中國機械工程學刊第三十九卷第二期第 163~170 頁(民國一百零七年)
Journal of the Chinese Society of Mechanical Engineers, Vol.39, No.2, pp 163~170 (2018)

Numerical Simulation and Optimization of Shot Peening Process Parameters

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Keywords : finite element, residual stress, shot peening, numerical simulation

ABSTRACT

In this paper, a finite-element (FE) model of shot peening (SP) process is developed for multiple shot impacts on 304 stainless steel sheet by using LS-DYNA code. The model is partially validated by experiments using single shot. Then numerical simulations of multiple shot impacts are performed and the residual stress profiles below the target surface are investigated so that the effects of shot velocity, radius and yield strength of shot material on averaged residual stress profiles are obtained. Finally, the FE model is applied to optimization of SP process parameters by determining the optimal regression equation with the maximum compressive residual stress as function of shot velocity, radius and yield strength by means of stepwise regression analysis. The optimal model proposed is practical for engineers.

INTRODUCTION

Shot peening (SP) is a cold-working process which is usually employed to improve the fatigue strength of metallic parts or members (Arakawa et al., 2014; Mapelli et al., 2012; Rakita, 2013; Soady, 2013; Wang, 2012; Žagar and Grum, 2013). The SP process is widely used in aerospace, automotive and power generation industries, etc. Empirical methods (Curtis, 2003) or experimental methods (Chang et al., 2011; Feng et al., 2013; Fu et al., 2014; Miao et al., 2010) have been carried out to investigate the effect of SP process. For example, thermal fatigue and wear tests were conducted by Chang et al. (2011) to evaluate the effects of SP on thermal cracking and the mechanical properties of H13 tool steel. Their experimental results showed the SP process could enhance the surface hardness to HV 561 and extend the limit of fatigue strength by two to three times. However, empirical methods are lack of theoretical support, and the experimental methods are generally destructive, costly and time-consuming.

Because numerical simulation is cheap and easy to perform, it has attracted many researchers for SP process (Johnson, 1972; Kim et al., 2012; Majzoobi et al., 2005; Meguid et al., 1999; 2002; Miao et al., 2009; Mylonas and Labeas[a, b], 2011; Schiffner and Droste gen. Helling, 1999; Shivpuri et al., 2009). For example, Johnson (1972) pioneered in conducting finite-element (FE) analysis of SP process using a pseudo-dynamic approach. In his approach, he took into account only the inertial properties of the shot. Meguid *et al*. (1999) conducted dynamic elasto-plastic analysis of the process, and discussed the effect of shot velocity, size and shape on the time histories of the equivalent stress trajectories, equivalent plastic strains and unloading residual stresses of a target exhibiting bilinear material behavior, but only for a single shot impact. Shivpuri *et al*. (2009) investigated effects of process parameters and surface material response on the development of subsurface residual stress using 3D pseudo-dynamic explicit model. Kim *et al*. (2012) proposed the 3D angled multi-shot FE model. However, the optimization of SP parameters is not practical enough for engineers.

304 stainless steels are essential for many applications owing to their excellent properties such as corrosion resistance and optimum hardness at room temperature, for example, they can be used as material for the arms of some Load-Haul-Dump machines. The SP process with multiple shot impacts is very suitable for improving the fatigue strength of such structural components. In this paper, a FE model

Paper Received May, 2015. Revised August, 2015. Accepted September, 2015. Author for Correspondence:Hong-Ling Zhao.

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of SP process is developed for multiple shot impacts on 304 stainless steel sheet with 100% coverage by using LS-DYNA code and multi-linear material model. The FE model is partially validated by the experimental results obtained from a series of single-shot tests. Then numerical simulations of multiple shot impacts are performed and the residual stress profiles under the surface are investigated so that the effects of shot velocity, radius and yield strength of material on averaged residual stress profiles are obtained. Finally, the FE model is applied to optimization of SP process parameters by determining the optimal regression equation with the maximum compressive residual stress as function of shot velocity, radius, and strength by means of stepwise regression analysis. The optimal model proposed is practical for engineers.

