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Statistical Analysis of Compositional Factors Affecting the Compressive Strength of Alumina-Loaded Epoxy (ALOX)

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Statistical Analysis of Compositional Factors Affecting the Compressive Strength of Alumina-Loaded Epoxy (ALOX)

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ABSTRACT

Detailed statistical analysis of the experimental data from testing of alumina-loaded epoxy (ALOX) composites was conducted to better understand influences of the selected compositional properties on the compressive strength of these ALOX composites. Analysis of variance (ANOVA) for different models with different sets of parameters identified the optimal statistical model as, $\hat{y}_i = -150.71 + 29.72T_i + 204.71D_i + 160.93S_{1i} + 90.41S_{2i} - 12.228T_iS_{1i} - 20.366T_iS_{2i} - 137.85D_iS_{1i} - 90.08D_iS_{2i}$ where $\hat{y}_i$ is the predicted compressive strength, T_i is the powder type, D_i is the density as the covariate for powder volume concentration, and $S_{ii}(i=1,2)$ is the strain rate. Based on the optimal statistical model, we conclude that the compressive strength of the ALOX composite is significantly influenced by the three main factors examined: powder type, density, and strain rate. We also found that the compressive strength of the ALOX composite is significantly influenced by interactions between the powder type and the strain rate and between the powder volume concentration and the strain rate. However, the interaction between the powder type and the powder volume concentration may not significantly influence the compressive strength of the ALOX composite.

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1. Introduction

Alumina-filled epoxy, denoted ALOX, is a composite material consisting of a powder material, composed of hard polycrystalline alumina oxide (Al_2O_3) particles, dispersed in a much softer epoxy matrix. A wide variety of ALOX composites can be fabricated by varying the type of alumina powder, volume concentration of powder, and epoxy type. Mechanical strength is an important property governing the suitability for use of these ALOX formulations as an encapsulant providing electrical insulation when subject to large mechanical stresses. A series of experiments was designed to measure the compressive strength under different strain rates, as indicated by peak stress, for different ALOX materials formed by varying parameters or factors (independent variables) controlling the composition.

Figure 1 and Table 1 show the $2 \times 3 \times 3$ factorial design scheme (Box *et. al*, 1978) used to study the effects on the compressive strength (dependent variable) due to a qualitative variable (powder type) and two quantitative variables (powder volume concentration and strain rate). In this study, we did consider the size of the specimens as a variable affecting the compressive strength of ALOX composites. Also, we only considered one epoxy type (Z-hardened Epon 828) due to lack of experimental data available for the other epoxy type (459-hardened Epon 826). Therefore, any effects on the compressive strength of the ALOX composites stemming from the specimen size and epoxy matrix were arbitrarily suppressed in the statistical analysis.

The compositional parameters, powder type and powder volume concentration, are controlled during fabrication of cylindrical ALOX billets. The two powder types investigated are denoted as T64 and AA18. The T64 powder type, produced by Alcoa, designates sintered and milled tabular α -alumina particles having the largest dimension primarily between 10-17 microns and the AA18 powder type, produced by Sumitomo, designates a faceted near spherical particle of α -alumina formed by vapor deposition with nominal diameter between 14.4-16.8 microns. The powder volume concentration in the ALOX composites was set to three levels: 38 %, 43 %, and 48 %. The test parameter, strain rate, is controlled by the test types and the test settings. Samples of the composite materials were tested at three strain rate levels: 10^{-4} s^{-1} , 10^{-1} s^{-1} and 2850 s^{-1} . The quasi-static uniaxial compression test (Figure 2a) was conducted to obtain the shear response of the ALOX material at strain rates of 10^{-4} s^{-1} and 10^{-1} s^{-1} . Quasi-dynamic Split Hopkinson Pressure Bar (SHPB or Kolsky Bar) tests (Kolsky 1949, Figure 2b) were conducted to obtain the shear response of the ALOX composites near a strain rate of 2850 s^{-1} . The quasi-dynamic strain rate in SHPB testing was largely dependent on the dynamic response of the specimen and was difficult to set exactly at the level of 2850 s^{-1} . Consequently, there was a variation at this level ranging from 2823 s^{-1} to 2990 s^{-1} .

A detailed statistical analysis of the experimental data from these tests on the ALOX composites will show that the compressive strength of the ALOX composites is significantly influenced by the three parameters examined and the interaction terms between the parameters. The refined final statistical model with density used as a covariate for the powder volume concentration shows an ability to predict the compressive strength of the ALOX composites with high degree of statistical confidence. This report describes the experimental test matrix designed for factorial

analysis and statistical analysis of variances to reach the optimal statistical model to predict the compressive strength of the ALOX composites.

Figure 1. A schematic of the factorial design used for the ALOX study. The blue rectangular plane for a given powder volume concentration denotes an experimental space for six independent tests. Eighteen unique test conditions are shown for three powder volume concentrations as the numbers in the circles.

