Simulation for Crankshaft Fillet Mechanical Impact Process

Jun Sun¹,²,³, Xianfu Liu²,³, Xiangyi Hu²,³, Jianhua Zhang²,³, Ping Cui⁴

¹Tianrun Crankshaft Co., Ltd, Technology Center, Weihai 264200, China
²Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Ministry of Education of China, School of Mechanical Engineering, Shandong University, Jinan 250061, China
³National Demonstration Center for Experimental Mechanical Engineering Education, School of Mechanical Engineering, Shandong University, Jinan 250061, China
⁴Shandong Qilu Electrical Machinery Manufacture Co., Ltd, Jinan 250100, China

*Corresponding author e-mail: jhzhang@sdu.edu.cn

Abstract. The residual stress of crankshaft fillet is an important factor to influence service life of crankshaft. To improve the strengthening effect of compressive residual stress of large crankshaft fillet more efficiently and cost-effectively, a new method of fillet mechanical impact process was proposed. In order to explore the feasibility of this way, ABAQUS was used to study residual stress in surface and depth of fillet under different processing parameters. The simulation results show that several parameters including impact angle, impact speed and impact rotation angle are key factors to influence the impact strengthening effect of residual stress. Only by selecting optimized parameters can the desired strengthening effect be achieved. The simulation analysis also provides a foundation for further experimental fillet mechanical impact test.

1. Introduction

As an irreplaceable part of engine, the crankshaft is subjected to alternating load during working process [1]. Because of that, fatigue cracks can be formed at the crankshaft fillet, which will cause the failure of crankshaft [2]. Therefore, to improve service life of crankshaft, fillet needs to be strengthened. There are some ways to strengthen the fillet of crankshaft, such as nitriding, shot peening, fillet rolling and so on [3]. Through nitriding, surface microstructure of fillet is changed to improve the fatigue strength and wear resistance [4], but the cost of nitriding process is high and the nitriding layer is not easy to be controlled. Shot peening is a way of using particles to impact the fillet and the surface near fillet is easy to be destroyed if there is no protection. Fillet rolling is the main way to improve service life of crankshaft, through inducing compressive residual stresses near the fillet surface [5-7]. However, for large crankshaft, it is prone to be bended because of the large rolling pressure during rolling process.

To avoid bending of large crankshaft during rolling process and improve strengthening effect of large crankshaft fillet more efficiently and cost-effectively, a fillet mechanical impact process was proposed in this paper. ABAQUS was used to simulate the process of fillet mechanical impact and the factors affecting the fillet impact strengthening were analyzed in the following.
2. Principle of fillet mechanical impact process
The illustration of fillet mechanical impact process was shown in Fig. 1.

![Fig. 1 Illustration of fillet mechanical impact process. (a) Integral 3D impact device; (b) partial enlarged detail of impact device; (c) illustration of impact rotation angle](image)

Impact device was mounted at supporting arm, as shown in Fig. 1(a). The large crankshaft was tightened and loosened through supporting arm. The $n$ (rotate speed) of large crankshaft can be controlled by a servo motor. When crankshaft rotated with a certain speed, fillet was impacted by an impact hammer in a $\theta$ (impact angle), which was driven by impact cylinder, as shown in Fig. 1(b, c). Through adjusting inlet pressure of impact cylinder to change the $v_c$ (impact speed) of impact hammer, the impact force can be changed. The optimum impact position of fillet can be decided by changing impact angle. By adjusting rotate speed and impact frequency, the magnitude of $\theta_r$ (impact rotation angle) can be changed.

3. Simulation of fillet mechanical impact process
3.1. Establishment of constitutive equation
To achieve the strengthening of fillet, a plastic strain layer will be formed during the fillet mechanical impact process. Therefore, in order to simulate the plastic strain layer of fillet accurately, J-C constitutive equation was chosen in the paper [8]. QT700-2 was selected as the material of large crankshaft in the simulation. According to the stress and strain value of crankshaft fillet in actual production and relevant reference [9], the constitutive equation of QT700-2 can be expressed as follows:

$$
\sigma(\varepsilon, \dot{\varepsilon}, T) = \left(440 + 864.4\varepsilon^{0.215}\varepsilon\right) \left[1 + 0.0659\ln\left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right)\right] \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{0.397}\right]
$$

(1)
Where $\varepsilon$ is strain, $\dot{\varepsilon}$ is strain rate, $\dot{\varepsilon}_0$ is reference strain rate, $T_0$ is room temperature, $T$ is working temperature and $T_m$ is melting point of material.

### 3.2. Simulation model and pretreatment

According to design requirement, the radiiuses of fillet and impact hammer head were 6.22±0.25 mm and 5 mm, respectively. For improving simulation efficiency, the model of crankshaft was simplified, as shown in Fig. 2(a). The impact hammer was set as rigid body. The friction type between impact hammer surface and fillet surface was set as penalty. The friction coefficient and damping coefficient were set at 0.2 and 0.5, respectively. As shown in Fig. 2(b,c), the fillet impacted by hammer was meshed more finely than other part of crankshaft. The meshing type of crankshaft and impact hammer were hexahedral element (C3D8R) and tetrahedral element (C3D4), respectively. All the simulation conditions of fillet mechanical impact process were summarized in Table 1.

