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Procedia CIRP 95 (2020) 1015–1020

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20th CIRP CONFERENCE ON ELECTRO PHYSICAL AND CHEMICAL MACHINING

Combining process and machine modelling: A Cold Spray Additive Manufacturing case

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Abstract

Cold Spray is a new addition to the Additive Manufacturing field that uses the kinetic energy of unmelted sprayed particles to build the layers. The process simulation for obtaining the velocity range of the particles is key for improving the adhesion quality. In this study, a modeling approach is presented that divides the overall process into two separate sections calculating in a reasonable time if the initial conditions are suitable. The first section comprises a CFD model from which the velocity range is acquired and the second section comprises an FEA simulation of the particles' impact on the deposition plate.

Keywords: Additive Manufacturing; Cold Spray; Simulation ; Modeling; Metal components; Computational fluid dynamics (CFD)

Table 1: Abbreviations explanation

Abbreviation	Explanation
FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics
CS	Cold Spray
AM	Additive Manufacturing
HVOF	High-Velocity Oxygen Fuel
DPM	Discrete Phase Method
CAD	Computer-Aided Design
PEEQ	Equivalent Plastic Strain
Al	Aluminum

1. Introduction & Process mechanism

Cold Spray (CS) is a material deposition process that has been successfully used as a coating method in the past [1]. CS can be used to produce coatings of a wide variety of metals, metal-based composites, and alloys, including those materials that have high melting temperatures (e.g. tantalum, niobium, superalloys). Furthermore, the process is also suitable for depositing materials that are extremely sensitive to the presence of oxygen and will readily oxidize at modest temperatures thus affecting the performance of the produced parts/coatings. Examples of oxygen-sensitive coatings that are commonly produced with CS are aluminum, copper, titanium, and carbide composites (e.g. tungsten carbide) [2] and last but not least, coatings made from amorphous alloys [3]. Additional developments in CS are related to the deposition of ceramic materials on metals, notably titanium dioxide for photocatalytic effects. In addition, CS has significant potential to be used as an Additive Manufacturing (AM) method [4], [5], having the advantage not to downgrade the mechanical properties of the finished product unlike thermal spraying techniques, e.g., plasma spraying, arc spraying, flame spraying, or high-velocity oxygen fuel (HVOF), where the powders are molten during the spraying process [6],[7]. In addition, CS use can be enhanced by the expanding use of AM in the industry for components in critical areas e.g. aerospace, automotive/motorsport industry [8], [9].

2212-8271
10.1016/j.procir.2021.01.178

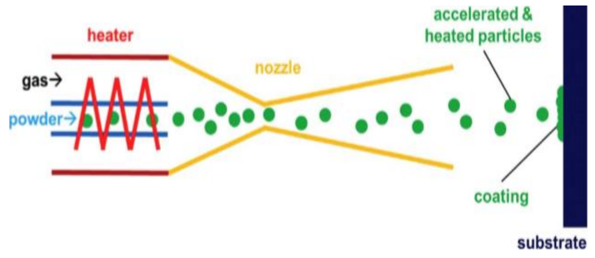

Fig. 1. Schematic of cold spray process.[7]

During CS, solid powder particles (1 to 50 micrometers in diameter) are accelerated to supersonic velocities using the expansion of a gas jet at high pressure. The kinetic energy of the particles, supplied by the gas, is converted to plastic deformation energy during impact with a substrate, and the particles adhere to the surface [7],[10]. To achieve a uniform thickness, the spraying nozzle is scanned along the substrate.

2. Motivation

The CS process is a new member of the AM methods thus there is a need for further analysis in order to optimize the finished product. The CS deviates from existing methods, in terms of modeling the individual steps of the process e.g particle acceleration in the nozzle, particles impact on the deposition plate which leads to a complex, time-demanding approach. The target of the research was to create a process model that can be easily utilized in order to determine the final result of the process in reasonable time only by knowing and controlling the same process parameters one would control on the physical equipment, like gas pressure and temperature, powder particles temperature, and diameter. This allows an understanding of the impact of each of the abovementioned parameters make at the particles' speed and temperature and therefore controlling the adhesion quality. The main difference is that there is no need to investigate the velocity of the particles and thus there is no need for an experimental process based on velocity step increment or through trial and error.