Table 1. Summary of experimental data and test conditions for ALOX composites

Test No.	Test Condition*	Powder Type	Powder Concentration (% by volume)	Strain Rate (s^{-1})	Density (g/cm^3)	Peak Stress (MPa)
ALX-UC14	1	T64	38	0.0001	2.236	177.5
ALX-UC01	7	T64	43	0.0001	2.385	187.3
ALX-UC13	13	T64	48	0.0001	2.500	194.5
ALX-UC07	2	T64	38	0.1	2.307	214.5
ALX-UC08	8	T64	43	0.1	2.384	226.6
ALX-UC09	14	T64	48	0.1	2.495	229.8
T64-38-AVG	3	T64	38	2855	2.232	335.1
T64-43-AVG	9	T64	43	2895	2.386	365.8
T64-48-AVG	15	T64	48	2865	2.504	394.1
ALX-UC02	6	AA18	38	0.0001	2.246	160.8
ALX-UC11	12	AA18	43	0.0001	2.396	168.9
ALX-UC12	18	AA18	48	0.0001	2.522	180.0
ALX-UC03	5	AA18	38	0.1	2.248	195.7
ALX-UC05	11	AA18	43	0.1	2.389	212.0
ALX-UC04	17	AA18	48	0.1	2.519	231.7
AA18-38-AVG	4	AA18	38	2990	2.245	313.9
AA18-43-AVG	10	AA18	43	2853	2.395	331.8
AA18-48-AVG	16	AA18	48	2823	2.516	367.1

*-The schematic of the test conditions is graphically described in Figure 1.

Figure 2. (a) ALOX specimen prepared for quasi-static uniaxial compression test; (b) Split Hopkinson pressure bar set-up for quasi-dynamic strain rate test showing fragment spray due to failure of the sample).

2. Analysis

In order to identify the major compositional influences on the compressive strength of ALOX and to investigate the interactions between the parameters, we employed a factorial design scheme. SAS (Statistical Analysis Software) Version 9 was used to carry out analysis of variance (ANOVA, see Appendix A) tests to determine whether the experimentally treated levels for each parameter made an impact on the experimental results (e.g. compressive strength of ALOX). ANOVA tests start with an over-parameterized linear model which includes the major independent parameters as well as the interactions terms. Statistically, significance of each parameter is tested and insignificant terms are dropped from the model to reach a final model which represents the experimental data.

2.1. Analysis of variance

We first consider the following $2 \times 3 \times 3$ factorial model[†]:

$$y_l = \delta + aT_l + \sum_{j=1}^2 b_j V_{jl} + \sum_{j=1}^2 c_j S_{jl} + \sum_{j=1}^2 d_j T_l V_{jl} + \sum_{j=1}^2 e_j T_l S_{jl} + \sum_{j=1}^2 \sum_{k=1}^2 f_{jk} V_{jl} S_{kl} + \varepsilon_l \quad (1)$$

where y_l is the peak compressive stress (or strength), T_l is the independent variable for powder type l ($T_l = 0$ if the powder type is AA18 or 1 if T64), V_{jl} is the powder volume concentration ($V_{1l} = 1$ if the powder volume concentration is 43% or 0 otherwise; $V_{2l} = 1$ if the powder volume concentration is 48% or 0 otherwise), S_{kl} is the strain rate ($S_{1l} = 1$ if the strain rate is 0.0001 or 0 otherwise; $S_{2l} = 1$ if the strain rate is 0.1 or 0 otherwise), and ε_l is the error term.

In this model $a = 0$ implies no main effect of powder type, $b_1 = b_2 = 0$ implies no main effect of the powder volume concentration, and $c_1 = c_2 = 0$ implies no main effect of the strain rate. Also $d_1 = d_2 = 0$ implies no interaction between the powder type and the powder volume concentration, $e_1 = e_2 = 0$ implies no interaction between the powder type and the strain rate, and $f_1 = f_2 = 0$ implies no interaction between the powder volume concentration and the strain rate.

Since there is no replicated experiment for each combination of the factors, we assume that there is no three-way interaction. This assumption is checked in the ensuing analysis using different models, and it turns out to be a reasonable assumption for the given data. In model (1), the interaction term between the powder type and the powder volume concentration, that is d_1 and

[†] The most general way of expressing the corresponding analysis of variance model is in Appendix A. We express the model in a different way using indicator variables so that the expression is consistent with the rest of the approaches that accommodate covariates.

d_2 , is insignificantly different from zero with a p-value of 0.3748[‡]. (Refer to the SAS output of the ANOVA for model (1) in Appendix A.) Therefore, we further fit the following reduced model.

$$y_l = \delta + aT_l + \sum_{j=1}^2 b_j V_{jl} + \sum_{j=1}^2 c_j S_{jl} + \sum_{j=1}^2 e_j T_l S_{jl} + \sum_{j=1}^2 \sum_{k=1}^2 f_{jk} V_{jl} S_{kl} + \varepsilon_l. \quad (2)$$

For this model (Equation 2), all the main factors (T_l , V_{jl} , and S_{jl}) and interactive factors ($T_l S_{jl}$ and $V_j S_{jl}$) are significant at the significance level of $\alpha=0.1$ (or with 90 % likelihood). If we use the higher level of significance of $\alpha=0.05$ (or with 95% likelihood), the interaction term between powder type and strain rate ($T_l S_{jl}$), which has a p-value of 0.0784 for testing $c_1 = c_2 = 0$, becomes insignificant (Refer to the SAS output of the ANOVA for model (2) in Appendix A). This result implies that the degree of interaction between powder volume concentration and strain rate ($V_j S_{jl}$) is higher than that of $T_l S_{jl}$.

