

# On the residual stress modeling of shot-peened AISI 4340 steel: finite element and response surface methods

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Received: 9 August 2017 / Accepted: 12 October 2017

**Abstract.** Shot peening is a well-known process in applying the residual stress on the surface of industrial parts. The induced residual stress improves fatigue life. In this study, the effects of shot peening parameters such as shot diameter, shot speed, friction coefficient, and the number of impacts on the applied residual stress will be evaluated. To assess these parameters effect, firstly the shot peening process has been simulated by finite element method. Then, effects of the process parameters on the residual stress have been evaluated by response surface method as a statistical approach. Finally, a strong model is presented to predict the maximum residual stress induced by shot peening process in AISI 4340 steel. Also, the optimum parameters for the maximum residual stress are achieved. The results indicate that effect of shot diameter on the induced residual stress is increased by increasing the shot speed. Also, enhancing the friction coefficient magnitude always cannot lead to increase in the residual stress.

**Keywords:** Shot peening process / residual stress / AISI 4340 steel / response surface methodology / modeling

## 1 Introduction

Shot peening is a process in which several high-speed shots impact to a certain target to apply the residual stress [1]. This process is effective enough to improve the fatigue strength of components and structures [2]. The overall view of this process is shown in Figure 1. As can be seen, a high-speed shot is hit to the target surface and induces the residual stress. This residual stress, which is often compressive, can reduce the possibility of propagating cracks since cracks need tensile stress to grow (mode I) and the existence of compressive residual stress leads to higher strength of propagation.

Many researches about the induced residual stress using shot peening process have been done. For example, Al-Obaid presented a study about the mechanics of shot peening process, experimentally and theoretically [4]. Bagherifard et al. [5] introduced a numerical model of severe shot peening to predict the generation of a nanostructured surface layer of material. Miao et al. [6] presented an experimental-based study on the amount of induced residual stress. They also studied the variation of the surface roughness and the shapes that remain after each impact of shots. Bhuvaraghan et al. [7] employed a discrete numerical model to increase the accuracy of both residual

stress prediction and plastic strain during shot peening process. Zhiming et al. [8] studied effects of applied pressure when high-energy shot peening process on the stress corrosion cracking of the weld joint of 304 austenitic stainless steel. Sun et al. [9] evaluated effects of shot peening process on the microstructure of 2196 Al-Li alloy and the induced residual stress. Meguid et al. [10] presented a 3D finite element analysis of peening of strain-rate sensitive materials by a model of multiple impingement. They analyzed stresses and strains in the areas of impacts. Miao et al. [11] presented a study about the simulation of shot peening process and the applied residual stress, and also they pointed out some basic theory of this process based on the simulation. Seddik et al. [12] used response surface methodology to evaluate the effect of shot peening process variables such as shot speed and diameter on the applied damage AISI 316L material. Unal [13] presented a study to optimize shot peening parameters by response surface methodology. He also extracted some models for the surface roughness, hardness, and arc height. Nam et al. [14] used response surface methodology to optimize shot peening process of an aircraft structural part. They evaluated the effect of four parameters such as nozzle distance, pressure, impact angle, and exposure time on the coverage. Badreddine et al. [15] pointed out an approach to evaluate shot velocity in ultrasonic shot peening numerically and experimental. Rodriguez-Sanchez et al. [16]

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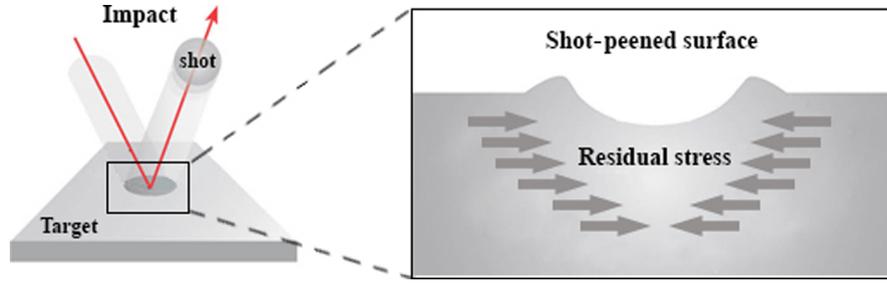


Fig. 1. Schematic of shot peening process [3].

