The influence of fillet rolling on fatigue strength – experiment and calculation

R. Schaal\textsuperscript{1}, B. Kaiser\textsuperscript{2}, B. Pyttel\textsuperscript{2} & C. Berger\textsuperscript{2}

\textsuperscript{1} SIEMENS AG, Mülheim an der Ruhr, Germany
\textsuperscript{2} Institute of Materials Technology, Darmstadt University of Technology, Germany

Abstract

Fillet rolling is a method that significantly improves the fatigue strength of members. Residual compressive stresses induced in the surface layer during the fillet rolling process are able to retard or prevent crack propagation. Large gains in fatigue strength up to 200\% can be achieved. A procedure was developed to enable the fatigue strength calculation of fillet-rolled members. Two main topics had to be considered: The application of the FEM to simulate the rolling process and to calculate the residual stresses and the application of fracture mechanics to assess the effect of the compressive residual stresses on crack propagation. The influence of different process parameters can be investigated. After the simulation of fillet rolling the redistribution of the residual stresses dependent on cyclic loading can be determined by a FEM calculation. All the calculated results can be compared to measured results obtained from the X-ray diffraction method. Good correlation has been obtained for both the magnitude and the distribution pattern of the residual stresses. Fracture mechanics concepts were used to determine the fatigue strength and the depth of crack arrest. Stress intensity factors can be calculated both for the residual stresses and the loading stresses. Adding these two stress intensity factors an effective stress intensity factor can be calculated that characterises the ability of a crack to propagate. Comparing this effective stress intensity factor with the threshold value of fatigue crack propagation the fatigue strength of the rolled member can be found. The calculated fatigue strengths are slightly smaller than experimentally determined. The paper shows the FEM-simulation of the fillet-rolling process, the calculation of the redistribution and the results of fatigue strength calculation of notched components and crankshafts.
1 Introduction

In many cases of technical practice the surface layer is the most stressed area of cyclic loaded components and therefore the origin of fatigue crack initiation and failure. Different methods can be applied to improve the fatigue strength of the surface layer, following an improvement of the fatigue behaviour of the whole component. As one of these methods, the surface strengthening method "surface rolling" is widely used, especially in the automotive industry on fillet rolling of crankshafts, valves, gears or bolts.

In the past, several experimental investigations were carried out to show the effectiveness of this method on different types of steels, cast iron but also on light metals as titanium, aluminium or magnesium (e.g. [1-3]). In our times, the application of numerical methods becomes more and more important to reduce time and costs for development and design. Though, for fillet rolled parts, conventional assessment of the fatigue behaviour shows several disadvantages.

Considering fatigue crack initiation as criteria to define the fatigue strength of fillet rolled parts, only a small increase can be detected. In the case of an initiated crack, starting from the surface, the growth of the fatigue crack can be retarded or even stopped due to the compressive residual stresses. Using the phenomena of fatigue crack arrest due to compressive residual stresses, the notch effect is eliminated under optimised rolling conditions and an increase of fatigue strength up to 200% can be reached.

Using common methods to calculate the fatigue strength of fillet rolled parts, the possibility of fatigue crack arrest is not considered. Hence, no use of the significant increase in fatigue by fillet rolling can be made.

Therefore, a procedure was developed to calculate the fatigue strength of fillet rolled members, which includes crack growth behaviour by applying methods of fracture mechanics [4]. The procedure to calculate the fatigue strength of fillet rolled members consists of the following steps:

- FE-simulation of the fillet rolling process to calculate residual stresses
- Calculation of the redistribution of the residual stresses due to cyclic loading
- Application of fracture mechanics concepts to calculate the fatigue strength:
  - Calculation of stress intensity factors for loading and residual stresses
  - Superposition of the stress intensity factors
  - Derivation of the fatigue limit of the fillet rolled component from the fatigue crack threshold $\Delta K_{th}$
2 Calculation of residual stresses

2.1 FE-simulation of the fillet-rolling process

The FE-method was applied to calculate the residual stress distribution caused by the contact of the component and the rolling tool. Due to this contact, the surface layer is deformed in a partially plastic manner leaving the formation of macroscopic residual stresses.

Applying the FE-modelling, variations of geometry, material and parameters of the fillet rolling process can be investigated and optimised easily.

Fig. 1 shows the FE-Model of a V-notched specimen to simulate the fillet rolling process. The simulation of the rolling process was made only over a small but sufficient area. The elastic-plastic material behaviour was described by a stress-strain curve, derived in a modified compression test from the rolled material.

2.2 Results of the FE-simulation

Fig. 2 shows the axial residual stresses of the fillet rolling simulation calculated for the V-notched specimen (material 1.7224, 42CrMo4, R_m=1066 N/mm², R_p0,2=958 N/mm²). The applied rolling load was 5 kN.

Resulting from the contact between two parts (Hertzian contact), the residual stresses show a maximum amount of compression beneath the surface.