Based on these two analyses, we conclude the following:

1. The compressive strength of the ALOX composite is significantly influenced by the three main factors examined: powder type, powder volume concentration, and strain rate.
2. The compressive strength of the ALOX composite is not significantly influenced by the interaction between the powder type and the powder volume concentration.
3. The compressive strength of the ALOX composite is significantly influenced by interactions between the powder type and the strain rate and between the powder volume concentration and the strain rate.

The above statistical findings will be used to refine the statistical model with a density term replacing the powder volume concentration. The compositional and mechanical implications of the findings in relation to the compressive strength of the ALOX will be given in a later section. In the following sections we'll be introducing a material property of the ALOX (i.e., density) replacing the powder volume concentration, as a covariate.

2.2. Analysis of covariance with density as a covariate

Since the material density is highly correlated with the powder volume concentration (a correlation of 0.988 as shown in Figure 3), we use the density as a covariate for the powder volume concentration and consider the following model,

$$y_l = \delta + aT_l + bD_l + \sum_{j=1}^2 c_j S_{jl} + dT_l D_l + \sum_{j=1}^2 e_j T_l S_{jl} + \sum_{j=1}^2 f_j D_l S_{jl} + \sum_{j=1}^2 g_j T_l D_l S_{jl} + \varepsilon_l \quad (3)$$

where D_l is the independent variable for material density.

[‡] When the observed significance level, also known as the p-value is less than the level of significance, α , the test statistic is significant and the null hypothesis is rejected.

Figure 3. Density versus powder volume concentration plot for ALOX. Also shown are the best-fit regression line, the 95% confidence interval for the regression line, and the coefficient of correlation $R=0.98807$)

We note that in this model, the discrete variable, powder volume concentration, is replaced by the continuous variable, density, and thus the summation over the different categories of the powder volume concentration ($\sum_{j=1}^2 b_j V_{jl}$) in (2) is no longer needed. We also note that the term

$\sum_{j=1}^2 g_j T_l D_l S_{jl}$ represents the three-way interaction among the powder type, density and strain rate, and can be viewed as the proxy for the three-way interaction among the powder type, strain rate, and powder volume concentration in Model (1). In this model $g_1 = g_2 = 0$ implies no three-way interaction among the three main factors. As shown in the SAS output of the ANOVA for Model (3) in Appendix B, the estimates of g_1 and g_2 are found to be simultaneously insignificant with a p-value of 0.400. This supports the assumption of no three-way interaction among the three main factors in Model (1). Therefore, we drop the three-way interaction term $\sum_{j=1}^2 g_j T_l D_l S_{jl}$ from Model (3) and consider the following model.

$$y_l = \delta + aT_l + bD_l + \sum_{j=1}^2 c_j S_{jl} + dT_l D_l + \sum_{j=1}^2 e_j T_l S_{jl} + \sum_{j=1}^2 f_j D_l S_{jl} + \varepsilon_l \quad (4)$$

In this model the coefficient d is found to be insignificant with the p-value of 0.7575 referring to the SAS output of the ANOVA for Model (4) in Appendix B, and thus there is no interaction between the powder type and the density. Therefore, we further drop the term $dT_l D_l$ and obtain the following model.

$$y_l = \delta + aT_l + bD_l + \sum_{j=1}^2 c_j S_{jl} + \sum_{j=1}^2 e_j T_l S_{jl} + \sum_{j=1}^2 f_j D_l S_{jl} + \varepsilon_l \quad (5)$$

This model is consistent with Model (2) in that the three conclusions drawn from Model (2) continue to apply with the density covariate replacing the powder volume concentration term. The estimates of the coefficients a , b , c_j , e_j , and f_j are all found to be statistically significant as indicated in the SAS output of the ANOVA for Model (5) in Appendix B. Since Equation (5) accounts for only the linear effect of the density, we tried an added squared density term into model (5) in order to check the second order effect of the density. However, as shown in the SAS output of the ANOVA for Model (5) with the squared density term in Appendix B, this effect is found to be insignificant with a p-value of 0.3155.

2.3. Analysis of covariance with density and logarithm of strain rate as covariates

The strain rates investigated cover a broad range (10^{-4} s^{-1} to 2850 s^{-1}) and the three levels (10^{-4} s^{-1} , 10^{-1} s^{-1} , and 2850 s^{-1}) we prescribed for testing are distributed rather uniformly. Therefore, we employ the following third approach with the logarithm of the strain rate as the second covariate.

$$y_l = \delta + aT_l + bD_l + c \log S_l + dT_l D_l + eT_l \log S_l + fD_l \log S_l + gT_l D_l \log S_l + \varepsilon_l \quad (6)$$

where $\log S_l$ is the logarithm of the strain rate.

