Effect of Fillet Rolling Load on the Fatigue Performance of a Micro-Alloy Steel Diesel Engine Crankshaft

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Abstract. Fillet rolling process is an effective method used to improve the fatigue performance of crankshafts by hardening the fillet region and inducing compressive residual stresses. This paper summarizes the work conducted to investigate the effect of rolling load on fatigue behaviour of a micro-alloy steel crankshaft used in diesel engine applications. Based on the staircase test methodology, component-scale resonant bending fatigue tests were conducted to obtain stress versus number of cycles curves and to evaluate the fatigue endurance limits of the crankshaft at un-rolled condition and fillet-rolled conditions at three different loads. Test data was analysed by Dixon-Mood method to calculate the endurance limits. Results showed that the endurance limit increased significantly with fillet rolling process in comparison to un-rolled condition. Endurance limit further increased with the increasing rolling load however with a limited extent above which excessive hardening deteriorates the fillet region; that is the workability limit. The outcomes of this study has shed light on the fillet rolling process to select the optimum rolling load for the used design and material conditions.

1. Introduction
Crankshaft is one of the most critical parts of an internal combustion engine and drives the engine system parts by converting the reciprocating motion of the piston into rotational motion. During service, crankshafts are subjected to a significant number of cyclic loadings; such as inertia forces due to rotating and reciprocating parts and gas explosion forces. Main stresses created on the crankshaft due to these forces are the cyclic bending and torsion.

Fatigue failures on crankshafts are mostly observed at fillet regions since they are dynamically and geometrically the most critical regions and stress concentrations are eventually present. Other critical regions for crack initiation are the pin surface and oil hole ends on the crankshaft surface.

In order to improve the fatigue and wear performance of the crankshafts a variety of surface treatment processes are applied such as; nitriding, induction hardening and fillet rolling. Among these, fillet rolling process is a widely used process in automotive industry which improves fatigue strength of the crankshaft fillet region [1].

Fillet rolling process aims to develop compressive residual stresses and increase the hardness at the fillet region by for local mechanical loading. Developed compressive stresses increase the fatigue life by compensating the tensile stress components created during working conditions in addition to the increased surface hardness which also improves the fatigue strength. In order to obtain a suitable geometry for the roller to fit onto, an undercut having a radius of curvature is formed at this region, which is called the undercut region.
As any failure on the crankshaft will result in catastrophic failures on the engine, studies on the crankshaft durability optimization by fillet rolling process have been in the scope of a large number of studies which are based on experimental and analytical approaches.

Effect of process parameters have been studied by numerous researchers. By crankshaft rig tests of crankshafts with different rolling conditions and by the X-Ray measurement of residual stresses, Ko et.al. [2] have developed a correlation between rolling load, surface hardness and residual stresses with the applied bending moment. By using the experimental data, optimum conditions for rolling load, fillet geometry and material were identified by CAE analysis. Effect of fillet rolling process was on a ductile cast iron crankshaft was evaluated by Çevik et.al. [3] by resonant bending fatigue tests of crankshafts at the fillet-rolled and un-rolled conditions. Regul’ski et al [4], have studied the effect of rolling by the use of fatigue tests of non-hardened crankshafts with fillet and hardened and non-hardened crankshafts without a fillet. By analysing of the test results a procedure of fatigue testing was proposed to obtain the in-service fracture patterns of motorcycle crankshafts.

Various studied have been conducted on component scale testing of the crankshafts to determine the stress versus numbers of cycles (S-N) curves. The possibility of the damage formation on the test rig in case of two-piece failure of the crankshaft has been the starting point of the studies concerning proposal of failure criteria of laboratory tests for many years. Later on, resonance shift failure criterion has been one of the widely used methods which is based on the resonance shifts induced by crack formation and subsequent stiffness drop in resonant bending fatigue rig tests. Feng and Li [5] developed an electrodynamic test machine and automotive component testing procedure and proposed the relationship between crack formation, stiffness and resonance shift. Surface failure criterion which is based on the crack initiation has also been a subject of many studies. According to this criterion, any crack that can be identified visually can be accepted as failure [1, 6]. Chien et al [7] studied the crack arrest phenomenon on the subsurface due to the presence of compressive residual stresses by finite element mapping of stress intensity factors against the fillet depth. Spiteri et al [8] conducted an experimental work to qualify and validate the crack arrest theory proposed by Chien et al (8) followingly.

This study aimed to evaluate the effect fillet rolling process and the applied rolling loads on the fatigue performance of a micro-alloy steel crankshaft. For this purpose, component scale resonant bending fatigue tests were conducted with the crankshaft samples at 4 different fillet rolling conditions; un-rolled at fillet-rolled at 3 different loads. Moment amplitude versus number of cycles to failure curves were obtained at these 4 conditions. The endurance limits were calculated by Dixon-Mood analytical method and compared with respect to the fillet-rolling condition. The correlation of endurance limit improvement with the rolling load and limits of improvement were evaluated.

