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Article

Improvement of Gear Durability for an 86 kW Class Agricultural Tractor Transmission by Material Selection

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Abstract: This study was conducted to ensure gear durability and design optimal transmission of agricultural tractors. A field test was conducted using an 86 kW agricultural tractor for plow and rotary tillage, which are typical agricultural operations. The field test was completed after about 107 h due to transmission noise and operational problems. As a result of disassembling the transmission, it was found that the range shift A and B gears were damaged. In the case of the range shift A gear, it was judged that plastic deformation occurred due to low contact stress, and the bending stress was low, therefore gear tooth breakage occurred in the range shift B gear. In order to ensure the durability of the transmission, four materials of alloy steel for machine structural use, such as SCr420, SNCM220, SCM822, and SNC815, were selected, and the safety factor and service life according to the gear materials were compared using simulation software. As a result of simulation analysis, SCM822 satisfied the target life value and was selected as a material for change. The damaged range shift A and B gears were changed to SCM822, and an axle dynamometer test was performed for the verification of the modified transmission. After conducting the axle dynamometer test, the transmission was disassembled, and it was confirmed that the range shift A and B gears were in normal condition. Therefore, it was considered that the durability of the transmission was ensured by satisfying the target life requirements of the gears. In the future, the transmission simulation model for 86 kW class agricultural tractor is expected to be utilized for the development of tractor transmissions, cost reduction, and optimal design.

Keywords: agricultural tractor; transmission; gear; material; strength; life

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1. Introduction

The global tractor market is expected to gradually increase from USD 45.3 billion in 2017 to USD 73.9 billion in 2027, with a combined annual growth rate (CAGR) of 5.5% [1]. The tractor production in Korea was 57,369 units in 2019, accounting for about 68% of major production of agricultural machinery, and their utilization rate was 98.7%, which was the highest among agricultural machinery [2]. In particular, the import of agricultural machinery in Korea increased by about 156% from USD 85 million in 2015 to USD 133 million in 2018, mostly in the form of high horsepower tractors (75 kW or higher), which are difficult to produce in Korea [3]. In view of this trend, the demand for high zzzhorsepower tractors has steadily increased; however, there is still a lack of original technology for developing high horsepower tractors in Korea. Therefore, it is necessary to use original technology to design and evaluate high horsepower tractors in Korea.

Agricultural tractors have irregular and fluctuating loads depending on agricultural operations (e.g., plow tillage, rotary tillage, baler operation, and loader operation), so it is important to ensure the durability of tractor components [4]. Transmission is a key component of a tractor for proper gear selection, and it accounts for over 30% of the tractor's total price [5]. In particular, among the various gear pairs of the transmission, the gears of the main and range shift are mainly used during driving and agricultural operation. As a result, failure is likely to occur in the main and range shift gears. If the gear is damaged during agricultural operations, it affects the entire transmission and may cause tractor failure and accidents [6]. Therefore, it is necessary to analyze the durability of tractor transmissions. Additionally, following the occurrence of gear failure, the strength of the damaged gear must be improved. There are methods that can be used to change gear specifications, such as tooth, width, module, and pressure angle, in order to increase gear strength [7]. However, changing gear specifications affects the transmission structure, which may incur high costs. On the other hand, if the material and heat treatment of the broken gear are changed, there is no need to change the structure of the transmission, so this strategy can be used to improve the strength of broken gears [8].

Recently, various studies have been conducted to ensure durability of tractor transmissions. The durability of tractor transmission is mainly evaluated using field test, dynamometer test, and simulation analysis. A field test was conducted to evaluate the fatigue life of a tractor using field data [2]; in order to measure the dynamic load of the tractor according to various agricultural operations, a tractor load measurement system was developed, and a field test was performed for major agricultural operations. Fatigue life was calculated using rainflow counting (RFC), the Smith-Watson-Topper (SWT) model, and S-N curves based on torque data measured in the field. The results showed that the fatigue life values under moldboard plow tillage, subsoiler tillage, rotary tillage, and baler operation were 13,599, 285, 278,884, and 525,977 h, respectively. The results of tractor gear fatigue life were significantly different according to agricultural operations, and it was suggested that the simulation model developed in this study could be used for evaluating fatigue life using dynamic field data. A dynamometer test of transmission was conducted to analyze the types of gear tooth wear using a gear monitoring system [9]. Gear tooth wear is an inevitable phenomenon that has a significant influence on gear dynamic features. Gear vibration analysis has been used to diagnose gear tooth defects, but gear wear monitoring techniques are not well established. Accordingly, a gear wear monitoring system was developed, and gear performance with reference to gear wear was analyzed. Two averaged logarithmic ratios (ALR) were defined with fixed and moving references to provide complementary information for gear wear monitoring. Since a fixed reference was utilized in the definition of the ALR, it reflected the cumulated wear effects on a gear state. Increases in ALR values indicated that the gear state was further deviating from its reference condition. Accordingly, it was judged that the proposed indicators and gear monitoring system can prevent gear failure in advance.

A simulation analysis was conducted to evaluate the durability and performance of a tractor transmission [10]. In order to evaluate the performance of a hydro-mechanical transmission (HMT), a test bench was installed based on the engine of the HMT platform, and a simulation model of HMT was developed using software for analyzing gear-train. To compare the results of the simulation, a bench test using the platform was performed according to the gear stages. The similarities between the measured and simulated data were analyzed using a t-test; no significant differences for the axle torque, rotational speed, and power transmission efficiency were observed.

In conclusion, there have been insufficient studies evaluating the fatigue life of simulation-based tractors while considering actual field dynamic loads. Therefore, it is necessary to optimize tractor transmission gears based on simulations utilizing dynamic field load condition data measured for each agricultural operation through field experiments and dynamometer tests. In Korea, tractor companies design and mass-produce transmissions for agricultural tractors, and it is difficult to check and repair damaged transmissions when they break down in the field [11]. However, simulation analysis allows for easy identification of and improvements to such failures.