**Table 1.** Mechanical and physical properties of shot and target [18].

Features	Shot	Target
Elasticity module (GPa)	210	205
Yield stress (MPa)	2600	1511
Tensile strength (MPa)	–	1864
Poisson ratio	0.28	0.29

evaluated the influence of shot peening on fatigue crack in a welded T-shaped structure experimentally. Zhang et al. [17] analyzed the effects of both random and regular multiple shot peening on the residual stress using numerical modeling.

In this research, not only the effect of shot peening parameters on the induced residual stress in AISI 4340 steel is presented, but also a strong model for prediction of residual stress is introduced. To these ends, firstly, the process is simulated by FEM method. Then, after validation, response surface methodology (RSM) is applied to reduce the number of runs regarding four main parameters of shot peening process such as shot speed, shot diameter, friction coefficient, and the number of impacts. Next, all achieved data are analyzed by using analysis of variance to find the effect of each parameter on the residual stress and their interactions. Then, a strong model is presented to predict the residual stress, accurately. Finally, the maximum residual stress is achieved by finding the optimum values of shot peening parameters.

## 2 Materials and methods

In this study, as mentioned, the effect of shot peening process of AISI 4340 steel on the induced residual stress is evaluated. The mechanical and physical properties of the shot and target are presented in Table 1.

In the shot peening process, strain rate is too high, so using the Johnson–Cook model (Eq. (1)) to predict the material behavior during the process can be helpful. This model is presented in equation (1).

$$\sigma = [A + B(\varepsilon_p)^n][1 + C \ln(\dot{\varepsilon}^*)][1 - (T^*)^m] \quad (1)$$

where  $T$  is the absolute temperature in K,  $\varepsilon_p$  is the plastic strain,  $\dot{\varepsilon}$  is the strain rate,  $A$ ,  $B$ ,  $C$ , and  $m$  are materials constants. Also,  $n$  is the work hardening exponent. The

**Table 2.** Johnson–Cook coefficient of AISI 4340 steel [18].

$A$ (Pa)	$B$ (Pa)	$n$	$m$	$T_m$ (K)	$T_r$ (K)
1439.51	944.198	0.26	1.03	1793	298

non-dimension variables of strain rate and temperature are as follows.

$$\dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}, \quad T = \frac{(T - T_r)}{(T_m - T_r)} \quad (2)$$

where  $\dot{\varepsilon}_0$  is the reference strain rate,  $T_r$  is the reference temperature, and  $T_m$  is the melt temperature. The Johnson–Cook coefficients of AISI 4340 steel are presented in Table 2.

In addition, there are some relevant coefficients which called Mie–Gruneisen constants [18]. These constants are relative to hydrostatic pressure at the moment of contact which are accessible from Table 3.

In Table 3,  $C_0$  is the bulk speed of sound in the material,  $S_\alpha$  is the linear Hugoniot slope coefficient and  $\Gamma_0$  is the Gruneisen's gamma at reference state. Furthermore, the strain rate dependence parameter  $C$  and the reference strain rate  $\dot{\varepsilon}_0$  are equal to 0.011 and 1, respectively [17].

## 3 Simulation procedure

Nowadays, finite element method is a promising step for predicting and analyzing all processes. In this research, shot peening process simulation is accomplished by using Abaqus-V6.12 code. The modeling process is 3D, and all dimensions and geometrical features such as shot diameter, sheet dimension as well as mesh qualities are based on the literature [17]. In the modeling, both shot and target are considered as deformable materials. As a matter of fact, shot diameter is equal to 1 mm, and the target is a sheet which has width and length 1.3 mm and 2.5 mm, respectively. To reduce the time consumption during the running process, both shot and target are modeled quarterly. A number of 332 elements with type C3D10M is used for shot. Also, the target is meshed by 7840 C3D8R elements. The overall view of the simulation process is shown in Figure 2.

