Failure Analysis of a Helical Gear

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Abstract

This paper reports the result of an investigation of a premature failure of a helical gear in a reducer gearbox used in a continuous hot rolling steel re-bars mill in Thailand. Standard investigative procedures were employed in the analysis. It was found that the gear failed by fatigue fracture. Beach marks on the fracture surfaces were clearly visible. Detail examination of the surface of the gear revealed that extensive surface damage had occurred in the form of pitting. Sub-surface damages in the form of spalling were also observed. Such observations indicated that the gear was under excessive contact stress during operation. Stress analysis did, in fact, confirm such hypothesis. These surface and sub-surface damages lead to fatigue crack initiation followed by crack growth and eventual fracture. Excessive contact stress resulted from the replacement of the original 300 kW motor by a new, more powerful 600 kW motor in order to roll thicker billets. It is concluded that the helical gear failed by fatigue fracture initiated by surface and sub-surface damages resulting from excessive contact stress. The lesson learned from this case is that one must be careful when replacing key components of machines or other engineering systems. The effects of such replacement must be thoroughly analysed.

Keywords*:* Helical gear, Helical gear failure, Failure analysis, Fatigue failure

1. Introduction

Helical gears are extensively used in numerous engineering applications including gearboxes. Gearboxes are key components of machines and are extensively used in steel industry. Failures of gears not only result in replacement cost but also in process downtime. This could have a drastic consequences on productivity and, more importantly, late delivery. In the case being investigated, for example, the downtime was 12 days and 3,840 metric tons of steels were lost before the failed gear could be replaced.

The causes of gear failure are numerous including faulty designs, improper applications and manufacturing errors. Design errors include such things as improper gear geometry, improper materials, poor material quality, inappropriate lubrication system, or several others. Application errors include things such as improper mounting and installation, poor cooling and lubrication, and poor maintenance. Manufacturing errors could be poor machining or faulty heat treatments [1]. Surface pitting is one of the principal modes of failure of mechanical elements that are subjected to rolling contact, like gears, bearings, etc., and governs the service life of the components [2]. The complete contact fatigue process starts with micro-pit formation followed by crack initiation, crack growth, and the break away of surface material layer [3]. In practice, it is common that contact fatigue damage will first occur in the dedendum of smaller gear (which is usually the driving gear) of a gear set [4]. Damage due to contact fatigue in gear teeth usually occurs in one of three areas; along the pitch line, in the addendum, and the dedendum [5]. The pits formed on the surface lead to stress concentrations which serve as initiation sites for the cracks and eventually the failure [6]. Pitting under pure rolling can occur even under proper lubrication conditions, since oil, as an incompressible fluid, will merely transmit the contact load [7]. This work aims at identifying cause of failure of a helical gear in a hot rolling steel rebar mill in Thailand in order to prevent or minimize the reoccurrence of similar failures in the future.

2. Background

The failed helical gear was used in a reducer gearbox at the first stand in a hot rolling steel mill in Thailand. The mill produced steel re-bars sized 6-12 mm diameter with the capacity of 20 tons/hour. The first stand was designed for rolling billets with cross-section of 100 mm square and 6 m long. Due to the shortage of the required sized billets, thicker 120 mm square billets were used in order to increase the power so that thicker billets could be rolled, the original 300 kW motor was replaced by a more powerful 600 kW motor without changing the reducer gearbox. The average of current and voltage were 700 amps and 720 volts, respectively, during the rolling operation. The reducer gearbox failed after approximately 15,000 hours which was much lower than the expected working life of 30,000-50000 hours on continuous running condition [8].

The failed helical gear has 69 teeth, and the face width of 128 mm. The module of the gear is 8 mm, the helix angle 13 degrees and the pressure angle 20 degrees. The reducer gearbox ratio and input shaft revolution are 15.90 and 400 rpm, respectively. The mechanical power is 300 kW and the safety factor is 1.75. Relevant layout of the reducer gearbox is shown in Fig. 1.

