IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Failure Analysis of a Flexspline of Harmonic Gear Drive in STC Industrial Robot: Microstructure and Stress Distribution

To cite this article: Jianlin Zheng and Wei Yang 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **452** 042148

IOP Conf. Series: Materials Science and Engineering **452** (2018) 042148 doi:10.1088/1757-899X/452/4/042148

Failure Analysis of a Flexspline of Harmonic Gear Drive in STC Industrial Robot: Microstructure and Stress Distribution

Jianlin Zheng[1, 2, *] and Wei Yang[1]

[1]State Key Laboratory of Mechanical Transmission, Chongqing University, Chongqing 400030, China
[2]Ningbo Longtai Medical Technology Ltd., Ningbo, Zhejiang, 315000, China

[*]Corresponding author e-mail: xiaomimir@sina.com

Abstract. The failure process and failure mechanism of the flexspline in harmonic reducer system after 500h operation were analyzed. The microstructure, element composition and mechanical properties of flexspline were studied by optical microscope (OM), scanning electron microscope (SEM), atomic emission spectrometry (AES), infrared carbon sulfur analyzer and microhardness tester. The stress distribution of the key parts of the flexspline was calculated by LS-DYNA finite element simulation software. The results revealed that the main reason for the failure of the flexspline was the local micro crack and the variation of the dimensional accuracy, the essential reason was grain and ferrite phase inappropriately. In addition, the stress of the failed flexspline was concentrated near the crack, the maximum stress was increased by 26%, which compared well with empirical conclusion. This work can offer a reference for the further improvement of the flexspline.

1. Introduction

There is essential difference between harmonic gear drive and traditional gear transmission. Harmonic gear drive mainly depends on the interaction between the flexspline and the wave generator, and the flexspline is one of the most critical components in the whole transmission system [1-3]. However, due to the constraints of operating conditions and materials processing, there is still an obvious disparity in the quality of flexspline. The principal part of the SHF-32-80 harmonic gear drive in STC industrial robot as is shown in Fig. 1.

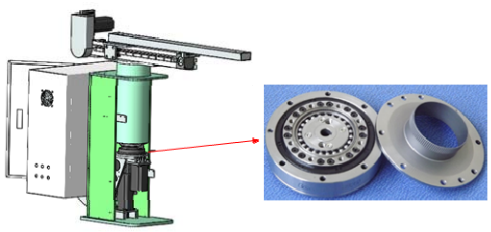

Figure 1. STC industrial robot and flexsplie

In practical application, the flexspline is subjected to transformation stress and cyclic loading, and is prone to fatigue failure. After use for a period of time, the flexspline can be damaged or even broken except for the oxidation and sticking of the surface of the gear teeth. These phenomena are not only detrimental to the smooth transmission of the system, but also cause production accidents. At present, researching aimed at the failure of the flexspline, some researchers paid more attention to the failure analysis of the meshing driving force [4, 5]. For instance, Peter, Tuttle and Ghorbel [6-8] studied the failure mechanism of the meshing driving force in the processes of harmonic drive, respectively. Others focus on the effect of hybrid stress on the surface of the flexspline. Such as Maiti et al. [9] reported the development and evolution of strain wave generating cam, Routh [10] considered the stress distribution in the process of gear pair, and Kiyosawa et al. [11-13] explored the influence of the tooth profile of the flexspline on the harmonic drive. In addition, some scholars discussed the stress distribution of different teeth profile [14-18]. It can be seen that the previous research mainly analyzed the failure problem of harmonic gear drive based on single meshing driving force, alternating stress or tooth contact stress.

In fact, it is less than enough to analyze the stress of the tooth surface only from the macroscopic point of view. The failure of components is often caused by internal defects. The difference of transmission principle will inevitably lead to the different operating environment and the change of failure mechanism. However, the studies on this aspect are rarely reported. If the joint effect of macro and micro is analyzed, the failure mechanism of flexspline can be used to provide more theories for improving and enhancing the performance of flexspline. Based on this reason, this work started from the essential factors of the material, and tried to find the root cause of the failure of the flexspline through the analyses of macrostructure and microstructure. Meanwhile, combined with the finite element software to analyze the stress distribution of different microstructures, and then fundamentally identified the failure mechanism of flexspline.