To validate the process, results of the literature [18] are used. The verification of simulated process is shown in Table 4. As can be seen, residual stress coming from the

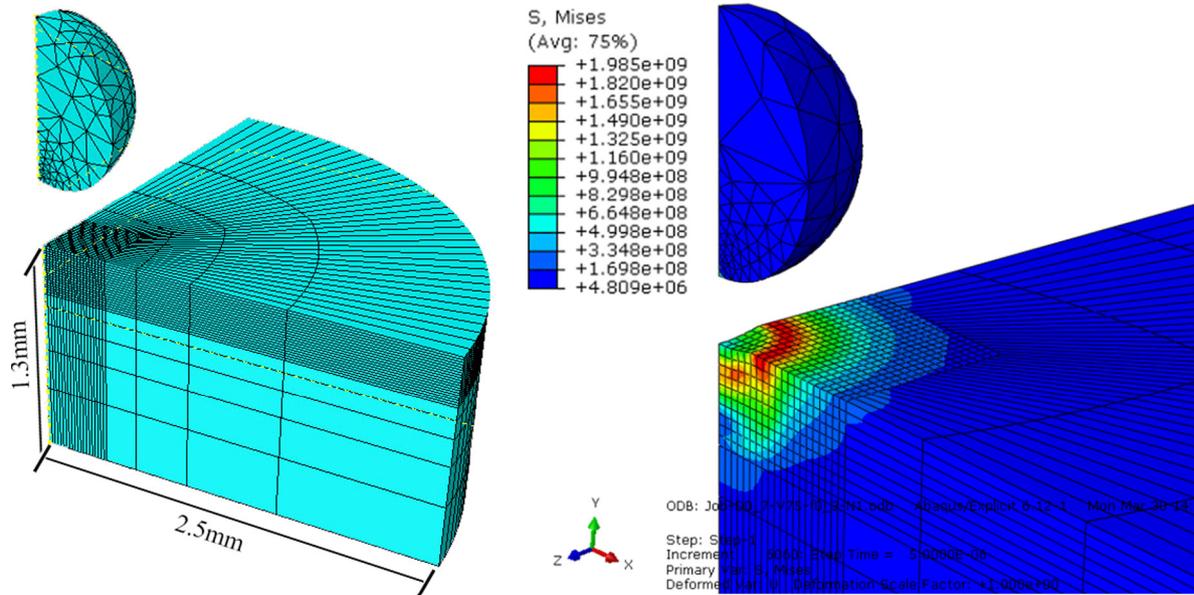


Fig. 2. Simulation of shot peening process.

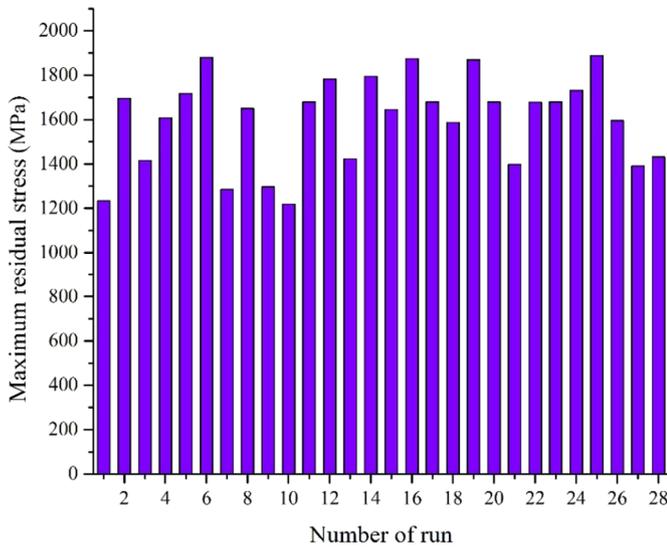


Fig. 3. The design of 28 experiments.

Table 3. Mie–Gruneisen constants for AISI 4340 steel [18].

$C_0$ (m/s)	$S_\alpha$	$\Gamma_0$
3935	1.587	1.69

Table 4. Validation of residual stress in the simulation of shot peening process (AISI 4340 steel).