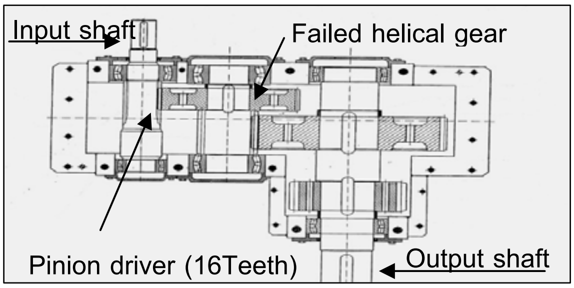

Fig. 1 Location of the failed gear

3. Investigation procedure

The failed gear was first inspected visually and macroscopically. The material in the vicinity of the fracture of the failed gear was then taken as samples and metallographic specimens were prepared for optical microscopy examination and microhardness measurement. Chemical analysis of the gear material was performed in order to identify the type of steel used. The fracture surfaces of the gear tooth were ultrasonically cleaned and examined under a scanning electron microscope (SEM). Applied stress was determined based on actual operating conditions and relevant dimensions.

4. Results and discussion

4.1 Visual examination

The appearance of the failed helical gear is as shown in Fig. 2. Visual examination of the gear revealed two broken teeth as shown in Fig. 2a. The arrows in Fig. 2c showed the initial pitting and final pitting on the contact side.

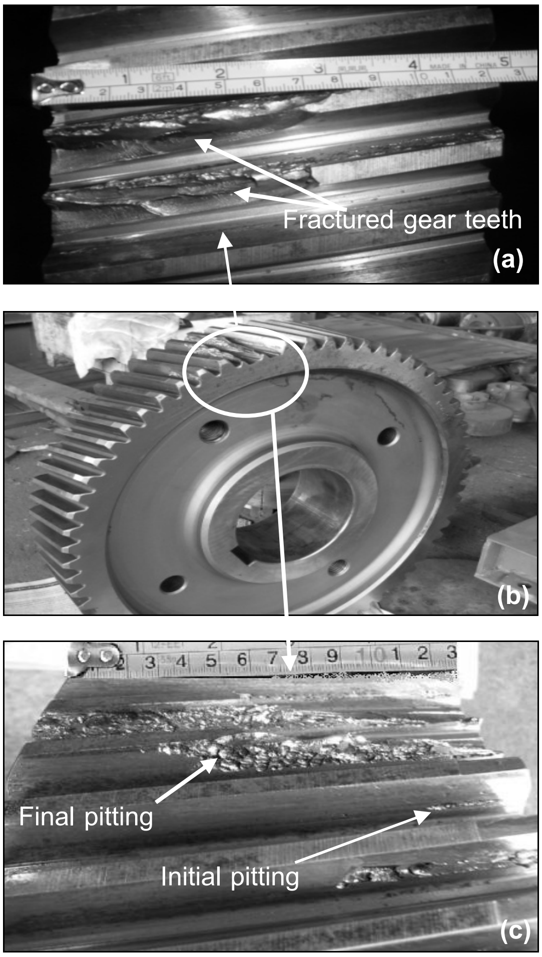

Fig. 2 Fracture and pitting occurrence in the failed gear

4.2 Fracture morphologies

The fracture surfaces and tooth surfaces of the failed gear were examined with using SEM in order to identify the type of fracture. SEM examination indicated that although there were pitting and spalling areas on the active side of the gear tooth as shown in Fig. 3a, b. The presence of extensive sub-surface spalling at the active surface side of the gear tooth was an indication that during operation the gear tooth was subjected to a contact stress that would have been high enough to initiate fatigue cracks. Beach marks, which are one of the typical characteristics of fatigue fracture, were clearly visible on the fracture surface as shown in Fig. 4. The width of the beach marks are about 44 μm.

