

Potentials of Crankshaft Fillet Rolling Process

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ABSTRACT

Crankshaft is a dynamic component that copes with elevated alternating stresses. In order to ensure the service reliability, fillet rolling process is being applied. The state of the art empirical assumptions to consider the effect of fillet rolling process on crankshaft fatigue are conservative. This leads to an over-engineering of the crankshaft. However, calculation of the compressive residual stresses due to surface treatment is a demanding task. The quality of the durability analysis can only be increased by an accurate consideration of the fillet rolling effect. Therefore, Hegenscheidt-MFD, FEV Motorentechnik and Institute for Combustion Engines (VKA) cooperated to enlighten the phenomenon of the fillet rolling process. Process calculations are applied and validated by the measurements and tests. The calculated residual stresses are then superposed with the dynamic loads calculated by FEV Virtual Engine. The calculations are applied based on a state of the art inline four cylinder gasoline engine. The results show that there is an increase in safety factors even more than a factor of 2.5, in case of spheroidal cast iron.

CITATION: Cevik, M., Hochbein, H. and Rebbert, M., "Potentials of Crankshaft Fillet Rolling Process," *SAE Int. J. Engines* 5(2):2012, doi:10.4271/2012-01-0755.

INTRODUCTION

As the central engine component, the crankshaft directly influences the engine dynamics, NVH behaviour, friction and costs. Hence, modern demands of crankshaft can not be only summarized by the durability throughout the engine life. Additional demands that are being considered more intensely can be summarized as:

- Small bearing diameters in order to ensure low friction losses (low mechanical losses)
- Utilization of low-grade materials and/or low-cost production processes in order to ensure low costs
- Lightweight design to reach the low mass and mass inertia to ensure fuel economy

Since the stated demands conflict with each other, an optimal layout of crankshafts is a challenging task. Due to this fact, the importance of crankshaft after-treatment processes is increasing significantly. The main reason is that the durability behavior of the material can be increased considerably without changing the material type and/or

design of the component. Crankshafts are predominantly subjected to either a heat treatment, such as nitriding or induction hardening, or a mechanical surface treatment, such as fillet rolling process. The decision is given usually according to the material type, production batch size and strength and hardness requirements against fatigue and wear. Sequential application of a heat and a following mechanical surface treatment is also possible but not common.

Fatigue problems of crankshafts occur primarily at the fillet region between the crank web and bearing (especially pin bearing) due to high cycle fatigue. Hence, the fillet rolling process provides a customized solution for the crankshaft fillet area, which is very suitable for mass production. This led to a significant increase in the application of this process during the past decades, especially for the passenger car engines. The [Figure 1](#) below shows the market share development of the crankshaft after-treatment processes for in-line four-cylinder crankshafts concerning the number of units.

The potential of the different crankshaft after-treatment methods is a well-investigated subject. However, most of the

