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Fatigue analysis of Diaphragm spring in double dry clutch including manufacturing process

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Abstract

In the automotive light-duty passenger vehicles, double dry clutch provides high comfort and fuel efficiency to passengers with automated gear box. Its functional performance and quality depends on its diaphragm spring. Fatigue analysis on this component and correlation is quite complex because of several manufacturing processes involved like stamping, heat stabilization and shot-peening. The procedure to predict the diaphragm fatigue strength is described in the paper; also it integrates the new simulation softwares capabilities to handle the process effects for evaluation of diaphragm.

This paper outlines the different simulation stages involved to access the fatigue assessment on diaphragm spring; also it is done at various life situations of vehicle: normal, parking, overloading conditions. A great attention is paid for correlation through measurement fitting in simulation.

Between each manufacturing process simulation, the deformed shape and its residual stress-strain data are mapped using customized scripts. After the process simulations, fatigue actuation on diaphragm is done for new, semi-worn and worn positions of clutch. Miner's damage and its summation are done at each critical point in diaphragm to determine its total life under nominal design.

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Keywords: Fatigue with manufacturing processes, Dual dry clutch, Diaphragm spring.

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Nomenclature

σ_a	Alternate stress
σ_f	Fatigue stress
σ_m	Mean stress
σ_u	Ultimate stress
N_i	Number of cycles
N_{fi}	Number of cycles to reach failure
R	Radius in Belleville outer diameter

1. Introduction

Improvement in modern simulation tools enables to integrate complex process simulations in design assessment for efficient fatigue validation. Double dry clutch diaphragm springs undergoes several manufacturing processes such as stamping, heat stabilization and shot-peening to improve its fatigue strength under various operating conditions.

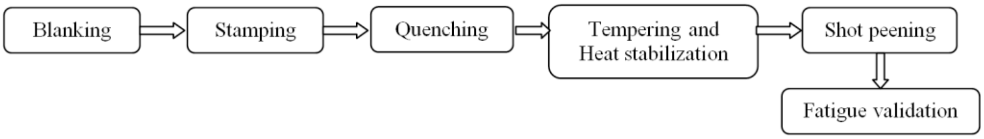


Fig. 1. Simulation flow including manufacturing process

2. Manufacturing process simulation

2.1. Stamping

Stamping is the first stage in manufacturing process simulation for diaphragm spring. After blanking, the embossment is stamped from Belleville washer to finger, mainly to improve its stiffness. At this stage the material involves extensive tensile deformation without being damaged. The stamping shape and its thickness variation after spring back are shown in Fig. 2.

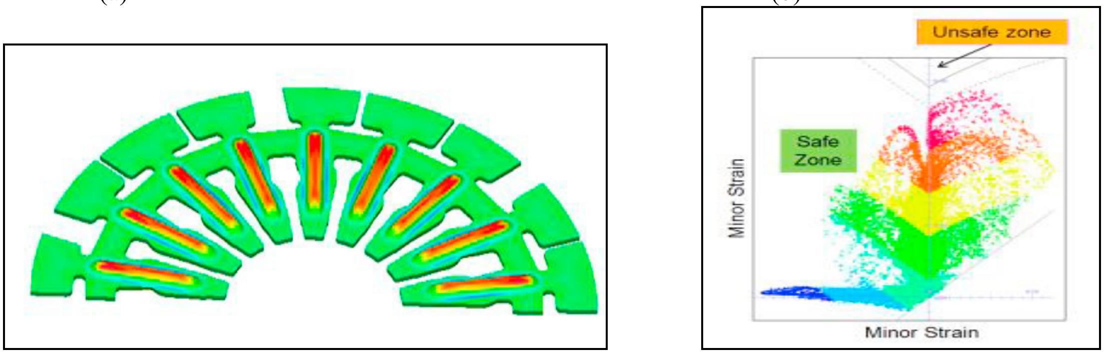

(a) (b)

Fig. 2. (a) Stamped diaphragm spring; (b). Forming Limit Diagram (FLD) for stamped diaphragm.

Forming limit diagram (FLD) is based on element failure theory based on strain. This diagram is composed of lines, with combination of major and minor element strains to define the safe region.