3. State of the Art

Additive manufacturing using cold spray technology can be used to develop parts and components rapidly with deposition rate [2], being faster than other additive manufacturing methods. In addition, there is no need for inert gas or a vacuum-sealed environment for the parts while being manufactured, thus allowing the creation of much larger structures. Manufacturing with cold spray technology provides advantages such as extended design freedom, a more efficient buy-to-fly ratio when compared to machining, and capable of fusing dissimilar metals to create hybrid metal parts. Although CS expands the field in terms of manufacturing freedom and materials that can be used, this creates extensive effort in analysing the parameters of the process. Due to the complex nature of the process, the numerical method has a fundamental role in studying particle behavior [11], [12]. The main assumption that needs to be taken into account is that the particles typically have a spherical shape [13]. Regarding the CFD analysis, the Reynolds Average Navier-Stokes equation along with the realizable k-ε turbulence model for the fluid was selected, which are used to eliminate the possibility of unstable behavior of the fluid, in boundary regions close to the wall [14]-[17]. Concerning the simulation of the high-velocity impact of the particles on the substrate, the explicit finite element analysis is used for both 2D and 3D models. Based on literature 2 main models are used in the explicit analysis. In all methods, mesh refinement is used in critical areas and uniform mesh in the impact region of the substrate [18]. The Lagrangian formulation is used to control manually the velocity of the starting from a low value, usually subsonic, with a specific increment up to supersonic range [19]. Also, in order to simulate the interactions within the particle domain such as particle to particle and particle to the substrate interactions, the Johnson-Cook plasticity model is implemented [20]. To avoid the problem of highly distorted elements in the Lagrangian analysis, some cases use the Eulerian formulation which is effective for extreme deformation as a result of fixed elements/nodes in space, through which material flows [21].

4. Approach

Due to the complexity and thus the high demand for the computational power of the complete model analysis, the cold spray model was split up into two separate simulations. The first one was a CFD analysis to determine the particle velocity and the mass concentration and the second one was an explicit analysis regarding the impact of the particles on the deposition plate. The modeling of the process is presented in distinct steps in Fig. 3.

4.1. Case configuration

To deliver powder on the deposition plate, one nozzle was placed in the normal direction and close proximity to the processing area. The purpose of this device is to provide an adequate flow of metal powder, heated below the melting point, with high relative velocity to the plate in order to achieve adhesion due to plastic deformation and thus build-up rate targets, while at the same time creating a powder "spot" of the required dimensions.

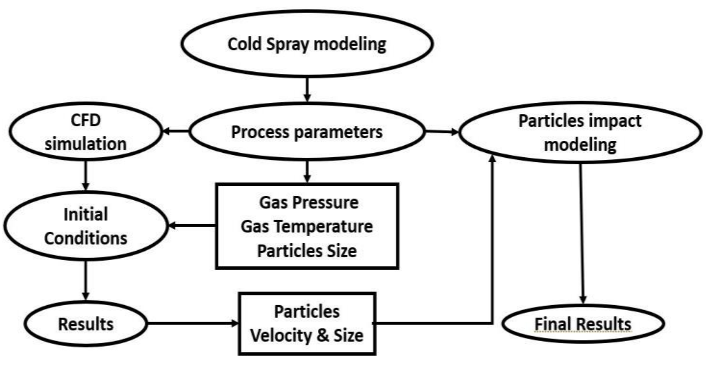

Fig. 2. Proposed model schematic

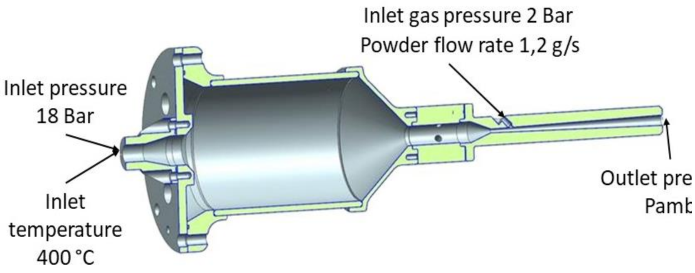

Fig. 3. Nozzle geometry

The deposition nozzle consists of a convergent-divergent geometry with different inlets for the carrier gas and the powder. In the first segment, the carrier gas enters the nozzle and accelerates up to the diverging point of the nozzle where the injection of the powder happens.