2. Materials and methods

The investigation was mainly focused on the flexspline, which was the main part of the SHF-32-80 harmonic gear drive in STC industrial robot and failed after running for 500 h. With a torque of 250 N·m and a rated speed of 2000 rpm, the robot performed the operation in strict accordance with the rules. The failed flexspline was compared with the SNCM439 [1] flexspline, which was in compliance with the JIS G4053-2003 executive standard.

Microscopic morphology was evaluated using a field emission scanning electron microscope (SU 70). The fractography, which was etched by Kroll’s reagent (2 mL HF, 5 mL HNO3, and 100 mL deionized water), was investigated using a metallographic microscope (OLYMPUS-GX51). Surface composition and grain size was evaluated via electron probe (EPMA-1720). The chemical composition was analyzed by emission spectrometer (ICP-AES) and infrared carbon sulfur analyzer (HCS-140). The hardness was measured by a digital microhardness tester (HXD-1000). Finally, the stress distribution of the critical parts of the flexspline was calculated with the finite element simulation software LS-DYNA.

3. Results and discussion

3.1. Metallurgical analysis

Gear teeth profile of failed flexspline as is shown in Fig. 2. Obvious cracks were observed at the tooth root of the failed flexspline (Fig. 2a); local spalling and wear were found near the top of the tooth surface, and the spalling and wear were more serious in the vicinity of the fracture area (Fig. 2b). Literature [5, 8, 14] lead to the fact that wave generator and flexspline of harmonic gear drive were apt to vibrate under the condition of heavy load and high speed, thus the meshing between flexspline and circular spline was interfered, and the tooth top part of the failed flexispline had strict abrasion, even appears flange and burr.

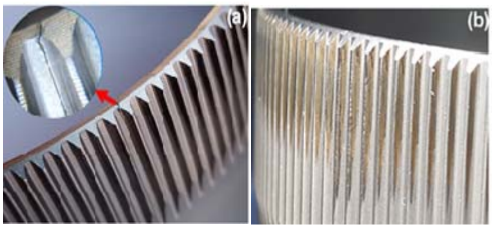

Figure 2. Gear teeth profile of failed flexspline.

The surface morphology of the tooth top of the failed flexspline was shown in Fig. 3. The area of the tooth top was divided into two parts: the working side (the white frame area of Fig. 3a) and the free side (the yellow frame area of Fig. 3a). More marks that parallel to the direction of the gear tooth were discovered in the free side. These marks were judged as tool marks after processing materials. In addition, at the junction of the tooth top and the working surface, the sharp tooth top corner became blunt through impact, and the deformed metal turned to the tooth top (the red frame area of Fig. 3a). The scratches, which were formed in the process of operating and perpendicular to the direction of the gear tooth, were observed from the morphology of the enlarged working side (Fig. 3b).

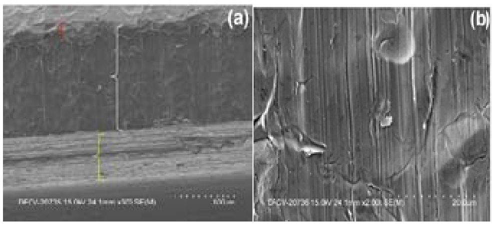

Figure 3. The surface morphology of the tooth top of the failed flexspline.

SEM image of the failed flexspline as was shown in Fig. 4. In Fig. 4a, the working surface of the gear tooth became uneven after impact and was covered by the impact craters. Figs. 4b to 4d were observed in the images of local enlargement of working surface. As we can see clearly from these figures, plastic deformation was serious (Fig. 4b), there were slight local spallings and some iron filings in the matrix (Fig. 4c), and the cracks were generated in some regions (Fig. 4d). It can be concluded that the failure of the flexspline was caused by the high speed impact rolling deformation of the working surface, therefore, the size of the tooth surface had been changed, the micro cracks were produced locally, and the wear resistance of the material surface was destroyed.