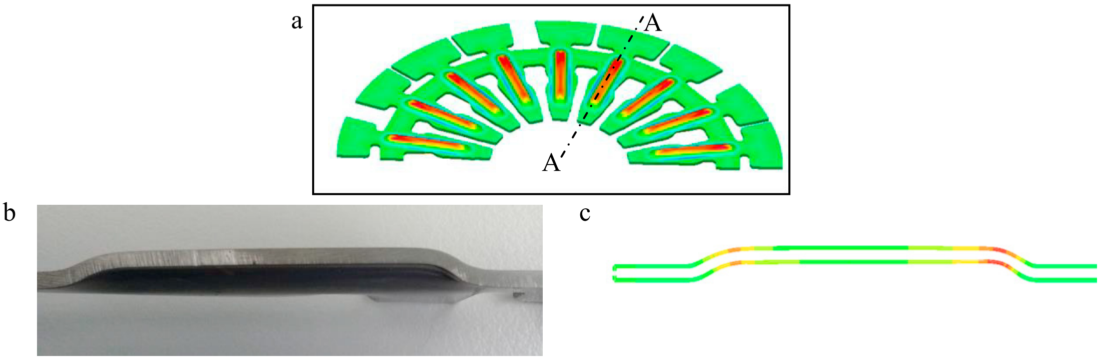


Fig. 3. (a) Stamped diaphragm spring in simulation; (b). Sectional view from produced diaphragm spring; (c). Cross-sectional ‘A-A’ view from simulation.

The thickness variation is observed to be less than 15% after stamping, which is shown in Fig. 3 and it is also confirmed through measurements. Stamped shape, its residual stresses and strains from stamping are transferred to quenching process simulation.

2.2. Quenching, tempering and heat stabilization

Quenching and tempering consists of a two-stage heat-treatment process. Stage 1 includes hardening, in which the diaphragm spring is austenitized to approximately 900°C, which results in carbon getting trapped inside the austenitic lath. To achieve the desired cone in Belleville washer, it is pressed and allowed to cool using water flow in the tool. This leads to the hard and brittle martensitic stage. In simulation, 900°C temperature material curve is used homogeneously to simulate the quenching process and it is clamped in cooling tool to avoid warpage.

Stage 2 consists of tempering the material to obtain the desired material properties. In this stage, the diaphragm is reheated at a relatively low temperature leading to precipitation of carbides in the microstructure. The result is a component with the appropriate combination of hardness, strength and toughness.

Quenching and tempering achieves an extremely fine-grained and homogeneous microstructure. Thickness variations after process simulation are shown in Fig. 4.

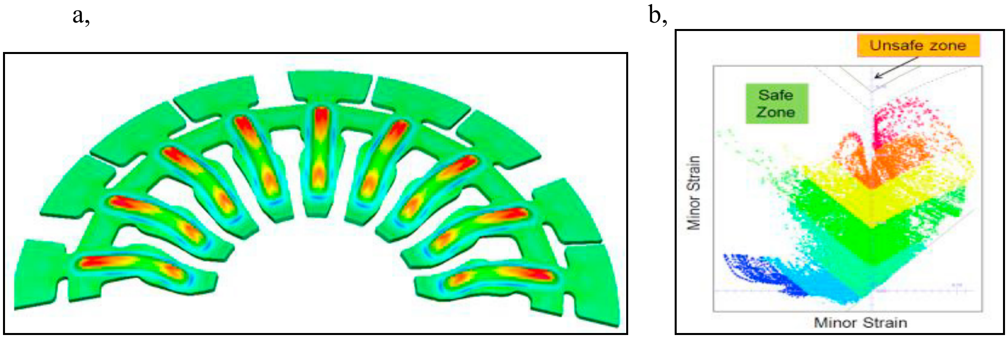
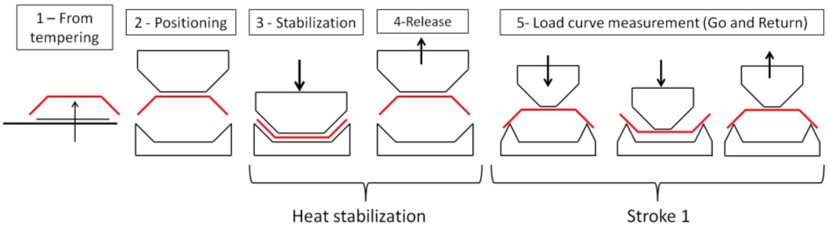


Fig. 4. (a) Quenched and tempered diaphragm spring; (b). FLD after process.

