st} = \frac{M_t}{M_u}, \tag{1}$$

As shown in equation (1), the definitions of the parameters are shown in the nomenclature part. In the internal combustion engine design handbook, the strengthening factor of the nitriding is about 1.3. While for the electromagnetic induction, the value of this parameter varies within the range 1.3 to 1.5 [15]. So it's a bit difficult to accurately determine which approach can provide more obvious strengthening effect just based on this parameter. On the other hand, according to the theory of fatigue reliability, the fatigue limit load of a given part is usually distributed according to the normal model. So the comparative study of the strengthening effect should be conducted based on the professional hypothesis distribution test [16].

In this paper, the strengthening effect of these two surface treatment techniques was comprehensively compared. First a modified statistical analysis method of the fatigue limit load (SAFL) was proposed to analyse the fatigue test data of the crankshaft. Then the fatigue test data of two types of crankshaft after different surface treatments were chosen to conduct the modified fatigue limit load analysis. Finally the standard hypothesis testing were selected to check the consistency of the mean values between the fatigue data from different treated crankshafts. The main conclusion of this paper is that the strengthening effect on the fatigue property caused by the electromagnetic induction quenching is much higher than that from nitriding, which makes this surface treatment technique more useful in engineering applications.

2 Method

2.1 Experiment method

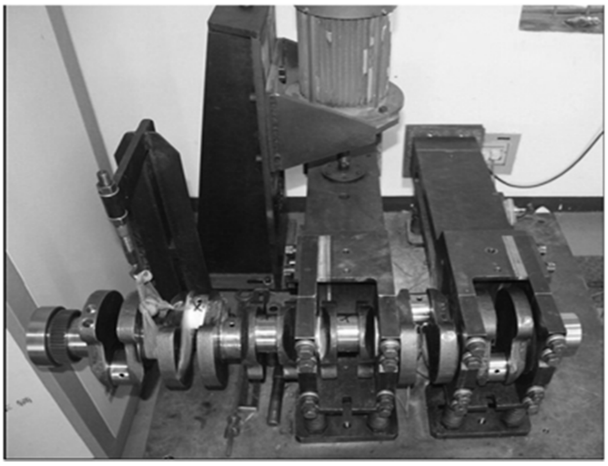

Fig. 1 *The experiment setup of the crankshaft*

In this paper, the comparison was carried out based on the fatigue test results of two types of steel crankshafts with the same structural parameters and different surface treatment techniques. As shown in Figure 1, the bending fatigue experiment in this paper is operated based on this equipment. During the fatigue experiment process, a cyclic bending moment generated by the electromotor is applied on the crankshaft to approximately simulate the working condition of the part. As a result of this, the fatigue crack caused by this load will appear at the fillet of the crankpin to reduce the stiffness of the system. Correspondingly the rotate speed of the electromotor will decline to make the dynamic response of the system unchanged, as well as the effective value of the alternating bending moment. When the reduction of the speed has reached a determined value, the crankshaft is considered broken [17-18].

2.2 Statistical analysis method

In previous related study, some experts discovered that sometimes the fatigue life in different experiment cases are quite different from each other although the fatigue load applied in each case are the same. In other words, the fatigue test results show obvious dispersibility. So corresponding statistical analysis of the test data is necessary. On the other hand, the length of the serve life of crankshaft is usually associated with the demands of the working life. As a result of this, compared with the usual fatigue life prediction under a given load, it's more meaningful to determine the fatigue limit load within a given serve time. Based on this assumption, the whole process of the research in this paper is carried out according to the following three steps:

Step 1: In this step, two groups of the same steel crankshaft were chosen and treated with different surface strengthening techniques respectively. Then the standard bending fatigue tests were conducted on both groups and corresponding results were recorded.

Step 2: A statistical analysis approach was chosen to analyse the fatigue test results in both groups and corresponding fatigue limit load distributions were determined.

Step 3: The standard distribution property test was chosen to check whether the distribution properties of the fatigue limit loads of the crankshafts after being treated by different surface strengthening techniques are the same or not. In this way, the strengthening effect of the both techniques can be compared accurately.