Therefore, the purposes of this study were to verify the type of gear failure for an 86 kW class agricultural tractor through a field test, to analyze the strength of the damaged gear by changing gear materials using simulation analysis, and to verify the durability of the transmission built with the selected gear materials through dynamometer tests. The novelty of this study is that a field test was performed using a tractor under development, and a gear material that reached the target lifespan was selected through simulation analyses of the damaged gear, as verified through dynamo tests. This study can contribute to the development of original technology for the optimal design and durability evaluation of agricultural tractors. The major objectives of this study were as follows: (1) analyze gear failure type for the 86 kW class agricultural tractor through a field test; (2) compare the strength and life of the damaged gear with different gear materials using commercial software; (3) verify the modified the tractor transmission through dynamometer tests.

2. Materials and Methods

2.1. Field Test

2.1.1. Agricultural Tractor

The 86 kW class agricultural tractor (Luxen1100, Kukje Machinery Co., Ltd., Ocheon, Korea) was used in the field test, as shown in Figure 1. The tractor had an empty vehicle weight of 4080 kg, and its dimensions were 4020 × 2270 × 2790 mm^3 (length × width × height). The ratios of the front and rear axles were 40.4% and 59.6%, respectively. The tractor was equipped with an 86 kW engine (4045HFK04, John Deere, Moline, IL, USA). The rated torque of the tractor was 340 Nm at the rated rotational speed of 2400 rpm, and its maximum torque was 461 Nm at 1600 rpm. The agricultural tractor used for the field test was equipped with the mechanical transmission of a power shuttle. A total of 32 travel speeds (16 forward and 16 backward) of the tractor were determined by a combination of gear stages that were selected according to agricultural operation. The specifications of the agricultural tractor used in the field test are shown in Table 1.

Figure 1. The 86 kW class agricultural tractor for the field test used in this study.

Table 1. Specifications of the 86 kW class agricultural tractor used in this study.

Item	**Specification**	
Model	Luxen1100	
Length × Width × Height (mm^3)	4020 × 2270 × 2790	
Weight (kg)	Gross weight (kg) Weight distribution (%)	4080 40.4 and 59.6
Engine	Rated power (kW) Max. torque (Nm)	86 @2400 rpm 461 @1600 rpm
Transmission	Main shift	4 stages (1, 2, 3, and 4)
	Range shift	4 stages (A, B, C, and Creep)
	Forward × Reverse	16 × 16
Tire	Front Rear	13.6–24 8PR 18.4–34 10PR

2.1.2. Working Conditions

To confirm the type of gear failure, field experiments were conducted in Daeya-myeon, Gunsan-si, Jeollabuk–do Province, Korea. The size of the test site was 1980 × 100 m^2, and its latitudinal and longitudinal coordinates were 35°58′06″ N and 126°44′14″ E, respectively. The field test was conducted for typical agricultural operations, such as plow and rotary tillage, as shown in Figure 2. The plow and rotary tillage operations account for over 20% in the Korean agricultural environment [12]. The plow (WJR4PS, Woongin Machinery Co., Ltd., Gimje, Korea) and rotary (WJ255SE, Woongin Machinery Co., Ltd., Gimje, Korea) were selected as the attached implements mainly used in Korea after considering the horsepower of the tractor. The specifications of the plow and rotary are shown in Table 2. The field test was performed under full-throttle conditions of 2400 rpm and four-wheel drive mode (4WD). The plow tillage was performed in the F10 stage of 6.71 km/h, and the rotary tillage was performed in the F8 stage of 4.12 km/h. The field test conditions were selected to be the same as the conditions under which the farmers performed the agricultural operations [13]. In addition, the plow and rotary tillage were performed alternately based on the average daily agricultural operation hours in Korea of 8 h.

(**a**) (**b**)

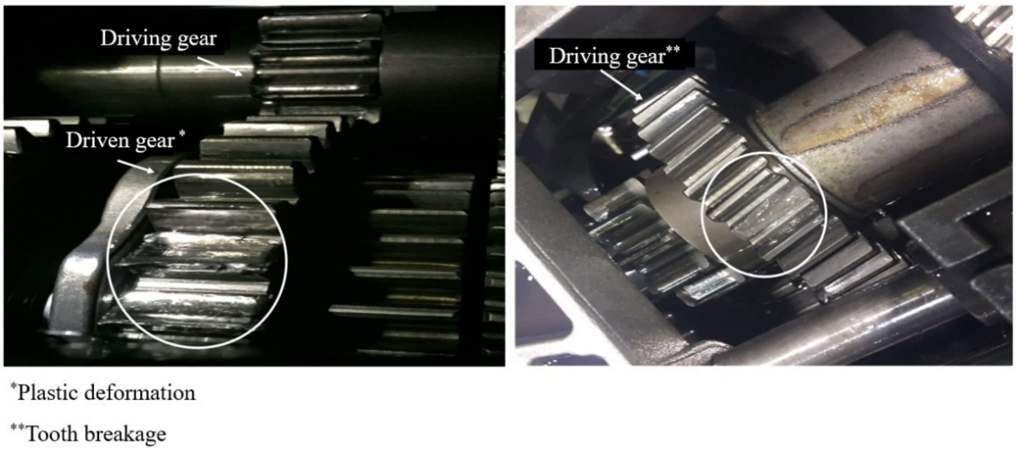
Figure 2. Photos of the 86 kW class agricultural tractor during the field test: (**a**) plow tillage; (**b**) rotary tillage.

Table 2. Specifications of the attached implements for tractor used in this study.

