Multiphysics Modelling of Warm Shot Peening of AISI 4140 Steel

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Abstract. Aiming at the effect of the elevated temperature on shot peening, the multiphysics modeling of warm shot peening is carried out by coupling the processes of heat transfer and shot peening. The temperature field and thermal stress field resulted from the analysis of heat transfer are imported into the model of shot peening to simulate the process of warm shot peening. The obtained results show that the maximum temperature is located in the subsurface layer after multiple shot impacts under 100% peening coverage, and an obvious temperature gradient can be found along the material depth; with the increase of heat flux load, the resultant compressive residual stresses in the surface and subsurface decrease, while the depth of the compressive residual stress increases; the peened surface roughness increases only if the heat flux density exceeds a critical value; the predicted residual stresses in the cases of $q = 1 \times 10^7$ W/m$^2$ and $q = 2 \times 10^7$ W/m$^2$ are in good agreement with the experimental results.

1. Introduction
Shot peening (SP) is a well-established mechanical surface treatment widely used in the aerospace and automobile industries, which is mainly aimed at improving the fatigue life of metallic components under the service environment [1-2]. In the process of shot peening, a large number of shots with high velocities impact the surface of a metallic component randomly. The indentations surrounded by plastic regions followed by elastic regions are produced in the peened surface layer. The elastic-plastic deformation results in the beneficial compressive residual stresses which can effectively enhance the resistance of the metallic component exposed to fatigue loading [3]. The experimental studies of shot peening have been existed for a long time, and got the rich achievements [4]. With the development of the finite element method and computational power, numerical modeling of shot peening process is accepted by many researchers [5-6]. When compared with the experimental study, numerical simulation costs smaller and studies the mechanism of shot peening more conveniently. In recent years, a lot of models [7-9] of shot peening are proposed to predict the shot peening results, such as residual stress, surface roughness, and work hardening. The numerical study of shot peening effectively promotes the development of shot peening technology.

Warm shot peening (WSP) is thermomechanical treatment technique deriving from the conventional shot peening on which the shot peening process is carried out at elevated temperature [10-11]. Schulze et. al [12-13] built a new device to conduct the experiments of warm shot peening, as shown in Fig.1, the warm shot peening nozzle mixes the hot blast air and shot flow to heat the metallic component in the process of shot peening. Research shows that the larger plastic region and depth of compressive residual stresses can be obtained by warm shot peening [12-14]. However, to
our best knowledge, it is a pity that there are little literatures reported on the numerical modeling of warm shot peening. Therefore, the multiphysics modeling of warm shot peening is performed in this paper, and the corresponding products: temperature filed, residual stress field and surface roughness are studied in detail.

![hot air flow](image1)
cold air flow with shot
![hot air flow](image2)
cold air flow

Fig. 1 Warm shot peening of AISI 4140 steel [12-13]

2. Modeling of warm shot peening

2.1 Heat transfer analysis

In order to simulate the heat transfer process of warm shot peening, a three dimensional cylinder-shape finite element model with the diameter of 10mm and height of 4mm is developed, as shown in Fig. 2. Eight-node linear heat transfer brick elements (DC3D8) are used to mesh the finite element model, and the finest element size is 40µm. The initial temperature of the three dimensional model is 300K, and the heat flux load is applied on the center area with the dimension of 2mm×2mm which is located on the model’s top surface. Two constant heat flux densities are $1\times10^7 \text{ W/m}^2$ and $2\times10^7 \text{ W/m}^2$ respectively. The transient temperature field can be obtained by

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho \cdot c} \nabla^2 T$$

(1)

where $T$ is the temperature field, $t$ is time, $\lambda$ is the thermal conductivity ($\lambda = 42\text{ W/K/m}$ for AISI 4140 steel), $\rho$ is density ($7850\text{ kg/m}^3$), $c$ is specific heat ($580\text{ J/(kg\cdot K)}$) and $\nabla$ represents the gradient.

The convective heat transfer between the outer surface of the cylinder-shape model and the ambient air is conducted by

$$q = h_c (T_s - T_a)$$

(2)

where $q$ is the heat flux density, $h_c$ is convective heat transfer coefficient, $T_s$ is the temperature of the model’s outer surface and $T_a$ is the ambient temperature (300K). The effect of the thermal radiation is ignored.