For comparison, the results of two X-ray measurements of the axial residual stresses of real fillet rolled specimens are shown. The calculated and measured values correspond very well.

3 Redistribution of residual stresses during cyclic loading

Especially during the first loading cycles, residual stresses can redistribute because of plastic deformation. After these cycles residual stresses become relatively stable and will not change substantially due to the further cyclic loading. Only this stable residual stresses are able to influence the crack growth behaviour significantly. For this reason, the redistributed residual stresses must be determined in relation of the type of loading, the mean value and the amplitude of the loading stress.

The redistribution of the residual stresses was calculated with the FE-method, applying one half cycle of the compression portion of the cyclic loading. The redistributed residual stresses were determined after this half cycle.

Fig. 3 shows the residual stresses of the V-notched specimen (applied rolling load 5kN) calculated for a axial loading of 440 MPa with a stress ratio R=-1. For comparison, measured values of residual stresses are shown (X-ray-measurements of rolled specimens after 2·10⁶ loading cycles).
Figure 1: Finite element model for the simulation of the fillet rolling process.

Figure 2: Residual stresses after fillet rolling (FE results and measured by X-ray).
4 Application of fracture mechanics concepts

4.1 Effect of compressive residual stresses on the crack propagation

Linear-elastic fracture mechanics was used to assess the effect of the residual stresses on an initiated crack starting from the surface of the fillet rolled specimen. To estimate the fatigue strength of a part with a crack, the crack growth behaviour in the threshold region had to be considered. The cyclic stress intensity factor – characterising the fatigue crack growth behaviour – was derived from the superposition of stress intensity factors calculated for loading and residual stresses (Fig. 4). The $\Delta K_{\text{eff}}$-concept [5] was used to characterise the ability of crack growth. For simplification, crack opening was fixed at a $K_{\text{op}}=0$. The effective cyclic stress intensity factor can therefore be calculated by:

$$\Delta K_{\text{eff}} = K_{\text{max}} = K_{\text{Load,max}} + K_{RS} \quad (1)$$

As an example Fig. 5 shows the calculation of the stress intensity factors for loading and residual stresses near the fatigue limit. Because of the maximum of residual stresses beneath the surface, the amount of $K_{RS}$ increases with increasing...
crack depth. Due to this, the effective stress intensity factor $\Delta K_{\text{eff}}$ is decreased through the increasing effect of the residual stresses. The crack growth is retarded or even stopped if the cyclic stress intensity factor equals the threshold value $\Delta K_{\text{eff,th}}$. The condition of fatigue limit can be described by:

$$\Delta K_{\text{eff}} = \Delta K_{\text{eff,th}}$$  \hspace{1cm} (2)

The fatigue limit was defined as the loading, for which this condition is reached at least for one point.

Figure 4: Effect of the compressive residual stresses on the cyclic stress intensity factor $\Delta K$.

Figure 5: Crack arrest due to residual stresses from fillet rolling.
4.2 Results of fatigue strength calculation

The concept was used to calculate the fatigue strength of specimens under axial tension-compression and bending loading. The influence of different parameters of the fillet rolling process e.g. the applied rolling load but also of different design parameters on the fatigue strength were investigated. The concept of fatigue strength calculation of fillet rolled parts proved to be able to describe the influence of this parameters very well.

Fig. 6 shows the results of fatigue strength calculation and experiments for the V-notch specimen (rolling load 5kN) for different stress ratios R. The experimental results represent a survival probability of 50%.

For $R=0$, a slightly higher result was calculated, other ratios show slightly smaller results. The calculated and experimental results show a good agreement, especially if the significant increase of the fatigue limit through fillet rolling and the simplification of the calculation model is taken into account.

![Figure 6: Results of fatigue strength calculation.](image)

5 Application of the concept

The concept was applied to calculate the fatigue strength of crankshafts [6], [7]. The simulation of fillet rolling was applied on a FE-model representing the stroke bearing of a crankshaft. The redistribution of the residual stresses could be calculated depending on the crankshaft loading. An increase of the fatigue strength up to a factor of 3 could be determined by the calculation verifying the experimental results.

The application of the concept shows the two big advantages of the concept: On the one hand it is difficult and expensive to estimate residual stress distributions
in complex structures like a crankshaft, on the other hand the effectiveness of the fillet rolling for a special component must be tested after manufacturing in expensive and time consuming experiments until now. The new concept gives the opportunity to reduce time and costs for development and design.

6 Conclusion

A concept was presented to calculate the fatigue strength of fillet rolled members. The compressible residual stresses – the main reason for the large increase of fatigue strength – were calculated by a FE-simulation of the fillet rolling process. The redistribution of the residual stresses due to cyclic loading was considered. The fatigue strength was calculated using fracture mechanics concepts. Experimental results and calculations show a good agreement. The application of this concept in the development and design process – for example for crankshafts in the automotive industry – allows a reduction of time and costs through minimizing components testing and optimizing the rolling parameters in the early design phase.

References