Experimental design of fuse link with ceramic alloy: Cracking problem

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Abstract

Low-voltage (LV) fuse systems, which open a circuit by cutting the current when it exceeds a given value for an adequate period, are used in nonresidential, commercial and industrial buildings. LV-fuse systems consist of a fuse base, fuse link, and a detachable operating handle. The fuse link is made of a ceramic alloy. In this study, a full-factorial experimental design with two levels was used to solve the fracture problem of fuse links. In this scope, performance criteria (compressive strength), factors affecting the performance criteria (moisture ratio, shaping duration, drying duration and firing duration) and factor levels were determined in the initial stage. Main effects and interactions among factors were investigated, and factor-level combinations that maximize the compressive strength were determined according to the analysis results. Finally, the relationship between compressive strength and experimental factors was presented in the form of $f = y(x)$ for prediction purposes.

Keywords: analysis of variance; ceramic alloy; experimental design; fuse system; process improvement.

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Experiments are carried out under controlled conditions in order to discover an unknown effect, test or establish a hypothesis or illustrate a known effect. Traditional experiments, in which one factor is changed and other is kept constant, have some negative aspects in terms of workload, time and costs. In addition, it is not possible to determine potential interactions that occur between two or more factors. The term "designed experiment" or "experimental design" refers to conducting trials upon subject input factors of a system or process to certain purposeful modifications in an effort to determine the effects caused by those modifications on the output [1].

Central composite full factorial experimental designs investigate the effects of two or more factors or input parameters on the output response of a process. All levels of each factor in the experiment are made to match with each level of other factors in the experiment, thus ensuring that all potential combinations of the factors in determined levels are analyzed [2]. The general notation for a central composite full factorial experimental design run at b levels is b^k = # runs, where k is the number of factors. A 2^k full-factorial design is a special type of central composite full factorial experimental design that allows simultaneous operation of the impacts of two-level factors [3,4].

Problem-solving and process-improvement studies related to various fields of activity utilizing experimental design (ED) have increased, particularly in recent years. Studies by Savaşkan *et al.* [5], Williams [6], Moreb and Savsar [7], Temiz and Erol [8], Chan and Calleja [9], Esme *et al.* [10], Pınar *et al.* [11], Raksiri and Chatchaikulsiri [12], Rangabathan *et al.* [13] and Yan and Chyan [14] are good examples. Central composite factorial experimental designs; the Taguchi Method; and response-surface techniques were used in these studies. The studies mainly addressed manufacturing industry. In the present study, a 2^4 full-factorial design was used to solve the cracking problem of fuse link with ceramic alloy produced in the electrotechnical industry. Although there is already a considerable amount of research done in those areas, as far as the authors know there is no work reported utilizing an experimental design on fuse systems.

MATERIALS AND METHODS

Problem definition

A low-voltage (LV) fuse system is a fuse system that opens a circuit by cutting the current when it exceeds a given value for an adequate period of time. These systems are used in nonresidential, commercial and industrial buildings. LV-fuse systems consist of a fuse base, fuse link and a detachable operating handle [15].

This study focused on solving the cracking problem of low-voltage fuse systems, recurring problem in a company that manufactures electrical material with porcelain isolation. The company experienced the cracking problem in manufacturing fuse links after starting to use a new ceramic alloy from a local producer. Since cracks in the fuse system could cause an

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explosion or fire by disabling it in the case of a short circuit, they are very risky in terms of safety. For that reason, the “cracking problem” was one that should be solved.

Selection of response variable

The main cause for cracking was the temperature of the copper wire conducting current through the fuse system. Heat, which formed inside the fuse-link body from the copper wire, expanded water and air inside the sand placed in the body to keep temperature and compression low, creating compression inside the fuse-link body and causing it to crack. In order to overcome this problem, the following solution methods were considered:

1. Expansion of the fuse-link interior volume. (Increasing the volume of the sand placed inside the fuse-link body decreases the effect of temperature and compression).
2. Reducing the number of fuse wires from two to one. (The distance from the heat source to the body will increase and the body will be less heated. Furthermore, since each single wire has less volume than a double wire, it would be possible to increase the volume of the sand inside the body).
3. Improving the resistance to compression ratio by making certain modifications in the manufacturing of the fuse-link body.