After tempering the diaphragm spring, heat stabilization is done in mechanical software. The residual stresses and strains data after tempering are mapped using customized scripts to the mesh from process simulation software and a numerical equilibrium is performed. Heat stabilization stages are shown as line diagram in Fig. 5. (a), where in stage-3, the diaphragm spring stabilization is done by inverting at specific angle using the tool and cooled. The tool is released in stage-4 after specified time. Now its performance and resistance against Belleville washer angle stability (ageing phenomenon) are increased. In stage-5 and 6, the diaphragm load curve (Go and return curve) is measured to confirm its stability, which is detailed in Fig. 5. (b) As stroke-1.

The load curve evolution of diaphragm spring during heat stabilization and at each stroke is shown in Fig. 5. (b).

a,



b,

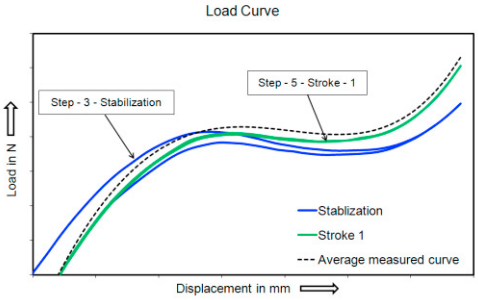


Fig. 5. (a) Heat stabilization stages; (b) Belleville washer Load curve of the diaphragm spring.

Including the process simulation (residual stresses, strain and stamped shape), the correlation between simulation and measurements is well managed. Without process simulation, the load curve will be completely different and it is not realistic to compare with real measurement.

3. Fatigue simulation

Following heat stabilization process simulation, the diaphragm is simulated under different operating conditions, new, semi-worn and worn. Also, adjacent component stiffness, like fixed cover, pulling cover, pressure plate and cushion disc are included in simulation in-order to have realistic release bearing load versus displacement under given input torque. To understand the induced stress in diaphragm spring from simulation and to be confident, strain data by strain gauges at critical location (Refer Fig. 8.(a)) from measurements are correlated with simulation which is shown in Fig. 6.

a,

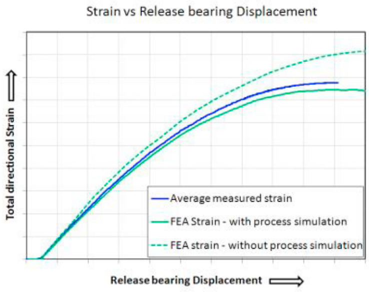


Fig. 6. (a). Strain correlation between measurement and simulation with effect of process simulation.

Based on strain correlation, it is clear the diaphragm spring with process simulation shows closer results with measurements and stresses with process simulations are confidently considered for fatigue validation. For the given mission profile, fatigue damage are calculated for different life situations.

- Parking condition.
- Normal operating condition.
- Full load operating condition.

a,

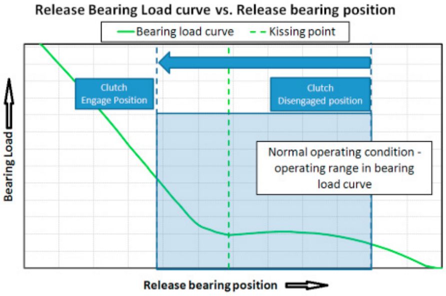


Fig. 7. (a). Release bearing load curve of diaphragm spring in normal operating condition.

The critical locations in the diaphragm spring are indicated on Fig. 8 and these locations were analyzed to calculate the damage.

a b

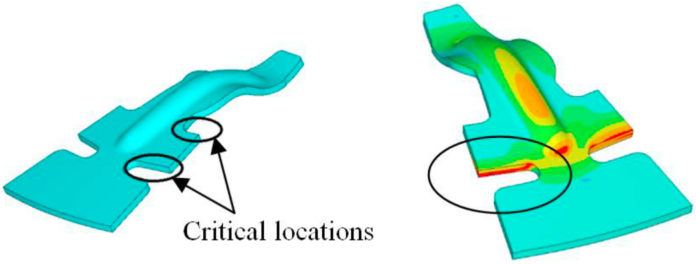


Fig. 8. (a) Critical location is diaphragm spring (Inner and outer diameter of Belleville); (b). Stress plot of diaphragm spring.