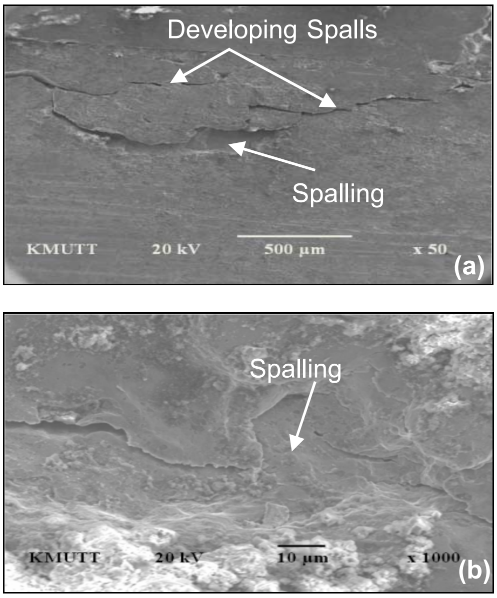

Fig. 3 Spalling of gear surface

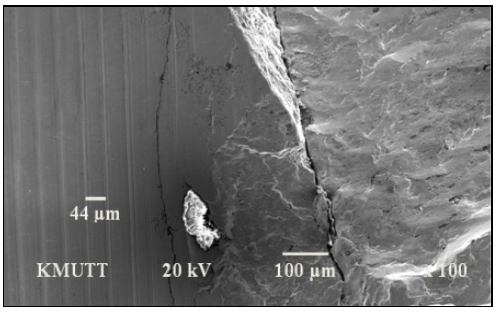

Fig. 4 Beach marks

4.3 Hardness profile

The microhardness distribution across of the gear tooth thickness at the pitch line was measured using a Vickers hardness tester (Mitutoyo model MVKH1) with 300 gm load. The results are shown in Fig. 5. The maximum hardness at the case and minimum at the core were found to be 713.2 HV (60.7 HRC) and 440.5 HV (44.5 HRC), respectively. Fig. 5 indicated that the gear had been case hardened by carburization which is normal practice for gear heat treatment.

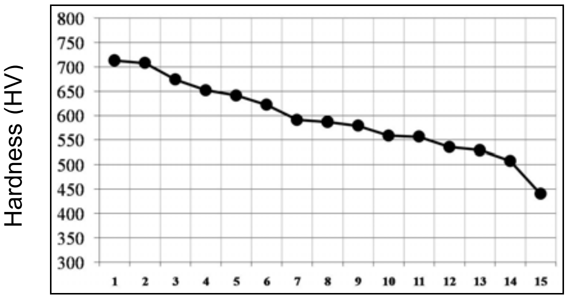

Fig. 5 Microhardness distribution of the failed gear tooth

4.4 Composition analysis

Chemical composition of the gear material was analysed using a spectrophotometer. The average values of the analysis are shown in Table 1. The compositions indicate that the gear was made from low alloy steel to JIS- SCM415 standard [9], commonly and widely used in making gears [10].

Table. 1 Chemical compositions of the failed gear and JIS-SCM415 (%wt)

Material	Failed Gear	SCM415
C	0.146	0.13-0.18
Si	0.212	0.15-0.35
Mn	0.435	0.60-0.85
S	0.006	0.030(max)
P	0.0103	0.030(max)
Cr	1.182	0.90-1.20
Mo	0.183	0.15-0.30

4.5 Microstructure examination

Specimens from the failed gear tooth were metallographically prepared and examined under an optical microscope (LECO: IA32-Image analysis system). The case microstructure is tempered martensite as shown in Fig. 6a. The core is a mixture of ferrite and pearlite as shown in Fig. 6b. The microstructure indicated that the gear heat treatment condition was carburized, quenched, and tempered which is common practice in heat treatment of SCM415 steel. The crack that leads to final fracture is transgranular and is filled with oxides as shown in Fig. 7. No abnormality was found in the microstructure.