In this model $g = 0$ implies no three-way interaction among the powder type, density, and strain rate. This in turn implies no three-way interaction among the powder type, powder volume concentration, and strain rate, and thus supports the assumption in Model (1). The estimate of g is insignificant with a p-value of 0.8470 (see SAS output of the ANOVA for Model (6) in Appendix B), and thus we drop this three-way interaction term and consider

$$y_l = \delta + aT_l + bD_l + c \log S_l + dT_l D_l + eT_l \log S_l + fD_l \log S_l + \varepsilon_l \quad (7)$$

In this model the estimate of d is insignificant with a p-value of 0.7803 (SAS output of the ANOVA for Model (7) in Appendix B), and we consider a further reduced model.

$$y_i = \delta + aT_i + bD_i + c \log S_i + eT_i \log S_i + fD_i \log S_i + \varepsilon_i \quad (8)$$

Model (8) is consistent with Models (2) and (5) in that there are all three main effects and the same two pairs of interaction terms. However in this model some effects (interactions between density and powder type) are found to be insignificant (see SAS output of the ANOVA for Model (8) in Appendix B), and this may be attributable to an incorrect model specification of the log of the strain rate.

Since the effect of the $\log S_i$ is not linear as evidenced by the plot shown in Figure 4, we add a non-linear term, $(\log S_i)^2$, to Model (8) and obtain the following Model (9).

$$y_i = \delta + aT_i + bD_i + c \log S_i + eT_i \log S_i + fD_i \log S_i + h(\log S_i)^2 + \varepsilon_i. \quad (9)$$

In this model the estimate of h is significant with a p-value less than 0.0001 (see SAS output of the ANOVA for Model (9) in Appendix B).

Figure 4. Compressive strength versus strain rate plot for ALOX on a semi-logarithmic scale.

2.4. Analysis of covariance with logarithm of strain rate as a covariate

The fourth approach employees the logarithm of the strain rate as covariate, and powder volume concentration instead of density. The model can be represented as,

$$y_l = \delta + aT_l + \sum_{j=1}^2 b_j V_{jl} + c \log S_l + \sum_{j=1}^2 d_j T_l V_{jl} + eT_l \log S_l + \sum_{j=1}^2 f_j V_{jl} \log S_l + \sum_{j=1}^2 g_j T_l V_{jl} \log S_l + \varepsilon_l \quad (10)$$

In this model $g_1 = g_2 = 0$ implies no three-way interaction among the powder type, powder volume concentration, and the log of the strain rate. The estimates of g_1 and g_2 are insignificant with a p-value of 0.9829 as shown in Appendix B for the ANOVA for model (10). Thus, we drop this three-way interaction term. In further analysis, we find that the interaction between the powder type and the powder volume concentration is insignificant similar to the previous analysis with Model (1), and thus the term $\sum_{j=1}^2 d_j T_l V_{jl}$ is deleted from the model. The squared term, $(\log S_l)^2$, is introduced to account for a possible non-linear effect, and the following model is fitted.

$$y_l = \delta + aT_l + c \log S_l + \sum_{j=1}^2 b_j V_{jl} + T_l \log S_l + \sum_{j=1}^2 f_j V_{jl} \log S_l + \sum_{j=1}^2 g_j T_l V_{jl} \log S_l + h(\log S_l)^2 + \varepsilon_l \quad (11)$$

Similar to Model (9), the quadratic effect of the log of the strain rate is significant with a p-value less than 0.0001 (see SAS output of the ANOVA for model (11) in Appendix B). However the interaction between the powder type and the log of strain rate is less significant with a p-value of 0.1039. This is consistent with the result from Model (2), where the interaction between the powder type and the strain rate is moderately significant with a p-value of 0.0784.

3. Results

As summarized in Table 2, the final Models (2), (5), (9), and (11) all have about the same R^2 (coefficient of determination) over 0.99. So, we used Mean Squared Error (MSE) as a measure for selecting the optimal model.

$$MSE = \frac{\sum_{i=1}^n (Y_i - \hat{Y}_i)^2}{n - p} \quad (12)$$

where Y_i is the measured compressive strength, $\hat{Y}_i$ is the predicted compressive strength from the final model, n is the number of tests, and p is the number of parameters in the model.

Table 2. Summary statistics for the Models in (2), (5), (9), and (11)

Model	R^2	MSE	Error DF
(2)	0.9984	27.4389	6
(5)	0.9984	18.8502	9
(9)	0.9967	30.5741	11
(11)	0.997	35.0159	9

R^2 – R-square or coefficient of determination

MSE – Mean Squared Error

DF – Degree of Freedom is defined as the number of tests minus the number of parameters in the model)

Since the Mean Squared Error (MSE) is the smallest for Model (5), this model may be used for further analysis such as prediction. An interactive statistics package, MINITAB Release 14, was used to obtain the best-fit least square estimates for Model (5) and the results are shown in Equation (13).

$$\begin{aligned}\hat{y}_l = & -150.71 + 29.72T_l + 204.71D_l + 160.93S_{1l} + 90.41S_{2l} \\ & - 12.228T_lS_{1l} - 20.366T_lS_{2l} - 137.85D_lS_{1l} - 90.08D_lS_{2l}\end{aligned}\quad (13)$$

From this general best-fit model we obtain a set of reduced models that relate the compressive strength to density for different powder types and strain rates. These models are summarized in Table 3 and the detailed output from MINITAB is listed in Appendix B as “Further analysis of Model (5)-Minitab”.