![Heat flux lead](image3)

Fig. 2 Heat transfer model

Fig. 3 shows the distributions of temperature and thermal stress induced by the heat flux load before shot peening. The maximums of temperature and thermal stress, which increase with the increasing heat flux density, are both on the top surface of the finite element model, and the obviously
gradient can be found. The obtained temperature field and thermal stress field are simultaneously imported into the shot peening model by the means of analytic field, to simulate the process of warm shot peening.

Fig. 3 Gradient distribution of temperature and thermal stress under the heat flux load
2.2 Shot peening model
A cuboid-shape finite element model with the dimension of $2\text{mm} \times 2\text{mm} \times 4\text{mm}$, taken from the cylinder-shape heat transfer model, is used to simulate the process of shot peening, as shown in Fig. 4. The shot with the diameter of 0.43mm is treated as the rigid body, considering that little deformation is produced when compared with the cuboid-shape model. The shot initial velocity is applied to the reference point of the rigid body which is at the shot geometric center, and the value of the initial velocity is estimated by [15]

$$v = \frac{16.35 \times p}{1.53 \times k + p} + \frac{29.50 \times p}{1.196 \times R + p} + 4.83 \times p$$  \hspace{1cm} (3)$$

where $p$ represents the jet pressure (bar), $k$ is the shot mass flow (kg/min) and $R$ is the shot radius (mm). According to the given experimental conditions [12-13], the shot initial velocity is computed as 37.3m/s by Eq. (3). The center area with the dimension of $1\text{mm} \times 1\text{mm}$ on the top surface of the cuboid-shape model is vertically impinged by the shots, and the bottom surface is completely constrained. Eight-node linear brick elements with reduced integration and hourglass control (C3D8R) are used to mesh the cuboid-shape finite element model, and the finest element size is 10µm to simulate the very high gradient stress and strain.

Two hundred shots are created to simulate the process of shot peening under 100% peening coverage of the treated area, as shown in Fig. 4. The shot peening coverage is defined as the ratio of the area covered by peening indentations to the total treated surface area. [16] The generation of these shots is flexibly constrained by a linear distribution function between two shot centers [17]

$$P_c = \begin{cases} 
100\% & l \leq 2r \\
\frac{l}{2r} & l \geq 2r 
\end{cases} \hspace{1cm} (4)$$

where $P_c$ represents the probability of shot generation, $l$ is the distance between the randomly generated shot center and the prior shot center, $r$ is the indentation’s radii induced by single shot impact. Fig. 5 shows the shot peening coverage with and without the flexible constraint for the experimental conditions [18]. The coverage without the flexible constraint means that the distribution of indentations produced by multiple shot impacts on the peened surface is completely randomly. Obviously, the predicted coverage with the flexible constraint is more close to the experimental results.
Based on the shot peening model, the simulation of warm shot peening process is performed by importing the temperature field and thermal stress field resulted from the heat transfer simulation into the shot peening model as the initial conditions. In order to study the influence of heat flux load on the shot peening, Johnson-Cook model is employed to calculate the dynamic flow stress, which is related to the temperature ($T$), equivalent plastic strain ($\varepsilon_p$) and equivalent strain rate ($\dot{\varepsilon}_p$), i.e.

$$\sigma_f = [A + B(\varepsilon_p)^n] \cdot [1 + C \ln \left(\frac{\varepsilon_p}{\varepsilon_0^p}\right)] \cdot \left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]$$

where $A$, $B$, $C$, $n$ and $m$ are material constants, $\varepsilon_0^p$ is the reference strain rate, $T_r$ is the room temperature and $T_m$ is the melting point. For AISI 4140 steel, $A=594\,\text{Mpa}$, $B=615\,\text{Mpa}$, $C=0.023$, $m=0.142$, $n=1.1611$, $T_m=1800\,\text{K}$, $T_r=300\,\text{K}$ \cite{19}.

