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Optimization of shot peening parameters by response surface methodology

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ABSTRACT

In this study, the shot peening parameters which directly influence the arc height of the Almen strip and its characteristics are optimized within the context of Almen intensity, surface roughness and surface hardness via response surface methodology. Determination of the Almen intensity by trial and error method depending on the experience of the technician (measuring the arc height of Almen strips by changing the parameters repeatedly for each shot peening process) makes the optimization approaches valuable. The optimization is considered to perform by selecting surface roughness and surface hardness as the responses in order to classify the shot peening processes by taking into consideration of wide range of plastic deformation level. The effect of input parameters air pressure, shot diameter and peening duration on the Almen intensity, surface roughness and surface hardness is to be determined by using ANOVA regression analysis. Based on the estimated models, optimum peening conditions are introduced via response optimizer. The model adequacy is verified by the confirmation tests.

1. Introduction

Almen intensity plays a crucial role in determining the amount of the plastic deformation of shot peening process [1–3]. Thus, it is located on the top level of the parameters list considered against the failure mechanisms such as fatigue [4–6] and corrosion [7]. Also it has remarkable influence on important mechanical properties such as surface roughness [8], surface hardness and residual stress [9,10]. Therefore, Almen intensity is determined with shot peening of Almen strips until the desired plastic deformation rate is obtained by adjusting the pre-conditions such as air pressure, shot diameter, peening duration and surface coverage before exactly the same application is exposed to the actual machine parts [11]. This situation leads to a large number of Almen strip waste depending on the technician's technical expertise [12]. The studies performed by mathematical [13,14] and modelling approaches [15,16] to determine the Almen intensity have attracted attention and provide useful insights to the practical applications. Even in recent years, the studies have been oriented to residual stress and ultra fine-nano structure formations [13,17–19]. The reason for this is the Almen intensity is directly considered as the major causal agent of all the mechanical and microstructural changes in the material.

In recent years, studies related with shot peening dwell on the plastic deformation effect on the microstructural changes and integration of ultra fine-nano grain formation on the surface only by using the parameters higher than the conventional ones [20]. In other words, only creating excessive plastic defomation via severe shot peening could ensure the surface nanocrystallization [21]. However, surface severe plastic deformation methods increase the surface hardness up to higher levels and leads to form a brittle layer on the surface. Selection of bigger medias and higher deformation ranges causes surface roughness increase up to 2–3 times with compared to conventional shot peening [22]. Most of literature studies depict the improvement of fatigue strength is observed by means of surface nanocrystallization subjected to severe shot peening [23–26]. In rare cases, although the formation of nanocrystalline layer on the surface, significant improvements are not observed on the fatigue strength [22] and even in some cases the fatigue strength is negatively affected [27]. This is due to lack of the surface finish before and after surface treatment, materials behavior alteration and prolonged treatments. Therefore, two or three stage shot peening processes are applied and the results are analyzed [20,28].

In this study, the factors that influence the Almen intensity are intended to be optimized by taking into consideration of not only the level of desired plastic deformation insurance but also desired surface roughness and surface hardness. The response of Almen intensity, surface roughness and surface hardness have been investigated with the alteration of shot peening process parameters by means of "response surface methodology".

2. 2. Experimental methods

The most widely used strip (A strip) has been selected for the shot peening process. It is manufactured from AISI 1070 spring steel [2]. Fig. 1 shows the A strip specifications and the arc height (deflection) after the shot peening treatment.

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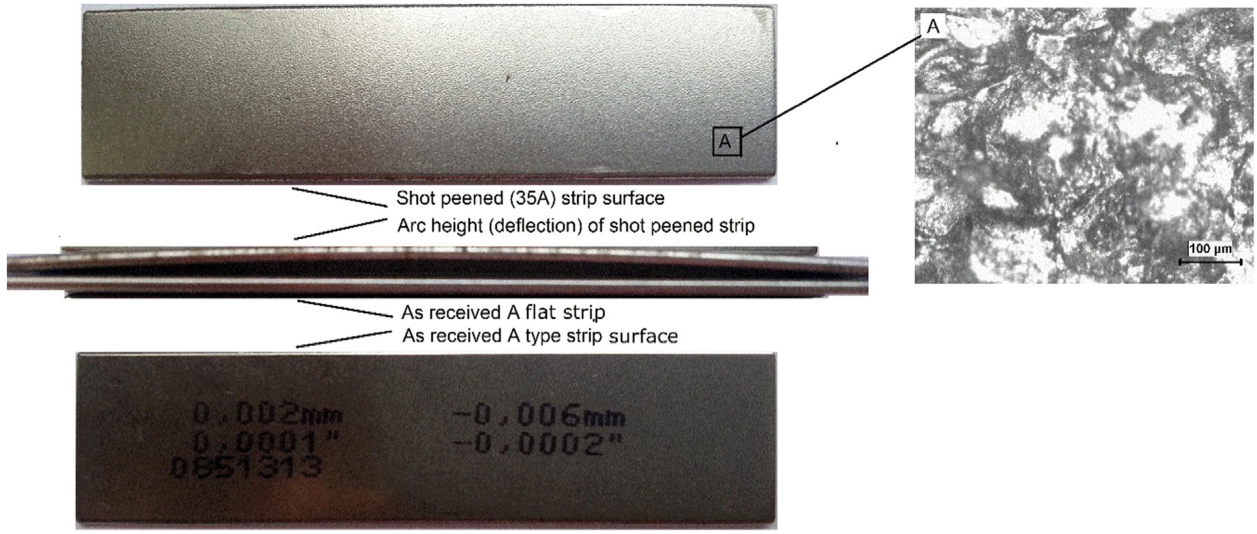

Fig. 1. Comparison of shot peened and as received A strip surface and arc height (deflection).