THE FE MODEL AND EXPERIMENTAL VALIDATION

The situation envisaged is that of sixteen same shots with radius R impinging a target at normal incidence. The arrangement of the shots for successive impacts can be observed in Figure 1.

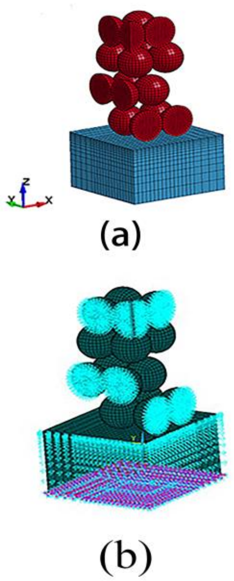

Fig. 1. The FE model of the multiple impact simulations: (a) meshes, (b) Boundary condition.

Target geometry, mesh discretisation, boundary conditions and material properties

The dimensions of the target are $6R\times6R$ square sheet with 2.1 mm thickness. In order to obtain well-proportioned impingement, the shots are arranged in the following way: the first impact occurs with 4 shots colliding with the target sheet simultaneously; the second collisions take place with 4 shots moving a distance of R along $-x$ direction and y direction respectively compared with the first 4 shots; the third 4 shots moving a distance of R along x direction compared with the second 4 shots, the last 4 shots moving a distance of R along $-x$ direction and $-y$ direction respectively compared with the third 4 shots. The coverage percent is set to be 100%. As dynamic explicit finite element code used for solving general nonlinear problem, LS-DYNA can be employed to simulate complex problems with plentiful cell library. Therefore, the meshes of shots and target are constructed with SOLID164 of LS-DYNA code. The meshes in the impact region of $4R\times4R$ need to be refined to $0.08R\times0.08R$. Farther from the impact region, coarser meshes are used. Considering the symmetry of SP process, a quarter of the model is adopted to save the computational costs, as shown in Fig. 1(a).

It can be assumed that ideally spherical shots impact frictionlessly and vertically on the target surface. Non-reflecting boundary conditions are applied at the four side surfaces of target paralleling with the XOZ and YOZ planes respectively since the effect of target sheet size on the simulation output is negligible. Moreover, the four side surfaces are imposed as symmetrical condition. The bottom surface is fixed to ground so the no-slip constraint is imposed to the bottom surface, as shown in Fig. 1(b).

To ensure accuracy, the multi-linear material model is used for the target and the shots, namely, the stress-strain curve is fitted as multi-linear by using arrays. Since our project aims to study the SP of low strength steels such as 304 stainless steel, 304 stainless steel is chosen as the materials of target. Table 1 lists the chemical composition of 304 stainless steel used in the numerical simulation and it's properties are as following: Young's modulus of 193 GPa, Poisson's ratio of 0.3, density of 7930 kg m^{-3}, yield strength of 300 MPa and tangent modulus of 74.23 GPa (Gang, 1992).

Table 1. Chemical composition of the 304 stainless steel (Gang, 1992)

Element	at.-%
Cr	18.0-20.0
Ni	8.0-11.0
S	≤0.030
P	≤0.035
C	≤0.06
Si	≤1.00
Mn	≤2.00

The shot material can be either the same as the target or different from it. Generally speaking, the strength of shots is higher than that of target. Therefore, in this section the material of shots is chosen as the same as that of the target, but the effect of different shot materials with four yield strengths is also calculated and discussed in Results and discussion section.

Model Validation

Experiments are performed in order to validate the FE model. A numerically controlled pneumatic shot blasting machine is used for SP process of 304 stainless steel sheet. G3 shots made of stainless steel with radius of 0.6mm are employed; and their material properties are the same as ones of the target sheet which are described before. The shot velocity *v* is set to be 120 m/sec, and the surface coverage is 100%. Only normal impingement has been considered during the experimental process.

