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Predicting shot peening coverage using multiphase computational fluid dynamics simulations

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ABSTRACT

A three-dimensional non-steady state shot peening simulation platform for coverage prediction is developed based on commercial Computational Fluid Dynamics (CFD) ANSYS-FLUENT software. To simulate the air–peen flow, the airflow is treated as a continuum phase governed by the Reynolds-averaged Navier–Stokes conservation equations, while the peen is taken as a discrete phase in which the trajectories of the peens are tracked individually. Two-way air–peen interactions are solved by exchanging mutual momentum during the peening process. User Defined Functions (UDFs) for particle loading distribution in the nozzle, particle dispersion, particle rebound, and nozzle movement are developed and incorporated into ANSYS-FLUENT. A numerical procedure based on the Eulerian–Lagrangian approaches is used in the solution. The air–peen simulation results based on the above model and numerical procedure is found to be in excellent agreement with the literature experimental data. For coverage prediction, both single dimple area and multiple impact coverage models are developed and validated by both experimental data and in-house Finite Element Method (FEM) simulation result. The obtained simulation results for coverage are in good agreement with existing experimental data. In addition, the simulations for two other configurations, that is, round-flat and airfoil NACA0012 specimens, are also performed to demonstrate the capability of the simulation platform. The present work shows that the multiphase shot peening simulation platform developed here can be used to accurately predict air–peen flow and coverage and to further optimize shot peening processes under real operating conditions.

1. Introduction

Shot peening, is a cold working process to create compressive residual stress in a thin layer at metal surface by peening impact, is widely used to improve the fatigue life of metallic components [1–4]. In shot peening processes, spherical peens (ceramic, cast iron, or glass peens, etc.) are accelerated and directed onto the work piece to be treated [3–5]. The impact of the peens causes plastic deformation on the surface layer of the work piece. After the shot peening process, a high compressive residual stress is generated at the surface. This compressive residual stress in the surface layer of the work piece is known to greatly improve the fatigue strength. The quality of peening process can be determined through two factors, which is the coverage area and peening intensity. These two main factors can be controlled by a number of parameters, and can be broadly categorized into three parameter groups, namely, peen, work piece, and process conditions [1–4]. The peen parameters include size and shape of peens, material properties, and peen velocity. The work piece parameters include geometry configuration and material properties. The process parameters include media mass flow rate, air pressure, impact angle, distance from nozzle exit to work piece, peening time, etc.

Coverage level is defined as the percentage ratio of the total indentation area to total treated surface area [1,6–11]. The coverage area has substantial influence on the reliability and uniformity of the treated surface and the thickness of the residual stress layer. Coverage area is formed by multi-impacts and overlapping indentations in peening process. Coverage level depends on media flow rate, peen size, peen velocity, angle of impact, and peening time. Experimentally, there are three different ways to practically determine the coverage: which are visual inspection, blue-ink, and replicate [1,6–11]. For practical purposes, a 98% coverage area and above can be considered as complete (100%) coverage area. Over 100%, say 200% coverage is attained by peening for twice the length of time required to attain 98% [1,6–11].

Coverage level plays an important role in assessing the quality of the peening process [1,3,11]. When coverage level is less than 100%, it is defined as “under-peening”. Under such circumstances, there will be some un-peened area with extension stress, uneven residual stress distribution, or undesirable compressed stress. This can result in earlier extension of cracks and significant reduction in fatigue life; especially if the mode failure is stress corrosion [1,3,11]. Typically, the desired coverage level requires 100% coverage or above, with an even-residual stress

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distribution [3,11]. However, for 100% coverage and above, the multiple impacts and overlapping indentations can cause excessive residual stress in the component, leading to micro-crack formation and further reducing the peening benefit [1,6,7]. Hence, it is necessary to check both the coverage area and compressive residual stress of the work piece to achieve optimum quality of peening process.

Recently, multiphase Finite Volume Method (FVM) and Finite Element Method (FEM) simulation models have been widely proposed in the literatures to understand the complex physical phenomena of multiphase flows (particle and airflow) and shot peening process, respectively. The insightful understandings gained from those numerical simulations can be used to enhance the quality of metal shot peening process. Nonetheless, the recent proposed multiphase FVM flow simulations were only used to investigate the airflow behaviour, particle behaviour, particle–airflow interaction, particle–particle interaction, particle distribution, and particle velocity [12–19] without including dimple area and coverage area prediction. On the other hand, the proposed FEM was currently used to compute the dimple size, coverage, intensity, roughness, residual stress, strain, etc. [20–26] by assuming a certain impact angle, peen velocity and distribution without considering carrier airflow. In addition, these FEM simulations were often limited to the small number of peen and peen distribution due to the memory storage and time consuming. Hence, to bridge the gap in shot peening simulation models, we propose to use User Defined Functions embedded in a multiphase flow simulation module to predict the coverage area of a specimen surface under multiple impacts and overlapping indentations.