Researches	Residual stress (MPa)	Depth of residual stress ( $\mu\text{m}$ )
Shivpuri et al. [14]	1590	104
Current research	1570	92

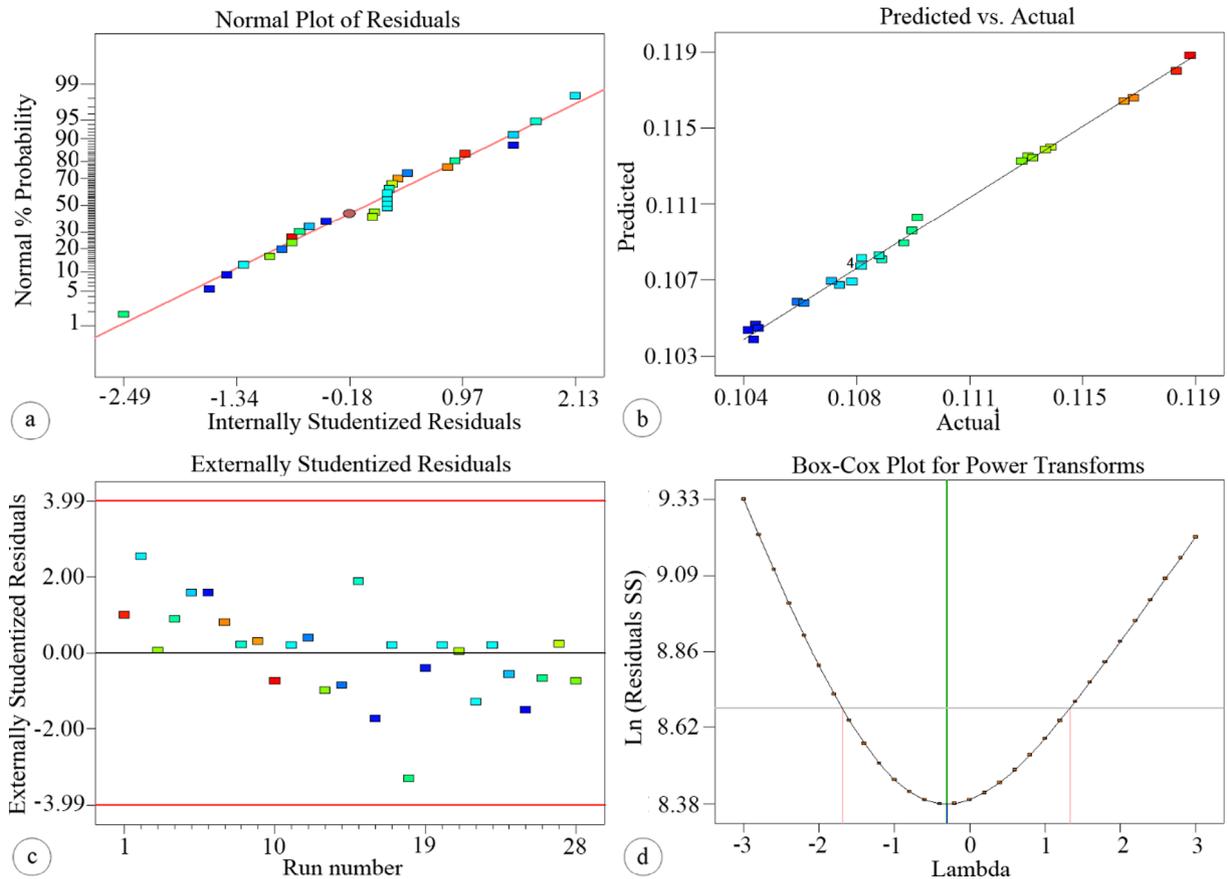
FEM has an acceptable accordance with the results of literature [19]. To ensure that the simulation can predict the process properly, depth of induced residual stress is also considered, as another way of credibility. Predicted depth also has a proper agreement with the literature.

## 4 Statistical modeling

In this section, firstly, the design of experiments is presented to reduce the number of runs. Then, response surface methodology and its models are expressed. Also, the analysis of variance (ANOVA) and some assumptions of the data analyzing are presented.

### 4.1 Design of experiments

Design of experiment (DOE) is one of the best methods for reducing the number of experiments. Response surface method (RSM), as a statistical-based DOE method, is considered to evaluate the process parameters. In fact, after an acceptable numerical modeling, the RSM method is done using Design-Expert-V7, as a statistical software by which statistical components are used to formulate a test plan. A general plan of 28 tests with 4 replicates in central point is used which is shown in Figure 3. Each point has the same distance from the central point, and each predictor is changed over three levels. The factors range has been entered in term of  $\pm 1$  levels. Also, this design utilizes face-centered alpha equal to 1.