The residual stress analysis was performed by X-ray Diffraction (XRD) technique using Proto manufacturing company (Canada) with "LXRD" machine. The instrument was aligned as per ASTM E915, and operated with Mn-Kα radiation (25 kV, 20 mA). The analysis zone was limited by a collimator of 2 mm in diameter. The (311) diffracting planes were chosen. Dual 512 channel position sensitive detector was used with 29^o diffraction angles (2θ) scanned. Successive layers of material were etched away by saturated solution of NaCl-water and electro-polished by electrolytic polisher Proto-8818 so that profiles of residual stress against depth can be obtained. Thickness removed was checked with a micrometer. All measurements were carried out at room temperature.

Table 2. The calculated and measured residual stress values. (R=0.6 mm, and v=120 m/sec, σ_s =300 MPa)

Depth (μm)	Calculated values (MPa)	Measured values (MPa)
18.1	- 323	- 313
40.4	- 437	- 425
68.2	- 488	- 495
102	- 475	- 465
145	- 401	- 381
198	- 264	- 216
263	- 122	- 134
344	- 9.69	- 9.99
444	- 48.9	- 47.8

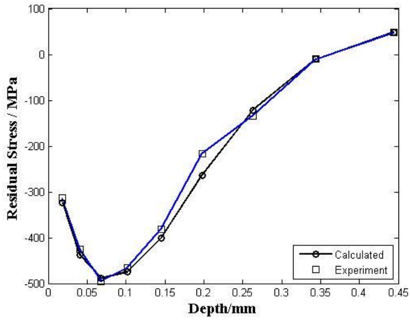

Fig. 2. The calculated versus measured residual stress profiles (R=0.6 mm, v=120 m/sec, σ_s=300 MPa).

The parameters employed for numerical simulation are exactly the same as ones used in the experiments, namely, shot radius R=0.6 mm; yield strength of shot σ_s=300 MPa; v=120 m/sec. The numerically calculated versus experimentally measured residual stress values for different depths are listed in the Table 2 and plotted in Figure 2. It can be seen that, the numerical prediction stands in good agreement with experimental results.

RESULTS AND DISCUSSION

The effects of SP parameters on residual stress profile and optimization of process parameters are investigated in this section.

Effect of shot size

After SP process, the small plastic indentations are formed causing stretching of top layers of the exposed surface of the target, consequently, residual stress is created. It can be predicted that a nearly uniform stress distribution will be achieved with 100% coverage. Therefore, it can be assumed that a residual stress distribution varies over depth below the target surface, but is uniform in the XOY plane direction, so the numerically calculated residual stresses are averaged over a local representative area for each element layer in this paper.

The numerically calculated residual stress profiles for different shot radius at three velocities (80, 100, 120 m/sec) are illustrated in Figure 3. From Fig. 3, it can be seen that the magnitude of residual stress initially increases with the increase of the depth below surface; then, it reaches its maximum value at certain depth, decreases thereafter. It can be deduced that maximum residual stress doesn't appear at the target surface, but appears a little bit below the surface. Moreover, when shot velocity and yield strength are kept constant, both the depth and magnitude of the maximum residual stress increase with the increase of shot radius. This result can be explained as: during SP process, if the shots are assumed to be rigid, bombarding the target with shots at certain velocity means that the kinetic energy of shots is converted to kinetic energy of bouncing shots and elastic energy and plastic energy in target. Since the kinetic energy of shots increases with the increase of shot radius, peening with larger shots results in deeper peening treatments. But the increase in the kinetic energy of shots must be limited, which will be discussed in the following sections.

Effect of shot velocity

From the kinetic energy formula $E=mv^2/2$, it can be deduced that, when the shot mass m is kept constant, the kinetic energy E of shot is proportional to the square of the shot velocity v^2, and the effect of shot velocity on residual stress profile in the peened surface is very significant.