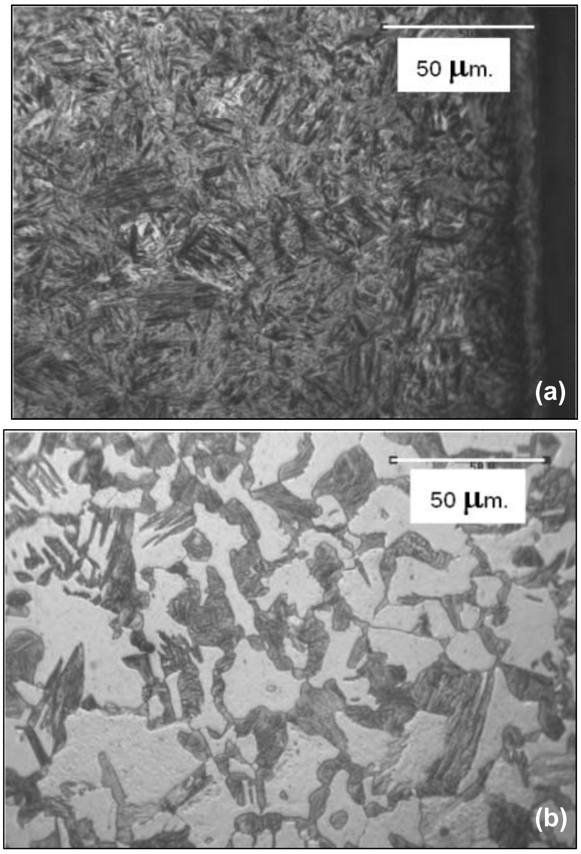

Fig. 6 Optical micrographs showing the microstructure of the gear tooth (a) tempered martensite, (b) mixture of pearlite and ferrite

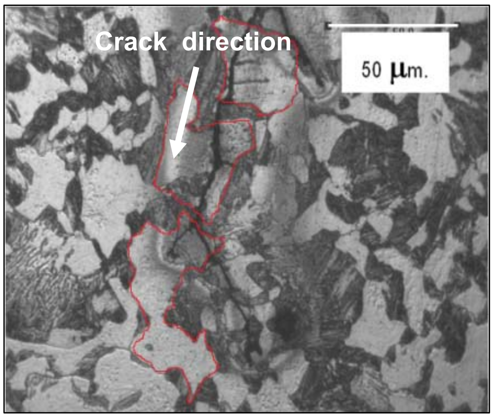

Fig. 7 Transgranular crack

4.6 Contact stress calculation.

The contact stress on the gear surface under normal operating condition was calculated using the following equation Eq. (1) [11].

$$\text{Contact stress } (\sigma_c) = P_H \sqrt{\frac{K_a K_s K_m K_v}{I_h}} \tag{1}$$

The parameters used in the equation and the values are shown and explained in Table 2. The calculated contact stress (σ_c) was 5,037 MPa. According to reference [11] allowable contact stress for the gear material is 1,550 MPa. The calculated contact stress due to normal operation was 3.2 times higher than the allowable stress.

Table. 2 Parameters and values for calculating contact stress

Parameters	Symbol	Values	Unit
Modulus of elasticity	E	2.07×10^{11}	Pa
Transmitted load	W_t	155.78	kN
Normal load = (W_t/cos20)	W	165.77	kN
Effective modulus of elasticity	E'	2.2747×10^{11}	Pa
Effective radius	R_x	0.01826	M
Width teeth	b_w	0.128	M
Dimensionless load = ($W/E' R_x b_w$)	W'	2.168×10^{-4}	-
Maximum Hertzian contract pressure ($p_H = E'(W'/2\pi)^{1/2}$)	p_H	1.33617×10^{9}	Pa
Application or overload factor	K_a	1.75	Table 14.8 ref[11]
Size factor	K_s	1.15	Table 14.9 ref[11]
Load distribution factor	K_m	1.38	
Dynamic factor	K_v	1.1	
Geometry correction factor for pitting resistance	I_h	0.215	Table 15.2 ref[11]

[a] Taken from reference [11]

5. Conclusions

1. The helical gear failure was caused by excessive stress on the surface of gear teeth, some 3.2 times higher than the allowable contact stress of gear material. Excessive stress was due to the replacement of original motor by a more powerful one.

2. The fracture starts from pitting at surface of a gear tooth followed by fatigue crack initiation, crack growth, and final fracture. The pitting occurred as a result of excessive stress.

3. Modifying existing machines by replacing critical components must be done with great care. Thorough analysis of possible consequences must be performed in order to avoid failure.

6. Acknowledgement

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