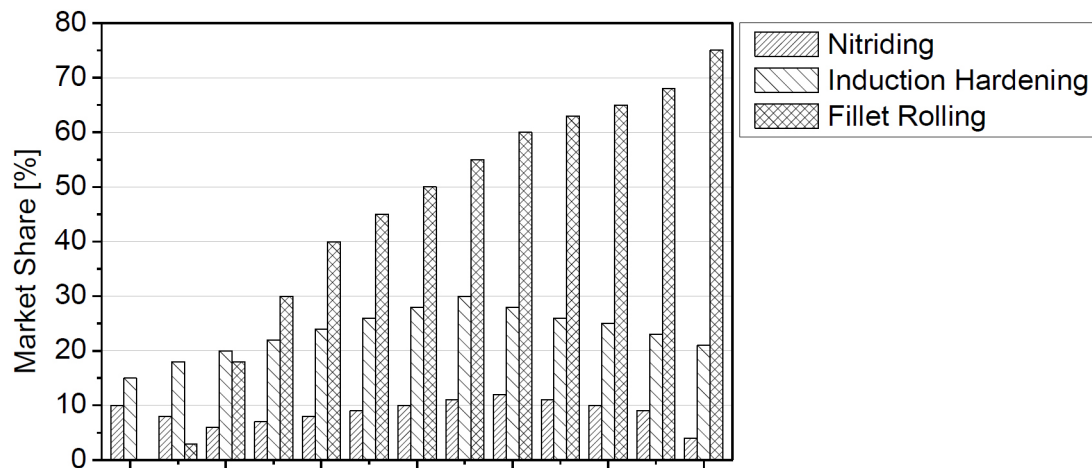


Figure 1. Market share development for in-line four-cylinder crankshafts

current investigations estimate the potentials based on the component pulse tests [1], [2], [3], [4]. An alternative is to apply finite element method (FEM) to simulate the treatment process via computer. Due to high micro-structure influence and the complexity of the interactions, the simulation of heat treatment processes require very high efforts and the reliability of the endurance strength evaluation is rather low. However, simulation of the mechanical treatment processes, such as fillet rolling, is less complex, since it is not heat-dependent and process boundary conditions are easy to model in FEA. Therefore, in this paper the potentials of the fillet rolling process are not only proven by the component pulse tests, but also with the aid of the FEA. This approach is developed to be able to use it also during the conceptual phase, in which no prototype of the crankshaft exits.

FILLET ROLLING PROCESS

Deep rolling process is applied to pre-machined deformable surfaces via pivot rotating tools, in order to yield the surface layers under contact pressure to increase the fatigue strength. Crankshafts are deep rolled on the fillets, which are usually the most critical regions for passenger car crankshafts; hence, the process is called fillet rolling [5]. In a first step the crankshaft is clamped in the fillet rolling machine that is technically derived from a turning lathe as depicted in Figure 2-a. In the following step the roller heads are clamped by hydraulic pressure simultaneously to each pin and main bearing (see Figure 2-b). On the one side, two fillet rollers are engaged with each fillet. On the opposite side, the supporting rollers contact with the whole bearing surface in order to enable the force flow and reduce the resulting moments. Each roller with the same appropriate contour, which has a smaller radius than the crankshaft fillet radius, is pressed into the fillet at a defined angle of typically 35° . The fillet is rolled 360° along the circumference several times, usually 12 times. The rollers are made of high strength powder metallurgy steels with 67-68 Rockwell hardness and can machine up to 5000 crankshafts each. Straightening is the

final step, in which the global deformation of the crankshaft, due to fillet rolling, is compensated by appropriate rolling on specific fillets, in order to assure the smooth running of the crankshaft about its rotation axis. This step does not cause any change in fatigue strength [6].

The effectiveness of the process depends on the machine parameters (rolling force, rolling angle, cycles, etc.), geometrical parameters (crankshaft dimensions, fillet radii and roller geometry) and material parameters (E-modulus, yield, tensile and compressive strength of the material). Fillet rolling slightly elongates and bends the crankshaft, whereas the bending can be corrected by roll straightening. Furthermore, hardening is limited to bearing fillets and an extra hardening step for the bearing surfaces may still be required. However, good suitability to mass production, fast processing, economic energy consumption, high reproducibility, reliability and simple procedure lead to a remarkable increase in market share in passenger car engines as illustrated in Figure 1. High penetration depths of residual stresses of up to 5 mm and very low surface roughness of about $1 \mu\text{m}$ can be achieved. Moreover, fillet rolling is the most effective method to increase the fatigue strength, especially for cast iron. Steel exhibits a lower increase in fatigue strength than cast iron, due to its lower mean stress sensitivity.

EFFECT OF FILLET ROLLING PROCESS ON FATIGUE BEHAVIOUR

The reasons for the high improvement in fatigue strength after the application of fillet rolling are fourfold [7], [8], [9], [10]:

- Creation of compressive residual stresses in the fillets via plastic deformation

The highest influence on the improvement of fatigue strength (σ_W) is caused by the type-I (mode-I) compressive residual stresses (σ_E), also referred to as macro residual