4.2. Gas flow simulation

The first iteration consists of the system as described, with the addition of a deposition plate added to the fluid domain but without any injection of particles. This was done in order to observe the behavior of the carrier gas, as the presence of the plate is expected to have a high influence on gas behavior, especially close to it. The simulation was run in a steady-state mode. Based on the research of W.-Y. Li et al. on the effect that standoff distance creates on coating deposition characteristics and relative deposition efficiency in cold spraying applications, the selected standoff distance to perform the simulations was 12mm due to the relative deposition efficiency which aluminum particles have at that distance [22]. In addition to this, in order to directly compare the results with already existing experiments thus verifying them the research of Wen-Ya Li and Wei Gao on 3D numerical modeling of the high-velocity impact of particles in cold spraying by explicit finite element analysis where simulations with the same material (aluminum Al 1100) were performed [19]. The initial boundary conditions (carrier gas pressure, temperature) that were used to set the baseline of the model have also been extracted from literature [23]-[26]. The results are presented in Fig. 4.

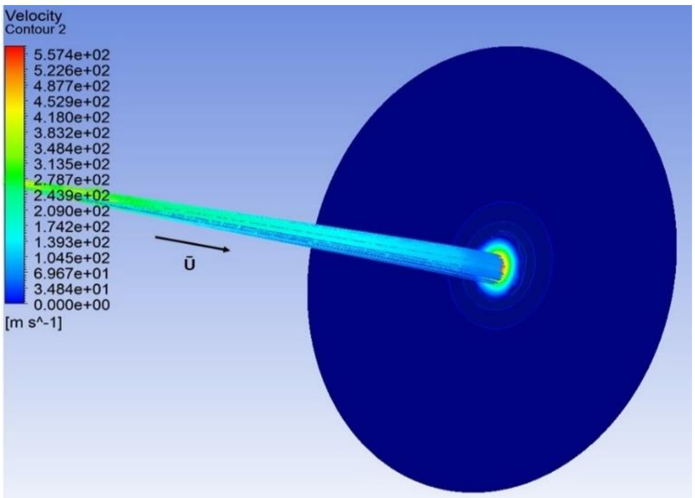

Fig. 4. Velocity of the carrier gas

For the first iteration, a series of important conclusions were drawn. To begin with, the velocity reached by the carrier gas when exiting the nozzle was calculated as there was information for only the inlet pressure of the system. Also, the interaction with the deposition plate and the distribution of the pressure on the deposition plate was studied.

4.3. Gas and powder flow simulation

Having established in the 1st iteration that the velocity of the carrier gas was within the theoretical limits of the process as found in the literature [1], [7], [11], [13], the injection of powder particles was introduced to the simulation for the 2nd iteration. Table 1 summarizes the boundary conditions used. The insertion of the particles was done utilizing the discrete phase model (DPM) of ANSYS, which allows for dilute particulate flows to be simulated.

Table 2. Boundary conditions

Parameter	Value
Inlet air temperature	400 °C
Inlet air pressure	18 bar
Environmental pressure	101325 Pa
Environment temperature	20 °C
Powder particle size	25 μm (average)
Powder mass flow	1.2 g/s
Powder material	Aluminum
Powder initial temperature	25 °C
Powder inlet pressure	2 bar
Deposition plate standoff distance	15 mm
Deposition plate temperature	20 °C
Angle between nozzle and plate axis	0°

From this simulation particle trajectories, particle velocity vectors, and particle concentration on the deposition plate, were extracted. Fig.4 and Fig. 5 present the trajectories of the particles, starting from the injection point. There is no initial injection velocity, but the injection occurs due to the pressure difference between the powder tank pressure and the pressure inside the nozzle at the location of the injection.