Item	Specification	
	Plow	**Rotary**
Model	WJR4PS	WJ255SE
Length × Width × Height (mm^3)	3410 × 2020 × 1530	1000 × 2780 × 1240
Working width (mm)	1400	2510
Weight (kg)	930	815
Number of blades	8	66
Required power (kW)	80–100	80–100

2.1.3. Gear Failure Types

The field test was completed after 107 h due to gear noise in the transmission and defective driving operation. Figure 3 shows the results of the gear failure type after the field test, and Figure 3a details the damaged range shift A gear. The gear failure type was judged to be plastic deformation due to wear. It was confirmed that there was a gloss around the pitch line of the gear, which meant that the abrasive wear had preferentially progressed. As the wear continued to occur on the surface of the gear, it was considered that plastic deformation had occurred on the outside of the teeth of driven gear, which had relatively small tooth widths and exceeded the carburizing depth of the gear. The plastic deformation is maintained even after the load is removed, and it is caused by the rolling and sliding action of the gear under excessive load and friction. It also often occurs when high contact stress is applied to the gear tooth surface.



(**a**) (**b**)

Figure 3. Results of gear failure type after field test: (**a**) range shift A gears; (**b**) range shift B gears.

Figure 3b displays the damaged range shift B driving gear; the gear failure type was judged to be gear tooth breakage, which was caused by the propagation of cracks that started inside this part as bending stress above the fatigue limit of the material was repeatedly applied to the gear root. Accordingly, it was determined that a large load was repeatedly generated during plow and rotary tillage, and the gear tooth breakage occurred in the range shift B driving gear.

2.2. Simulation Analysis

2.2.1. Tractor Power Transmission System

A transmission consists of four main shifts (1, 2, 3, and 4) of the synchromesh type and four range shifts (A, B, C, and Creep) of the constant mesh type. A tractor's power transmission system is constructed as shown in Figure 4. The engine power is directly connected to power take-off (PTO) or transmitted to front and rear shift (F/R shift), main shift, and range shift. After that, power is transmitted to differential gear, final reduction gear, and front and rear axles according to four-wheel drive. In this study, the main shift and range shift gears, which were in charge of shifting according to agricultural operation and used most often, were set as main analysis parts.

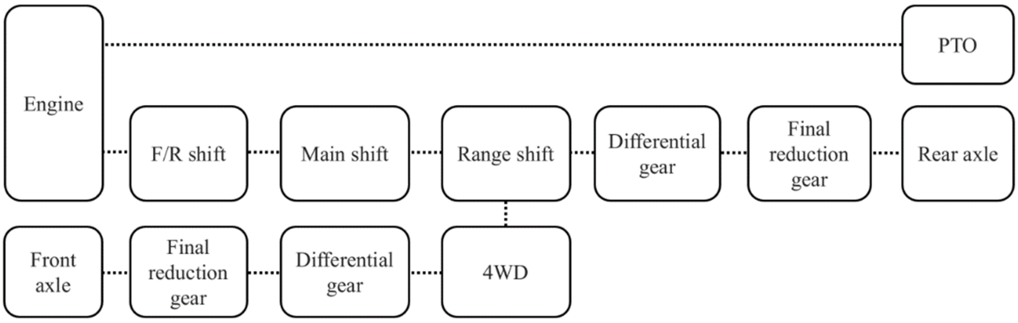


Figure 4. Power flow of the 86 kW class agricultural tractor used in this study.

2.2.2. Simulation Modeling

A simulation program used for the strength analysis and life evaluation of the gears for the 86 kW class agricultural tractor in this study was KISSsoft (Ver. 03/2019, KISSsoft AG, Bubikon, Switzerland), which has been widely used for the design and analysis of complex mechanical systems. KISSsoft performs analyses of mechanical elements based on international gear strength standards, such as the International Organization for Standardization (ISO). In this study, stress, safety factor, and service life were calculated using the "cylindrical gear pair" module of KISSsoft. Figure 5 shows the transmission simulation model for the 86 kW class agricultural tractor developed in this study. The simulation model was configured the same as the tractor transmission, and it was composed of F/R shift, main shift, range shift, and differential gear.

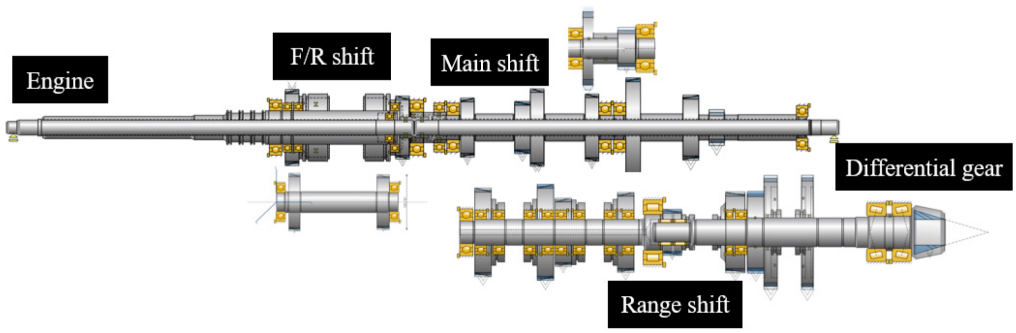


Figure 5. Simulation model of the 86 kW class agricultural tractor transmission developed in this study.

2.2.3. Gear Materials

Changing gear materials enables the simple improvement of a problem without complex design modifications [14]. Gears are made of various materials, such as steel, non-steel metals, and plastics, depending on use. In general, alloy steel for machine structural use is utilized for products requiring high strength, such as gears, shafts, and bolts [15]. In addition, the carburizing process, which only coats high carbon steel on a surface by penetrating carbon into the surface of low carbon steel, can make a surface hard and interior soften, so it is used for highly loaded gears [16].