**Fig. 4.** Checking the ANOVA assumptions, (a) normal probability, (b) predicted values versus actual, (c) externally studentized residuals, and (d) Box–Cox plot for power transformation.

## 4.2 Response surface methodology

Response surface approach is a statistical method that can be used for both prediction and optimization. Optimizing an output variable as a response is the target, in which the variables are affected by several input parameters. In this method, some techniques are used to develop the functional relationship between a response,  $y$ , and a number of associated control as input variables such as  $x_1, x_2, \dots, x_k$ . In general, such relationship is unknown but can be approximated by a low-degree polynomial model (usually first or second-degree) such as equations (3) and (4) [19]:

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \varepsilon \quad (3)$$

where  $\beta_0$  is the main effect level,  $\beta_i x_i$  is the main effect, and  $\varepsilon$  is the error. Also, the relationship between response and variables can be estimated by a second-degree polynomial model of the form (Eq. (4)) [20]:

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i < j} \beta_{ij} x_i x_j + \sum_{i=1}^k \beta_{ii} x_i^2 + \varepsilon \quad (4)$$

In this model,  $\beta_0$  is the main effect level,  $\beta_i x_i$  is the main effect,  $\beta_{ij} x_i x_j$  is the interaction effect,  $\beta_{ii} x_i^2$  is the curvature effect, and  $\varepsilon$  is the error.

## 4.3 Analysis of variance (ANOVA)

After the test conditions definition, assessment of 28 tests is started using analysis of variance (ANOVA). For any ANOVA analysis, there are four assumptions that should be considered based on the literature [20] and the design expert<sup>®</sup> software:

- Normal probability plot of the studentized residuals (checking for the normality of residuals).
- Studentized residuals versus predicted values (checking for constant error).
- Externally studentized residuals to look for the outliers, i.e., influential values.
- Box–Cox plot for power transformations.

Figure 4 shows how the data related to residual stress come from FEM are proper to be analyzed by ANOVA. In other words, the mentioned assumptions should be met before applying ANOVA. Firstly, as can be seen in Figure 4a, all data of studentized residuals should be in a normal form. According to the figure, it is clear that all of them follow the normality since they do not have any specific shape in distribution. Also, the second assumption can be accepted since the predicted values are matched with actual ones (Fig. 4b). To find the outliers, Figure 4c is a proper way and according to that, there is no outlier data and all of them are in the defined range. Finally, Box–Cox

**Table 5.** Analysis of variance for response surface method.

Source	Sum of squares	Degree of freedom	Mean squares	<i>F</i> -value	<i>P</i> -value Prob> <i>F</i>	Significance
Model	5.145E−004	14	3.675E−005	254.64	<0.0001	Yes
<i>D</i>	8.266E−006	1	8.266E−006	57.27	<0.0001	Yes
<i>V</i>	3.960E−004	1	3.960E−004	2743.68	<0.0001	Yes
$\mu$	2.912E−006	1	2.912E−006	20.18	0.0006	Yes
<i>N</i>	5.204E−005	1	5.204E−005	360.55	<0.0001	Yes
<i>D</i> · <i>V</i>	4.271E−007	1	4.271E−007	2.96	0.1091	No
<i>D</i> · $\mu$	4.259E−007	1	4.259E−007	2.95	0.1095	No
<i>D</i> · <i>N</i>	3.066E−006	1	3.066E−006	21.24	0.0005	Yes
<i>V</i> · $\mu$	4.678E−007	1	4.678E−007	3.24	0.0951	No
<i>V</i> · <i>N</i>	1.022E−006	1	1.022E−006	7.08	0.0196	Yes
$\mu$ · <i>N</i>	1.163E−008	1	1.163E−008	0.081	0.7810	No
<i>D</i> <sup>2</sup>	1.832E−008	1	1.832E−008	0.13	0.7274	No
<i>V</i> <sup>2</sup>	5.542E−006	1	5.542E−006	38.40	<0.0001	Yes
$\mu$ <sup>2</sup>	1.784E−006	1	1.784E−006	12.36	0.0038	Yes
<i>N</i> <sup>2</sup>	2.040E−006	1	2.040E−006	14.13	0.0024	Yes
Residual	1.876E−006	13	1.443E−007	–	–	–
Lack of fit	1.876E−006	10	1.876E−007	–	–	–
Pure error	0.000	3	0.000	–	–	–
Total	5.164E−004	27	–	–	–	–

plot shows the Lambda value for transformation. As it can be seen, for the residual stress, this value should be selected equal to  $-0.3$  to provide the best transformation.

