Control of the vibratory peening machine using the Almen intensity procedure

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Abstract

The effects of the vibratory peening process parameters on Almen intensity were investigated using the Design of Experiments (DOE) method. A specific vibratory peening machine was built. The tub vibrates vertically and rests on airbags. A non-standard fractional screening design was performed to evaluate the effects of the seven adjustable controlling parameters of the machine on Almen intensity. The Analysis of variance (ANOVA) showed that the eccentricity and frequency of the rotating shafts, and the media height above the treated specimen, were the parameters to adjust for the control of Almen intensity. A first order empirical model was fitted. The model included both primary factors and two-factor interactions. Its predictions showed that Almen intensity increases with the increase of the eccentricity, frequency and media height above the part. On the other hand, the media mass, airbag pressure, part position and lubrication rate did not show a significant influence on Almen intensity.

Keywords Shot peening, Vibratory peening, Almen intensity, DOE method.

Introduction

Vibratory peening is a surface treatment process that combines the effect of vibratory finishing and shot peening. The process aims to increase both the service life, as well as the surface finish of the treated component. The specimen to be peened is fixed inside a vibrating tub [1] which is filled with media. Plastic deformation results from the impacts of the media on the surface. This produces compressive residual stresses like in the shot peening process [2], but with much lower average surface roughness, close to that obtained from vibratory finishing [1].

Different designs of vibratory peening machines were used to investigate the benefits of the process on industrial components or on Almen strips [1-8]. The parameters controlling the peening are dependent on the individual design of the vibratory peening system and cannot be compared with other designs. Eventually, it is necessary to find out the controlling parameters for this design. In this study, we used the DOE method to build an empirical model, which relates the vibratory peening parameters such as the rotating shafts eccentricity, frequency and media height above the part, to Almen intensity.

Experimental Methods

A new vibratory peening machine was designed and built for this study, similar to the vibratory peening machine used in the study of [3]. The tub rests on airbags and is filled with 3 mm diameter ball bearing media. Two shafts with eccentric weights rotating in opposite directions at each side of the tub are used to produce a vibration in the vertical direction. The treated specimen is fixed onto a holder, which is mounted on a rail through the cover to allow the adjustment of the media height above the specimen. The holder is clamped on the rail during the treatment. Seven parameters were identified which can be adjusted on this machine, namely: the eccentric weights on the shafts (X_Ecc), the media mass inside the tub (X_Mass), the rotating shaft frequency (X_Freq), the airbag pressure (X_Press), the media height above the part (X_Height), the horizontal part position (X_Pos) and the lubricant flow rate (X_Lub). The range of variation of these parameters is listed in Figure 1.

The DOE method was used to screen the effect of the seven primary factors on Almen intensity. A non-standard fractional screening design was selected to consider the constrains on the modalities between X_Ecc and X_Freq, and between X_Mass and X_Height, such as described in Figure 1 (b) and (c). A 16-run matrix design was generated by the JMP Pro software [9]. Two replications were performed, and additional runs were done when the Almen intensity values were different between the replications. A total of 41 runs were performed.

(a)

Factors	i, j **or** k	**Min**	**Max**
X_Ecc (kg/shaft)	1	15	24
X_Mass (kg)	2	300	500
X_Freq (Hz)	3	15	30
X_Press (bars)	4	2	2.8
X_Height (cm)	5	10	25
X_Pos (-)	6	Left	Center
X_Lub (rpm)	7	20	50

(b) (c)

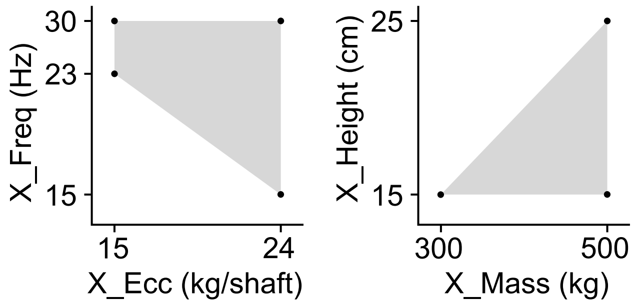

Figure 1. Factors ranges for the DOE. (a) The upper and lower bounds of the seven operating parameters with their associated variable name i, j or k for the identification in Equation (2). (b) Limited modality variation domain of X_Freq as a function of X_Ecc. (b) Limited modality variation domain of X_Height as a function of X_Mass.