To apply the first solution, the interior volume of the fuse-link body should be expanded. However, since no modification can be made to exterior dimensions due to standards, expansion of the interior volume will result in decreased body thickness, which might lead to problems such as reduced resistance to impacts. In the second method, the number of wires would be reduced to one in order to increase the interior volume of the fuse-link body. However, it would be necessary to increase the thickness of the wire to handle the current properly. Since this solution will require other high-cost modifications in terms of wire breakage and circuit opening at high voltage – the operation principle of the fuse system — it does not seem applicable at this stage.

For these reasons, it was decided that improving the resistance to compression in the fuse-link body by making modifications in the manufacturing parameters of the fuse link is the most feasible alternative. Thus, the response variable (performance criterion), which is the output of the experimental process under various settings within the data range, was determined to be “compressive strength of LV-fuse links.”

Determination of factors and factor levels

The factors thought to have an effect on compressive strength of the LV fuse link are listed below [16,17]:

- humidity ratio of raw material,
- shaping time,
- drying time,
- drying temperature,
- firing time and
- firing temperature.

Since all of the products manufactured in the factory are fired in a common furnace and dried in a common drying furnace, it is not possible to change firing time and drying temperature. These two factors, which can also affect other products, are included in the uncontrollable-factors group. In this case, controllable factors, which affect performance criteria, were found to be humidity ratio, shaping time, drying time and firing temperature.

The humidity ratio for raw material used by the manufacturer is 5%. Since the humidity ratio recommended for ceramic materials is generally 4%, as an alternative to the existing situation a humidity ratio of 4% is appropriate.

Raw materials in the factory are shaped by a press. Since a short pressing time causes expansion and void formation inside the material immediately after the pressing process, shortening the material’s resistance, applied pressure time should be extended as much as possible. On the other hand, pressing periods longer than five seconds will mean failure to achieve production targets. Finally, five seconds was chosen as an alternative to the currently used pressing time of three seconds.

When the material is kept in drying room for a prolonged time, the humidity ratio decreases which might cause burning of the material or formation of cracks during firing. For this reason, instead of currently used twelve-hour drying period, a nine-hour drying time was selected.

The firing temperature currently used is 1290 °C. However, increased firing temperatures are desirable for ceramic materials. Therefore, as an alternative, the furnace temperature should be increased to 1310 °C, the highest possible value.

The controllable experimental factors and their levels are presented in Table 1. In the next stages of the paper, the symbols of the factors will be used.

Table 1. Experimental factors and their levels

Factor	Symbol	Low Level (-1)	High Level (+1)
Humidity ratio, %	*A*	4	5
Shaping time, s	*B*	3	5
Drying ime, h	*C*	9	12
Firing temperature, °C	*D*	1290	1310

RESULTS AND DISCUSSION

Conducting experiments

In 2^k full factorial design, since experiments are conducted in all probable combinations of all factor levels, a total of 16 (2^4) different combinations were tested in this study. Experiments were executed in random order to correctly evaluate experimental errors. Five measurements were made for each combination of factors. After manufacturing under the conditions presented in Table 2, the fuse links were tested under internal pressure. During the tests, no horizontal or longitudinal external loads were placed on the bodies. One side of each body was sealed by a bolted-on lid, the other side by a fixed lid. Hydraulic oil was used in inlet of the bolted-on lid. Internal pressure was generated by a hand-operated hydraulic-compression testing device and displayed on the manometer. The internal pressure was increased until cracks appeared on the surface of the body, which led to substantial oil leakage. The maximum pressure value at which the body began to leak was recorded for every sample in the Table 2 as the performance criteria.

Data analysis

Minitab 16 statistical software was used for data analysis. In the first stage, a null hypothesis assuming that the main effects and interactions were equal to zero was tested using *F* test. In Table 3, *p* values smaller than 0.05 indicate that all effects and interactions are not equal to zero at a 5% significance level. In other words, compressive strength basically depends on the main effects of *A*, *B*, *C* and *D*, and the interaction of *B***C*.