Table 5 shows the ANOVA analysis for identifying the significant parameters effect on residual stress. According to the table, a value of *P*-value less than 0.05 indicates that the model terms are significant. As can be seen in Table 5, all the shot diameter (*D*), shot speed (*V*), friction coefficient ( $\mu$ ), and the number of impacts (*N*) are significant model terms. Also, in this model, some parameters have interactions with each other. Shot diameter interacts with the number of impacts. In addition, there is an interaction between the shot speed and the number of impacts.

## 5 Results and discussion

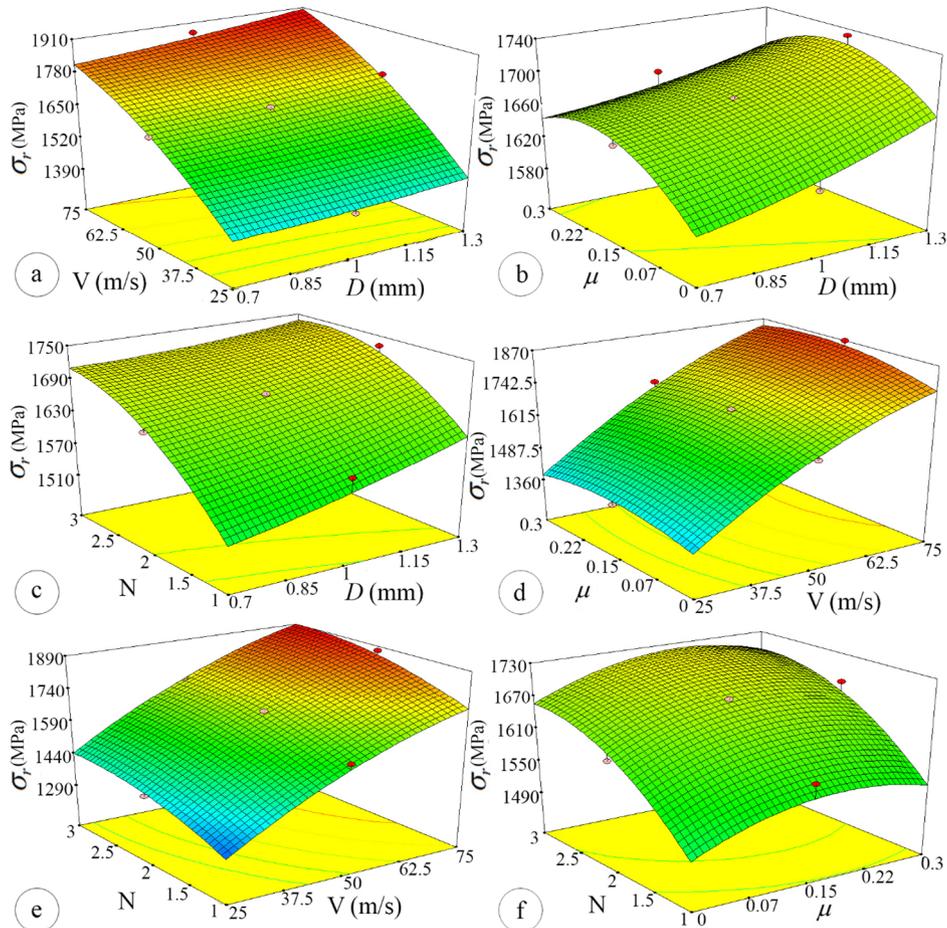
Generally, all shot peening parameters are effective on the process residual stress, but analyzing the effect of each parameter as well as the interactions between all parameters are important for recognizing the most significant parameter. After applying ANOVA, analysis of variance, significant factors can be identified. The results of effective factors on the residual stress of AISI 4340 steel are shown in Figure 5. As can be seen from Figure 5a, the residual stress is increased by increasing the shot speed [17]. The interesting point of Figure 5a is that shot diameter at speed 25 m/s is not effective on the residual stress. However, when shot speed is increased, diameter gradually becomes influential so that at shot speed 75 m/s, the residual stress is increased about 100 MPa by increasing the shot diameter from 0.7 to 1.3 mm. Figure 5b shows that the applied residual stress always is not increased

