Numerical analysis of single particle impact in the context of Cold Spray: a new adhesion model

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Abstract. A new adhesion model for numerical simulation of single particle impact in the context of Cold Spray is introduced. As in other studies, cohesive forces are put between the particle and substrate to account for adhesion. In this study however, the forces are put only when a local physical criterion is met. The physical phenomenon most often attributed to Cold Spray adhesion is a shear stress instability. The Johnson-Cook material law is used with a shear damage softening law to enable strong localization at the interface without the need for an extremely fine mesh. This localization is then detected as a drop in local yield stress value by the algorithm, which then implements a local cohesive force. The evolution of this cohesive force is defined by an energy dissipative cohesive model, using a surface adhesion energy as a material parameter. Each cohesive link is broken once all its associated surface energy is dissipated. A criterion on the damage value is also used to break a cohesive bond prematurely, to account for the effect of erosion at higher speeds. This model is found to reproduce the Cold Spray-like adhesion behavior with observed critical and maximum speeds.

1. Introduction

The Cold Spray process consists in coating an object with a thin layer of a metallic or amorphous material by projecting very small particles at high speed in a pressurized carrier gas. It is used industrially to create a coating on a piece of material to give it new surface characteristics, to create a new piece altogether in an additive manner like in 3D printing, but also to repair damaged structures and surfaces easily[1]. The first experiments showed that the projected particles adhere only for certain pairs of particle-substrate materials and within a specific velocity range [1,2]. Many hypotheses, such as the presence of a shear stress instability at the interface upon impact, have been formulated to explain these experimental observations [3]. They were based on the subsequent observation of the microstructures and their association with numerical results giving the histories of temperatures and other parameters at the interface [4].

These numerical results relied mainly on explicit dynamic finite element calculations [5]. However, most finite element calculations are unable to simulate the very significant crushing of soft particles against a rigid substrate or the deep penetration of hard particles into a softer substrate, so they often resort to a remeshing method [3]. Some calculations are based on coupled Euler/Lagrange formulations: these lead to better results when one of the two objects is subjected to very high strains[6].

Solid SPH methods also appear to lead to good predictions in the case of highly distorted meshes. They also enable local material tearing to be easily simulated [7,8]. Nevertheless, the common point of these simulations is that while striving for a precise evaluation of the material behaviour, they do not include any adhesive forces at the interface during the computation, and instead conclude on adhesion based on a post-computation criterion looking at the evolution of different variables [9].

To the author's knowledge, only a few finite element or SPH fast dynamics numerical simulations use tools to account for adhesive forces during impact [7,10]. In [10], a cohesive zone defined by a cohesive stress value is put on the whole contact surface, and the particle is said to rebound when the contact surface drops to zero.

The new adhesion model presented in this paper differs from this approach as it involves: an adhesion activation criterion based on shear stress instability, an adhesion deactivation criterion based on surface energy dissipation, and an adhesion deactivation criterion based on erosion of the elements. It follows a study on adhesion in dynamics impacts, using the same model but without any criteria[11].

2. Numerical model

2.1. Geometry, limit conditions and mesh

A ball of radius R_b=12.5µm impacts a substrate of sides L_s≈73.7µm and height H_s≈33.1µm (approximate values due to the SPH packing method) at a chosen initial velocity. To simulate a semi-infinite substrate, elastic impedances are put on every side but the impacted one.

The SPH method is used to mesh both parts in a hexagonal compact lattice. The SPH particle radius is R_{SPH}=1.25µm. A complete description of the model can be found in [11] and more explanations on the SPH method for solids can be found in [11–13]**.** The coarse mesh used, for quick computations, contains 15776 elements in the substrate and 737 elements in the impacting particle.

