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Quantitative prediction of critical velocity and deposition efficiency in cold-spray: A finite-element study

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ABSTRACT

Using finite element simulations, we examined the impact deformation of three different particle/substrate systems during cold-spray. A new approach based on the equivalent plastic strain averaged over the impact particle ($\overline{PEEQ}^2$) was employed to analyze the deformation and a rate parameter R_{EQ}, the steady rate of change of $\overline{PEEQ}^2$, was introduced. An excellent correlation between this rate parameter and experimental deposition efficiency is obtained. For the first time, a quantitative prediction of the deposition efficiency for cold-spray has been generated.

Cold gas dynamic spray, or simply cold-spray, has gained great attention as a rapid and versatile coating and additive manufacturing technology [1–3]. During the spray process, powder particles of deposited material are accelerated by an expanding gas stream toward a substrate. Upon impact with the substrate, the particles undergo intense plastic deformation to break the thin oxide films on particles and substrate to induce intimate contact and subsequent adherence of deformed particles on the substrate, and each other, to form a coating [4–6]. One particular signature of cold-spray technology is its low-temperature operation, which brings a few significant advantages such as retention of particle microstructure, minimal substrate modification, and avoidance of particle/substrate oxidation and chemical degradation [1–6]. These advantages make cold-spray an ideal coating technique for temperature-sensitive materials, e.g., polymers [7,8] and nanocrystalline materials [9,10], and oxidation-sensitive materials e.g., aluminum and copper [6,11]. Apart from coatings, cold-spray is also regarded as a promising technology for 3D prototyping and free-form fabrication [2,3,12,13], and provides potential alternatives for electroplating, soldering, and painting [4,14,15].

In cold-spray, the creation of particle/substrate bonding is induced via plastic deformation and thus necessitates sufficient amount of impact energy. As evidenced in various experiments [6,16], there exists a *critical velocity* beyond which sufficient deposition is achieved. Therefore the critical velocity signals *bonding* between the sprayed material and substrate. In the work done by Assadi et al. [16], successful bonding in cold-spray is attributed to the occurrence of the adiabatic shear instability during impact. Through finite element analysis (FEA) simulations, it was demonstrated that the onset of the shear instability is manifested by an abrupt increase in temperature to approach melting for the material at contact interface when the particle velocity is beyond a threshold value. The same concept was echoed by several other studies [11,14,17,18] that followed, and FEA simulations were performed to capture the onset of shear instability in order to predict the critical velocity. However, it was shown in our previous study [19] that the onset of shear instability strongly depends on the environmental parameters in FEA simulations, such as particle/substrate contact conditions and the deformation control techniques, and can be influenced by local perturbations. Thus although the onset of shear instability captures some characteristic material behaviors at high impact velocities, it does not provide a precise measure to quantitatively determine the critical velocity.

After the critical velocity is reached, a subsequent increase in the particle velocity will lead to a rapid increase in the deposition efficiency (defined as the weight of adhered material divided by the total weight of the material sprayed). This upward trend continues till the adverse effects, such as strong erosion [20], develop at high impact velocities, following which the deposition efficiency will quickly plateau or even start to decline with a further increase in the velocity [4,6,20]. The critical velocity and the deposition efficiency curve thereafter are directly relevant to the spraying window and are thus of great technological importance for cold-spray applications. So far the deposition efficiency has been determined on a *trial-and-error* basis, and this lack of predictability