Shot peening treatment has been performed manually in Peenmatic 2000S device with 200% constant coverage, 90 mm nozzle distance and 90^0 impact angle. The coverage finally has been applied particularly for the reduction of surface roughness and also leads to the saturation of arc height after the exposure of plastic deformation substantially. So, preconditions for determining the characteristics of shot peening, shot diameter, air pressure and peening duration are aimed to assess in terms of Almen intensity, surface roughness and surface hardness. Shot peening parameters and the responses are shown in Table 1.

In the process, S110, S180 and S230 cast steel shot media is used. Commonly used shot media in shot peening process is presented in Fig. 2 (with the permission of Celik Granul Sanayi A.S.). Surface roughness of Almen strips is measured by using Mitutoyo Surface Roughness Tester, surface hardness measurements are performed by using Qness GmbH Q10 microhardness tester. Ra is obtained by measuring the values on three different points and averaging them. The hardness values are determined via 25 gf load through 10 s by measuring on five different points and averaging them.

The optimization of the shot peening process parameters by means of arc height, surface roughness and surface hardness are performed via DOE statistical method by using Minitab. The effect of the parameters are investigated on the outputs via response surface methodology (RSM) and L18 factorial design is applied.

Table 1
Shot peening input parameters and obtained arc heights (Almen Intensity) surface roughness and surface hardness.

Test No	Peening Duration (s)	Shot size (mm)	Air pressure (kPa)	Arc height (mm)	Almen intensity	Roughness Ra (um)	Hardness (HV)
1	2	0,4572	520	0,07	7 A	1266	286
2	3	0,4572	520	0,09	9 A	1317	289
3	10	0,5842	207	0,14	14 A	1893	293
4	20	0,2794	482	0,16	16 A	1611	295
5	30	0,2794	482	0,18	18 A	1786	302
6	40	0,2794	448	0,18	18 A	1707	307
7	15	0,4572	414	0,24	24 A	2412	374
8	25	0,5842	380	0,25	25 A	2666	376
9	50	0,2794	482	0,26	26 A	2229	371
10	45	0,2794	620	0,29	29 A	2844	394
11	15	0,5842	414	0,29	29 A	3111	399
12	45	0,2794	690	0,31	31 A	2946	404
13	50	0,5842	380	0,31	31 A	3385	402
14	25	0,5842	413	0,31	31 A	3449	407
15	50	0,2794	690	0,33	33 A	3318	419
16	25	0,5842	448	0,33	33 A	3664	427
17	20	0,5842	482	0,34	34 A	3748	454
18	50	0,2794	723	0,35	35 A	3496	448

2.1. Response surface methodology

Design of experiment (DOE) is a statistical approach and applied for determining the large number of coefficients that affect the experimental investigations and the other input parameters [29,30]. In this study, the effect of the input parameters shot diameter (s), air pressure (p) and peening duration (s) on the Almen intensity, surface roughness and surface hardness are discussed.

$$\text{Arc height}: \text{f}\ (\text{A}, \text{B}, \text{C}) \tag{1}$$

$$\text{Surface roughness}: \text{f}\ (\text{A}, \text{B}, \text{C}) \tag{2}$$

$$\text{Surface hardness}: \text{f}\ (\text{A}, \text{B}, \text{C}) \tag{3}$$

Response surface approach could be expressed by response surface "Y" as second order polynomial regression equation.

$$Y = b_0 + \sum b_i x_i + \sum b_{ii} x_i^2 + \sum b_{ij} x_i x_j + e_r \tag{4}$$

3. Results and discussion

3.1. Analysis of variance and regression model for Almen intensity

The regression coefficients evaluated by using ANOVA has determined the statistical significance of each factor in terms of Almen intensity (arc height) (Table 2). Although the selection of the confidence level of 95%, the whole factors have *P* values less than 0.05. The analysis reveals they are statistically significant for the optimization. The model for the arc height is compatible with total variance by means of $R^2 =$ 93,87%. If the R^2 is closer to 1, model predicts the response quite better. R^2(adj) coefficient is also close to 1, so achieves the model high significance [31].

Data normality has been investigated by means of normal probability plot. Residual normal probability plot for Almen intensity (arc height) is shown in Fig. 3. According to the normal probability plots, the all residuals has fallen to the straight line. The result confirms that errors are positioned normally and scattering has not been observed for Almen intensity (arc height).