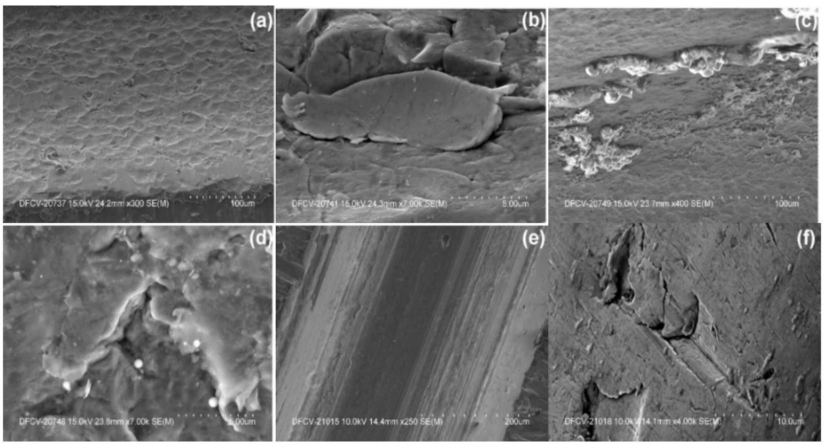

Figure 4. The morphology of the gear tooth bottom.

In addition, Fig. 4e shows the morphology of the gear tooth bottom. In this figure, the transition arc was complete, the surface of the gear tooth on both sides was rough and the tool marks were still obvious. These morphologies indicate that the gear tooth bottom was not treated by polishing. Fig. 4f shows the morphology of the working face close to the gear tooth bottom. Impact traces were not found on the tooth surface, but wear and tear traces were strong. The tool marks, abrasive wear and metal mosaic were observed on the working surface. In a word, the tooth surface of the failed flexspline is without polishing pretreatment, so surface is roughness, tool marks are clear, all these will lead to abnormal contact of the working process, partial rupture, easy dregs, and it is difficult to form oil film lubrication layer.

The specimen was cut from the fracture surface of the failed flexspline. Metallographic structures of the failed flexspline and the SNCM439 standard flexspline were observed as shown in Fig. 5. As the figure shows, there is no brittle inclusion in the crystallization phase of the failed flexspline. The structure were mainly sorbite and a small amount of ferrite (Fig. 5a), while the tissue of the SNCM439 standard sample was the sorbite (Fig.5b). In addition, the grain size of the failed flexspline was the grade of 8.5, while the SNCM439 standard sample has a grain size of the grade of 11. The strength and plasticity of flexsplines were different from those of the SNCM439 standard ones, was concluded based on two aspects of comprehensive factors that the ferrite strength is poor and the coarse grain would result in a decrease in both plasticity and strength (Hall-Petch formula).

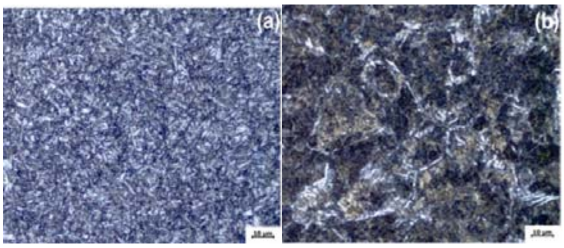

Figure 5. Metallographic structures of the flexspline.

3.2. Chemical composition analysis and mechanical property test

Chemical composition analysis is a key step in failure analysis. Table 1 compares the chemical compositions of the failed flexspline with the SNCM439 standard flexspline which is specified as an example of general chemical composition of structural steel. Among the chemicals, the contents of Cr, Ni and Mo in the failed flexspline are 0.22%, 0.05% and 0.05%, respectively, and they are all lower than the minimum value stipulated by the standard. However, with low content of Mo, Cr and Ni, have reductions in mechanical properties such as tensile strength, corrosion resistance and wear resistance.

Table 1. Comparison of chemical compositions of the failed flexspline

Classification	C	Si	Mn	P	S	Cr	Mo	Ni
SNCM439	Max 0.43	Min 0.15	Min 0.6	Max 0.025	Max 0.025	Min 0.60	Min 0.15	Min 1.60
Specimen	0.51	0.3	0.67	0.017	0.010	0.22	0.05	0.05

After the metallographic sample was repolished, microhardness measurement was carried out, and the result is shown in Table 2. It can be seen that the hardness of the microhardness of the flexspline is 87 smaller than that of the standard. Therefore, it is more likely to fail.