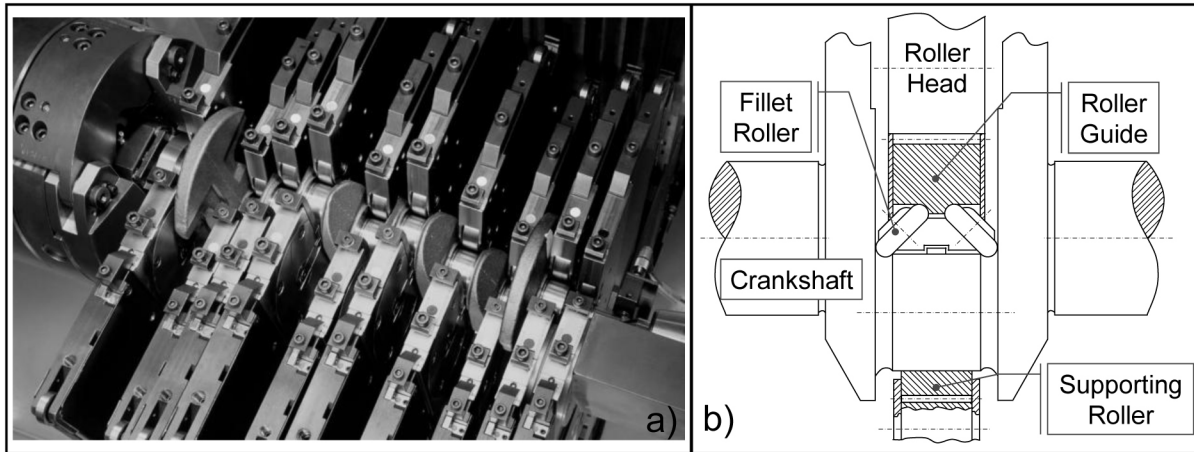


Figure 2. a) In-line four-cylinder crankshaft in a fillet rolling machine, b) Sketch of the fillet rolling process

stresses, which influence the endurance strength (σ_D) as follows:

$$\sigma_D = \sigma_W - M_E \cdot \sigma_E \quad (\text{Eq. 1})$$

where the residual stress sensitivity (M_E) is calculated as:

$$M_E = [\sigma_A(R' = -1) - \sigma_A(R' = 0)] / \sigma_{mean}(R' = 0) \quad (\text{Eq. 2})$$

- Work hardening of the fillet surface layer, which results in increased hardness and structure transformation into martensite depending on the material

Work hardening, also called strain hardening or cold working, results in an increase in hardness, yield, tensile and fatigue strength by increasing the dislocation density in the structure that hinders the presence and movement of other dislocations for the sake of ductility [11]. In case of austenitic microstructures, an additional increase in hardness by formation of martensite can be provoked, where face-centered-cubic austenite structure is transformed into body-centered-cubic martensite. This phenomenon is also called cold surface hardening and the higher hardness results in an elevated tensile strength, as given in Equation 3 [11]:

$$TS[\text{MPa}] = 3.45 \cdot HB \quad (\text{Eq. 3})$$

Since these effects may be cancelled by annealing, a possible heat treatment should be applied beforehand.

- Increase of surface quality by levelling the roughness peaks

Reduction of the roughness from 50 μm to 1 μm may lead to a higher fatigue strength of more than 30 % due to decreased micro notch effect for crack initiation [12].

The first three points refer to the increase of fatigue strength until crack initiation (S-N curve until crack initiation), which is valid for the crankshaft without any

propagating cracks. However, once a crack initiation starts, crankshaft continues to operate until total damage (S-N curve until total failure).

- Deceleration of the crack propagation

An additional improvement can be reached in the “S-N curve until total failure”, since the compressive residual stresses can decelerate or even stop the crack propagation along the penetration depth [8]. According to the linear elastic fracture mechanics approach [13] a crack does not propagate, if the allowed stress intensity factor, K_{IC} , is lower than the maximum stress intensity, K_{max} , (Eq. 4). The maximum stress intensity factor is calculated for all three crack modes as in Equation 5, where σ is the principle stress in each direction and a is the crack length [16].

$$K_{IC} \geq K_{max} \quad (\text{Eq. 4})$$

$$K = \sigma \cdot \sqrt{\pi \cdot a} \quad (\text{Eq. 5})$$

SIMULATION METHODOLOGY

An implicit FEM is selected to simulate the fillet rolling process, since the process velocity is low (120 1/min) and such that dynamic effects may be neglected. The commercial software Abaqus® is utilized for the simulations. The goal of the simulation is to accurately model the process with acceptable calculation duration. Therefore, one half crank is selected for the fillet rolling process calculation. The crank model consists of a numerically discretized half crank. 1st order hexahedron and 2nd order tetrahedron elements are found to be proper for the modelling. In order to reduce the number of nodes, the upper part of the web is discretized with 1st order tetrahedron elements, since it is far enough from the investigated region. Figure 3 shows the procedure for the fillet rolling process calculation.