3. Result and discussions

3.1. Temperature field

The temperature increment caused by the plastic deformation induced by multiple shot impacts can be calculated by

$$\Delta T = \frac{\eta}{\rho \cdot c} \int_{0}^{\varepsilon_p} \sigma \, d\varepsilon_p$$

where $\eta$ is the converting efficiency from plastic work to heat (ranging generally between 0.9 and 1.0), $\sigma$ is the equivalent stress.
Fig. 6  Temperature field

Fig. 6 shows the temperature field of the representative region with the dimension of 0.5mm×0.5mm×0.5mm induced by multiple shot impacts under different heat flux loads. With the increase of heat flux load, the temperature in the surface and subsurface increase significantly, which is attributed to the severe plastic deformation. Fig. 7 shows the distribution of the temperature along the depth, and the in-depth temperature is the area-averaged value. The maximum temperatures corresponding to the heat flux loads are all located in the subsurface with the distance of 0.1mm from the top surface, and then the temperature decreases along the depth direction, which shows the obvious temperature gradient.

3.2 Surface roughness

Surface roughness is one of the most common parameters used for evaluation of the shot peening. Peak-to-valley roughness (PV) is defined with Eq. (7) as the distance between the highest peak \( R_p \) and the lowest valley \( R_v \) within the sampling length

\[
PV = R_p + R_v \tag{7}
\]
The surface topographies after multiple shot impacts under different heat flux loads are shown in Fig. 8, and the z direction displacements of the nodes on the representative area with the dimension of 0.5mm×0.5mm are used to evaluate the peened surface roughness [20]

\[ PV = \max(U_z) - \min(U_z) \]  

where \( \max(U_z) \) and \( \min(U_z) \) are the highest peak and the lowest valley within the reference area. From Fig. 8, the values of PVs are 0.019mm in the case of \( q = 0 \) w/m², 0.019mm in the case of \( q = 1\times10^7 \text{ w/m}^2 \), and 0.021mm in the case of \( q = 2\times10^7 \text{ w/m}^2 \), respectively. It is therefore concluded that the PV would increase with the increasing temperature only if the heat flux load exceeds a critical value.

![Surface topographies of the reference area after multiple shot impacts](image)

**Fig. 8** Surface topographies of the reference area after multiple shot impacts

### 3.3 Residual stresses

As result of the elastic springback of material surrounding the plastic region induced by multiple shot impacts, the residual stress field is produced, as shown in Fig. 9. The compressive residual stresses are mainly located in the peened surface and subsurface, and the maximum compressive residual stress decreases with the increase of heat flux load. It should be noted that some tensile residual stresses are produced in the peened surface, which are related to the uneven plastic deformation and surface roughness. In order to study the effect of heat flux load on the resultant residual stresses, the comparisons of the distributions of the area-averaged residual stresses are shown in Fig. 10. It can be clearly seen that, with the increase of heat flux load, the compressive residual stresses in the peened surface and subsurface decrease, while the depth of the compressive residual stresses increase. The predicted residual stresses in the cases of \( q = 1\times10^7 \text{ w/m}^2 \) and \( q = 2\times10^7 \text{ w/m}^2 \) are in good agreement with the experimental results [12-13], which verifies the effectiveness of multiphysics modelling of warm shot peening.
Fig. 9 Residual stress fields induced by warm shot peening

Fig. 10 In-depth residual stresses
4. Conclusions
By coupling the analysis of heat transfer and simulation of shot peening, multiphysics modeling of warm shot peening is carried out, and the obtained conclusions are drawn as following:

1. The 100% shot peening coverage with the flexible constraint is more close to the experimental results.

2. The maximum temperature induced by warm shot peening is located in the subsurface layer, and the obvious temperature gradient can be found along the depth direction of the peened material.

3. The peened surface roughness would increase only if the heat flux load exceeds a critical value.

4. With the increase of heat flux load, the compressive residual stresses in the surface and subsurface layers decrease, while the depth of compressive residual stress increases.

5. The predicted residual stresses in the cases of $q = 1 \times 10^7 \text{ W/m}^2$ and $q = 2 \times 10^7 \text{ W/m}^2$ are in good agreement with the experimental results.

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