Previous research has indicated that for a given part, the fatigue limit load distribution under a specified life obeys a normal distribution model. As a result of this, the standard deviation hypothesis and average hypothesis test were chosen. Among these two methods, the standard deviation hypothesis was usually firstly applied to check whether there is obvious error among the standard deviations of two sets of distribution data. The equation of this method can be expressed in formula (2)[19]:

$$F=\frac{S_x^{\ 2}}{S_y^{\ 2}}=\frac{\sum_{i=1}^{i=m}x_i^{\ 2}-(1/m)(\sum_{i=1}^{i=m}x_i)^2}{m-1}\Bigg/\frac{\sum_{i=1}^{i=n}y_i^{\ 2}-(1/n)(\sum_{i=1}^{i=n}y_i)^2}{n-1}, \tag{2}$$

Where x and y are both normal variables and independent to each other. In this paper, x is the crankshaft fatigue limit load distribution group after nitriding treatment and y is the same group of the crankshaft after electromagnetic induction quenching. The upper limit value of the F can be determined based on the sizes of both subsamples the significant degree α . If $F\langle F_\alpha$, the standard deviation value of the two subsamples can be considered to be the same. Then the average hypothesis test can be applied to check whether the average values of the two samples are the same or not. The equation of this method can be expressed in formula (3)[20]:

$$t=\frac{\left(\bar{x}-\bar{y}\right)}{\sqrt{\left((m-1)S_x^2+(n-1)S_y^2\right)\Big/(m+n-2)}\sqrt{(1/m+1/n)}}\,, \tag{3}$$

Where $\bar{x}$ and $\bar{y}$ are the average values of the normal variables. Like the standard deviation hypothesis, the upper limit value of the t can be determined based on the sizes of both subsamples and the given significant degree α . If $t\langle t_\alpha$, the two subsamples come can be considered to be from the two different parents, but the average values of them are the same. In other words, the two surface treatment techniques have the same strengthening effect. Otherwise, the surfaces treatment technique which can provide higher average value can be considered to be more effective in improving the strength of the part. In this way, the comparison of the strengthening effect of the two techniques can be conducted.

3 Results

3.1 Statistical method selection

Based on the former research process in the method part, the distribution property of the fatigue limit load is the primary factor for the following research. At present, the statistical analysis approach applied in this field is usually the modified fatigue limit load analysis approach (SAFL). The theoretical foundation of this approach is shown in Fig. 2 [21-22].

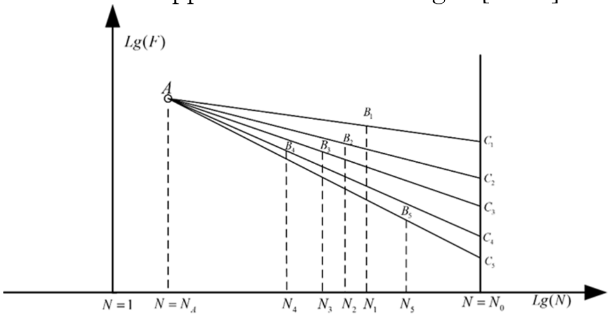

Fig. 2 *Relation between stress and life in couple log coordinate*

As shown in Fig. 2, a point A at a low fatigue life (usually 10^3) exists in the couple log coordinate made by the stress and the fatigue life. In addition, the S-N curves under different stress levels will cross through this point. According to this theory, the fatigue limit load under a given limit fatigue life (usually 107 for the steel parts) can be determined as:

$$\lg C_i=\lg S_A\frac{\lg N_0-\lg N_i}{\lg N_A-\lg N_i}+\lg S_i\frac{\lg N_0-\lg N_A}{\lg N_\mathrm{i}-\lg N_A}\,, \tag{4}$$

Where N_A is the low fatigue life point, S_A is the stress amplitude which can be determined through a least squares fit approach of the experiment data. Based on this approach, the distribution property of the fatigue strength can be determined to provide the basic parameters for the further comparative analysis.

3.2 Example one

Based on the statistical analysis approach in the previous chapter, it's convenient to determine the fatigue limit load property by analysing the fatigue test data of a given component. Tab. 1 shows the structural parameters of a six-cylinder crankshaft (the code number in this case is N1). The material of this crankshaft is 42Crmo, a typical type of high strength alloy steel. In this paper, both the electromagnetic induction quenching and nitriding approaches were applied in improving the fatigue strength of this crankshaft, corresponding fatigue test results were shown in Tab. 2 and Tab. 3.