by increasing the friction coefficient magnitude. This issue should be considered, especially when achieving the maximum residual stress is the goal. From Figure 5c, it turns out that by increasing the number of impacts, residual stress is increased [18]. Also, it seems that the effect of shot diameter on the residual stress is reduced in higher the number of impacts. Figure 5d shows that almost there is no interaction between friction coefficient magnitude and shot speed because change in each of them does not change the effect of others. Based on Figure 5e, the number of impacts does not rely on the shot speed. As can be seen in Figure 5f, at lower friction coefficient magnitude, the variation of residual stress gradually is limited by increasing the number of impacts.

According to Figure 5, it turns out that analyzing the interaction between parameters can make the prediction of the process more easily and accurately. For better prediction, a quadratic model (Eq. (5)) is presented which has the most accuracy.

$$\begin{aligned} \sigma^{-0.3} = & 0.13554 - 2.75921 \cdot 10^{-3} D - 4.13736 \cdot 10^{-4} V \\ & - 0.015475 \mu - 7.24878 \cdot 10^{-3} N \\ & - 2.17834 \cdot 10^{-5} D \cdot V + 3.62577 \cdot 10^{-3} D \cdot \mu \\ & + 1.45911 \cdot 10^{-3} D \cdot N - 4.55950 \cdot 10^{-5} V \cdot \mu \\ & + 1.01089 \cdot 10^{-5} V \cdot N + 1.79754 \cdot 10^{-4} \mu \cdot N \\ & - 9.36291 \cdot 10^{-4} D^2 + 2.34523 \cdot 10^{-6} V^2 \\ & + 0.036960 \mu^2 + 8.89238 \cdot 10^{-4} N^2 \end{aligned} \quad (5)$$

where *d* is the shot diameter, *v* is the shot speed,  $\mu$  is the friction coefficient magnitude, and *n* is the number of impacts. The multiple correlation factor, *R*<sup>2</sup>, and adjusted *R*<sup>2</sup> values for the above model are equal to 99.6% and 99.3%, respectively.



**Fig. 5.** Effect of shot peening parameters on the maximum residual stress (compressive).

There is also another model which is simpler than equation (5). This model (Eq. (6)) is based on the shot peening parameters without any interaction.

$$\begin{aligned} \sigma^{2.83} = & -2.52003 \cdot 10^8 + 2.26538 \cdot 10^8 D \\ & + 1.76202 \cdot 10^7 V + 3.07551 \cdot 10^8 \mu \\ & + 1.56577 \cdot 10^8 N \end{aligned} \quad (6)$$

In the above model, the multiple correlation factor  $R^2$ , and adjusted  $R^2$  values are equal to 91.9% and 90.5%, respectively. These models can be used by industries to predict the residual stress induced by shot peening process in the AISI 4340 steel.

To provide an order for the process parameters effect, sensitivity analysis can be a helpful instrument. In fact, knowing about the reaction of residual stress by changing the shot peening parameters can make the control of the process much easier. The sensitivity analysis is shown in Figure 6. The actual factors for this analysis are shot diameter 1 mm, shot speed 50 m/s, friction coefficient 0.15, and the number of impacts 2. The slope of curve identifies the effectiveness. As can be seen, shot speed has the most significant effect on the induced residual stress. The next parameter is the number of impacts, based on the

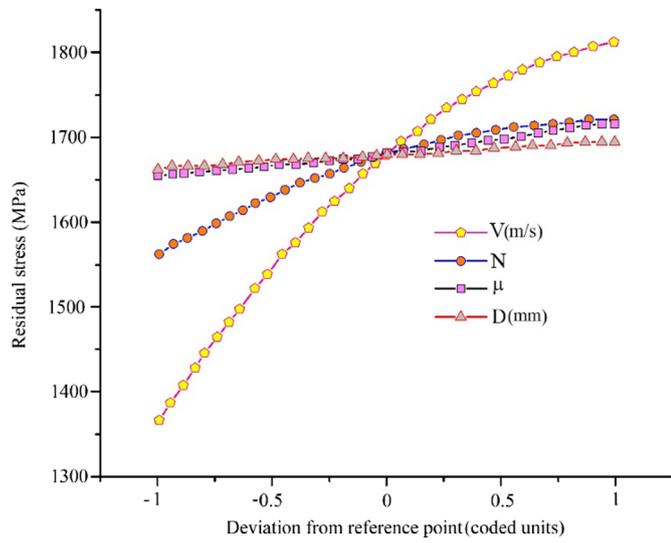
importance, and as shown friction coefficient magnitude and shot diameter have the same influence on the residual stress.