In multiphase flow simulations, the Lagrangian–Eulerian (LE) approach is widely used to calculate the properties of carrier airflow and particle motion in many applications [12–15]. The carrier airflow is represented in Eulerian frame of reference using Reynolds-Averaged Navier–Stokes conservation equations, while discrete phase (solid particles) is represented in Lagrangian reference frame by tracking their integrated trajectories through the calculated flow field. The key factor of the LE approach is that it takes into account the influence of turbulent fluctuations on particle drag and dispersion, as well as the influence of solid particles on turbulence of airflow. This is so-called the "particle–airflow" interaction or two-way interaction model. In this study, the particle dispersion process is modelled by treating the turbulent flow as a random field, which is known as the stochastic particle dispersion model [17–19]. The trajectory of the particles is computed using the mean velocity and turbulent fluctuation velocity of the airflow phase. The turbulent fluctuation velocity is simulated as a random Fourier series dependent on fluctuation frequency and turbulent spectrum.

Many different theoretical models have been developed for predicting coverage area, for example, Kirk and Abyaneh model [6,7] and Holdgate model [10]. In the Kirk and Abyaneh model, the coverage is expressed using classical Avrami equation in terms of the ratio of total indent area to the target area. This requires the determination of single dimple area and shot spread area experimentally. The Holdgate model states that if the coverage level of a reference area is known at time t, the coverage after a time interval of *dt* can be predicted. However, this requires the determination of the coverage ratio after an initial interval time of shot peening. Several studies were devoted to deal with the numerical simulation of shot peening process using different approaches. However, most of the works did not focus on the prediction of coverage, but on the general understanding of development of stress state. Even though a few studies focused on predicting the coverage, they were limited by a small number of impacting peens and insufficient consideration of peen velocity and distribution.

Due to the massive operating parameters affecting shot peening performance, it is difficult to analyse all these parameters. Hence, in the present work, only peen velocity, single dimple area and total coverage area will be studied in great details and validated against experimental data.

In this study, the multiphase flow simulations adopting User Defined Functions are performed to predict the coverage area of shot peening process. The paper is arranged in the following: we present our mathematical model in Section 3, numerical method in Section 4, validation study in Section 5, numerical results and discussions in Section 6, and lastly, conclusion in Section 7.

2. Nomenclature

g	gravitational constant (m/s)
P	pressure (N/m^2)
u	velocity of airflow (m/s)
p	pressure of airflow (Pa)
f	external body forces (kg·m/s^2)
E	total energy of airflow (W)
q	total thermal energy of airflow (W)
e	enthalpy of airflow (W)
T	static temperature (K)
M	Mach number
c	speed of sound (m/s)
R	universal gas constant (J/mol·K)
k	turbulent kinetic energy (m^2/s^3)
F_D	drag force (kg·m/s^2)
C_D	drag coefficient
Re	Reynolds number
V_p	velocity of peen (m/s)
d_p	diameter of peen (m)
Δt	time step size (s)
n	current time step
$n+1$	next time step
$n-1$	previous time step
Δ	mesh grid size (m)
N	total number of impacts
a_i	single dimple area (m^2)
A	treated area (m^2)
$\dot{m}$	media mass flow rate (kg/s)
C	coverage area (%)
V_i	impact velocity (m/s)
E_c	empirical coefficient
B	Brinell hardness
e_{norm}, e_{tan}	restitution coefficients
U	instantaneous velocity of airflow (m/s)
t	peening time (s)

Greek letters

μ	dynamic viscosity (Pa·s)
μ_t	turbulent dynamic viscosity (Pa·s)
ν	kinematic viscosity (m^2/s)
τ	stress tensor of airflow (kg/s^2)
γ	specific heat capacity
ω	dissipation rate (m^2/s^3)
ρ_p	density of peen (kg/m^3)
ζ	Gaussian distribution number
θ_i	impact angle (degree)
ρ	density of airflow (kg/m^3)

Subscripts

norm	normal direction
tan	tangential direction

3. Mathematical models and assumptions

In the present work, the so-called "Peen–Airflow" and "Coverage" solvers have been developed for peen–flow interaction and coverage prediction. Fluid carrier is assumed to be compressible ideal gas flow