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Development of Accelerated Failure-free Test Method for Automotive Alternator Magnet

Qiang Liu · Azianti Ismail · Won Jung†

Department of Industrial and Management Engineering, Daegu University

자동차 교류발전기용 자석에 대한 가속 무고장시험방법 개발

Qiang Liu · Azianti Ismail · 정 원†

대구대학교 산업경영공학과

Many automotive components for power generation such as motors and alternators have been widely using ferrite magnets. To ensure a high level of efficiency could be achieved in an alternator, the assembled magnets must be in good enough durability. Recently, some hairline cracks have been found on the magnet produced by manufacturers in Korea. Thus, there is an increasing concern that some of the magnets produced could cause further problems after being assembled in the alternator. Based on the standard alternator test (RS0008 : 2006), this paper has developed an accelerated failure-free test for magnets in alternator to demonstrate that assembled magnets will meet durability objective specified by the manufacturer. This guarantees the target life of the magnet with 90 percent reliability and 90 percent confidence level (R90C90). Temperature and rotation speed were selected as accelerated stress factors.

Keywords : Alternator Magnet, Accelerated Failure-free Test Design, Weibull Distribution

1. Introduction[1)]

The overall performance of the alternator would be badly affected if the important part, the magnet, is of low quality. Therefore, proper magnet testing is needed to certify that the reliability and quality of the assembled magnets are up to the standards. Due to the increasing price of sintering NdFeB recently, the magnet manufacturer has replaced it with the alternative-grade magnet to be assembled in the alternators. Magnet manufacturer recently has faced some problem regarding the quality of the magnet in which some hairline cracks have been found on the sample test. The magnet manufacturer must guarantee that the magnets produced with high standard of quality before shipping them to the alternator manufacturers.

Therefore, an accelerated test method is needed to demonstrate the life of magnet since the crack in the magnet will affect the performance and functionality of the alternators.

Based on the magnet manufacturer requirements to ensure only high quality magnet to be shipped, an accelerated failure-free test for an alternator has been developed to demonstrate that assembled magnet will meet its durability objective of 160,000km (or 10 years) at the 90 percent confidence level. Zhang et al. [1] have discussed on the performance test of voltage regulator for alternator by using a static system which was proven to be simple, cheap and reliable. Dateppli Inc. together with Wright-K Technology Inc. have designed an alternator performance test under extreme conditions which is capable of measuring voltages, currents and

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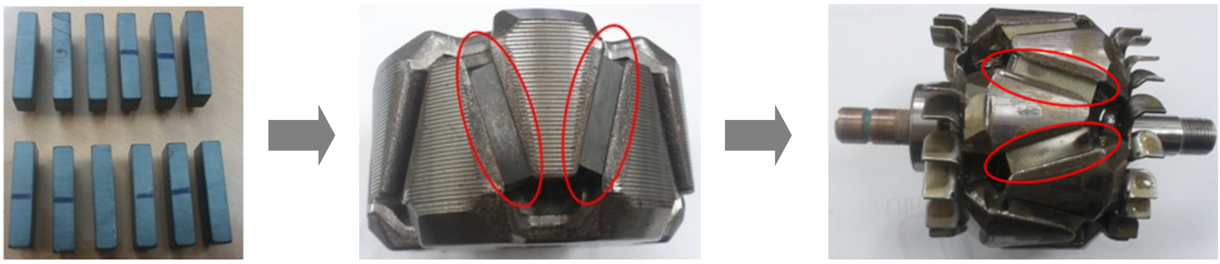
† Corresponding Author : wjung@daegu.ac.kr



<Figure 1> Assembly of Magnets in the Alternator

temperature at various points of the alternator [2]. For electric vehicles, Sim et al. [3] have presented development and performance measurement of micro-gas turbine driven automotive alternators.

Most of the tests are developed for the overall performance of the alternator but none is for specific parts like the assembled magnet. Thus, this paper is significant in developing an accelerated failure-free test for assembled magnets inside the alternator. In an alternator, a voltage is generated (induced) when an electric conductor (wire or wire loop) cuts through the lines of force of a magnetic field which is produced by magnets. By rotating a wire loop uniformly between the North and South poles of a permanent magnet, a sinusoidal voltage curve is generated. In <Figure 1>, there are 12 magnets that are located around the rotor of the alternator.

2. Standards and Test Specifications

In the international standards, ISO 8854 : 2012 [4] and SAEJ56 [5] suggest suitable test methods for automotive alternators which specify electrical characteristics of the alternator with general requirements. Important elements such as proper test conditions and measurement procedures described in these standards are used as references in developing the alternator magnet accelerated failure-free test.