![Fig. 2](image_url)

**Fig. 2** Simulation model of crankshaft fillet. (a) the overall simulation model; (b) mesh of crankshaft model; (c) sectional mesh of crankshaft model

| Simulation conditions |
|-----------------------|
| Crankshaft Material | QT700-2 |
| Radius of fillet (mm) | 6.22±0.25 |
| Impact hammer Material | YG8 |
| Weight (Kg) | 0.56 |
| Head radius (mm) | 5 |
| Impact parameters | |
| Impact angle (°) | 35, 45, 55 |
| Impact speed (m/s) | 5, 10, 15 |
| Impact rotation angle (°) | 3, 4.5, 6 |

![Fig. 3](image_url)

**Fig. 3** Residual stress of crankshaft fillet under different impact angles. (a) $\theta$=35°; (b) $\theta$=45°; (c) $\theta$=55°
3.3. Results and discussion

3.3.1. Effect of impact angle. In a single impact process, Fig.3 shows the depth distribution of residual stress of fillet under different impact angle of 35°, 45° and 55°. The impact speed was set at 10 m/s. When impact angle were 35°, 45° and 55°, the maximum compressive residual stresses of fillet were 426.8MPa, 434.1MPa and 446MPa, respectively. With the changing of impact angle, position of the maximum residual stress also changes. Only when the impact angle was 45°, the position of maximum residual stress was in the middle of fillet and the compressive residual stress was evenly distributed, as shown in Fig.3(b). Therefore, 45° is a more suitable impact angle than others.

3.3.2. Effect of impact speed. When quality of impact hammer keeps constant, the impact force is determined by impact speed [10]. When impact angle is 45°, Fig.4 shows the depth distribution of residual stress of fillet under different impact speed of 5 m/s, 10 m/s and 15 m/s in a single impact process. When impact speed is 5 m/s, the maximum compressive residual stress of fillet is 426.8MPa, which can not satisfy the requirement of fillet strengthening according to practical experience. When impact speed is 15 m/s, although the maximum compressive residual stresses of 450 MPa reaches the
requirement, the plastic deformation is large, which can influence the dimensional accuracy of crankshaft fillet. When impact speed is 10 m/s, the maximum compressive residual stress is 434.1 MPa. Plastic deformation not only covers the fillet evenly but also keeps a suitable depth, as shown in Fig.4(b).

3.3.3. Effect of impact rotation angle. When impact speed is 10 m/s and impact angle is 45°, Fig.5 shows the residual stress of crankshaft fillet under different impact rotation angle. With the impact rotation angle increasing from 3°, 4.5° to 6°, the maximum compressive residual stress of fillet surface were 444MPa, 429.6MPa and 425.7MPa, respectively. It can be seen that the impact rotation angle has little influence on the maximum residual stress basically under the same \( v_c \) and \( \theta \). As shown in Fig.5(a), because of the small impact rotation angle of 3°, the plastic deformation is so large to influence the area of connecting rod journal. When the impact rotation angle is 4.5°, the residual stress of fillet surface is evenly covered and the area of connecting rod journal is not been influenced, as shown in Fig.5(b). On the contrary, from Fig.5(c), it can be seen that the residual stress doesn’t cover fillet surface evenly when impact rotation angle is 6°. Apart from this, small compressive residual stress exists between two impact points. Therefore, it is important to choose suitable impact rotation angle for crankshaft fillet mechanical impact process.

4. Conclusions
Based on the simulation results and analysis in the present paper, the proposed method of fillet mechanical impact process is a feasible way for strengthening large crankshaft fillet. It can be drawn that impact angle, impact speed and impact rotation angle are important factors to influence the strengthening effect of fillet. Only by choosing optimized parameters can the desired strengthening effect be achieved. From the simulation results, the satisfied process parameters of impact angle, impact speed and impact rotation angle were 45°, 10 m/s and 4.5°, respectively. The simulation results can also provide a foundation for further experimental fillet mechanical impact process.

5. References
[1] Sergio Baragetti, Stefano Cavalleri, Angelo Terranova. A Numerical and Experimental Investigation on the Fatigue Behavior of a Steel Nitrided Crankshaft for High Power IC Engines [J]. Journal of Engineering Materials and Technology, 2010, 132(3): 031014.
[2] K S Choi, J Pan. Simulations of stress distributions in crankshaft sections under fillet rolling and bending fatigue tests [J]. International Journal of Fatigue, 2009,31(3): 544-557.
[3] Xinghua Yang, Xiaodong Tang, Maoquan Xue. The surface strengthening techniques of spheroidal graphite cast iron crankshaft [J]. Machinery Design & Manufacture, 2011, (1): 151-153.
[4] Birong Liu. Research on Surface Heat Treatment of Nodular Cast Iron Crankshaft with Gas Soft-nitriding [J]. Tractor & Farm Transporter, 2006, 33(6): 86-89.
[5] W.Y. Chien, J. Pan, D. Close, S. Ho. Fatigue analysis of crankshaft sections under bending with consideration of residual stresses [J]. International Journal of Fatigue, 2005, 27(1): 1-19.
[6] Simon Ho, Yung-Li Lee, Hong-Tae Kang, ChengJ Wang. Optimization of a crankshaft rolling process for durability [J]. International Journal of Fatigue, 2009, 31(5): 799-808.
[7] Gül Çevik, Riza Gürbüz. Evaluation of fatigue performance of a fillet rolled diesel engine crankshaft [J]. Engineering Failure Analysis, 2013, 27: 250-261.
[8] Zhanqiang Liu, Jihua Wu, Zhenyu Shi, Pifen Zhao. State of the art of constitutive equations in metal cutting operations [J]. Tool Engineering, 2008, 42(3): 3-9.
[9] Jinquan Liu, Rui Zhang, Hailin Guo. Constitutive relation of aluminum bronze in high speed impact loading [J]. Transactions of Materials and Heat Treatment, 2016, 37(1): 223-229.
[10] Qungui Du, Zhiquan Sun Chongxi, Xiaochen Zhai Impact Dynamics Modeling and Simulation Analyses of Pneumation Cylinders [J]. China Mechanical Engineering 2016, 27(8): 1053-1058.