2. Experimental Procedure

2.1 Material
A micro-alloyed steel of 38MnVS6 grade crankshaft, produced by forging, was used in this study. After forging process, crankshafts were controllly cooled down and no subsequent heat treatment is applied after cooling. Spectrometric analysis were carried out with the specimens from the steel crankshafts and chemical composition is shown on Table 1.

| Table 1. Chemical Composition of 38MnVS6 Forged Steel. |
|----------|---|---|---|---|---|---|---|---|---|---|---|
| Material | C  | Si | Mn | V  | P  | S  | Cr | Mo | Ni | Cu | N  | Al | Fe |
|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 38MnVS6   | 0.38| 0.56| 1.42| 0.10| 0.01| 0.01| 0.14| 0.02| 0.09| 0.16| 0.01| 0.01| Rest |
2.2 Fillet Rolling Process

In the frame of this study, crankshafts with 4 different fillet rolling conditions were studied in order to correlate the fatigue strength with the amount of rolling load. Namely, crankshafts with the unrolled condition and fillet-rolled at 15kN, 20kN and 24kN were used at the pin fillet region.

In this study, an undercut depth of 1.55mm was applied on the fillet regions. An undercut is machined at the journal corners during machining process of the crankshaft to create a suitable form for the roller to fit on. Figure 1 shows the 2D projection view of the undercut region, describing the radius and depth profiles.

![Figure 1. 2D view of the undercut region.](image)

Fillet rolling is applied to the undercut region of main and pin journals of the crankshaft hydraulically by the use of a rigid rolling apparatus. Rolling apparatus is composed of a primary roller associated with two secondary rollers that deform both corners of the crankshaft journal simultaneously during rolling operation. Rollers apply to the crankshaft journal at an angle of 55° to crank axis. Figure 2 demonstrates the main components of the crankshaft; undercut region and rolling operation schematically.

![Figures](image)
Rolling operation was conducted at the pin fillet region with the given loads (15kN, 20kN and 24kN) on the primary roller at a frequency of 80 rpm with 12 crank revolutions. The secondary rollers used in this study are of disc shape with a diameter of 15 mm and a thickness of 5 mm. Radius of curvature of the roller at the rolling contact area is 1.45 mm.

2.3 Resonant Bending Fatigue Tests
Resonance fatigue testing method was used to evaluate the moment versus cycles to failure curve data of the crankshafts at 4 different fillet-rolled conditions. The resonant fatigue testing method is based on the mechanical stiffness theory. Under testing, the frequency of the test is stabilized at the resonance frequency of the component on the test rig, depending on the material’s Elastic Modulus and geometry of the system. With the formation and propagation of a crack on the specimen, the resonant frequency of the test rig decreases due to the decreasing cross-section and thus the decreasing mechanical stiffness of the system [9].

Specimens from crankshafts were cut for fatigue rig tests and tested under cyclic bending conditions on the resonant type fatigue test machine. Cyclic bending moments were applied on the fillet region of 5th pin journal, which is the most critical region of the crankshaft under service. Tests were conducted at completely reversed constant amplitude cyclic loads.

During the tests, the resonance test frequencies observed to be approximately 40 Hertz. In order to cover both crack initiation and propagation stages on the test specimens, a relatively large value of frequency limit of ±4 Hertz, 10% of the resonance frequency, was used.

For the applied bending moments, number of cycles to failure were recorded to construct the moment amplitude versus number of cycles to failure (M-N) curves of the crankshafts at 4 different fillet rolling conditions. Test run-out criterion was used as 10 million cycles. Thus, the fatigue strength values used in this study define the fatigue strengths at 10 million cycles.

Predefined bending moments, at a span length of 66.1mm, were applied to the pin fillet region next to main journal side throughout the tests. Figure 3 shows the schematic and actual views of the test specimen, test set-up and demonstrates the test failure region.
Figure 3. Schematic and actual views of the test set-up.

Staircase test methodology [10] was used for load amplitude selection for the fatigue tests. By the use of this method, first specimen was tested at a predefined load amplitude level based on experience. If the specimen failed, load amplitude level was decreased one step for the next test. If the specimen did not fail, a one step higher stress amplitude was used for the following test. This procedure was repeated until a valuable number of data is obtained to construct the M-N curve and for the endurance limit calculations.

3. Test Results

The number of cycles to failures were recorded against applied bending moment amplitude throughout the tests. The test data are demonstrated as the applied moment in Nm versus number of cycles to failure curves for each rolling condition on Figures 4, 6, 8 and 10 on a semi-logarithmic scale. The number of run-outs for each moment amplitude value were also shown on the figures. Figures 5, 7, 9 and 11 show the staircase moment steps and failure/run-out history around the endurance limit for each case.
Figure 4. M-N curve for the un-rolled condition.

Figure 5. Failure/Run-out history for the un-rolled condition.

Figure 6. M-N curve for the crankshaft fillet-rolled at 15kN.
Figure 7. Failure/Run-out history for the crankshaft fillet-rolled at 15kN.

Figure 8. M-N curve for the crankshaft fillet-rolled at 20kN.