Table 3. Estimated models for the peak stress for different powder types and strain rates

Strain Rate (s^{-1})	Powder Type	
	AA18 ($T_l=0$)	T64 ($T_l=1$)
0.0001 ($S_{1l}=1, S_{2l}=0$)	$\hat{y}_l = 10.2 + 66.9D_l$	$\hat{y}_l = 27.7 + 66.9D_l$
0.1 ($S_{1l}=0, S_{2l}=1$)	$\hat{y}_l = -60.3 + 114.6D_l$	$\hat{y}_l = -50.9 + 114.6D_l$
2850 ($S_{1l}=0, S_{2l}=0$)	$\hat{y}_l = -150.7 + 204.7D_l$	$\hat{y}_l = -121.0 + 204.7D_l$

Based on these two analyses, we conclude the following:

1. *The compressive strength of the ALOX composite is significantly influenced by the three main factors examined: powder type, density, and strain rate.* The compressive strength of the ALOX composite with T64 powders shows significantly higher compressive strength than the ALOX with AA18 powders. The compressive strength of the ALOX composite increases with density and strain rate.
2. *The compressive strength of the ALOX composite is not significantly influenced by the interaction between the powder type and the density.* Because there is no interaction

between the powder type and the strain rate, the relationships between the compressive strength and the density for different powder types are parallel for the same strain rate. This finding is shown as the three groups of two parallel lines with the same color in Figure 5. Within each group, the compressive strength of the ALOX composite with T64 powders shows higher compressive strength than the ALOX with AA18 powders. However, the rate of increase in compressive strength with respect to density is the same regardless of powder types used for the ALOX composites subjected to the same strain rate.

3. *The compressive strength of the ALOX composite is significantly influenced by interactions between the density and the strain rate.* This interaction is shown as the three groups of data with the same color showing different rates of increase in compressive strength (Figure 5). Regardless of different powder types used in the ALOX composites, the rate of increase in compressive strength with respect to density increases as the strain rate increases.
4. *The compressive strength of the ALOX composite is significantly influenced by interactions between the powder type and the strain rate.* The effect of the powder type on the compressive strength of ALOX is different depending on the level of the strain rate, and vice versa.

Figure 5. Compressive strength versus density plot for ALOX for T64 and AA18 powders subjected to three different strain rates. The straight lines are the estimated models based on Equation 13 and Table 3.

4. Conclusions

A $2 \times 3 \times 3$ factorial design was used to study the effects on the compressive strength (dependent variable) due to powder type, powder volume concentration, and strain rate. Detailed analysis of variance (ANOVA) identified the optimal statistical model as follows:

$$\begin{aligned}\hat{y}_l = & -150.71 + 29.72T_l + 204.71D_l + 160.93S_{1l} + 90.41S_{2l} \\ & - 12.228T_lS_{1l} - 20.366T_lS_{2l} - 137.85D_lS_{1l} - 90.08D_lS_{2l}\end{aligned}$$

where $\hat{y}_l$ is the predicted compressive strength, T_l is the powder type, D_l is the density as the covariate for powder volume concentration, and $S_{il}(i=1,2)$ is the strain rate.

Implications of the optimal statistical model to the compressive strength of the ALOX composites subjected to different strain rates are as follows:

1. The compressive strength of the ALOX composite with T64 powders shows significantly higher compressive strength than the ALOX with AA18 powders. The compressive strength of the ALOX composite increases with density and strain rate.
2. Within each group, the compressive strength of the ALOX composite with T64 powders shows higher compressive strength than the ALOX with AA18 powders. However, the rate of increase in compressive strength with respect to density is same regardless of powder types used for the ALOX composites subjected to the same strain rate.
3. Regardless of different powder types used in the ALOX composites, the rate of increase in compressive strength with respect to density increases as the strain rate increases.
4. The effect of the powder type on the compressive strength of ALOX is different depending on the level of the strain rate, and vice versa.

References

Box, G. E. P., Hunter, W. G, and J. S. Hunter, Statistics for Experimenters, Wiley, 1978.

Kolsky, H., An Investigation of the Mechanical Properties of Materials at Very High Rates of Strain, Proc. Roy. Phys. Soc., B62, 676-700, 1949.

SAS[®] (Statistical Analysis Software) Version 9, SAS Institute Inc.

MINITAB[®] Release 14 Statistical Software, Minitab Inc.