At the second stage, the terms that seemed statistically insignificant compared to other effects were neglected and the related statistics were then calculated with the remaining variables. Table 3 also shows the estimated effects and coefficients of the model. The *t*-tests revealed that the main effects of *A*, *B*, *C*, and *D* are significant at the level 1%, and the interaction of *B***C* is significant at the 5% level.

The absolute value of the factor effects given in Table 3 corresponds to the relative effect of the related experimental factor on the response variable. Since the effect of *A* has the highest absolute value, this factor is the most effective independent variable on compressive strength. The order of factors according to their effects on compressive strength is *A*, *D*, *B*, *C* and *B***C*, starting with the highest value to the lowest.

The positive coefficient means that compressive strength increases as the factor is changed from the low to high levels given in Table 1. On the other hand, if the coefficient is negative, a reduction in the compressive strength occurs as the factor is changed from the low to high levels. That is, the sign of the factor effect shows which level of the factor will give a higher response value. For example, the fact that the raw-material ratio (*A*) is negative means that a low level of this factor will increase compressive strength more than a higher level of the same factor.

In any designed experiment, examining a model for predicted response is important. Coefficients in such a model show the impact of any effect on the response

Table 2. Design matrix [18]

Run No.	Experimental factor								Compressive strength MPa (mean±*SD*)
	Uncoded				Coded				
	A	*B*	*C*	*D*	*A*	*B*	*C*	*D*	
1	4	3	9	1290	–1	–1	–1	–1	4.16±0.16
2	5	3	9	1290	+1	–1	–1	–1	3.42±0.24
3	4	5	9	1290	–1	+1	–1	–1	4.40±0.14
4	5	5	9	1290	+1	+1	–1	–1	3.46±0.22
5	4	3	12	1290	–1	–1	+1	–1	4.25±0.08
6	5	3	12	1290	+1	–1	+1	–1	3.54±0.11
7	4	5	12	1290	–1	+1	+1	–1	4.60±0.22
8	5	5	12	1290	+1	+1	+1	–1	3.81±0.30
9	4	3	9	1310	–1	–1	–1	+1	4.53±0.17
10	5	3	9	1310	+1	–1	–1	+1	3.80±0.25
11	4	5	9	1310	–1	+1	–1	+1	4.67±0.19
12	5	5	9	1310	+1	+1	–1	+1	3.94±0.18
13	4	3	12	1310	–1	–1	+1	+1	4.51±0.16
14	5	3	12	1310	+1	–1	+1	+1	3.88±0.14
15	4	5	12	1310	–1	+1	+1	+1	5.03±0.19
16	5	5	12	1310	+1	+1	+1	+1	4.15±0.15

Table 3. Anova results and estimated coefficients of the model; S = 1.82774, R^2 = 86.93%, R^2 (pred.) = 84.72% and R^2 (adj.) = 86.04%

Source	D.F.	Sum of squares	Adj. mean squares	F	P
Main Effects	4	1621.01	405.25	113.91	0.000
A	1	1181.95	1181.95	332.21	0.000
B	1	121.28	121.28	34.09	0.000
C	1	60.38	60.38	16.97	0.000
D	1	257.40	257.40	72.35	0.000
2-Way interactions	6	34.69	5.78	1.63	0.155
*A*B*	1	8.78	8.78	2.47	0.121
*A*C*	1	0.53	0.53	0.15	0.701
*A*D*	1	1.38	1.38	0.39	0.536
*B*C*	1	22.58	22.58	6.35	0.014
*B*D*	1	0.90	0.90	0.25	0.616
*C*D*	1	0.53	0.53	0.15	0.701
3-Way interactions	4	3.11	0.78	0.22	0.927
*A*B*C*	1	0.53	0.53	0.15	0.701
*A*B*D*	1	0.03	0.03	0.01	0.929
*A*C*D*	1	1.65	1.65	0.46	0.498
*B*C*D*	1	0.90	0.90	0.25	0.616
4-Way interactions	1	4.28	4.28	1.20	0.277
*A*B*C*D*	1	4.28	4.28	1.20	0.277
Residual error	64	227.70	3.56	–	–
Total	79	1890.80	–	–	–
Term	Effect	Coefficient	Std. error of coef.	*T*	*P*
Constant		41.344	0.2043	202.32	0.000
A	–7.688	–3.844	0.2043	–18.81	0.000
B	2.462	1.231	0.2043	6.03	0.000
C	1.737	0.869	0.2043	4.25	0.000
D	3.587	1.794	0.2043	8.78	0.000
*B*C*	1.062	0.531	0.2043	2.60	0.011