The material of the existing range shift A and B gears was SCM420. In this study, to improve the strength of the damaged range shift gears, four materials that are mainly used by tractor manufacturers in Korea (SCr420, SNCM220, SCM822, and SNC815) were selected [17]. Table 3 shows the chemical composition of the gear materials used in this study. Generally, the higher the carbon content of a material, the more effectively it can increase the strength of a gear. The carbon content of our selected materials was highest for SCM822.

Table 3. Chemical composition of the gear materials used in this study.

Material		Chemical Composition (%)					
		C	Si	Mn	Ni	Cr	Mo
SCM420	Min. Max.	0.18 0.23	0.15 0.35	0.60 0.85	-	0.90 1.20	0.15 0.30
SCr420	Min. Max.	0.18 0.23	0.15 0.35	0.60 0.85	-	0.90 1.20	-
SNCM220	Min. Max.	0.17 0.23	0.15 0.35	0.60 0.90	0.40 0.70	0.40 0.65	0.15 0.30
SCM822	Min. Max.	0.20 0.25	0.15 0.35	0.60 0.85	-	0.90 1.20	0.35 0.45
SNC815	Min. Max.	0.12 0.18	0.15 0.35	0.35 0.65	3.00 3.50	0.60 1.00	-

2.3. *Axle Dynamometr Test*

2.3.1. Axle Dynamometer Configuration

In this study, an axle dynamometer test was performed to verify the durability of the transmission to which the material selected in the simulation analysis was applied. The test bench was composed of an axle dynamometer, speedometer, air control unit, load control panel, fuel supply device, and temperature sensors for oil and coolant. Figure 6 shows the axle dynamo test of the 86 kW class agricultural tractor transmission used in this study.

Figure 6. A photo of the axle dynamometer test bench used in this study.

The axle dynamometer test was conducted under continuous equal load. The rear axles were connected to the axle dynamometer during the experiment, and load was applied to the transmission by braking with the brake in the rear axle. The load applied to the rear axles was determined based on the tractor weight, weight distribution ratio, maximum slip torque, and reduction ratio. The maximum slip torque was calculated using Equation (1) below. The weight distribution ratio of the rear axle was 0.6 according to the specifications of the 86 kW agricultural tractor, and the friction coefficient was 0.6 in consideration of the tire slip caused by heavy loads, such as plow tillage [18].

$$T_{slip} = W \times \omega_r \times r_r \times \mu \quad (1)$$

where T_{slip} is the slip torque (Nm), W is the tractor weight (kg), ω_r is the weight distribution ratio of the rear axle (%), r_r is the radius of the rear tire (m), and μ is the friction coefficient.

During the axle dynamometer test, the temperature of the engine and transmission oil, axle rotational speed, and axle torque were measured to check whether the transmission failed. The axle dynamometer test was stopped when the engine coolant temperature exceeded 100 °C or when the temperature of the transmission oil exceeded 90 °C. Cooling was then performed before checking for any abnormal problems [19]. When the ratio of engine torque and axle torque became the same, the axle dynamo test was performed under continuous equal load. In addition, the dynamometer test was performed with the differential locking device turned on. In this study, a 402.7 kW axle dynamometer was installed, and the load cell type was TrCD 224. This dynamometer had precision strain gauge load cell torque measurement system that provided high-accuracy torque measurements for the transmission durability test. The detailed specifications of the axle dynamometer used in this study are listed in Table 4.

Table 4. Specifications of the axle dynamometer used in this study.

Item	Specification
Model	TrCD 224
Max. power (kW)	402.7
Max. torque (kNm)	24.5
Max. slip speed (rpm)	715
Max. air pressure (kPa)	550
Max. coolant pressure (kPa)	270

2.3.2. Axle Dynamometer Test Conditions

The axle dynamometer test was performed to evaluate the durability of the range shift gears with changed gear materials. The test was carried out for 250 h under the same conditions of the accelerated life test performed in a previous study [20]. If the input torque was too much larger than the rated torque, the probability of failure mode deformation would have increased, and if it was too much lower, the test time would be excessively long. Therefore, it was important to determine an appropriate value for the test situation. In this study, the test torque was set to 1.2 times the rated torque, which was the maximum torque of the engine.

After simulation analysis, the service life of the gears was recalculated as the equivalent life using Equation (2). The equivalent life was calculated using the accelerated life calculation formula. This time, the torque ratio of field operation was applied to the actual working time rate, which was estimated from 0.68 to 0.84 for plow and rotary tillage operations in Korea, and 0.7 was applied with reference to tractor company specifications in this study [18]. In addition, the ratio of the rotational speed in the accelerated life test and field operation was calculated as 1 because it was performed at the same rated rotational speed in each part. We used ISO 6336 as the fatigue damage index for the tooth face and root, as shown in Table 5. The equivalent life of the gears was calculated by applying the fatigue damage index according to the tooth failure type [21].

$$L_{life} = L_{acc} \times \left(\frac{T_{acc}}{T_{field}}\right)^{\lambda} \times \left(\frac{N_{acc}}{N_{field}}\right) \quad (2)$$

where L_{life} is the life of field operation (hours), L_{acc} is the life of accelerated test (hours), T_{acc} is the torque of accelerated test (Nm), T_{field} is the torque of field operation (Nm), λ is the fatigue damage exponent, N_{acc} is the rotational speed of accelerated test (rpm), and N_{field} is the rotational speed of field operation (rpm).

Table 5. Fatigue damage index for tooth face and root in ISO 6336 standard.

Heat Treatment	Tooth Face	Tooth Root
Carburizing	6.610	8.738
Through hardening	6.610	6.225
Nitrification	5.709	17.035
Soft nitriding	15.715	84.003

3. Results

3.1. Safety Factor

In order to confirm the tendency of the developed simulation model for the 86 kW class agricultural transmission, the bending and contact safety factors were analyzed for the main and range shift gears in field test conditions.