The effects of shot velocity on residual stress are numerically calculated at five shot radii (0.3 mm, 0.4 mm, 0.5 mm, 0.6mm, 0.7 mm), and are shown in Figure 4(a)—(e). It can be seen that the basic trend is that the magnitude of residual stress increases with the increase of shot velocity. However, the magnitude of residual stress doesn’t increase linearly with the shot velocity. When R=0.5 mm, it noticeably increases by increasing v from 80 m/sec to 120 m/sec. When R=0.6 mm or 0.7 mm, it increases negligibly with the increase of v from 100 m/sec to 120 m/sec. This phenomenon can be explained by the following hypothesis: the kinetic energy of shots increases with

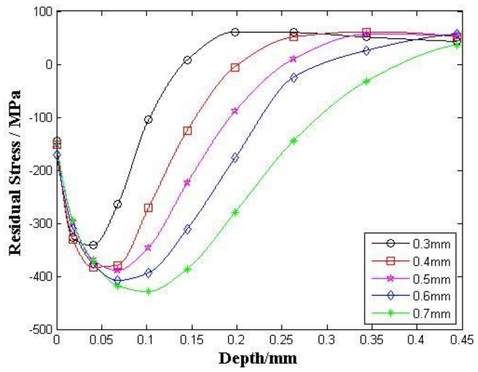

Fig. 3(a). Effect of shot radius on residual stress versus depth below the surface， v=80 m/sec.

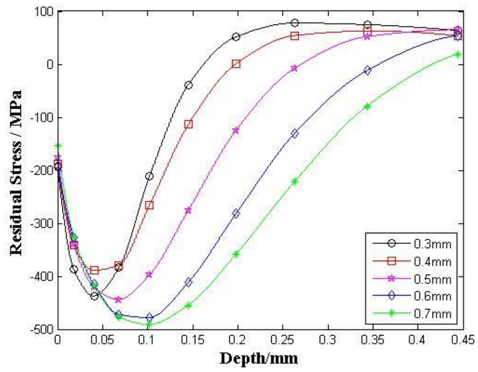

Fig. 3(b). Effect of shot radius on residual stress versus depth below the surface, v=100 m/sec.

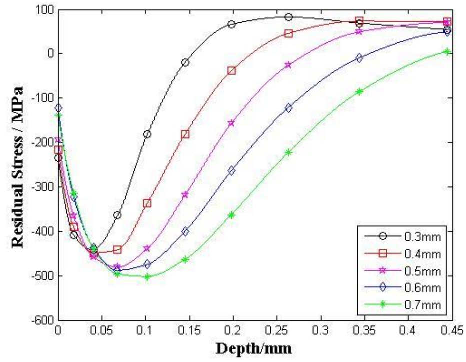

Fig. 3 (c). Effect of shot radius on residual stress versus depth below the surface, v=120 m/sec.

the increase of shot velocity and radius, consequently, plastic deformation of the target increases after the target is impinged by shots. Once plastic deformation reaches its threshold, increasing deformation of the target causes crack or failure. Therefore, shots with higher velocity and larger radius collide with the target, the magnitude of residual stress does not increase, on the contrary, it may decrease.

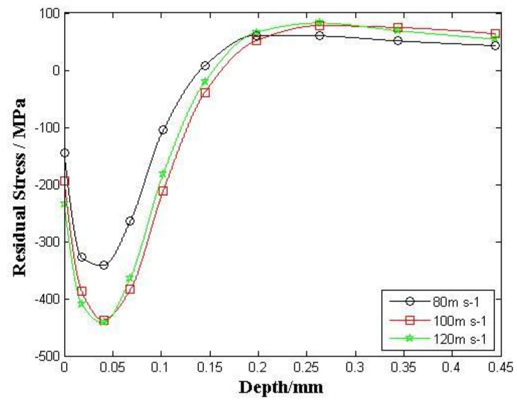

Fig. 4(a). Effect of shot velocity on residual stress versus depth below the surface, R= 0.3 mm

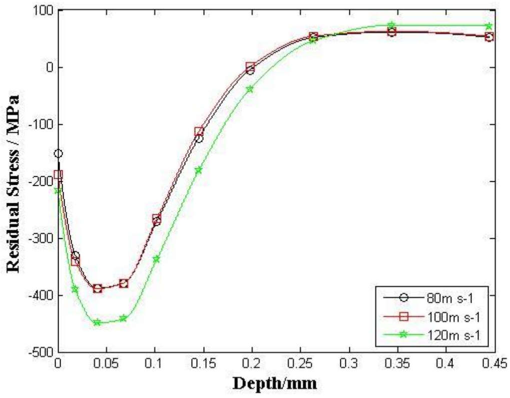

Fig. 4(b). Effect of shot velocity on residual stress versus depth below the surface, R= 0.4 mm