APPENDIX A

Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is concerned with comparison of the means of different treatments (or groups). A $2 \times 3 \times 3$ factorial model with all the main and interaction effects is

$$y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkl},$$

(A1)

for $i = 0, 1$, $j, k = 1, 2, 3$, and $l = 1, \dots, r$

where y_{ijkl} is the l^{th} measurement of the peak stress at the i^{th} , j^{th} , and k^{th} level of powder type (α_i), powder volume concentration (β_j), and strain rate (γ_k), respectively, μ represents the overall mean, α_i is the main effect of the i^{th} level of powder type, β_j is the j^{th} level of powder volume concentration, γ_k is the k^{th} level of strain rate, $(\alpha\beta)_{ij}$ is the interaction term between powder type and powder volume concentration, $(\alpha\gamma)_{ik}$ is the interaction term between powder type and strain rate, and $(\beta\gamma)_{jk}$ is the interaction term between powder volume concentration and strain rate, and ε_{ijkl} is the error term.

In the absence of replication, as in our experiment, the three-way interaction is not estimable and thus assumed zero, and the following model is considered:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + \varepsilon_{ijk} \quad (\text{A2})$$

This is a conventional way of expressing ANOVA models. In this model the sum of the terms representing the same type of effect is constrained to be zero, that is, for example $\sum_{i=1}^2 \alpha_i = 0$ and

$\sum_{i=1}^2 \sum_{j=1}^3 (\alpha\beta)_{ij} = 0$. Model (1) is an alternative representation of Model (A2) adjusting for the constraint. To be more specific, consider the main effect of the powder type: α_1 represents the effect of the powder type AA18 and α_2 represents the effect of the powder type T64 both from the overall mean. Then for the powder type AA18, the peak stress is $\mu + \alpha_1 = \mu - \alpha_2$ and for the powder type T64, the peak stress is $\mu + \alpha_2$ in Model (A2) while in model (1) for the powder type AA18, the peak stress is δ and for the powder type T64, the peak stress is $\delta + a$. In Model (A2) $\alpha_2 = 0$ (and thus $\alpha_1 = 0$) is equivalent to $a = 0$ in Model (1) and $a = 2\alpha_2$. Therefore testing for the main effect of the powder type in (A2), that is $\alpha_2 \neq 0$, is equivalent to testing for $a \neq 0$ in Model (1). Also in Model (A2) testing for the interaction between the powder type and the powder volume concentration, that is not all of $(\alpha\beta)_{ij}$'s are zero, in Model (A2) is equivalent to not all d_j 's are zero in Model (1).

APPENDIX B

**Analysis of variance of different factorial models applied to
ALOX
(DF-Degree of Freedom, PT-Powder Type; VC-Powder
Volume Concentration; and StD-Strain Rate)**

Analysis of Model (1) - SAS

The ANOVA Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	13	104438.1594	8033.7046	318.84	<.0001
Error	4	100.7856	25.1964		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.999036	2.013613	5.019600	249.2833

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	58.80	0.0016
VC	2	3326.06333	1663.03167	66.00	0.0009
StD	2	98518.74333	49259.37167	1955.02	<.0001
PT*VC	2	63.84778	31.92389	1.27	0.3748
PT*StD	2	220.04778	110.02389	4.37	0.0987
VC*StD	4	827.96333	206.99083	8.22	0.0328

Analysis of Model (2) - SAS

The ANOVA Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	104374.3117	9488.5738	345.81	<.0001
Error	6	164.6333	27.4389		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.998425	2.101309	5.238214	249.2833

Source	DF	Anova SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	53.99	0.0003
VC	2	3326.06333	1663.03167	60.61	0.0001
StD	2	98518.74333	49259.37167	1795.24	<.0001
PT*StD	2	220.04778	110.02389	4.01	0.0784
VC*StD	4	827.96333	206.99083	7.54	0.0160

Analysis of Model (3) - SAS

The GLM[§] Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	104415.5231	9492.3203	461.46	<.0001
Error	6	123.4219	20.5703		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.998819	1.819396	4.535452	249.2833

Source	DF	Type I SS**	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	72.02	0.0001
StD	2	98518.74333	49259.37167	2394.68	<.0001
Density	1	3360.42071	3360.42071	163.36	<.0001
PT*StD	2	290.44457	145.22228	7.06	0.0265
Density*PT	1	0.07690	0.07690	0.00	0.9532
Density*StD	2	720.25193	360.12597	17.51	0.0031
Density*PT*StD	2	44.09172	22.04586	1.07	0.4000

Source	DF	Type III SS ^{††}	Mean Square	F Value	Pr > F
PT	1	19.155100	19.155100	0.93	0.3718
StD	2	159.646410	79.823205	3.88	0.0829
Density	1	2955.390817	2955.390817	143.67	<.0001
PT*StD	2	35.102005	17.551002	0.85	0.4719
Density*PT	1	7.046298	7.046298	0.34	0.5797
Density*StD	2	734.389839	367.194919	17.85	0.0030
Density*PT*StD	2	44.091718	22.045859	1.07	0.4000

[§] GLM is the General Linear Model procedures which uses the method of least squares to fit general linear models with continuous and categorical parameters.

^{**} Type I SS (Sum of Squares), also known as the sequential SS represents the marginal contribution of the corresponding term to the total sum of squares when this term is added to the model with only the terms listed above this term.