The shot peening standard procedures of J442 and J443 were applied to construct the saturation curves with a minimum of 4 arc height measurements after different processing times. A standard Almen gauge was used for the arc height measurements. Almen A strips were peened for intensities that produced arc heights above 0.1 mmA or 0.3 mmN, and Almen N strips for intensities below 0.3 mmN. Almen A type of intensities were converted into Almen N type to have the same scale for the analysis of the DOE output. Three vibratory peening conditions from the design matrix were peened for both Almen A and N strips. The following equation was fitted on the results for the conversion:

$$N\ intensity = A\ intensity \times (7.05 \times A\ intensity + 0.76) \qquad (1)$$

The factors of major importance on Almen intensity were identified using an empirical relationship between the vibratory peening process parameters and Almen intensity, such as:

$$y = \beta_0 + \sum_{i=1}^{m} \beta_i x_i + \sum_{j=1}^{m} \sum_{k=1}^{m} \beta_{jk} x_j x_k + \varepsilon, \qquad for\ j < k \qquad (2)$$

where y is the Almen N intensity, β_0 is the intercept, β_i, β_{jk} are the partial regression coefficients associated to the factor effects, x_i, x_j and x_k are the variable modalities on a coded scale from -1 to +1, and ε is the error term. Table 1 details the i, j or k variable indices to identify the associated vibratory peening parameters. For $m = 7$, Equation (2) accounted for seven β_i and twenty-one β_{jk}, plus β_0, for a total of 29 regression coefficients. However, the 16-run design matrix was optimized to only fit the seven β_i of the primary factors with a minimal partial confusion between the factors. Thus, the least square method was not able to fit the 29 regression coefficients. An iterative regression approach was selected, in which empirical models with a limited number of partial regression coefficients were fitted.

It was considered that a maximum of 3 factors would be of major importance on Almen intensity, i.e. a maximum of $n_p = 6$ factor effects (3 primary factors + the 3 associated two-factors interactions). The empirical model of Equation (2) could be simplified with a set of maximum 6 non-negligible β_i, β_{jk} to neglect the remaining partial regression coefficients. An iterative regression routine was coded in Python to identify the set of non-negligible β_i, β_{jk} for $2 \leq n_p \leq 6$ which fit the data with the best regression quality.

At each iteration, an empirical model was built from Equation (2) with a selected set of β_i, β_{jk} and the remaining partial regression coefficients were set to zero. The least-squares method was used to fit the as-built model and the regression quality R^2 was computed. Eventually, all possible combinations of sets for $2 \leq n_p \leq 6$ β_i, β_{jk} , which are listed in Table 2, were tested. The list of sets was ranked by decreasing R^2 values and the factors of major importance were identified from the first set of the list.

Table 2. Partial regression coefficient sets selected in the iterative regression routine to identify the factors of major importance on Almen intensity. n_p stands for the number of factor effects in the selected sets, which includes both primary factors β_i and two-factors interactions β_{jk}.

	$n_p = 2$	$n_p = 3$	$\cdots$	$n_p = 6$
	β_1, β_2	$\beta_1, \beta_2, \beta_3$	$\cdots$	$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6$
	β_1, β_3	$\beta_1, \beta_2, \beta_4$	$\cdots$	$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_7$
	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	β_7, β_{67}	$\beta_7, \beta_{57}, \beta_{67}$	$\cdots$	$\beta_7, \beta_{46}, \beta_{47}, \beta_{56}, \beta_{57}, \beta_{67}$
Number of sets	168	1 946	$\cdots$	322 476

Experimental results

The 41 Almen intensity values resulting from the screening DOE are shown in Figure 2. The range of Almen intensities were found to be from 0.084 mmN to 0.194 mmA (converted to 0.427 mmN). Figure 2 (a) and (b) shows that the upper modalities of X_Ecc or X_Freq did not limit the range of Almen intensities. On the contrary, low modalities of X_Ecc and X_Freq allowed a limited Almen intensity range of [0.084, 0.2] mmN and [0.095 – 0.192] mmN, respectively.