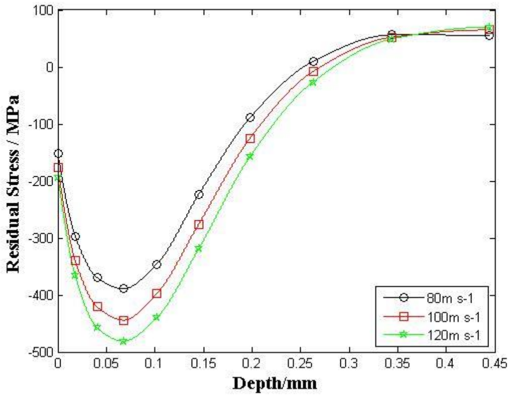

Fig. 4(c). Effect of shot velocity on residual stress versus depth below the surface, R= 0.5 mm.

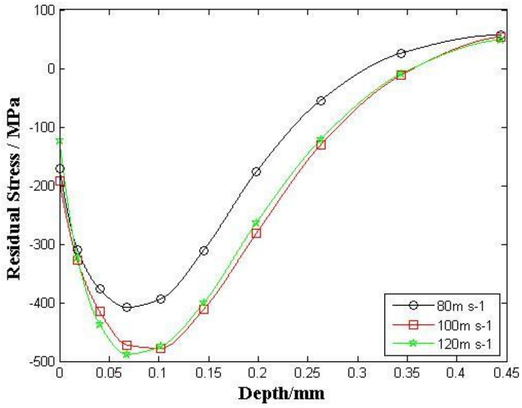

Fig. 4(d). Effect of shot velocity on residual stress versus depth below the surface, R= 0.6 mm.

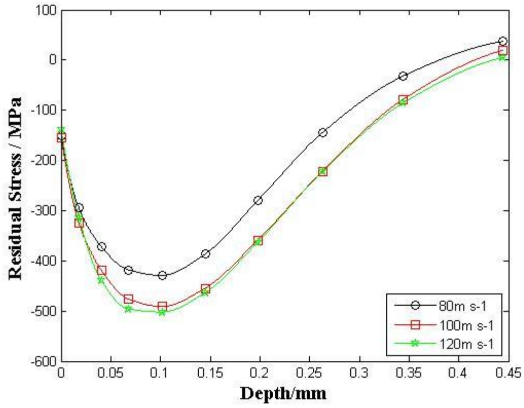

Fig. 4(e). Effect of shot velocity on residual stress versus depth below the surface, R= 0.7 mm

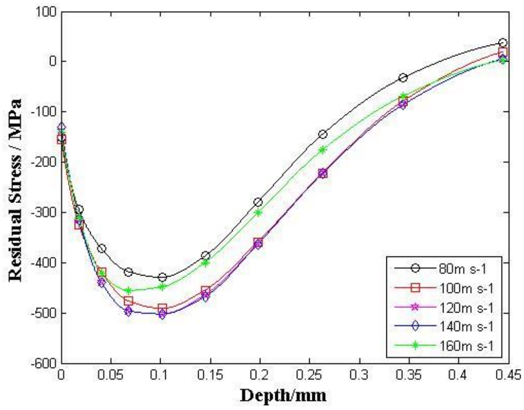

Fig. 4(f). Effect of shot velocity on residual stress versus depth below the surface, R= 0.7 mm and higher velocities combined with (e).

To prove this hypothesis, the residual stress profiles for higher shot velocities (140, 160 m/sec) when R=0.7 mm, are numerically calculated, and the results combined with Fig. 4(e) are shown in Fig. 4(f). From Fig. 4(f), it can be seen that the residual stress decreases somewhat when v increases from 120 m/sec to 140 m/sec. When v=160 m/sec, the residual stress is less than its counterpart at 100 m/sec. The numerical simulation in Fig. 4(f) shows, when the kinetic energy of shots is large (for instance, $v \geq 120$ m/sec, $R \geq 0.6$ mm for 304 stainless steel), further increase in shot velocity is useless; on the contrary, it becomes harmful to the SP process. In other words, the optimal process parameters can be determined on the basis of the maximum residual stress expected.