Figure 7 shows the results of the bending safety factor analysis for the main and range shift gears. The red line in Figure 7 represents 1.4, which is the appropriate bending safety factor suggested by ISO 6336 standard. The bending safety factors of main shift driving gears were 1.52, 1.72, 1.93, and 2.24 for gear stages A, B, C, and creep, respectively, and the bending safety factors of the range shift driving gears were 2.35, 1.25, 1.71, and 5.83 for gear stages A, B, C, and creep, respectively. The bending safety factors of the main shift driven gears were 1.35, 1.71, 1.82, and 2.27 for gear stages A, B, C, and creep, respectively, and the bending safety factors of driven gears were 1.98, 1.32, 1.42, and 2.49 for gear stages A, B, C, and creep, respectively. The bending safety factor values of the driving and driven gears were similar to each other, and the lowest value was observed in the range B stage. These results were judged to be similar to the field test results in which tooth breakage occurred in the range shift B gear.

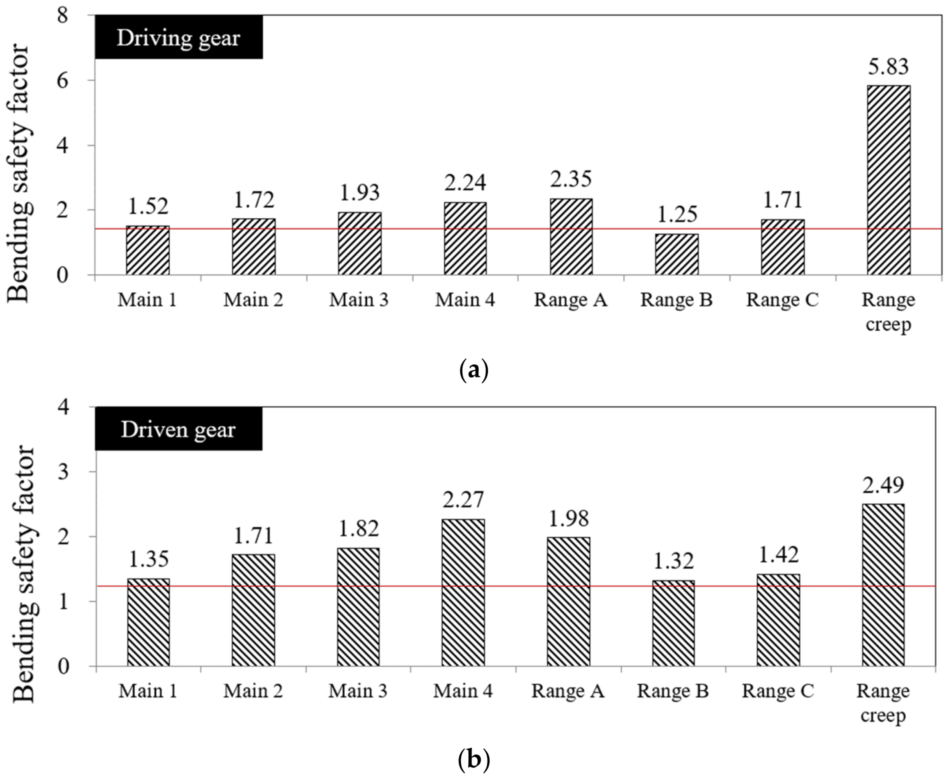
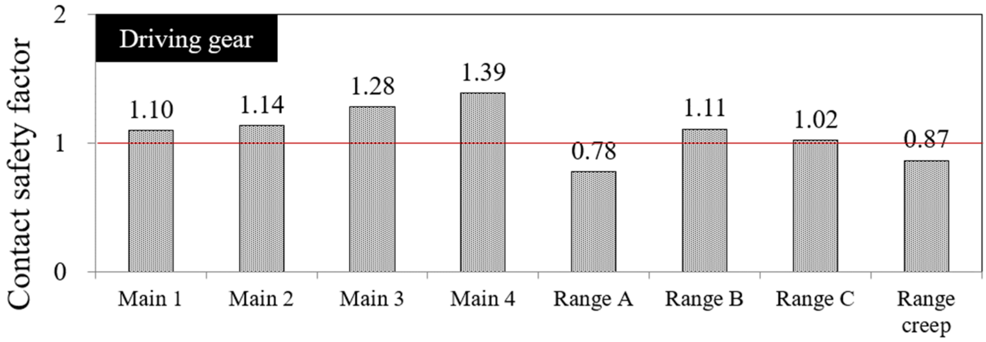
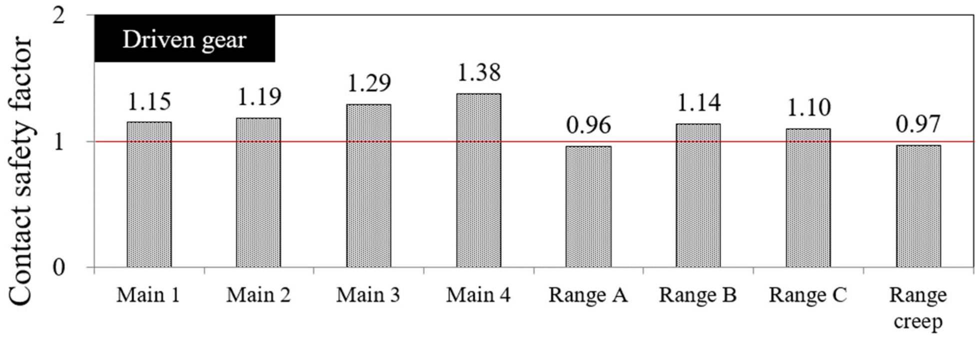


Figure 7. Results of bending safety factor for gears of the 86 kW class agricultural tractor transmission used in this study: (**a**) driving gears; (**b**) driven gears.