The iterative regression routine identified the set $\beta_1, \beta_3, \beta_{13}, \beta_{15}, \beta_{35}$ to fit the experimental results with the best regression quality. An empirical model was built to relate the parameters to Almen intensity. To respect a hierarchical model, β_5 was added into the model. The associated empirical model to predict Almen intensity was:

$$y = 0.758 + 2.67 \times 10^{-2} X_{Ecc} + 2.27 \times 10^{-2} X_{Freq} + 3.06 \times 10^{-3} X_{Height} + 1.07 \times 10^{-3} X_{Ecc} X_{Freq} + 8.03 \times 10^{-4} X_{Ecc} X_{Height} + 6.41 \times 10^{-4} X_{Freq} X_{Height} + \varepsilon, \quad (3)$$

where X_i are the vibratory peening parameters expressed in physical units. A p-value threshold of 0.1 was selected to state the importance of a variable [10]. The ANOVA analysis confirmed the model significance with a model *p*-value below 10^{-4}. Similarly, the non-significance of the error was showed with an error *p*-value of 0.57 [10]. The residuals analysis showed a normal, centered on zero and independent distribution. Besides, the residuals were found in the range of [-0.051, 0.041] mmN and no outliers were identified. Therefore, the assumption of the ANOVA was admitted and the model adequacy was confirmed.

The ANOVA analysis showed the importance on Almen intensity of the primary factors X_Ecc and X_Freq, as well as their associated two-factors interactions with X_Height with p-values below 10^{-4}. In addition, the importance of the two-factors interaction X_Ecc*X_Freq was confirmed with a *p*-value of 0.005. On the contrary, the primary factors X_Height had not a statistical influence on Almen intensity since its associated *p*-value was 0.524. However, the parameter had an influence on Almen intensity through its interaction with X_Ecc and X_Freq. Therefore, the three parameters X_Ecc, X_Freq and X_Height was considered to be the vibratory peening parameters of major importance on Almen intensity.