Moreover, from Fig. 4, it can be seen that the depth at which the maximum residual stress exists is nearly the same at the same shot radius, regardless of shot velocities. Therefore, it can be deduced that the effect of shot velocities on depth of maximum residual stress can be neglected.

Effect of yield strength of shots

In practical SP process, different materials with different yield strength are employed as shots. The yield strength of shots is one of main parameters which affect residual stress profile. The residual stress profiles versus depth below the surface are numerically calculated and shown in Figure 5 for four yield strength values of shots (σ_s=225, 300, 375 and 450 MPa) to be used in SP process of 304 stainless steel (R= 0.3 mm, v=80 m/sec). Fig. 5 shows that residual stresses of peened target surface increase somewhat with the increase of yield strength of shots, but the change is little and negligible, the maximum residual stresses remain to be －350 MPa. The simulation results are in good agreement with conclusion from the practical process workers of SP that, while yield strength of shots is higher than that of target, further increase of yield strength of shots has minimal effect on the residual stress in target surface peened.

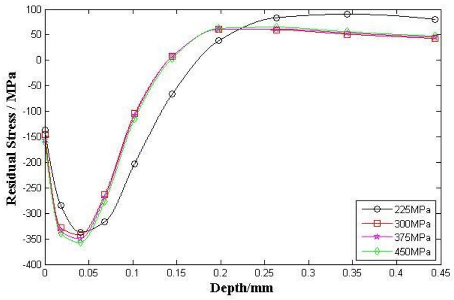

Fig. 5. Effect of yield strength of shots on residual stress versus depth below the surface (R=0.3 mm, v=80 m/sec).

Application to optimization of SP process parameters

For some metallic parts or members, a thin layer of high-magnitude compressive residual stress (CRS) near the surface needs to be created to inhibit crack formation. To establish relationship between SP process parameters and CRS of 304 stainless steel and to use this relationship to optimize the settings of process parameters, the optimal regression equation is determined with the maximum compressive residual stress (MCRS) σ_{xx} as function of shot velocity v, radius R, and strength σ_s by means of stepwise regression analysis here.

The controllable variables are v, R and σ_s (three factors) with σ_{xx} as the response variable. Four different values (four levels) are selected for each factor. Three factors along with their levels are shown in Table 3 using L16 orthogonal array. The numerically calculated results of MCRS are also shown in Table 3 for these 16 runs by applying the FE model developed.

Table 3. SP parameters (three factors) and their values (four levels) layout using L16 orthogonal array, and the numerical results of MCRS

Run No.	Shot velocity v (m/s)	Shot radius R(mm)	Shot strength σ_s(MPa)	MCRS σ_{xx}(MPa)
1	80	0.3	225	-352
2	80	0.4	300	-388
3	80	0.5	375	-401
4	80	0.6	450	-405
5	100	0.4	225	-418
6	100	0.3	300	-437
7	100	0.6	375	-442
8	100	0.5	450	-422
9	120	0.5	225	-454
10	120	0.6	300	-488
11	120	0.3	375	-443
12	120	0.4	450	-418
13	140	0.6	225	-453
14	140	0.5	300	-439
15	140	0.4	375	-415
16	140	0.3	450	-402

The SP parameters (three factors) and numerical results of σ_{xx} (response variable) in Table 3 are used to fit regression models. Three polynomial models including the first-order, second-order and third-order model are employed in stepwise regression analysis for the sake of comparison to obtain the optimal model. It is assumed that confidence level α=0.25. The significance of regression is tested by F distribution: $F_{0.25,\,1,\,15}$=1.43 (Montgomery, 2013) while adding a variable to the regression models. Percentage points of F distribution are calculated by using standard software packages for stepwise regression analysis when deleting a variable to the regression models. Three equations for polynomial models determined are as follows:

the first-order model,

$$\sigma_{xx} = -284.1 - 0.7163v - 134.8R\,,$$

the second-order model,

$$\sigma_{xx} = 309.2 - 9.894v - 0.9205\sigma_s + 0.04172v^2 - 152.40R^2 + 1.433\times10^{-3}\sigma_s^2\,,$$

the third-order model,

$$\sigma_{xx} = 564.3 - 5.430v - 4.932\sigma_s + 0.01373\sigma_s^2 + 1.270\times10^{-4}v^3 - 217.7R^3 - 1.215\times10^{-5}\sigma_s^3.$$