Figure 9. Failure/Run-out history for the crankshaft fillet-rolled at 20kN.
4. Endurance Limit Calculations

Dixon-Mood [11] method was used to calculate the endurance limits from the failure/run-out data around the transition region. This method is based on Maximum Likelihood Estimation which assumes a normal distribution of fatigue limit to calculate the mean (μ) and standard deviation (σ). The equally spaced stress (S) levels are sorted and numbered starting from the lowest stress level, $S_0$. Number for $S_0$ is denoted by $i=0$. Stress increment or stress step is denoted by $S_d$. The number of less frequent event at a stress level is defined by $n_i$. For statistical analysis, three parameters, $A$, $B$ and $C$, are calculated where

$$A = \sum_{i=0}^{i_{\text{max}}} x^n_1$$  \hspace{1cm} (1)

$$B = \sum_{i=0}^{i_{\text{max}}} ix^n_1$$  \hspace{1cm} (2)

$$C = \sum_{i=0}^{i_{\text{max}}} i^2x^n_1$$  \hspace{1cm} (3)

Mean fatigue limit is calculated by the equation

$$\mu = S_0 + S_d\frac{\sigma}{A} \pm 0.5$$  \hspace{1cm} (4)
If the more frequent event is failure, the plus sign is used in the above equation and if the more frequent event is survival the negative sign is used.

Standard deviation is calculated by the below formula

\[ \sigma = 1.62xS_d x (\frac{A_xC-B^2}{A^2} + 0.029) \text{ if } \frac{A_xC-B^2}{A^2} \geq 0.3 \]

or

\[ \sigma = 0.53xS_d \text{ if } \frac{A_xC-B^2}{A^2} < 0.3 \] (5)

(6)

Standard deviation equations proposed by Dixon and Mood are based on the assumption that stress increment value is on the order of 0.5 to 2.0 \( \sigma \).

Within this study, Moment values were studied instead of Stress values; and denoted by M.

Dixon-Mood calculations of endurance limits in terms of moment amplitudes are summarized on Table 2. Calculated mean endurance limit, standard deviation and lower and upper endurance limits for 95% confidence are listed. Results are discussed on the following section.

**Table 2. Endurance Limit Calculation Results**

| Moment Increment (M_d) (Nm) | Standard Deviation (\( \sigma \)) (Nm) | Fatigue Limit at 95% Confidence |
|-----------------------------|----------------------------------------|--------------------------------|
|                             |                                        | Lower (Nm) | Upper (Nm) |
| Un-Rolled                   |                                        | 322.24     | 311.01     |
| Rolled at 15kN              |                                        | 1591.70    | 1614.15    |
| Rolled at 20kN              |                                        | 1666.06    | 1688.51    |
| Rolled at 24kN              |                                        | 1660.76    | 1649.54    |

5. Discussions and Conclusions

In order to evaluate the success of Dixon-Mood method calculations of staircase test data, moment increments to standard deviation ratio for un-rolled and rolled crankshafts are calculated for each case which is found to be 1.89 for all cases; as same moment increments were used and a 8.77 Nm of standard deviation was obtained for all cases. For Dixon-Mood results to be evaluated as successful, this ratio should be within which is within the range of 0.5 to 2.0 where Dixon-Mood equations are based on. Thus it can be concluded that the calculated endurance limits can be regarded as successful evaluations.

When mean fatigue endurance limits of un-rolled and rolled crankshafts are compared mathematically, it can be derived that fatigue strength of rolled crankshafts are at least 5 times of the unrolled crankshafts. This fact describes that the fillet rolling is an effective process to improve the fatigue strength of crankshafts significantly by a convenient local deformation and hardening process. The mechanism of strengthening by fillet rolling process is mainly the compressive residual stresses developed and local hardening as a result of local plastic deformation. Compressive residual stresses compensate the tensile components of the service loads, and local hardness increase can retard the crack initiation which both improve the fatigue strength.
An improvement factor of 4.97 was calculated when the endurance limits of un-rolled and rolled crankshafts were compared. As seen from Table 2, increasing the fillet rolling load to 20 kN has resulted in a further increase in fatigue strength. However when a fillet rolling load was increased to 24 kN, a slight decrease of endurance limit was observed. This result shows that the maximum achievable fatigue strength can be obtained within the rolling load range of 20 kN and 24 kN. Depending on this data, the surface qualities of crankshafts rolled with 20 kN and 24 kN were examined.

Figure A on the appendix section shows the fillet surfaces of crankshafts rolled at 20kN and 24kN. An apparent difference in surface qualities of the crankshafts were observed as demonstrated on this figure. On the crankshaft where a rolling load of 24kN was applied, surface irregularities were observed which can act as crack initiation points and decrease the duration of fatigue crack initiation stage under cyclic loading. These findings explain the lower fatigue strength observed at 24kN rolling load condition with respect to 20kN.

Thus, it can be derived that the optimum rolling load for the crankshaft design and material combination used in the frame of this study is between 20 and 24kN and the workability limit of the design and material combination was reached within this fillet rolling load range. This finding has accepted to be an important guideline for selecting the correct fillet rolling load with this design optimization study.

6. Appendix

![Figure A](image1.png)

(a) 24kN  (b) 20kN

**Figure A.** Fillet surface qualities of 38MnVS6 crankshafts at 24 and 20kN rolling conditions.

7. References

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