Based on the operating conditions (like parking, normal and full load), the alternate stresses are extracted at critical point in diaphragm spring and mean stress corrections as shown in Fig. 9 are done to calculate the life in Wöhler curve.

$$\frac{\sigma_a}{\sigma_f} + \frac{\sigma_m}{\sigma_u} = 1 \tag{1}$$

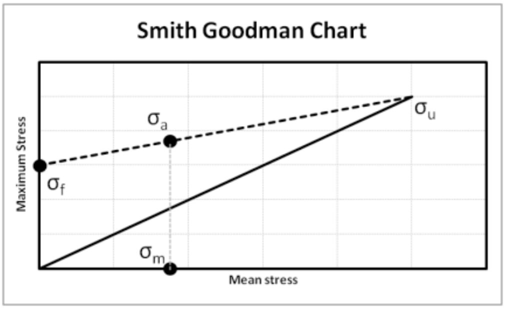


Fig. 9. (a). Smith Goodman Chart

The Wohler curve is developed based on fatigue tests on produced diaphragms until failure for different life situations. Also it is done at different batches of production and critical locations in diaphragm spring, which is shown in Fig. 10.

a,

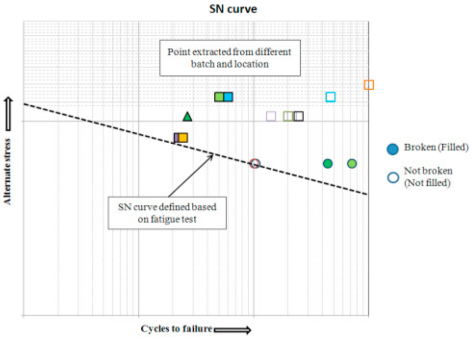


Fig. 10. (a) Wohler curve developed based on fatigue test

Damage summation is performed on critical locations via the Palmgren-Miner rule for various life situations.

$$\sum \frac{N_i}{N_{fi}} = 1 \tag{2}$$

After the damage summation, fatigue test is performed to increase the confidence level of the diaphragm spring design and stresses are well within the fatigue limit for given operating conditions.

a,

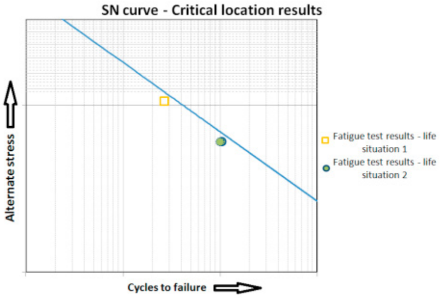


Fig. 11. (a) Wöhler curve and tested points for given life situation

Further to enhance the diaphragm robustness, direct optimization is carried out at critical locations and the parameters are defined using design explorer.

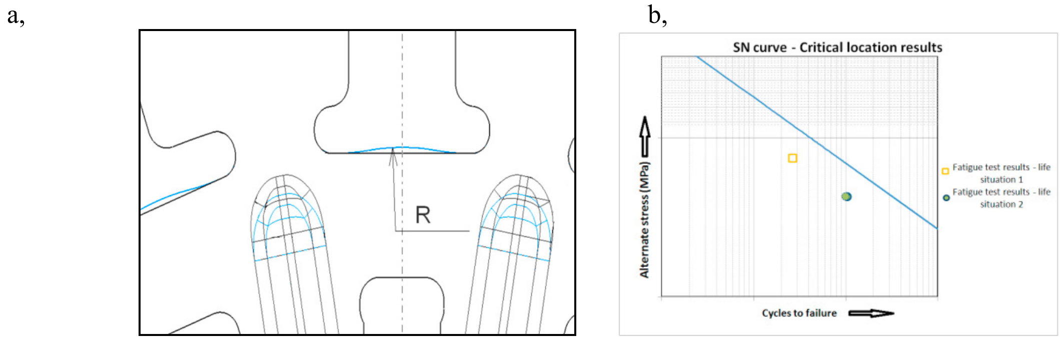


Fig. 12. (a) Design modification at outer diameter; (b) Wöhler curve and tested points for given life situation

The radius “R” is optimized by reducing the stress by 15% to gain the confidence level in fatigue simulation and to produce a robust design including process deviations, operating tolerances, geometrical tolerance and assembly fitting tolerances. Similarly other critical locations are optimized.

4. Conclusion

The stamped shape after spring back, residual stresses and strain, quenched (formed), tempering and heat stabilization process simulations for diaphragm spring plays a vital role in its mechanical characteristics and fatigue validations. A great attention is paid to correlate between simulation and measurement at each phase to increase the simulation confidence level.

As an improvement action, the quenching process (forming) simulation in hot temperature is under development to further enhance the hardness across its depth at different location in diaphragm spring.

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