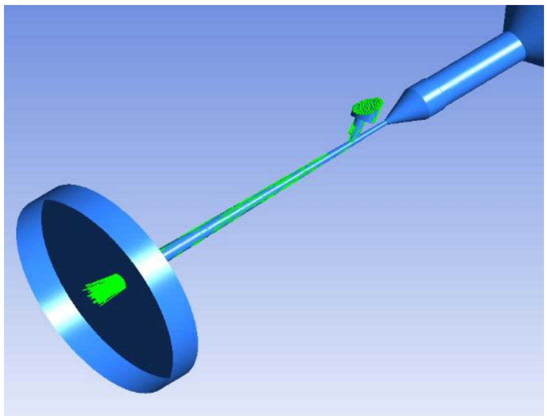

Fig. 5. Particle trajectories from the powder inlet until the exit of the nozzle

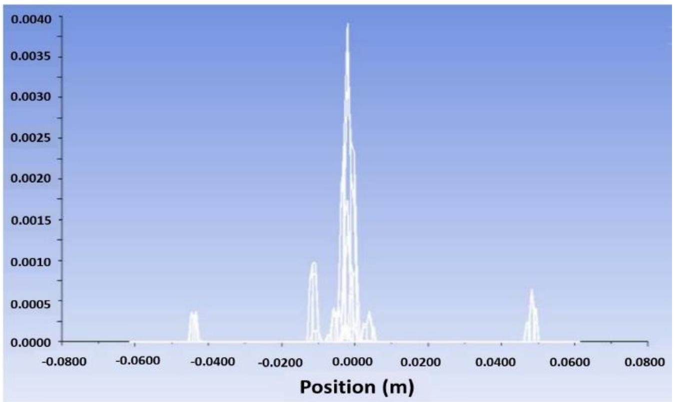

Fig. 6. Particles concentration on deposition plate at on Y-Z plane

In addition, the concentration of powder particles on the deposition plate is presented in Fig. 6. It is clear that the higher values are within -0.015 and 0.005 m from the centerline of the injection and it is almost on 0 as moving away from this area. Also, there are some extra spots at -0.045 and 0.048 m respectively with a small amount of particle concentration which is due to the interaction with the inner wall of the nozzle and the particle collisions. The values on the vertical axis in Fig.6 refer to the average concentration of the particles (in kg) reaching the deposition plate at each time step.

Regarding particle velocity, the achieved values close to the area of interest (-0.015-0.005 m) are in the limits of the cold spray process as found in the literature [1],[7],[11],[13], so the selected process parameters are deemed satisfactory.

4.4. Particles impact modeling

Due to the fact that there was no practical way to directly link the two models in order for the output of the first model to be used as input for the second one some necessary simplifications and assumptions have to be taken into account. The first assumption is that the particles will have a spherical shape, In addition to this, the quantity of the data such as the velocity distribution, the temperature of the particles, the particles interactions and the trajectories which are being presented in Fig. 6 have to be taken into account. Finally, the last assumption and simplification concern the particle distribution which also contains information both for the mass distribution and particle sizes. First, observing Fig. 7 containing the scalar of particles velocity before hitting the deposition plate, four main areas are distinctive. Thus, from the sidebar with the velocity magnitude, four average velocities can be extracted, listed below, to be used as inputs in the explicit analysis part.

- Blue region, 150m/s
- Green region, 250m/s
- Yellow region, 430m/s
- Red region, 550m/s

The particles at the second stage of the modeling (explicit analysis) were not auto-generated by the software but they have to be introduced from the geometry file itself (CAD file).

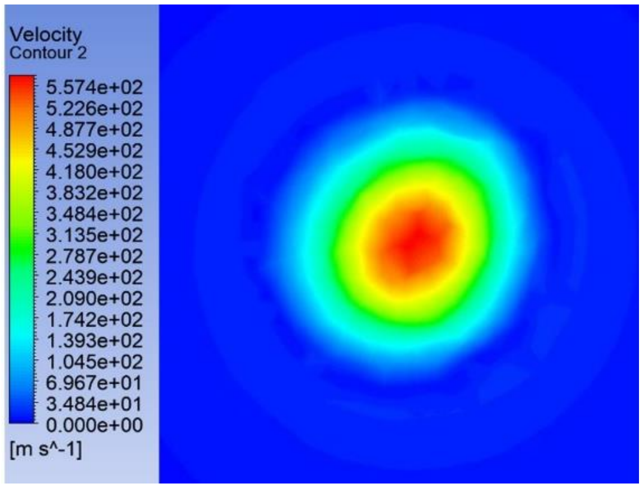

Fig. 7. Particles velocity magnitude before hitting the deposition plate

In addition, due to the fact that there was a variation in the diameter of the particles from 5 to 45 um with an average of 25 um, these values were chosen as benchmark values and thus a simulation for each velocity and particle diameter was performed. This method helped at defining which was the necessary velocity and diameter in order to achieve adhesion with the deposition plate. The results are summarized in Table 2. It can be observed that by using a 5-um particle size there is an indication of adhesion with the deposition plate only at the highest speed. In addition, when using a 25- and 45-um particle size, some particles adhere to the deposition plate at 430 m/s and some only to other particles and bounce back from the deposition plate. In the real world, this is also affected by the particle to particle collisions and thus the only conclusion that can be extracted is that there are the possibility and capability of adhesion. Finally, at 550 m/s the majority of both 25 um and 45 um size particles adhere to the deposition plate.