Table 2. Comparison of microhardnesses of the failed flexspline

Classification	Value
SNCM439	338.1
Specimen	251.1

3.3. Finite element analysis (FEA)

The HYPERMESH was used for the pretreatment of solid model, including mesh, add material attributes and determine boundary conditions according to actual work conditions. Then, the K file was imported into the LS_DYNA to do the finite element analysis. The specific parameters were shown in Table 3.

Table 3. Parameters of the flexspline drive.

Parameter	Value
Module m/mm	0.5
Tooth number of the flexspline Z1	100
Tooth number of the circular spline Z2	102
Transmission ratio	50
Aspect ratio of the flexspline	0.8
Radial deformation /mm	0.5

According to table 3, the flexspline structural models were established, as shown in figure 6.

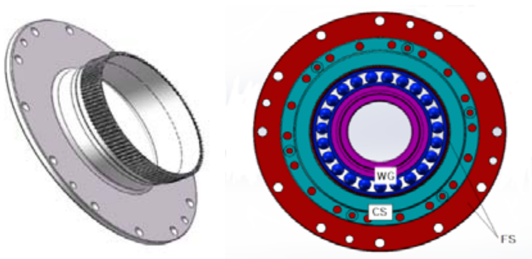

Figure 6. Structures of the flexspline.

The FEA result of stress distribution of the failed flexspline meshing parts was shown in Fig. 7. The stress was indicated in Mpa units. According to the FEA, the weakest regions were tooth root which near the working surfaces. The maximum stress of the failed flexspline calculated by FEA was 162.683 Mpa.

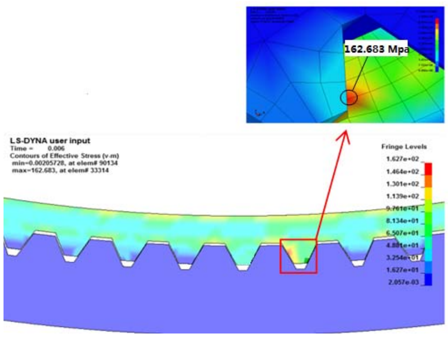

Figure 7. Stress distribution of the failed flexspline meshing parts.

By comparing the microstructure of the material, it was found that there are cracks at the tooth root surface, where the stress concentration and the alternating stress are the root causes of the failure of the flexspline. In order to better analyze the stress field of the failed flexspline, the influence of different fillet radii at bending part on the maximum stress of the flexspline under no load was studied by taking the failed flexspline as an analysis model. The fillet radius is 0~2 mm, and the other parameters are unchanged. The FEA result of stress distribution is shown in Fig. 8.

Fig. 8a shows that, when the flexspline is running, the force at bending part is the largest, and the radii of the fillet here directly affect the maximum stress of the flexspline.

Fig. 8b shows the maximum stress of the flexspline corresponding to different fillet radii: 1) when the radius is 0 mm, the maximum stress of the flexspline is the largest, reaching 714.7 Mpa; 2) when the radius is 0.2 mm, the maximum stress of the flexspline is 137.9 Mpa, and as the radius increases, the maximum stress of the flexspline decreases; 3) when the radius is about 0.8 mm, the maximum stress of the flexspline reaches the minimum, 94.2Mpa, with the radius increasing, the maximum stress of the flexspline increases; 4) when the radius is 2 mm, the maximum stress of the flexspline is 149.3 Mpa. Taken together, when the fillet radius is about 0.8 mm, the stress is minimum at bending part. By changing the fillet radius, the stress distribution of the flexspline, in a manner, can be improved.

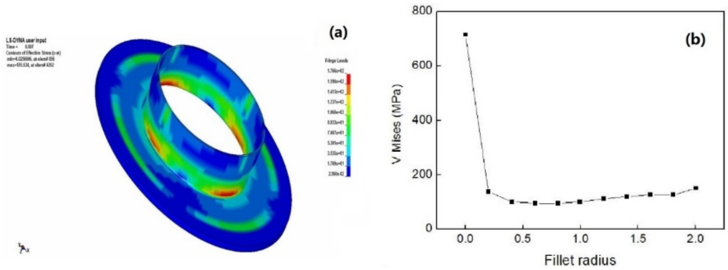

Figure 8. The influence of different fillet radii on the flexspline.

4. Conclusion

1) The main reason for the failure of the flexspline was that the working surface of the gear has local micro cracks, which results in abnormal contact and local rupture during the working process, thus the dimensional accuracy becomes worse and the service life is reduced.