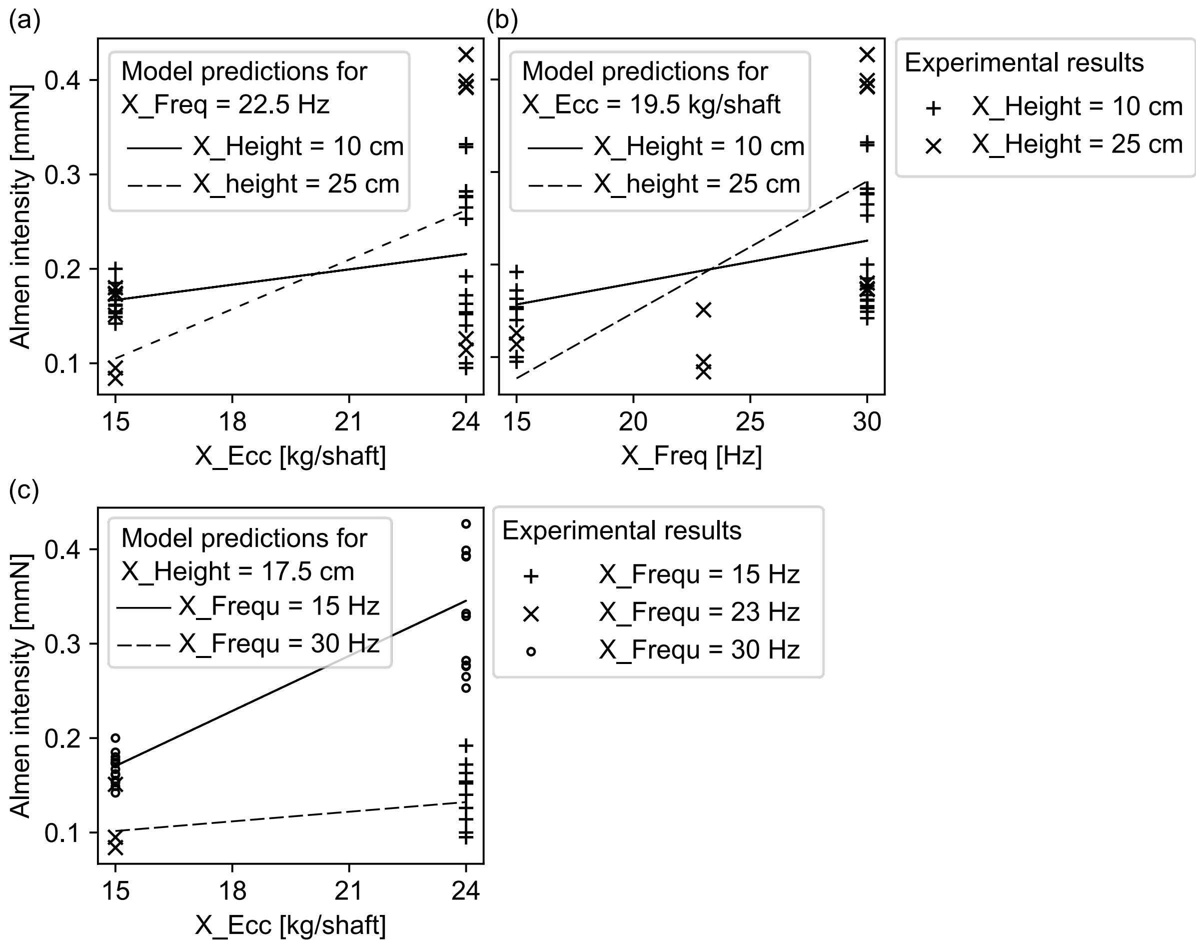

Figure 2. Comparison between the experimental results and the empirical model prediction. Interactions between X_Height and X_Ecc, X_Height and X_Freq and between X_Freq and X_Ecc can be observed by the difference of the gradients in the model predictions in (a), (b) and (c), respectively.

Almen intensities from the model predictions of Equation (2) are shown in Figure 2, as function of each important parameter. Almen intensity generally increases with all three parameters. At low levels of X_Height, the increase of Almen intensity as a function of X_Ecc and X_Freq is of lower importance, as shown in Figure 2 (a) and (b). This phenomenon is described by the two-factor interaction effects X_Height*X_Ecc and X_Height*X_Freq. However, higher Almen intensities are observed and expected for X_Height of lower importance when the level of X_Freq or X_Ecc is low. Similarly, the increase of Almen intensity is expected to be low for low frequencies, which is described by the X_Ecc*X_Freq two-factor interaction effect.

The model prediction showed that similar Almen intensities can be expected for different combinations of parameters. For example, predictions in Figure 2 (b) for X_Height =10 cm and X_Height =25 cm would both deliver an Almen intensity level of 0.195 mmN for X_Freq = 23.3 Hz. In addition, experimental results showed that Almen intensities in a range of [0.150, 0.175] mmN were observed for all levels of X_Freq.

Discussion and Conclusions

An iterative regression routine was used to identify that rotating shaft eccentricity (X_Ecc), rotational shaft frequency (X_Freq) and media height above the part (X_Height) are the factors of major importance on Almen intensity. It was also found that X_Mass, X_Press, X_Pos and X_Lub are non-influential on Almen intensity. This observation is limited to the range of factor modalities tested in this study. Besides, the media mass was adjusted without modification of the tub geometry, which had a direct consequence on the media height inside the tub. The adjustment of media mass from partitions of the tub, which would not influence the media movement near the treated part, was not tested.

X_Height did not have a direct statistical influence on Almen intensity. However, the adjustment of X_Height controlled the vibratory peening Almen intensity because of its important interaction with the factors X_Ecc and X_Freq. However, a sole effect of X_Height on the media-component interaction was shown in [4].

An empirical model was built to describe the relationship between the vibratory peening parameters and Almen intensity. Both experimental results and model predictions showed that higher Almen intensities were expected for higher eccentricities, frequencies, and media height above the part. Besides, similar Almen intensities were obtained for different vibratory peening conditions. However, the conclusions were based on a linear variation of Almen intensity. Yet, intermediate modalities of X_Freq led to a curvature in the relationship.

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