for each increase of one unit. Coefficients given in Table 4 were used to create Eq. (1), which indicates the relationship between the compressive strength and experimental factors:

$$Y = 41.344 - 3.844 \times A + 1.231 \times B + \\ + 0.869 \times C + 1.794 \times D + 0.531 \times BC \quad (1)$$

To calculate compressive strength based on Eq. (1), coded values of independent variables presented in Table 1 should be used. In case of real values, Eq. (2) should be used:

$$Y = -153.3810 - 7.6875 \times A - 2.4875 \times B - \\ - 0.8375 \times C + 0.1794 \times D + 0.3542 \times BC \quad (2)$$

R^2 values show which part of the response variable is explained by model terms. These values are calculated using the sums of squares in analysis of the variance table. According to the analysis results, approximately 86% of variability in compressive strength is explained by the factors included in experimental design.

In order to make pair-wise comparisons among the levels of the experimental factors, the Tukey HSD Test was used. According to Table 4, means that do not share the same grouping letter are significantly different. Confidence intervals, including nonzero values, also indicate that significant difference between the factor levels exists.

The main-effect graphics of the factors are presented in Figure 1. The main effect of a factor is the difference between average response variables, which were calculated when the factor was at high and low levels. According to the main-effect graph, the more difference factor-level changes create on response variable, the more vertical the line combining the levels is. The factor *A* appears to have a greater effect on the response, as indicated by a steep slope.

"Interaction" refers to effect of a factor on performance criteria is being dependent on another factor. In the presented analyses, *B*C* interaction, which was found to be significant, was analyzed in a multivari chart in Figure 2. It can be clearly observed that the

Table 4. Grouping Information and 95.0% confidence Intervals

Experimental factor	Level	Mean	Grouping	Confidence Interval		
				Lower	Center	Upper
Humidity ratio-*A*	4	45.19	*A*	-8.532	-7.688	-6.843
	5	37.50	*B*			
Shaping time-*B*	5	42.57	*A*	1.618	2.462	3.307
	3	40.11	*B*			
Drying time-*C*	12	42.21	*A*	0.8927	1.737	2.582
	9	40.48	*B*			
Firing temperature-*D*	1310	43.14	*A*	2.743	3.587	4.432
	1290	39.55	*B*			