Tab. 1 *The structural parameters of crankshaft N1*

Parameter	value
Crankpin length	36mm
Crankpin diameter	82mm
Fillet radius	5mm
Overlap	26mm
Crankpin width	29mm

Tab. 2 *The experimental results of crankshaft N1 (after nitriding)*

Bending moment /$N{\cdot}m$	Fatigue life
5523	331746
5302	452099
5155	1199703
5401	297553
5155	1487985
5400	288570
5278	244539
5215	1146848
5278	1021286
5155	1205913

Tab. 3 *The experimental results of crankshaft N2 (after electromagnetic induction quenching)*

Bending moment /$N{\cdot}m$	Fatigue life
5842	1182484
5965	502160
5793	1174642
5646	2945466
5867	590143
5916	564569
5768	3842252
5891	1200659
6014	242227

As shown in Tab. 2 and Tab. 3, the sample sizes in these two cases are eight and nine respectively. Based on the modified SAFL approach in the previous chapter, the fatigue limit load distribution property of each case can be determined, the results are shown in Tab. 4.

Tab. 4 *The failure probability estimation results of both cases*

Nitriding			Electromagnetic induction quenching		
Bending moment /$N{\cdot}m$	Failure serial number	Median rank	Bending moment /$N{\cdot}m$	Failure serial number	Median rank
5311	1	0.0745	4652	1	0.0673
5356	2	0.1809	4862	2	0.1635
5420	3	0.2872	4863	3	0.2596
5430	4	0.3936	4872	4	0.3558
5444	5	0.5	4902	5	0.4519
5465	6	0.6064	4932	6	0.5481
5498	7	0.7128	4935	7	0.6442
5569	8	0.8192	4941	8	0.7404
5632	9	0.9255	5002	9	0.8365
			5194	10	0.9327

According to the parameters in Tab. 4, the standard deviation of the crankshaft fatigue limit load after nitriding is 99$N{\cdot}m$, and the same parameter in the quenching case is 134$N{\cdot}m$. Based on these two parameters, the standard deviation hypothesis can be conducted. The result can be expressed as:

$$F=\frac{S_x^{\,2}}{S_y^{\,2}}=\frac{\sum_{i=1}^{i=m}x_i^{\,2}-(1/m)(\sum_{i=1}^{i=m}x_i)^2}{m-1}\Bigg/\frac{\sum_{i=1}^{i=n}y_i^{\,2}-(1/n)(\sum_{i=1}^{i=n}y_i)^2}{n-1}=1.83\,, \tag{5}$$

In this section, the sample sizes of both cases are 9 and 10 respectively. According to the standard F distribution demand, the upper limit of the parameter in this condition is 3.02 under the 0.05 significant degree. While under the 0.025 significant degree, the upper limit of the parameter is 3.78. So these two groups of data can be taken into the average hypothesis test. The result can be expressed as:

$$t=\frac{\left(\bar{x}-\bar{y}\right)}{\sqrt{\left((m-1)S_x^2+(n-1)S_y^2\right)\big/(m+n-2)}\sqrt{\left(1/m+1/n\right)}}=9.4\,, \tag{6}$$

According to the standard t distribution demand, the upper limit of the parameter in this condition is 1.74 under the 0.05 significant degree and 2.11 under the 0.025 significant degree. In this section, the analysis result is obviously much bigger than the upper limit. In other words, the fatigue limit load of the crankshaft after electromagnetic induction quenching is much higher than that of the crankshaft after nitriding.

3.3 Example two

Tab. 5 *The structural parameters of crankshaft N1*

Parameter	value
Crankpin length	36mm
Crankpin diameter	68mm
Fillet radius	3mm
Overlap	6mm
Crankpin width	26mm

In this paper, another type of steel crankshaft is also selected to study in order to give more detail conclusions. Tab. 5 shows the structural parameters of this four-cylinder crankshaft with the serial number of N2. The material of this crankshaft is the high strength alloy steel S45C. Corresponding fatigue test results were shown in Tab. 6 and Tab. 7.