Table 3. Results of particle size vs. velocity

Velocity	5 microns	25 microns	45 microns
150 m/s	Minor plastic deformation no adhesion	Minor plastic deformation no adhesion	Minor plastic deformation no adhesion
250 m/s	Minor plastic deformation no adhesion	Plastic deformation of the particles but no adhesion	Plastic deformation of the particles but no adhesion
430 m/s	Plastic deformation but no adhesion	Plastic deformation and partial adhesion	Plastic deformation and better adhesion than 25-um
550m/s	Plastic deformation and partial adhesion	Plastic deformation and good quality adhesion	Plastic deformation and finer adhesion than 25-um

In order to perform all the simulation in a reasonable time, 3 different CAD files were created with the same number of particles, changing only the particle diameter and particle to particle distance for each selected diameter respectively. When all the results were gathered, additional geometries were created in order to re-evaluate the results from the simulations at which there was an indication of adhesion. Thus, there was a higher accuracy of the particle to particle interactions and particle to deposition plate interactions. Also, a better estimation of the adhesion efficiency can be extracted due to the greater number of particles, aiding to identify the probability for adhesion in real conditions. In addition, the greater number is adding to bridge the gap over the difference between the number of particles that are automatically generated at the CFD simulation and the explicit analysis, at which the particles are introduced from the geometry file. In order to conform as much as possible with the CFD results both the final number of the particles and the approximate dimensions of the deposition plate were estimated based on the CFD results and more specifically on the DPM concentration on the X-Z plane.

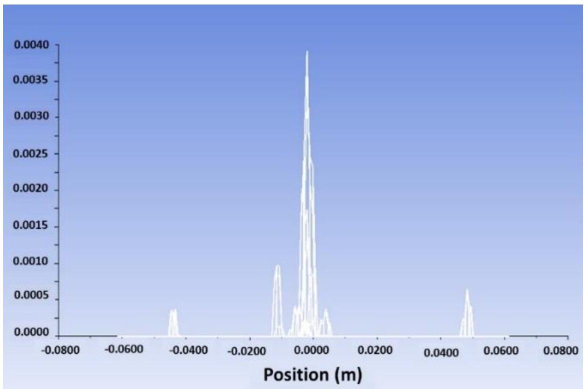

Fig. 8. Particles concentration on deposition plate at X-Z plane

To match the numbers from the image above Fig.8, the dimensions for the deposition plate were chosen as circular cross-section with a 0.6mm radius due to the higher concentration that is observed from -6mm to 6mm thus providing a reasonable simplification regarding computational resources. To calculate the average number of particles to introduce to the explicit simulation, the average number from the graph presented in Fig.8 was divided with the density Al 1100.

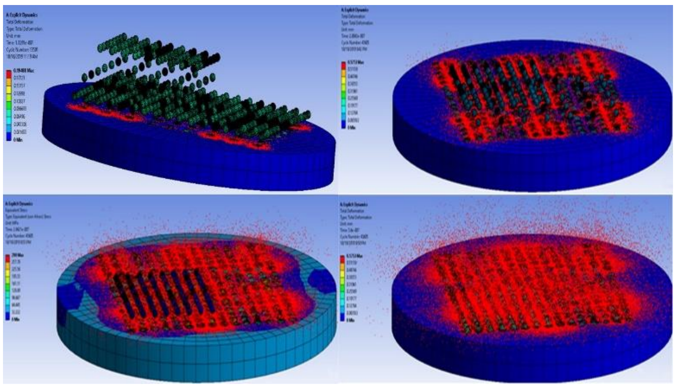

Fig. 9. Particles behaviour during the impact to the deposition plate

5. Validation

Due to the use of different nozzle geometries in other cases, the CFD results may differ completely among other cases. Also, due to the range of velocities indicated from the CFD section was among other studies range, the section of the 3D model which deemed the most critical was the impact on the deposition plate and thus there was a need to validate the results it produces. For validation Al-1100-H12 aluminum alloy (commercially pure Al) was adopted which was used in a similar study [19]. This study was chosen to compare the results due to the contiguous parameters of the problem such as spray angle, particle size, and material (aluminum is the material used in this case study). The initial conditions of the study were modeled with the developed 3D model. The results are presented in Fig. 10 and Fig. 11.