Figure 8 shows the results of the contact safety factor analyses for the main and range shift gears. The red line in Figure 8 represents 1, which is the appropriate contact safety factor suggested by ISO 6336 standard. The contact safety factors of main shift driving gears were 1.10, 1.14, 1.28, and 1.39 for gear stages A, B, C, and creep, respectively, and the contact safety factors of the range shift driving gears were 0.78, 1.11, 1.02, and 0.87 for gear stages A, B, C, and creep, respectively. The contact safety factors of the main shift driven gears were 1.15, 1.19, 1.29, and 1.38 for gear stages A, B, C, and creep, respectively, and the contact safety factors of the driven gears were 0.96, 1.14, 1.10, and 0.97 for gear stages A, B, C, and creep, respectively.



(**a**)



(**b**)

Figure 8. Results of contact safety factor for gears of the 86 kW class agricultural tractor transmission used in this study: (**a**) driving gears; (**b**) driven gears.

The contact safety factor values of the driving and driven gears were similar to each other, and the lowest value was observed in the range shift A gear. These results were judged to be similar to the field test results in which plastic deformation occurred in the range shift A gear.

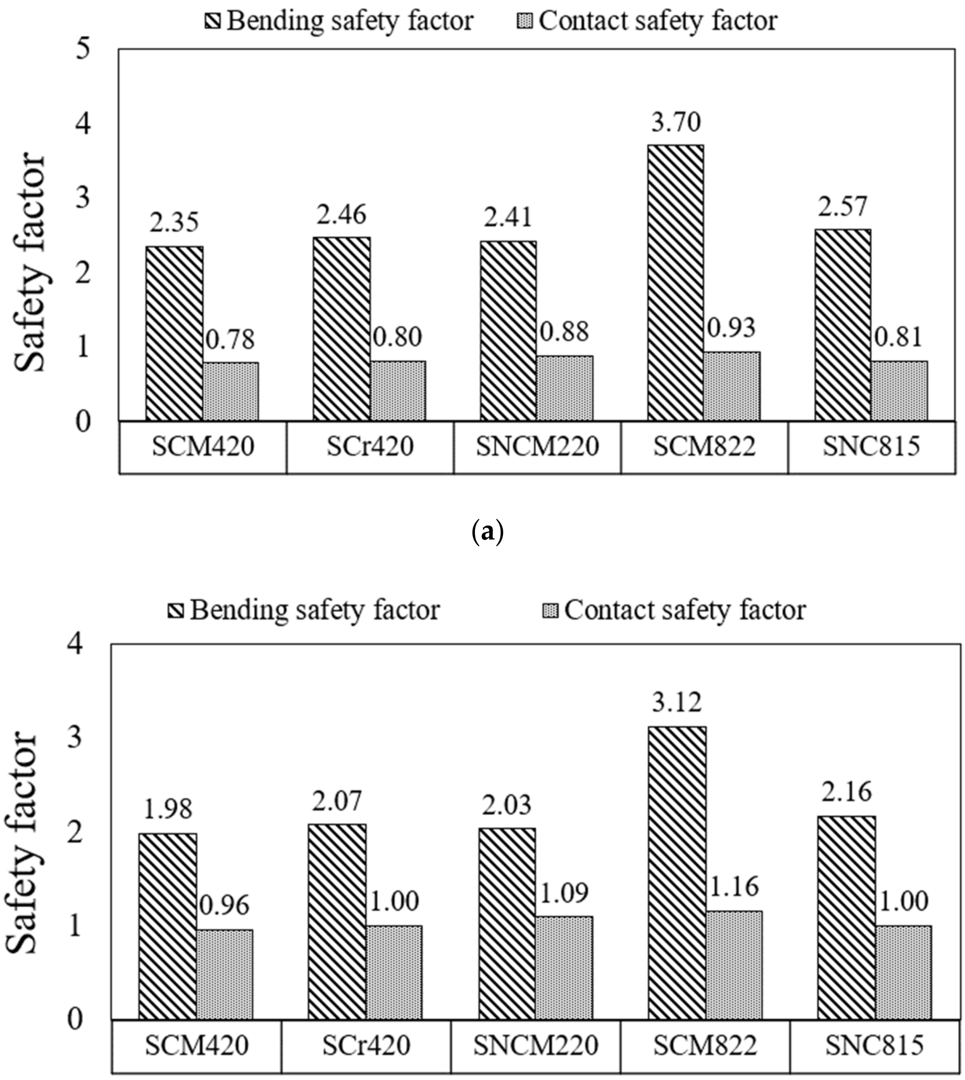
Accordingly, when the developed simulation model was compared to the field test results, it was judged that the transmission simulation model of the 86 kW class agricultural tractor ensured reliability following strength analysis.

3.2. Comparision of Gear Durability by Materials

3.2.1. Range Shift A

Figure 9 shows the results of the bending and contact safety factor analyses for the range shift A gears of the 86 kW class agricultural tractor transmission with different gear materials. In the case of the range shift A gear, it was important that the contact safety factor be improved because plastic deformation occurred during the field test. The contact safety factors of the range shift A driving gears were 0.80 with SCr420, 0.88 with SNCM220, 0.93 with SCM822, and 0.81 with SNC815, and the contact safety factors of the range shift

A driven gears were 1.00 with SCr720, 1.09 with SNCM220, 1.16 with SCM822, and 1.00 with SNC815. The contact safety factors of the range shift A gears were the highest with SCM822, which was 19.5% higher than that with SCM420.



(**a**)

(**b**)

Figure 9. Results of safety factor analyses for the range shift A gears with different materials: (**a**) driving gear; (**b**) driven gear.