By comparison of the coefficients, F-test, residual sum of squares, standard deviation, residuals in the three models, the third-order model is considered as the optimal regression model (confidence level α=0.25). The optimal regression curve versus the numerically calculated results of the MCRS σ_{xx} is shown in Figure 6, and it can be seen that the model is rather adequate. The optimal settings of the process parameters can be determined by the model and MCRS expected. For example, the arms of some Load-Haul-Dump machines are made of 304 stainless steel, and demand that the MCRS of the arms can achieve 450 MPa after SP process. The SP parameters can be determined as follows:

1. if v=100 m/sec, σ_s =300 MPa, then we can get R=0.495 mm;
2. if v=120 m/sec, σ_s =300 MPa, then we can get R=0.362 mm.

Given different shot strength, more sets of SP parameters can also be determined by the optimal model.

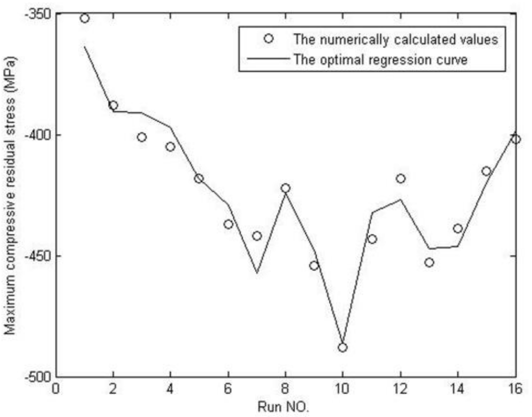

Fig. 6. Optimal regression curve versus the numerically calculated results of MCRS σ_{xx}.

CONCLUSIONS

A FE model of SP process is developed for multiple shots by using LS-DYNA code and multi-linear material model on 304 stainless steel, afterwards partially validated by the experiments. Then numerical simulations of multiple shot impacts are performed and the effects of shot velocity, radius and strength of material on residual stress distribution are obtained. Finally, the FE model is applied to optimization of SP process parameters. The results show as follows:

(1) When the yield strength of shots is kept constant (300 MPa), increasing either shot radius or velocity noticeably increases the magnitude of residual stress. However, since plastic deformation has its threshold, when the kinetic energy of shots is large (v≥120 m/sec, R≥0.6 mm), further increase in shot velocity is useless. On the contrary, it becomes harmful to the SP process. Moreover, the depth of the maximum residual stress increases with the increase of shot radius, but changes negligibly with shot velocity.

(2) When yield strength of shots is higher than that of target, further increase of yield strength of shots has minimal effect on the residual stress in target surface peened.

(3) Optimization of SP process parameters can be obtained by the optimal regression equation which is fitted by using SP parameters and numerical results of MCRS σ_{xx} by means of stepwise regression analysis. The optimal model proposed is practical for engineers.

ACKNOWLEDGMENT

This research was supported by the Sciences and Technology R&D Fund of Ma'anshan in Anhui province.

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噴丸强化処理工艺参数之數值模擬和優化研究

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摘要

本文運用 ANSYS/LS-DYNA 工具建立了 304 不銹鋼的多彈丸噴丸有限元模型，並且用單彈丸實驗資料進行了部分驗證。研究了在不同噴丸工藝參數（彈丸的速度、半徑和強度）下，經過噴丸處理的 304 不銹鋼板材殘餘應力場。最後，對模擬結果採用逐步回歸分析法建立了殘餘應力關於工藝參數的最優回歸模型，據此可根據所需的最大殘餘應力要求確定最佳工藝參數。所得模型具有實際指導意義。