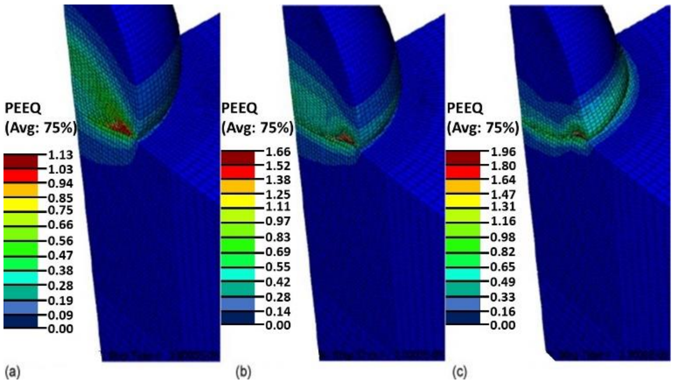

Fig. 10. Simulated contours of PEEQ for a 20 μm Al1100 particle impacting at 300 m/s (a), 350 m/s (b) and 400 m/s (c) [19]

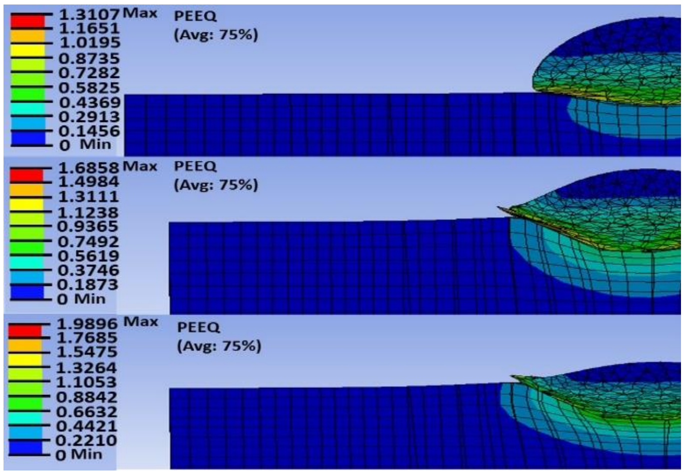

Fig. 11. Simulated contours of PEEQ for a 20 μm Al1100 particle impacting at 300 m/s (a), 350 m/s (b) and 400 m/s (c) using developed 3D model

Conclusions

Using this method, splitting the modeling of the cold spray process in two separated simulations with the necessary simplifications and knowing the implications this generates at the results, it is established that plastic deformation and adhesion between the particles and the deposition plate, with the provided initials conditions as shown at Fig.3 (particle size, temperature, pressure inlet, etc.) occurs in specific conditions mentioned above. Although the modeling of the process showed promising results, future work is recommended in order to achieve higher accuracy of the results which are already deemed satisfactory.

Based on the results from both simulations, further analysis could be performed as future work with more particles in random positions relative to each other in an effort to increase the number of possible real case scenarios that being simulated. Moreover, another field for future work is simulations with velocities in more than one axis to achieve particle to particle collision before hitting the deposition plate. Regarding the deposition plate, in order to reduce the number of assumptions and simplification of the proposed model, surface roughness could be introduced to the simulations which could be also useful to directly compare and quantify how much of a difference does the surface roughness. Furthermore, CFD simulations could be performed with higher gas pressure to achieve higher particle velocities and thus achieve sufficient requirements in the whole range of velocities and not only at the higher limits. Last but not least, an increase in available computational power to be able to simulate an even greater number of particles using even more fine mesh settings could contribute to both the reduction of the required time to perform the simulations and improving the accuracy of the simulation results.

Acknowledgment

This paper is partially supported by the European Union’s Horizon 2020 research and innovation programme, under the “AVANGARD – Advanced manufacturing solutions tightly aligned with business needs” project, Grant Agreement no. 869986.

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