

COLD SPRAY ADDITIVE MANUFACTURING OF POLYMERS: TEMPERATURE PROFILES DICTATE PROPERTIES UPON DEPOSITION

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ABSTRACT

The cold spray additive manufacturing process enables deposition of coatings and structures by impact bonding microparticles to surfaces through preheated, nozzle-accelerated gas flow. Most established models of gas-particle heat transfer in cold spray assume lumped thermal capacitance, which ignores particle temperature distributions and is typically valid for metals. However, recent advances in cold spray consider polymeric systems that differ categorically and considerably in thermophysical properties compared to metals. Particularly, the low Biot number (Bi) assumption may be invalid, impacting efficiency and quality of polymeric particle deposition. We describe herein a 1D transient gas-particle heat transfer model that simulates temperature profile evolution in a representative particle traveling through a cold spray nozzle. With this model, we simulated thermal histories of polymeric materials at realistic processing conditions. Polymer sprays with Bi consistently near 10^{-1} or greater demonstrated thermal inhomogeneities, in some cases straddling the glass transition temperature. Thermal stratification provides insight into physical conditions of a particle before deposition, which can guide processing parameters to improve deposition efficiency and quality of polymer cold sprays.

1. INTRODUCTION

1.1 Cold Spray

Cold spray was first discovered by Russian scientists in the 1980s, and has been widely studied to deposit a wide variety of metal coatings on surfaces at high deposition rates [1]. The cold spray process uses high-velocity gas flow to accelerate micron-sized particles, subsequently impacting them on a surface. The impact causes plastic deformation between the particle and surface, and with some probability termed the deposition efficiency (η_D), effects a bond between the particle and substrate for particle velocities exceeding a material-specific critical velocity (V_c). Gas conditions are tuned to avoid the melting phase change of the material in the process; accordingly, the process is termed “cold” spray and relies (macroscopically) on kinetic energy instead of thermal energy to achieve interlayer bonding. To impart this kinetic energy, an aerosolized stream of particles is combined with hot gas and accelerated through a nozzle. Converging nozzles are used to achieve (sub)sonic gas conditions, and converging-diverging nozzles are used to obtain supersonic conditions [2]. Nozzle choice depends on the critical velocity requirements.

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To date, research in cold spray has focused on metal coatings [3]. The cold spray of polymers has received less attention, with a few research groups demonstrating polymeric deposition in recent years [4-9]. Reported deposition efficiencies for polymers rarely exceed a few percent, while metals have reached nearly 100 % [4-7, 10]. Bush et al. demonstrated and characterized the deposition of semicrystalline high-density polyethylene (HDPE) [5], and subsequent work by Khalkhali and Rothstein reports extremal η_D approaching ~10 % for HDPE sprayed on to LDPE [8]. The deposition efficiency improved with increasing particle preheat and substrate temperatures; however, the particle temperatures were limited by the cold spray apparatus used. Thus, there are still unexplored process conditions that could be optimal for deposition. For instance, changing the nozzle geometry results in different temperature profiles as discussed herein. This temperature profile may have substantial impacts on deposition, especially above the glass transition temperature (T_g) of a given polymer.

Below T_g polymers are glass-like, with little motion of individual polymer chains. As the temperature rises above T_g , polymer chains move more freely and the material becomes less elastic. Amorphous polymers typically experience a decrease in elastic modulus by a factor of ~1000 in the glass transition range [11]. From this change in properties around the T_g , we hypothesize that the deposition efficiency can be greatly improved in the cold spray of polymers by carefully manipulating the spray conditions to bring portions of a polymer particle well above T_g . Therefore, modeling particle temperature as a function of spray conditions is an important prerequisite to achieving desired particle temperatures upon impact.

1D modeling has been used to rapidly simulate the temperature evolution of a representative particle as it traverses a nozzle and predict its temperature upon impact [5, 12-14]. Champagne and Helfrich coupled the 1D equations to a deposition efficiency model to determine optimal particle size [14]. Each of these models assumes lumped thermal capacitance, which implies essentially uniform temperature throughout the particle. However, this assumption is only valid when the particle Biot number (Bi), described by Equation 1, is less than 0.1.