^{††} Type III SS represent the marginal contribution of the corresponding term when this term is added to the model with all the terms listed except this term. Therefore given a model, Type III SS is useful to test for significance of certain terms (or effects). By definition Type I SS in the last line is the marginal contribution of that term in the presence of all the other terms, and thus identical to Type III SS in the last line.

Analysis of Model (4) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	9	104371.4313	11596.8257	553.83	<.0001
Error	8	167.5137	20.9392		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.998398	1.835637	4.575938	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	70.75	<.0001
StD	2	98518.74333	49259.37167	2352.49	<.0001
Density	1	3360.42071	3360.42071	160.48	<.0001
PT*StD	2	290.44457	145.22228	6.94	0.0179
Density*PT	1	0.07690	0.07690	0.00	0.9532
Density*StD	2	720.25193	360.12597	17.20	0.0013

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	10.281026	10.281026	0.49	0.5034
StD	2	156.324206	78.162103	3.73	0.0716
Density	1	3205.598539	3205.598539	153.09	<.0001
PT*StD	2	311.453260	155.726630	7.44	0.0150
Density*PT	1	2.138052	2.138052	0.10	0.7575
Density*StD	2	720.251934	360.125967	17.20	0.0013

Analysis of Model (5) – SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	104369.2933	13046.1617	692.10	<.0001
Error	9	169.6517	18.8502		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.998377	1.741665	4.341681	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	78.59	<.0001
Std	2	98518.74333	49259.37167	2613.20	<.0001
Density	1	3360.42071	3360.42071	178.27	<.0001
PT*Std	2	290.44457	145.22228	7.70	0.0112
Density*Std	2	718.19078	359.09539	19.05	0.0006

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1594.749675	1594.749675	84.60	<.0001
Std	2	155.517099	77.758550	4.13	0.0535
Density	1	3280.367158	3280.367158	174.02	<.0001
PT*Std	2	314.433628	157.216814	8.34	0.0089
Density*Std	2	718.190783	359.095392	19.05	0.0006

Analysis of Model (5) with the squared Density term - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Squares	Sum of Mean Square	F Value	Pr > F
Model	9	104390.5580	11598.9509	625.33	<.0001
Error	8	148.3870	18.5484		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.998581	1.727666	4.306783	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	79.87	<.0001
StD	2	98518.74333	49259.37167	2655.72	<.0001
Density	1	3360.42071	3360.42071	181.17	<.0001
PT*StD	2	290.44457	145.22228	7.83	0.0131
Density*StD	2	718.19078	359.09539	19.36	0.0009
DenSq	1	21.26468	21.26468	1.15	0.3155

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1613.599755	1613.599755	86.99	<.0001
StD	2	159.681855	79.840927	4.30	0.0538
Density	1	13.503179	13.503179	0.73	0.4183
PT*StD	2	284.787096	142.393548	7.68	0.0138
Density*StD	2	730.372669	365.186334	19.69	0.0008
DenSq	1	21.264678	21.264678	1.15	0.3155

Analysis of Model (6) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	100544.7443	14363.5349	35.96	<.0001
Error	10	3994.2007	399.4201		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.961792	8.017181	19.98550	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	3.71	0.0830
Density	1	2747.23379	2747.23379	6.88	0.0255
LogTSt	1	95406.65847	95406.65847	238.86	<.0001
Density*LogTSt	1	715.58052	715.58052	1.79	0.2104
Density*PT	1	30.87410	30.87410	0.08	0.7867
LogTSt*PT	1	147.23528	147.23528	0.37	0.5573
Density*LogTSt*PT	1	15.66821	15.66821	0.04	0.8470

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	44.934743	44.934743	0.11	0.7442
Density	1	3346.370579	3346.370579	8.38	0.0160
LogTSt	1	175.277154	175.277154	0.44	0.5227
Density*LogTSt	1	762.873016	762.873016	1.91	0.1971
Density*PT	1	23.702153	23.702153	0.06	0.8125
LogTSt*PT	1	11.490534	11.490534	0.03	0.8687
Density*LogTSt*PT	1	15.668215	15.668215	0.04	0.8470

Analysis of Model (7) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	100529.0761	16754.8460	45.96	<.0001
Error	11	4009.8689	364.5335		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.961642	7.659061	19.09276	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	4.06	0.0689
Density	1	2747.23379	2747.23379	7.54	0.0191
LogTSt	1	95406.65847	95406.65847	261.72	<.0001
Density*LogTSt	1	715.58052	715.58052	1.96	0.1888
Density*PT	1	30.87410	30.87410	0.08	0.7764
LogTSt*PT	1	147.23528	147.23528	0.40	0.5381

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	53.377541	53.377541	0.15	0.7093
Density	1	3363.841163	3363.841163	9.23	0.0113
LogTSt	1	173.472007	173.472007	0.48	0.5046
Density*LogTSt	1	758.746101	758.746101	2.08	0.1770
Density*PT	1	29.784835	29.784835	0.08	0.7803
LogTSt*PT	1	147.235279	147.235279	0.40	0.5381