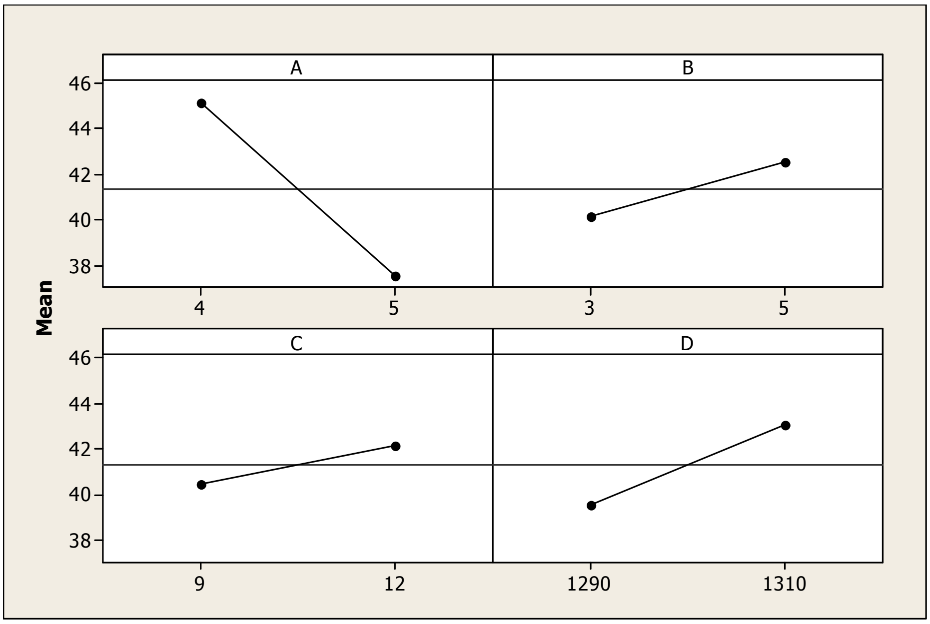

Figure 1. Main effects plot.

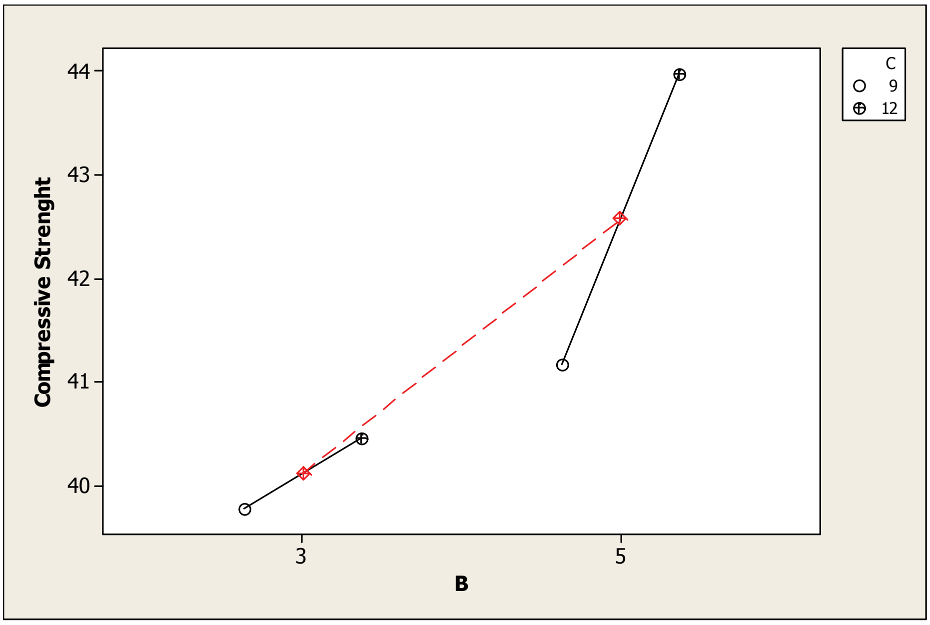

Figure 2. Multi-vari chart.

effect of the increase in drying time (*C*) on compressive strength was significantly different when shaping time (*B*) was at a high level (5 s).

A residual is the difference between an observation and its predicted value, according to the statistical model being studied. Experimental design is based on the assumption that residuals are normally and independently distributed. The residual graphs presented in Figure 3 were used to check the validity of this assumption. Since the residuals lie approximately along a straight line and a pattern — such as sequences of positive and negative residuals — is not observed, it was concluded that the residuals are normally and independently distributed.