2.2. Material law

The material law used for both parts is the common Johnson-Cook law, which takes into account equivalent plastic strain hardening, equivalent plastic strain-rate hardening and thermal softening. Here adiabatic heating is considered with 90% of plastic work converted in heat. A damage softening coefficient D is added to give the final equation (1) and get better localization at the interface, and to account for element erosion and improve general behaviour [10]. For stability purposes, the maximum allowed damage softening coefficient is set as 90% with no element deletion.

$$\sigma_y = \left[A + B\left(\varepsilon_{eq}^{pl}\right)^n\right]\left[1 + C\ ln\left(\frac{\dot{\varepsilon}_{eq}^{pl}}{\dot{\varepsilon}_{ref}^{pl}}\right)\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right](1 - D) \quad (1)$$

The material is aluminum for both parts with the parameters shown in table 1.

Table 1. Material parameters used for Aluminum

E (MPa)	Ro (kg/m^3)	nu	A (MPa)	B (MPa)	C	n	M	$\dot{\varepsilon}_{ref}^{pl}$ (s^{-1})	T_{ref} (°K)	T_{melt} (°K)	K (J/°K)
70.9e9	2710	0.3	148.4e6	345.5e6	0.001	0.183	0.895	1	300	916	904

The shear criterion defined in [14] is used for damage initiation with parameters too long to discuss here but given in input files for the "*Progressive failure analysis of thin-wall aluminum extrusion under quasi-static and dynamic loads*" example available online. A linear increase of damage until a maximum plastic equivalent deformation of 2 gives damage evolution. Discussion on the choice of the damage model is not of interest for this specific short paper but its extreme influence on the results should not be forgotten and is currently under investigation.

2.3. Adhesion model

A cohesive stress is applied between two elements if they have been in contact, have both met the activation criterion, and are separating. The activation criterion is a 30% drop in the local yield stress value. The Lagrange multiplier given by the contact algorithm is used for the cohesive stress value. The

work associated with this stress is updated at every step and compared to the maximum work allowed, defined by the product of an adhesive surface energy G_c=30J.m^{-2}and the surface associated with an SPH particle $\pi*R_{SPH}^2$. When this limit is reached, the bond is broken and the cohesive stress is no longer applied. The bond is also broken if one of the elements of the adhesive link has reached a maximum allowed damage value for adhesion MAXD.

3. Behaviour of the model

Four sets of computations were carried out, all with a final simulated time of around 0.177µs found to be high enough for energy variations to settle down. For each simulation are observed: the number of elements having been in contact, the number of adhesive couples having been activated, the number of adhesive couples having dissipated all of their assigned energy, the number of adhesive couples broken by damage, and the number of adhesive couples still active.