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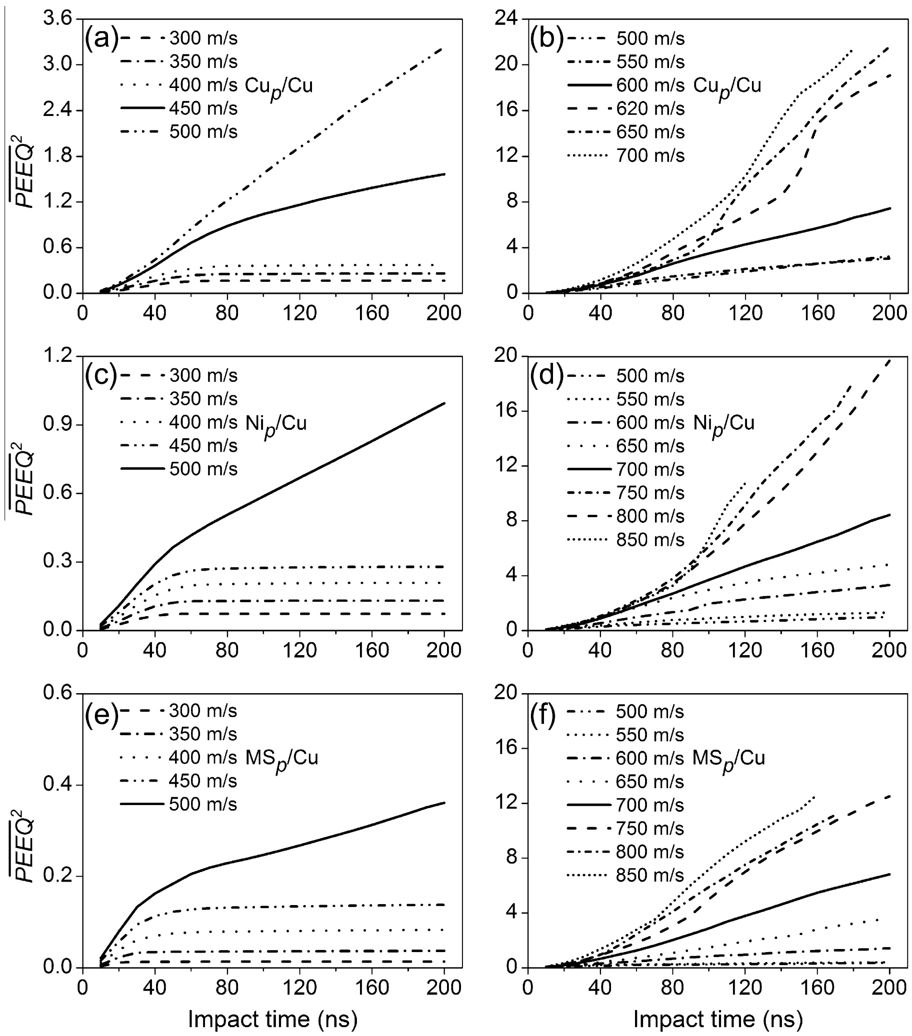

Figure 1. Representative $\overline{PEEQ}^2$ evolution versus impact time curves at different particle velocities, for Cu$_p$/Cu in (a and b), Ni$_p$/Cu in (c and d), and MS$_p$/Cu in (e and f).

incurs substantial cost to prescribe the desired spraying conditions, posing a significant obstacle in the application of cold-spray.

In this work, we present for the first time a quantitative prediction of the deposition efficiency in cold-spray using FEA simulations. A robust measure is invoked to quantify effective plasticity during the particle/substrate impact and to capture key events relevant to bonding and deposition. Our approach is applied to several particle/substrate systems, showing excellent agreement with experimental data, and can be easily transferred to various material couples. Therefore, our findings can help optimize the cold-spray process parameters in a time/cost-effective manner and substantially decrease the cost of cold-spray trial experiments that limit the current industrial applications of cold-spray.

Non-linear FEA simulations using Abaqus/Explicit [21] are employed to simulate the material deformation process during cold-spray (see Supplementary material for details on FEA simulation set-up). An axisymmetric particle/substrate model is used in the FEA simulations, with the substrate being copper while the particle material being either copper, nickel or mild steel (MS). The above selection of particle/substrate systems is based on (i) the availability of experimental data on deposition efficiency [22], and (ii) the comparable deformability of those materials. Here choosing materials of comparable deformability is to avoid the introduction of complex deformation modes, such as embedding, through hard/soft material coupling [11,23]. The elastic response of the material is assumed to be isotropic while the plastic response of the material is prescribed by the Johnson–Cook plasticity model [24] that describes the rate and temperature dependence of material behaviors during the plastic deformation

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

$$T^{*m} = (T - T_{ref})/(T_m - T_{ref}) \quad (2)$$

where σ denotes the flow stress, ε denotes the equivalent plastic strain (*PEEQ*), defined as $\varepsilon = \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl}}\,dt$, with $\dot{\varepsilon}^{pl}$ being the plastic strain rate, $\dot{\varepsilon}^*$ is the equivalent plastic strain rate normalized by a reference strain rate of 1, T_{ref} is the threshold temperature above which thermal softening occurs, and T_m denotes the melting temperature of each material selected (see Supplementary material for details on the model parameterization). The Johnson–Cook model effectively incorporates strain hardening, strain rate hardening, and thermal softening effects, and is widely used to describe the dynamic impact process in cold-spray [11,14,16,17]. The deformation process is considered to be adiabatic in this study as the amount of thermal conduction is negligible due to the thermal diffusivity distance being much shorter than the characteristic dimension of the material system during the fast impact [14,16,18,20] (see Supplementary material for details).

We have demonstrated in our previous work [19] that $\overline{PEEQ}^2$, where $\overline{PEEQ}^2$ is defined as the average *PEEQ* over all particle elements, exhibits characteristics that are prescribed by intrinsic