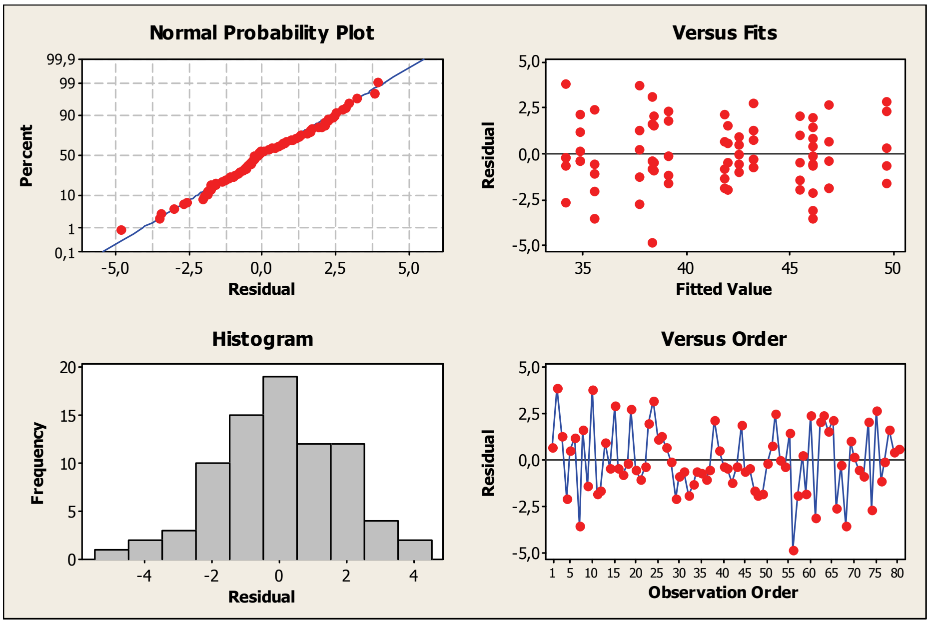

Figure 3. Residual plots.

CONCLUSIONS

Experimental design can be used at the point of greatest leverage to reduce design costs by speeding up the design process, reducing late engineering design changes and reducing product material and labor complexity. Designed experiments are also powerful tools to achieve manufacturing cost savings by minimizing process variation and reducing reworking, scrap and the need for inspection.

In the present study, a 2^4 full-factorial experimental design was used to overcome the problem of cracking in LV-fuse link bodies manufactured in the factory operating in electrotechnical industry. The ultimate goal is to improve the process of making the LV-fuse links. It was found that there was an interaction between shaping time and drying time; that the most important factor affecting the process was raw-material humidity ratio. The factor-level combination that maximizes the compressive strength were: humidity ratio of 4%, shaping time 5 s, drying time 12 h and firing temperature of 1310 °C. Achieved compressive strength with this combination was over 5 MPa, which eliminated the cracking problem. It would be suitable to use a new ceramic alloy in the manufacturing of fuse-link bodies as long as the manufacturing process has been modified based on the determined factor-level combinations.

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IZVOD

EKSPERIMENTALNI DIZAJN ZA ISPITIVANJE PATRONA OSIGURAČA OD KERAMIČKE LEGURE: PROBLEM PUCANJA

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(Naučni rad)

Osigurači za niskonaponske sisteme (NN), koji prekidaju strujno kolo kada jačina struje prekorači maksimalnu dozvoljenu vrednost za izvestan period vremena, koriste se u nestambenim, industrijskim i komercijalnim objektima. NN sistemi se sastoje od baze osigurača, kontakta osigurača i odvojive radne ručice. Kontakt osigurača je izrađen od keramičke legure. U ovom radu je korišćen potpuni faktorijelni eksperimentalni plan, sa dva nivoa, da bi se rešio problem pucanja kontakta. Određivana je pritisna čvrstoća kao pokazatelj kriterijuma kvaliteta, a faktori od uticaja na pokazatelj kriterijuma kvaliteta bili su odnos vlage i trajanje oblikovanja, sušenja i pečenja, s tim da su faktori nivoa određivani u početnoj fazi. Ispitivani su glavni efekti i intereakcije između faktora, a kombinacije faktor–nivo koje maksimiziraju pritisnu čvrstoću bili su određeni u odnosu na rezultate analiza. Na kraju, odnos između pritisne čvrstoće i eksperimentalnih faktora predstavljen je u obliku $f = y(x)$ u svrhu predviđanja pritisne čvrstoće.

Ključne reči: Analiza varijanse • Keramička legura • Eksperimentalni dizajn • Sistem osigurača • Poboljšanje procesa