Analysis of Model (8) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	100499.2912	20099.8582	59.71	<.0001
Error	12	4039.6538	336.6378		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.961357	7.360176	18.34769	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	4.40	0.0578
Density	1	2747.23379	2747.23379	8.16	0.0144
LogTSt	1	95406.65847	95406.65847	283.41	<.0001
Density*LogTSt	1	715.58052	715.58052	2.13	0.1705
LogTSt*PT	1	148.32455	148.32455	0.44	0.5194

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1707.365027	1707.365027	5.07	0.0438
Density	1	3457.623200	3457.623200	10.27	0.0076
LogTSt	1	168.799513	168.799513	0.50	0.4924
Density*LogTSt	1	749.392330	749.392330	2.2	0.1615
LogTSt*PT	1	148.324548	148.324548	0.44	0.5194

Analysis of Model (9) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	104202.6294	17367.1049	568.03	<.0001
Error	11	336.3156	30.5741		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.996783	2.218114	5.529389	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	48.46	<.0001
Density	1	2747.23379	2747.23379	89.85	<.0001
LogTSt	1	95406.65847	95406.65847	3120.50	<.0001
Density*LogTSt	1	715.58052	715.58052	23.40	0.0005
LogTSt*PT	1	148.32455	148.32455	4.85	0.0499
LStSq	1	3703.33817	3703.33817	121.13	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1715.785637	1715.785637	56.12	<.0001
Density	1	3781.098875	3781.098875	123.67	<.0001
LogTSt	1	154.822002	154.822002	5.06	0.0459
Density*LogTSt	1	742.877786	742.877786	24.30	0.0005
LogTSt*PT	1	149.146923	149.146923	4.88	0.0493
LStSq	1	3703.338166	3703.338166	121.13	<.0001

Analysis of Model (10) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	100889.6536	9171.7867	15.08	0.0017
Error	6	3649.2914	608.2152		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.965092	9.893168	24.66202	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	2.44	0.1696
VC	2	3326.06333	1663.03167	2.73	0.1432
LogTSt	1	95091.22645	95091.22645	156.34	<.0001
PT*VC	2	64.37262	32.18631	0.05	0.9489
LogTSt*PT	1	114.55718	114.55718	0.19	0.6795
LogTSt*VC	2	790.93584	395.46792	0.65	0.5551
LogTSt*PT*VC	2	21.00427	10.50213	0.02	0.9829

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1580.16676	1580.16676	2.60	0.1581
VC	2	3802.63063	1901.31531	3.13	0.1174
LogTSt	1	95111.52465	95111.52465	156.38	<.0001
PT*VC	2	62.74112	31.37056	0.05	0.9501
LogTSt*PT	1	113.82347	113.82347	0.19	0.6804
LogTSt*VC	2	791.27612	395.63806	0.65	0.5550
LogTSt*PT*VC	2	21.00427	10.50213	0.02	0.9829

Analysis of Model (11) - SAS

The GLM Procedure

Dependent Variable: Stress

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	104223.8023	13027.9753	372.06	<.0001
Error	9	315.1427	35.0159		
Corrected Total	17	104538.9450			

R-Square	Coeff Var	Root MSE	Stress Mean
0.996985	2.373773	5.917420	249.2833

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PT	1	1481.49389	1481.49389	42.31	0.0001
VC	2	3326.06333	1663.03167	47.49	<.0001
LogTSt	1	95091.22645	95091.22645	2715.66	<.0001
LogTSt*VC	2	791.72817	395.86408	11.31	0.0035
LogTSt*PT	1	113.75665	113.75665	3.25	0.1050
LStSq	1	3419.53380	3419.53380	97.66	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PT	1	1582.64385	1582.64385	45.20	<.0001
VC	2	3818.39953	1909.19977	54.52	<.0001
LogTSt	1	98400.30682	98400.30682	2810.16	<.0001
LogTSt*VC	2	799.53662	399.76831	11.42	0.0034
LogTSt*PT	1	114.61502	114.61502	3.27	0.1039
LStSq	1	3419.53380	3419.53380	97.66	<.0001

Further Analysis of Model (5) - Minitab

The regression equation is

peak stress = - 151 + 29.7 PT Index + 205 Density + 161 S1 + 90.4 S2
 - 12.2 PTI*S1 - 20.4 PTI*S2 - 138 Density*S1 - 90.1 Density*S2

Predictor	Coef	SE Coef	T	P
Constant	-150.71	38.14	-3.95	0.003
PT Index	29.720	3.550	8.37	0.000
Density	204.71	15.95	12.83	0.000
S1	160.93	54.12	2.97	0.016
S2	90.41	58.52	1.54	0.157
PTI*S1	-12.228	5.022	-2.44	0.038
PTI*S2	-20.366	5.020	-4.06	0.003
Density*S1	-137.85	22.63	-6.09	0.000
Density*S2	-90.08	24.49	-3.68	0.005

S = 4.34168 R-Sq = 99.8% R-Sq(adj) = 99.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	8	104369	13046	692.10	0.000
Residual Error	9	170	19		
Total	17	104539			

Source	DF	Seq SS
PT Index	1	1481
Density	1	2747
S1	1	45121
S2	1	54011
PTI*S1	1	0
PTI*S2	1	290
Density*S1	1	463
Density*S2	1	255

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