Table 6 shows the results of the service life analyses for the range shift A gears of the 86 kW class agricultural tractor. The service life values of the range shift A gears were 53.0 h with SCr420, 158.6 h with SNCM220, 312.6 h with SCM822, and 53.0 h with SNC815. The life value of the range shift A gears was the highest with SCM822, which was 771% higher than that with SCM420. The life values with SCr420 and SNC815 were similar, potentially due to their similar chemical compositions. The life value with SNCM220 was 332% higher than that with SCM420, but it was lower than the target life value of 250 h. It was confirmed that only SCM822 presented a life value higher than the target life value of 250 h.

Table 6. Results of service life analyses for the range shift A gears with different materials.

Material	Service Life (h)
SCM420	35.9 (100%)
SCr420	53.0 (148%)
SNCM220	158.6 (442%)
SCM822	312.6 (871%)
SNC815	53.0 (148%)

3.2.2. Range Shift B

Figure 10 shows the results of the bending and contact safety factor analyses for the range shift B gears of the 86 kW class agricultural tractor transmission with different gear materials. In the case of the range shift B gear, it was important that the bending safety factor be improved because plastic deformation occurred during the field test. The bending safety factor values of the range shift B driving gears were 1.31 with SCr420, 1.29 with SNCM220, 1.98 with SCM822, and 1.37 with SNC815, and the bending safety factor values of the range shift B driven gears were 1.18 with SCr420, 1.29 with SNCM220, 1.37 with SCM822, and 1.18 with SNC815. The bending safety factor values of the range shift B gears were the highest with SCM822, which was 57.4% higher than that with SCM420.

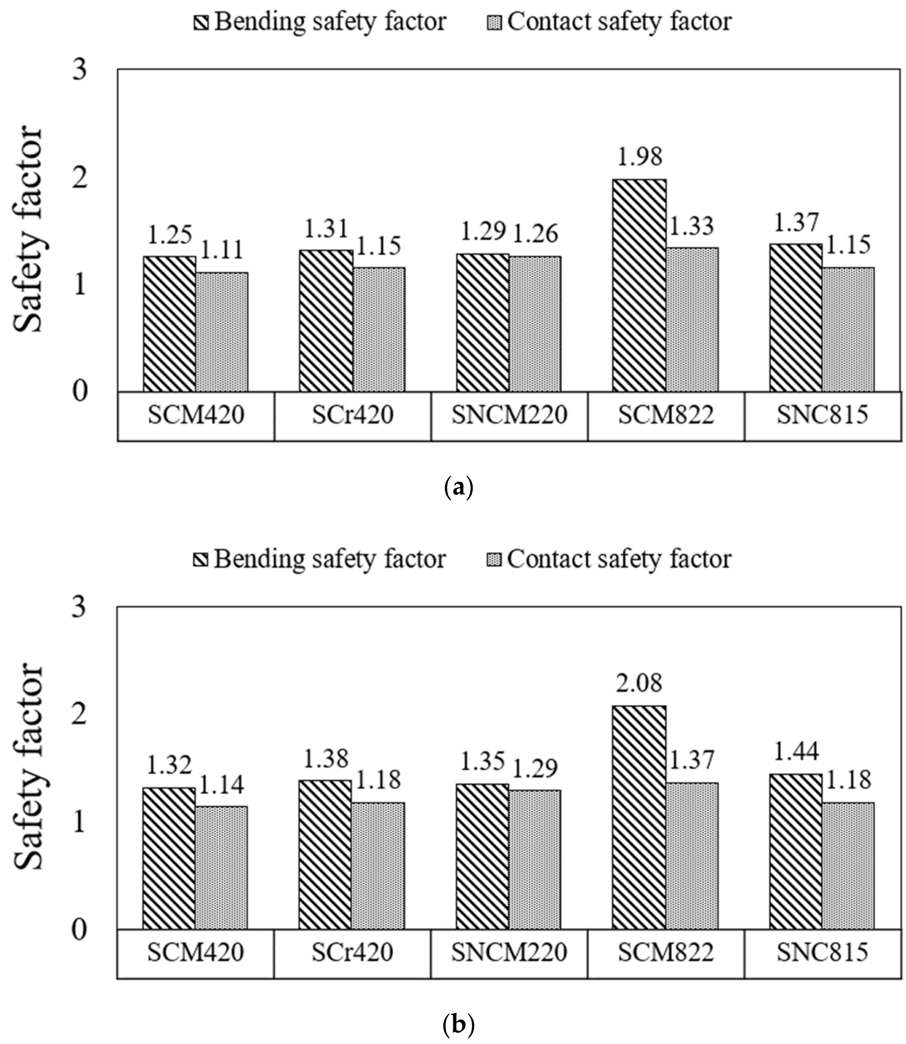


Figure 10. Results of safety factor analyses for the range shift B gears with different materials: (**a**) driving gear; (**b**) driven gear.

Table 7 shows the results of the service life analyses for the range shift B gears of the 86 kW class agricultural tractor. The life values of the range shift A gears were 63.5 h with SCr420, 52.8 h with SNCM220, and 123.1 h with SNC815. The life value with SCM 822 was higher than 1,000,000 h, which was determined to be infinite. The life values were shown to be high with SCM822, SNC815, SNCM220, and SCr420, though only SCM822 reached the target life of 250 h.

Table 7. Results of service life analyses for the range shift B gears with different materials.