In addition, a domestic standard that focuses on the reliability of the automotive alternators known as RS R0008 : 2006 [6] specifies not only the performance test but also environment test and life demonstration test in detail. Based on these standards, alternators are classified in two grades. Grade A alternators must have the requirement B10 life of 160,000km (or 10years) with the confidence level of 90 percent and grade B alternators must have B10 life of 100,000 km (or 5years) with the confidence level of 90 percent. The Weibull distribution is applied in the analysis of the alternator reliability. The rated rotation speed of alternator is specified at ω = 6,000rpm.

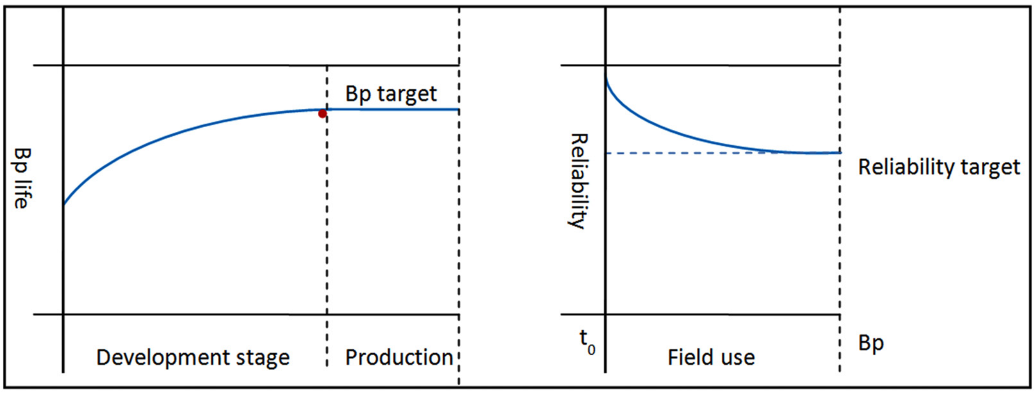
In order to guarantee grade A-reliability requirement of R90C90 life is 160,000 km, failure-free should be observed while testing six alternators at the speed of 18,000 rpm under the temperature of 100 ± 2 degree Celsius for 535 hours. For grade B, reliability requirement of R90C90 life is 100,000km; failure-free test duration has decreased to 335 hours under the similar test conditions.

3. Accelerated Failure-Free Test Development

In <Figure 2>(A), a product usually requires to go through the development stage before it is consider marketable [7]. Statistically significant accelerated failure-free tests are usually performed during the development stage to demonstrate that the design is reliable in achieving the customer's expectations of Bp life (the required lifetime). As in <Figure 2>(B) when the product is released, field usage data is used in further developing the accelerated failure-free tests for more precise in achieving the Bp life target.

To stay as a competitive magnet manufacturer, the company has pledged to ensure all magnets produced for alternators must fulfilled the requirement of R90C90 life of 160,000km (or 10 years). Therefore, the most efficient and economical test plan is needed to demonstrate that the magnets are failure-free of high speed rotation and high temperature.

At present, researches on demonstration test generally fall into three categories: sequential testing [8, 9, 10], tests based on the number of failures [11, 12], and tests based on failure time [13, 14, 15]. Probability Ratio Sequential Testing (PRST) assumes that the test failures are exponentially distributed. Upper test mean time between failures (MTBF), lower test MTBF, producer's risk and customer's risk should



(A) Product Development Stage (B) Product Field Use Stage

<Figure 2> Life cycle

be determined in advance when designing a PRST.

Test design based on the number of failures is also called binomial test because of the use of the binomial equation to represent reliability and confidence level. Test design based on failure times estimates means and the variances of the reliability target (failure rate, mean time to failure) first, and then computes the confidence interval for the reliability target (failure rate, mean time to failure). This test cannot be used for zero failure tests.

Test plan for the magnets is designed based on the binomial test because :

a) The method is widely accepted as a feasible, easy to understand and use;

b) Fit for zero failure to save test time;

c) It is hard to detect hairline crack failures of magnet real time during the test.

3.1 Theoretical Background

The failure behavior of the magnet can be described with the two parameter Weibull distribution [16] given by :

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

where β is the shape parameter and η is the scale parameter. Required lower confidence characteristics life is :

$$\eta_L = B_p \frac{1}{[-\ln(1-p)]^{\frac{1}{\beta}}} \quad (2)$$

where B_p represents the required lifetime.