As shown in Tab. 6 and Tab. 7, the sample sizes in these two cases are eight and nine respectively. Based on the modified SAFL approach in the previous chapter, the fatigue limit load distribution property of each case can be determined in Tab. 8.

Tab. 6 *The experimental results of crankshaft N1 (after nitriding)*

Bending moment /N·m	Fatigue life
4909	496300
4909	252286
4664	868306
4664	901425
4764	687944
4764	652265
4541	1435103
4541	2221044

Tab. 7 *The experimental results of crankshaft N2 (after electromagnetic induction quenching)*

Bending moment /N·m	Fatigue life
4300	1672344
4700	244397
4600	279267
4500	462782
4200	6812699
4400	2274229
4150	5047681
4400	1137654

Tab. 8 *The failure probability estimation results of both cases*

Nitriding			Electromagnetic induction quenching		
Bending moment /N·m	Failure serial number	Median rank	Bending moment /N·m	Failure serial number	Median rank
4038	1	0.0833	4244	1	0.0833
4040	2	0.2024	4306	2	0.2024
4053	3	0.3214	4313.64	3	0.3214
4076	4	0.4405	4328	4	0.4405
4094	5	0.5595	4373	5	0.5595
4150	6	0.6786	4391	6	0.6786
4216	7	0.7976	4402	7	0.7976
4229	8	0.9167	4406	8	0.9167

According to the parameters in Tab. 8, the standard deviation of the fatigue limit load of the crankshaft after nitriding is 77*N·m*, and the same parameter in the quenching case is 57*N·m*. Based on these two parameters, the standard deviation hypothesis can be conducted. The result can be expressed as:

$$F = \frac{S_x^{\ 2}}{S_y^{\ 2}} = \frac{\sum_{i=1}^{i=m} x_i^{\ 2} - (1/m)(\sum_{i=1}^{i=m} x_i)^2}{m-1} \Bigg/ \frac{\sum_{i=1}^{i=n} y_i^{\ 2} - (1/n)(\sum_{i=1}^{i=n} y_i)^2}{n-1} = 1.82, \tag{7}$$

In this section, the sample sizes of both cases are 9 and 10 respectively. According to the standard F distribution demand, the upper limit of the parameter in this condition is 3.44 under the 0.05 significant degree. While under the 0.025 significant degree, the upper limit of the parameter is 4.43. So these two groups of data can be taken into the average hypothesis test. The result can be expressed as:

$$t = \frac{\left(\bar{x} - \bar{y}\right)}{\sqrt{\left((m-1)S_x^2 + (n-1)S_y^2\right)\Big/(m+n-2)}\sqrt{\left(1/m + 1/n\right)}} = 6.87\,, \tag{8}$$

According to the standard t distribution demand, the upper limit of the parameter in this condition is 1.79 under the 0.05 significant degree and 2.2 under the 0.025 significant degree. In this section, the analysis result is obviously much bigger than the upper limit. In other words, the fatigue limit load of the crankshaft after electromagnetic induction quenching is much higher than that of the crankshaft after nitriding.

As mentioned in the introduction part, the strengthening factor is usually adopted in evaluating the strengthening effect caused by the surface treatment technique. Based on this parameter, the relative difference between the median value of the fatigue limit load of the crankshaft after different surface treatments in both cases is less than 10%, which means that no obvious effect can be discovered [23-24]. So compared with this method, the evaluation process in this paper can provide more comprehensive evaluation for both techniques, which makes it for suitable for application.

4 Conclusion

In this paper, the strengthening effect of these two surface treatment techniques was comprehensively compared. First a modified statistical analysis method of the fatigue limit load (SAFL) was proposed to analyse the fatigue test data of the crankshaft. Then the fatigue test data of two types of crankshaft after different surface treatments were chosen to conduct the modified fatigue limit load analysis. Finally the standard hypothesis testing were selected to check the consistency of the mean values between the fatigue data from different treated crankshafts. The main conclusion of this paper suggest that compared with nitriding, the electromagnetic induction quenching technique can enhance fatigue strength of steel crankshafts more obviously, thus makes this approach more useful in the application of the surface treatment process for the steel crankshafts arranged in high power diesel engines.

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