2) In addition, the material of the flexspline is relatively large and has ferrite phase. The strength and plasticity of the material are different from those of the standard sample, and it is easy to produce plastic deformation during the working process.

3) The maximum stress of the flexspline is near the working surface of the tooth root, 162.683 MPa. Moreover, with the increase of the fillet radius at the bend, the maximum stress of the flexspline wall decreases first and then increases slowly.

Acknowledgments
This work was financially supported by research innovation of graduate students in Chongqing fund (No. CXB226).

References

[1] C.W. Musser, Strain Wave Gearing, U.S. Patent 2,906,143. (1959)
[2] S. PARK, J. LEE, U. MOON, et al, Failure analysis of a planetary gear carrier of 1200HP transmission, Engineering Failure Analysis, 2010, 17: 521-529.
[3] K. Maniwa, S. Obara, Lubrication Mechanism between Wave Generator and Flexspline in Strain Wave Gearing under In-Vacuum and In-Air Environments (Measurement of Contact Electric Resistance between Mechanical Elements), Journal of Japanese Society of Tribologists, 2007, 52 (1): 40-50 (in Japanese).
[4] X. Zhao, W.Y. Liang, S.S. Li, Dynamic Contact Simulation Analysis of Helical Gear with LS-

DYNA, Mechanical Engineering and Automation, 2009, (3): 9-11.
[5] Y.C. Liu, F.L. Wu, M. Lan, et al. Dynamic Contact Simulation Analysis of Involute Gear with ANSYS/LS-DYNA, Mechanical Engineering Automa tion, 2011 (5): 43-45.
[6] J. Peter, Investigation of the Engagement of Harmonic Drives—Part II, Acta Tech. (Budapest), 1982, 94 (3-4): 223-233.
[7] T.D. Tuttle, W.P. Seering, A nonlinear model of a harmonic drive gear transmission, IEEE Transactions on Robotics and Automation, 1996, 12 (3): 368-374.
[8] F.H. Ghorbel, P.S. Gandhi, F. Alpeter. On the kinematic error in harmonic drive gears, Transactions American Society of Mechanical Engineers Journal of Mechanical Design, 2001, 123 (1): 90-97.
[9] R. Maiti, I. Biswas, V. Nema, et al, Design and development of strain wave generating cam for a new concept ‘harmonic drive’, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2013, 227 (8): 1870-1884.
[10] B. Routh, R. Maiti, A.K. Ray, et al, An investigation on secondary force contacts of tooth pairs in conventional harmonic drives with involute toothed gear set, Journal of mechanical engineering science, 2016, 230 (4): 622-638.
[11] Y. Kiyosawa, M. Sasahara, S. Ishikawa, Perfor- mance of a strain wave gearing using a new tooth profile [C]//1989 International Power Transmission and Gearing Conference, 5 th, Chicago, IL. 1989: 607-612.
[12] K. Kondo, J. Takada, Study on tooth profiles of the harmonic drive, ASME J. Mech. Des, 1990, 112(1): 131-137.
[13] O. Kayabasi, F. Eraincanli, Shape optimization of tooth profile of a flexspline for a harmonic drive by finite element modelling, Materials & design, 2007, 28 (2): 441-447.
[14] H. Dong, K.L. Ting, D. Wang, Kinematic fundamentals of planar harmonic drives, Journal of Mechanical Design, 2011, 133 (1): 011007.
[15] A.H. Elkhoiy, Tooth load sharing in high-contact ratio spur gears, Journal of Mechanisms, Transmissions, and Automation in Design, 1985, 107 (1): 11-16.
[16] J.X. Wang, X.X. Zhou, J.Y. Li, et al, Three dimensional profile design of cup harmonic drive with double-circular-arc common-tangent tooth profile, Journal of Zhejiang University, 2016, 50 (4): 616-624.
[17] S. Li, Diaphragm stress analysis and fatigue strength evaluation of the flex-spline, a very thin-walled spur gear used in the strain wave gearing, Mechanism and Machine Theory, 104 (2016): 1-16.
[18] S. Griza, A.P. Santos, T. Azevedo, et al. Failure analysis of a petrochemical plant reducing gear, Engineering Failure Analysis, 29 (2013): 56-61.