If n items are tested and r items fail, binomial distribution shows the relationship between confidence level CL and lower bound reliability RL as follows :

$$CL = 1 - \Sigma_{i=0}^{r} \frac{n!}{i!(n-i)!} R_L^{n-i}(1-R_L)^i \quad (3)$$

If failure-free can be observed until time t, (3) turns to the following equation [17] :

$$CL = 1 - R_L^n \quad (4)$$

Both in literature and in the practical field, (4) are often referred to as “success run.”

From (1) and (4), lower bound characteristics life for failure-free is :

$$\eta_L = t \frac{n}{[-\ln(1-CL]^{\frac{1}{\beta}}} \quad (5)$$

From (2) and (5), one can easily calculate the failure-free test duration for given required lower bound characteristic life by following equation :

$$t_{test} = B_p \left(\frac{\ln(1-CL)}{n \ln(1-p)} \right)^{\frac{1}{\beta}} \quad (6)$$

Equation (6) means that we test n samples until time t_{test}, if failure-free can be observed, the target B_p life and CL can be guaranteed. To be more practical in testing, an accelerated failure-free is needed in order to save time.

For Weibull distribution, we have

$$B_{p,acc} = \frac{B_p}{AF} \tag{7}$$

AF is the acceleration factor. Hence, accelerated failure-free test time can be calculated from the following equation :

$$t_{acctest} = \frac{B_p}{AF}\left(\frac{\ln(1-CL)}{n \times \ln(1-p)}\right)^{\frac{1}{\beta}} \tag{8}$$

In this work,

$$AF = AF_r AF_{temp} \tag{9}$$

Alternator in an automobile is driven by the engine, the rotation speed of the engine is in proportion to the speed of the automobile running, then

$$AF_r = \frac{\omega_{test}}{\omega_{use}} \tag{10}$$

where ω_{use} is rotation speed under use, ω_{test} is rotation speed under test.

Arrhenius model is used to calculate acceleration factor for temperature :

$$AF_{temp} = e^{[\frac{Ea}{K}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)]} \tag{11}$$

where Ea is the activation energy(eV), K is the Boltzman constant, and T is the temperature in Kelvin.

3.2 Customized Test for Alternator Magnet

The following are the customized test requirements which are suitable for testing magnets in the alternator to demonstrate that the magnets are failure-free.

3.2.1 Weibull Shape β Value for Magnets

Ranges of β value in various applications have been discussed in [18, 19, 20]. Nevertheless, research papers related to β value estimation for magnet are hardly available. Weibull shape βvalue plays an important role in reliability demonstration test. Kwon [21] has discussed the effect of βin designing test specification for Weibull life distribution. β result from [15] shows ferrite magnet β range from 2.43 to 5.97 and finally they estimate β at 3.73. The best way to find out the correct value of β is by testing the magnet until failure occurred. Then, β value is estimated from the failure distribution. This kind of test would take a lot of time and effort. In the case study regarding a starter motor test [16], it shows that the magnet test failure data has been fitted into the Weibull distribution and the β value is estimated to be 6.5.

3.2.2 The Selection of Test Temperature and Test Rotational Speed

MIL-STD-202G in Method 108A [22] provides high temperature life test method and specifies test temperature as eight level ranges from 70 to 500 degree Celsius. Kim et al. [23] have performed an accelerated life test at 95 degree Celsius for automotive engine mounting. On the other hand, the temperature of alternator life test is specified as 100 degree Celsius in [6]. These shows the temperatures around 100 degree Celsius are fit for the accelerated life test for automotive components. For this test plan, a temperature of 100 degree Celsius has been set for the magnet test which met both standards requirements.

For the test rotational speed, the alternator will produce a loud noise and additional heat which certainly will affect the safety of the testing equipment if it is running higher than 20,000 rpm. In addition to that, rotational speed higher than 20,000 rpm may also change the failure mechanism of the magnets. Rotational speed above 20,000 rpm is usually used for HALT which helps to find out the quality design problem. In the practice, rotational speed of 15,000 rpm [24], 18,000 rpm and 20,000 rpm are usually selected by engineers to test the alternator.

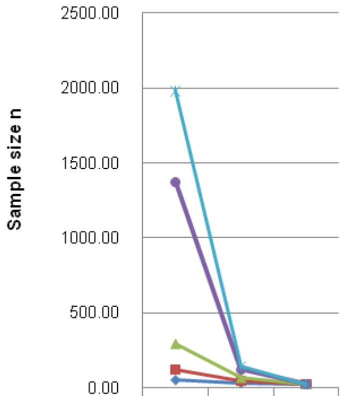
3.2.3 The Selection of Sample Size

In our case, we assume the life of a product follows a Weibull distribution with a known shape parameter β. The sampling plan is based on the binomial method. Equation (8) can be rewritten as :