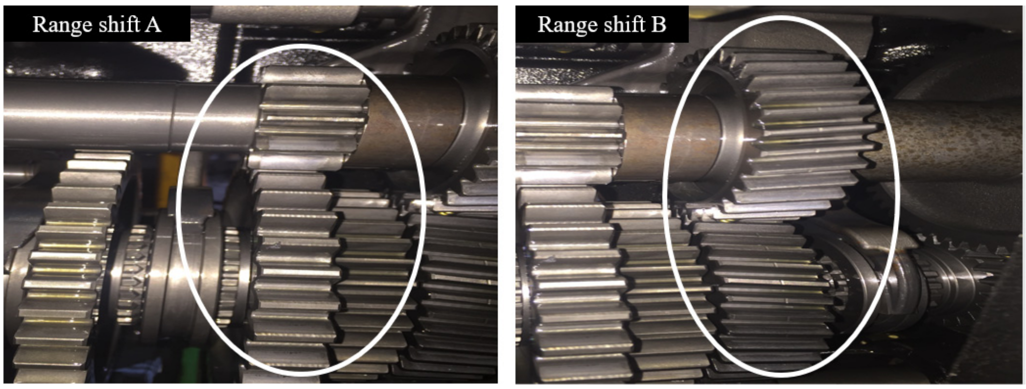
Material	Service Life (h)
SCM420	41.9 (100%)
SCr420	63.5 (152%)
SNCM220	52.8 (126%)
SCM822	∞ *
SNC815	123.1 (294%)

* ∞ indicates that the service life is 1,000,000 h or more.

Finally, based on the results of the simulation analysis, the materials of the range shift A and B gears in the transmission were changed from SCM420 to SCM822, which guaranteed the target life of 250 h.

3.3. Dynamometer Test

The dynamometer test was completed after 250 h each for range shift A and B stages. Figure 11 shows results of the range shift gears after dynamometer test. The transmission was disassembled and considered as a whole, and the type of damage was checked. We found that there was no damage to the range shift A and B gears. Accordingly, as shown in the results of the simulation analysis, it was confirmed that adequate service lives of the range shift A and B gears were guaranteed when the material of the damaged range shift gears was changed.



(**a**) (**b**)

Figure 11. Results of the dynamometer test for the range shift gears: (**a**) range shift A gears; (**b**) range shift B gears.

4. Discussion

In this study, the gear failure types of the 86 kW class agricultural tractor transmission were analyzed with a field test, and the damaged gears were changed using simulation analysis. Finally, the transmission was modified following a dynamometer test to verify that the changed material met the target life. Table 8 shows a comparison of the service life values for the modified range shift gears between the simulation analysis and the dynamometer test, which were both performed as accelerated life tests. Accordingly, we calculated the equivalent life in order to confirm whether the damaged gears reached the target life. The service life of the range shift A gear was found to be 312.6 h with the simulation analysis, and it was found to be 250 h or more with the dynamometer test. The service life of the range shift B gear was found to be infinite with simulation analysis and more than 250 h with the dynamometer test. The equivalent life of the range shift A gear was found to be 3632 h with simulation analysis and 2641 h or more with the dynamometer test, and the equivalent life of the range shift B gear was found to be infinite with simulation analysis and more than 5642 h with the dynamometer test.

Table 8. Comparisons of life for the changed range shift gears between the simulation analysis and dynamometer test.

Item	Range Shift A		Range Shift B	
	Simulation Analysis	Dynamometer Test	Simulation Analysis	Dynamometer Test
Service life (h)	312.6	>250	∞ *	>250
Equivalent life (h)	3632	>2641	∞	>5642
Required life (h)	2496			

* ∞ indicates that the service life is 1,000,000 h or more.

The life of a tractor transmission is usually determined based on the life of the lowest gear. Accordingly, the life value of the 86 kW class agricultural tractor transmission studied here was determined by the life value of the range shift A gear, which was more than 2641 h and thus reached the target life time of 2496 h or more, considering the tractor's service life and annual working hours. Therefore, it was judged that the durability of the tractor transmission was ensured by changing the material of the damaged gear during the dynamometer test. The simulation model of the 86 kW class agricultural tractor developed in this study is expected to be used for future optimal design and cost reduction.

5. Conclusions

This research was conducted to ensure the durability of a tractor transmission as a basic study of the development and optimal design of tractor transmissions. A field test was conducted using an 86 kW agricultural tractor for plow and rotary tillage, which are typical agricultural operations. The plow and rotary tillage were performed at the F10 (6.71 km/h) and F8 (4.12 km/h) gear stages, respectively. The field operation was completed after around 107 h due to transmission noise and operational problems during a forward and reverse movement. As a result of disassembling the transmission, it was found that the range shift A and B gears were damaged. For the range shift A gear, it was judged that plastic deformation occurred due to low contact stress, and for the range shift B gear, the bending stress was low, so gear tooth breakage occurred.

The simulation results showed that the contact safety factor of the range shift A gear was the lowest, and the bending safety factor of the range shift B gear was the lowest. Accordingly, it was observed that the simulation and field test results presented similar trends. In order to ensure the durability of the transmission, four materials of alloy steel for machine structural use, such as SCr420, SNCM220, SCM822, and SNC815, were selected, and the safety factor and service life values of the damaged range shift gears with different gear materials were analyzed.

The simulation analysis results demonstrated that the SCM822 material reached the design target life and was selected as the new gear material. The materials of the range shift A and B gears were changed to SCM822, and an axle dynamometer test was performed to verify the improvement of the modified transmission. After conducting the axle dynamometer test, the transmission was disassembled, and it was confirmed that the range shift A and B gears were in normal condition. Therefore, it was determined that the durability of the transmission was ensured because it reached its target life. However, a drawback of this study is that the axle dynamo test was only performed once for the transmission that reflected the changed gear material due to issues such as test time, test cost, and limited transmission samples. Accordingly, it was judged that additional dynamo tests are necessary to verify the target life of the tractor transmission.

Finally, in this study, we have proposed a method for improving the strength and service life of damaged gears. In the future, our proposed transmission simulation model for 86 kW class agricultural tractors is expected to be utilized for the development of tractor transmissions, cost reduction, and optimal design.

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