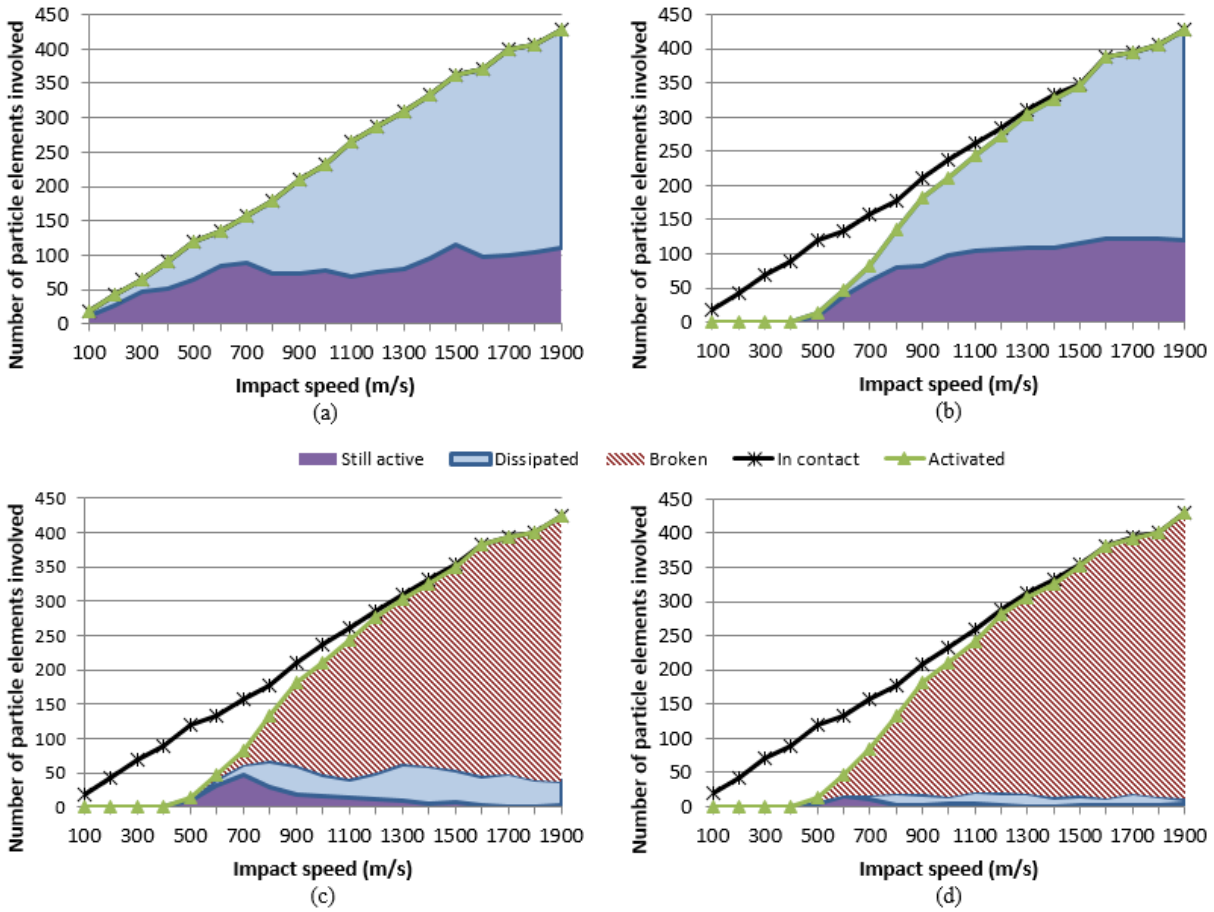

Figure 1. Model behaviour for different sets of parameters

Figure 1 shows the variation of these values with impacting speed for four scenarios. In scenario (a) no activation trigger nor erosion trigger were used, so all contacting elements undergo adhesion and some little adhesion is still present even for low speeds of 100m.s^{-1}, making it difficult to conclude on a critical speed. Scenario (b) shows the effect of the activation criterion based on a drop in local yield stress value. The activated surface is no longer the same as the contacting surface, resulting in adhesion only above 500m.s^{-1}, which can be seen as the critical velocity of the Cold Spray process. The surface under adhesion then converges to the surface in contact at high speeds, meaning that the activation criterion is met on an increasing part of the contacting surface. The number of adhesive links still active at final time however still stabilizes with increasing speed.

In scenario (c) the adhesion erosion criterion is used with a value of MAXD=0.5. The behaviour at low speeds is the same as in scenario (b), but once above 600m.s^{-1}, an increasing part of the adhesive

couples is broken before they can dissipate all their assigned energy. The presence of the deletion criterion results in a drop in the number of active adhesive links at final time with increasing impact speed, to finally get a maximum impact speed for adhesion at around 1700m.s^{-1}. The relation between contacting surface and adhesive surface is however unaffected. Scenario (d) uses a more strict criterion of MAXD=0.4, resulting in nearly no final adhesion over the whole impact speeds range.

The notion of final adhesion is here chosen as at least one adhesive couple being still active, but while convenient this choice is of course not realistic and the notion of "minimal final adhesive surface for sufficient particle adhesion strength" will later be implemented.

4. Summary and further work

A new cohesive model for particle adhesion during the Cold Spray process was introduced. This model where the occurrence of adhesion is based on physical mechanisms is shown to exhibit a sticking velocity window as in experiments, with a different behaviour than models lacking these criteria.

Current and further work includes: the study of the cases of copper/copper, copper/aluminum and aluminum/copper to ascertain the capability of the SPH model to correctly represent the high deformation behaviours for different couples of material; a mesh-dependency study; a complete parametric study to find the range of influence of the different parameters involved. Different criteria based on different physics could also be implemented for the onset and breaking of local adhesive links.

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