$$n = \frac{\ln(1-CL)}{\ln(1-p)(\frac{t_{acc\,test}AF}{B_P})^{\beta}} \tag{12}$$

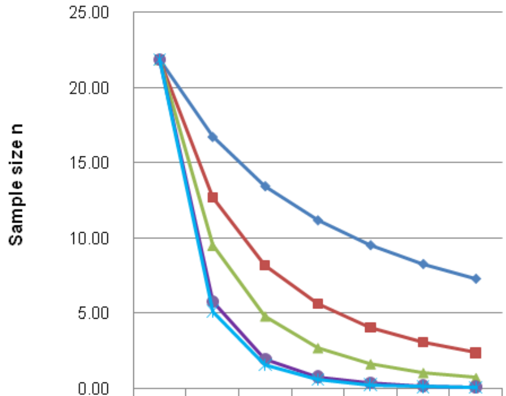
If testing a sample size n for time $t_{acc\ test}$ yields zero failures, then Bp life is demonstrated at a CL. The probability of type II error (customer's risk) is equal to (1-CL).

From equation (12), one can see that sample size n is



	100	150	200
n(β=1.2)	50.21	30.86	21.85
n(β=2.43)	117.77	43.97	21.85
n(β=3.73)	290.67	63.97	21.85
n(β=5.97)	1369.89	121.74	21.85
n(β=6.5)	1978.03	141.79	21.85

(A) Desired Test Time 100h~200h



	200	250	300	350	400	450	500
n(β=1.2)	21.85	16.72	13.43	11.17	9.51	8.26	7.28
n(β=2.43)	21.85	12.71	8.16	5.61	4.06	3.05	2.36
n(β=3.73)	21.85	9.50	4.81	2.71	1.64	1.06	0.71
n(β=5.97)	21.85	5.77	1.94	0.77	0.35	0.17	0.09
n(β=6.5)	21.85	5.12	1.57	0.58	0.24	0.11	0.06

(B) Desired Test Time 200h~500h

<Figure 3> Desired test time

determined by the desired test duration tacc test, required lifetime B_p, acceleration factor AF, β and CL. For example, <Figure 3> provides the contour plot for a specific accelerated failure-free test design. The objective is to demonstrate B10 of 2,000 running hours with a 90% CL, where acceleration factor AF =10 is assumed. Required sample size can be determined from equation (12). Value of n calculated from equation (12) is often not an integer, so n need to be rounded up to the nearest integer.

<Figure 3>(A) and <Figure 3>(B) show that reduction in test duration will lead to increase of the test sample size. From <Figure 3>(A), one can see that if test duration t is less than B_p/AF (200 hours in this example), then higher β will lead to bigger sample size in which this case may be up to 2,000 samples. With a high sample size, target reliability will guarantee even the real β to be small. <Figure 3>(A) is more suitable for low cost testing samples. If test duration t greater than B_p/AF as in <Figure 3>(B), then smaller β will lead to a more conservative result.

Now suppose that n1 samples are tested without failure to time t_1, B_p life is demonstrated at a CL confidence level. From equation (12):

$$n_1 = \frac{\ln(1-CL)}{\ln(1-p)(\frac{t_1 AF}{B_P})^{\beta}} \tag{13}$$

Next suppose that n_2 samples are tested without failure to time t_2, B_p life is demonstrated at the same CL confidence level. As before:

$$n_2 = \frac{\ln(1-CL)}{\ln(1-p)(\frac{t_2 AF}{B_P})^{\beta}} \tag{14}$$

From (13) and (14)

$$\frac{n_2}{n_1} = \left(\frac{t_1}{t_2}\right)^{\beta} \tag{15}$$

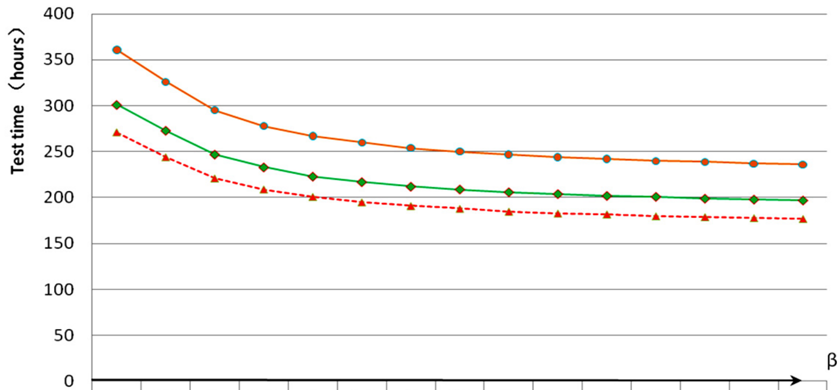
In some case we want to reduce the test duration, which would make:

$$L = \frac{t_1}{t_2} \tag{16}$$

Thus, combining equation (15) and (16), reduction in test duration ($t_2 < t_1$) will lead to increasing test sample size and vice versa:

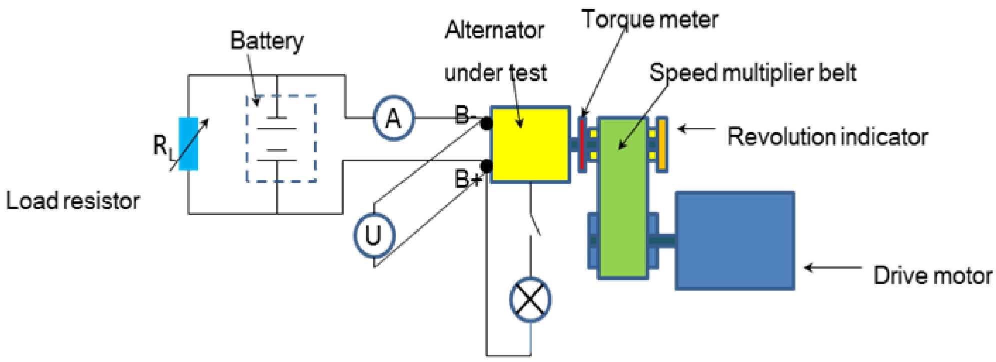
$$n_2 = L^{\beta} n_1 \tag{17}$$

In order to fulfill the requirement R90C90 life of 160,000 km for alternator magnets, accelerated failure-free reliability



	1.2	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
15000RPM	361	326	295	278	267	260	254	250	247	244	242	240	239	237	236
18000RPM	301	273	247	233	223	217	212	209	206	204	202	201	199	198	197
20000RPM	271	244	221	209	201	195	191	188	185	183	182	180	179	178	177

<Figure 4> Accelerated Failure-free Test Time Calculation



<Figure 5> Schematic of the Test Equipment

demonstration test plan is designed. Acceleration factor for three test conditions are calculated as 9.1, 11 and 12. Desired test duration is less than 300 hours. Using a conservative value of AF = 10, β = 1. 2, from <Figure 3>, we can get n = 14.

In order to make the test more accurate, the specimen magnets are assembled together in the automotive alternator sets. Thus, the sample size should be in a set of 12 which represents the quantity of magnet in one alternator.

Based on the accelerated failure-free test model, equation (8), <Figure 4> shows test time calculated in three levels recommended rotational speeds which are 15,000rpm, 18,000 rpm and 20,000rpm with the β value range from 1.2 to 8. Test time, t_{test} is a decreasing function of β for a fixed sample size and test condition. Furthermore, for a fixed sample size and test condition, test time calculated according to a certain β value can also be used to guarantee the reliability target which in case the actual β is higher than the β value used in the test.

As a result, the test plan has been designed for a set of 12 magnets at speed of 20,000 rpm under the temperature of 100 degree Celsius for 271 hours. With these parameters, R90C90 Life of 160,000km (or 10years) for the magnets with the β value above 1.2 can be guaranteed.

4. Design of the Test Equipment

The system for the alternator magnet test has been designed based on the accelerated failure-free test model. The equipment should be designed at high efficiency and safety [25]. The test system should be capable of testing at the rotational speeds up to 25,000rpm under the temperature range from -4 to 135 degree Celsius. The range of temperature can also meet the requirement of temperature cycle test for alternator as stated in [6]. For the rotational speed, the alternator will create a loud noise and excessive heat which will affect the safety of all the test equipment.

During the accelerated failure-free test, the alternator is driven by a drive motor and located in the temperature chamber. <Figure 5> shows the schematic of the experimental setup. The system consists of an alternator under test, a drive motor to drive the alternator, a temperature chamber to control the temperature, a battery to simulate the vehicle usage and sensors.

Alternators have long service life and must be able to withstand such intense conditions such as vibration, high/low temperatures, dirt, and moisture. Therefore, these conditions can be considered further on the test equipment to obtain more accurate test results.

5. Conclusions

An accelerated failure-free test for magnets in alternators which is used to guarantee B10 life could be achieved with the characteristics of test reliability and smaller sample size. It will be widely used to test the magnet with different parameters involved such as temperature and rotation speed. Suitable set up is needed to guarantee that results obtained are valid within the required specifications since the magnets are located inside the alternator. In this case, the sample size for magnet is determined as set of 12 magnets in an alternator rather than the quantity of the alternators to be tested.

Acknowledgement

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