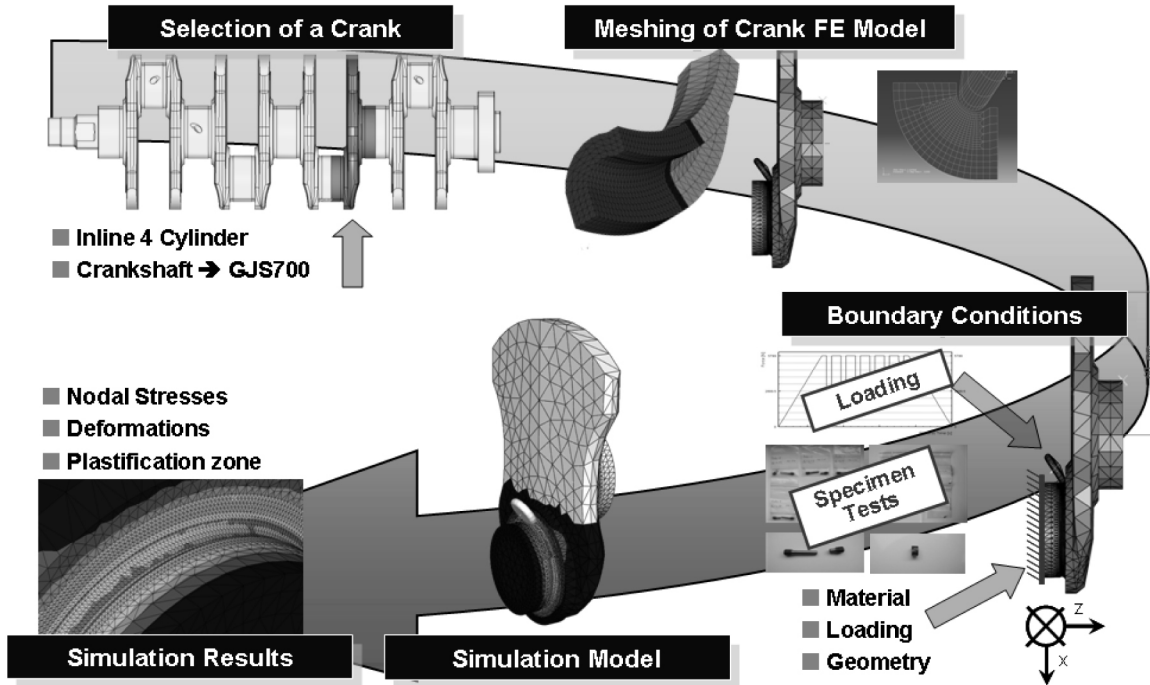


Figure 3. Fillet rolling calculation process flow diagram

The boundary conditions are determined based on the real procedure of the rolling machine. The machine operation parameters consist of:

- Process force (F_w), which is defined based on several parameters but primarily on the ultimate tensile strength of the material (σ_{UTS}). The required F_w can be calculated according to the empirical Equation 6, which depends also on the component fillet radius (r), roller radius (r_R), radial deformation of the radius (u_{rol}) and the roller angle (α_R).

$$F_w = 3.55 \cdot \frac{\sqrt{r \cdot u_{rol}}}{\frac{1}{r_R} + \frac{\cos \alpha_R}{r}} \cdot \sigma_{UTS} \quad (Eq. 6)$$

- Roller angle (α_R), which is typically selected as 35° , since cracks usually initiate from the vicinity of this angle. The force on each roller (F_{rol}) is calculated based on the fillet rolling process force (F_w) as following:

$$\frac{F_w}{\sin(180 - 2\alpha_R)} = \frac{F_{rol}}{\sin \alpha_R} \quad (Eq. 7)$$

- Applied load curve and number of cycles, which starts with three cycles of ramp-up phase, continues with six full load cycles and ends up with three ramp-down cycles. The complete process is finished in 6 seconds.

- Shape of the roller and fillet radius, which are geometrical parameters.
- The straightening procedure applied after fillet rolling process is not considered, due to the low effect on the stress relaxation and elevated computational effort.

Material Modelling

An elastic-plastic material model is considered due to high plastification magnitudes during the process. The material of the reference crankshaft is GJS700; therefore, the “cast iron plasticity” model is selected as the material model. It is an isotropic model and suitable for monotonic loading. It exhibits different flow characteristics in tensile and compression regions in order to consider the following effects [14]:

- Different yield strengths under tension and compression
- Inelastic volume change in tension, but little or no inelastic volume change in compression
- Different hardening behaviour under tension and compression

Hence, stress-strain curves under tension and compression are defined separately based on the uniaxial tensile and compression tests. The total strain rate, $\dot{\epsilon}$, is assumed to be a composition of elastic and plastic strain as follows:

$$\dot{\epsilon} = \dot{\epsilon}^{el} + \dot{\epsilon}^{pl} \quad (Eq. 8)$$