After evaluating shot peening parameter and sensitivity analysis, the optimization process is done to achieve the optimum values of parameters. In fact, achieving the higher residual stress is the goal of optimization. The optimum values of the shot diameter, shot speed, friction coefficient, and the number of impact are obtained using the statistical analysis by Design-Expert-V7 software. In the software, the optimization process is done by the definition of the constraints and goals. The maximum number of the solutions is 100 with 30 cycles per optimization. Duplicate solution filter is set at the middle value, which establishes the epsilon (minimum difference) for eliminating essentially identical solutions [21]. Also, the simplex fraction, which specifies how big the initial steps will be relative to the factor ranges [21], is selected equal to 0.1. The optimization constraints, factors, and the goals are presented in Table 6. Also, the desirability factor for the optimization is equal to 1.

According to the table, the maximum value of residual stress that can be achieved by shot peening process of AISI 4340 steel is equal to 1895.2 MPa.

**Table 6.** The optimization goals and the factors.

Input parameters	Goal	Lower limit	Upper limit	Optimum
$D$ (mm)	In range	0.7	1.3	1.26
$V$ (m/s)	In range	25	75	70.93
$N$	In range	1	3	2
$\mu$	In range	0	0.3	0.23
Residual stress (MPa)	Maximize	1218.8	1888.73	1895.2

**Fig. 6.** Sensitivity analysis for shot peening process of AISI 4340 steel.

## 6 Conclusion

In this study, effects of shot peening parameters on the residual stress of AISI 4340 steel are evaluated. Apart from that, an accurate model for prediction of the process is presented. Based on the results, following points can be concluded.

- A strong model has been presented to predict the induced residual stress by shot peening process in AISI 4340 steel. The multiple correlation factor,  $R^2$ , and adjusted  $R^2$  values for the presented model are equal to 99.6% and 99.3%, respectively.
- By considering the interactions between parameters it is shown that some parameters do not have a significant effect on the residual stress. As an instance, shot diameter at speed 25 m/s cannot be considered as an effective factor in the residual stress.
- Residual stress always is not increased by increasing the friction coefficient magnitude. In fact, there is the turning point for residual stress after which residual stress decreased by increasing the friction coefficient. This critical friction coefficient for AISI 4340 steel is about 0.15.
- Sensitivity analysis shows that after shot speed, the number of impacts is the most significant parameter of shot peening process of AISI 4340 steel. Friction coefficient and shot diameter almost are of the same rank from the eyes of effectiveness.

- The maximum induced residual stress of shot peening process of AISI 4340 steel is equal to 1895.2 MPa which happens at the shot diameter 1.26 mm, shot speed 70.93, number of impact 2 and friction coefficient magnitude 0.23.

## Nomenclature

- $A$  Johnson–Cook model constant (Pa)  
 $B$  Johnson–Cook model constant (Pa)  
 $C$  strain rate dependence parameter  
 $m$  Johnson–Cook model constant  
 $n$  work hardening exponent  
 $\varepsilon_p$  plastic strain  
 $T$  normalized temperature  
 $T_m$  melt temperature (K)  
 $T_r$  reference temperature (K)  
 $C_0$  bulk speed of sound in the material (m/s)  
 $S_\alpha$  linear Hugoniot slope coefficient  
 $\Gamma_0$  Gruneisen's gamma at reference state  
 $\dot{\varepsilon}_0$  reference strain rate ( $s^{-1}$ )  
 $D$  shot diameter (mm)  
 $V$  shot speed (m/s)  
 $N$  number of impacts  
 $\mu$  friction coefficient

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**Cite this article as:** A. Asgari, P. Dehestani, I. Poruraminaie, On the residual stress modeling of shot-peened AISI 4340 steel: finite element and response surface methods, *Mechanics & Industry* **18**, 605 (2017)