$$Bi = \frac{h_c L_c}{k} \quad [1]$$

L_c is a characteristic length defined as the ratio of the object volume to surface area, h_c is the convective heat transfer coefficient, and k is thermal conductivity of the particle. The Biot number is the ratio of conduction resistance L_c/k to convective resistance $1/h_c$. For a sphere, L_c is equal to one third of the radius R [15]. The rate of heat transfer inside a particle is markedly slower than the heat transfer to or from the edge in contact with fluid at values greater than ~0.1 [15]. Thus, a temperature gradient may exist depending on the timescale the object is subject to heat transfer. In micro-scale metallic particles assuming lumped capacitance is typically valid, meaning the entire particle can be treated as one temperature. However, this is not always the case in thermal spray processes. For polymers and ceramics, the Biot number tends to be close to or greater than the 0.1 threshold. Katanoda showed that a substantial temperature difference exists in cold sprayed Al_2O_3 and Ti6Al4V particles [16]. Ivosevic and colleagues showed that polymers in an High-Velocity Oxy-Fuel process (HVOF) exhibit extremely non-uniform temperature profiles [17]. Previous

works studying polymers in real cold spray systems have utilized 1D Isentropic models assuming lumped capacitance to estimate average particle temperatures upon impact. While proving to be a useful tool, these models ignore the expected temperature inhomogeneities in polymer particles. Bush et al. assumed a lumped capacitance model in making predictions for their experiments, but acknowledged that 3D temperature profiles may be crucial for accurate modeling of impact simulations [5].

Herein, we developed a model to simulate the temperature profile inside a representative spherical particle as it travels through high-speed nozzles characteristic of cold spray processing. We demonstrate with our results that the lumped capacitance assumption is not appropriate for the cold spray of polymeric systems by simulating temperature stratification in an experimentally demonstrated spray. A second hypothetical nozzle designed to spray polystyrene is used to demonstrate the substantial effects of a temperature distribution in an amorphous polymer. The range of temperatures observed in a particle may fall within the glass transition range of a given polymer, resulting in heterogeneous mechanical properties through a particle. Around the T_g , the mechanical properties change considerably in a 20 °C to 30 °C window [11]. Therefore, we expect temperature distributions to have profound implications on spray quality and deposition efficiency. The results herein can be used in conjunction with impact simulations to better understand the effect of temperature stratification on deposition physics, with the goal of maximizing deposition efficiency and deposition quality in polymer cold spray systems for additive manufacturing.

2. SIMULATION

2.1 Stratified Temperature Modeling

For transient heat transfer processes, Geankoplis and Bird et al. outline the shell balances for several geometries [15, 18]. When applied to a sphere, the unsteady-state energy transport equation as a function of radius r and time t becomes Equation 2.

$$\frac{\partial T}{\partial t} = \frac{-1}{4\pi\rho C_p r^2} \frac{\partial(Q_r)}{\partial r} \quad [2]$$

Where T is the temperature, ρ is the particle density, C_p is the particle heat capacity, and Q_r is the total heat flow at r . Q_r is described by Equation 3, where k is the thermal conductivity of the particle.

$$Q_r = -4\pi r^2 k \frac{\partial(T)}{\partial r} \quad [3]$$

To solve these equations, we employed the numerical method of lines. Equation 4 gives the boundary condition used to solve for the center of a sphere.

$$\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0 \quad [4]$$

Similarly, boundary conditions are needed for the surface of the sphere at the outer radius R . The heat transfer at the edge of the sphere is modeled using the convective heat transfer coefficient h_c . Equation 5 gives the condition for the surface of a sphere.

$$-k \frac{\partial T}{\partial r} \Big|_{r=R} = h_c(T_R - T_\infty) \quad [5]$$

The initial condition for time ($t = 0$) for particle temperature assumes a uniform temperature through the particle.

2.2 Particle Velocity and Gas Modeling

Particle motion was modeled by integrating the acceleration function derived from Newton's second law in Equation 6 [19].

$$\frac{dV_p}{dt} = \frac{\pi C_D \rho_g D_p (V_g - V_p) |V_g - V_p|}{8m} \quad [6]$$

Where V_p is the particle velocity, V_g is the gas velocity, m is the mass of the particle, D_p is the diameter of the particle, C_D is the drag coefficient, and ρ_g is the gas density.

C_D was calculated using correlations from Henderson that account compressibility, and span the subsonic, supersonic, and transition flow regimes [20]. The convective heat transfer coefficient was calculated using the Ranz and Marshall model [21]. The isentropic flow equations described by Shapiro were used to model the gas [22]. Champagne and Helfrich outline the 1D method used herein in detail [14, 19]. It was assumed that the gas properties remained constant from the end of the nozzle to the bow shockwave before the substrate. At the shockwave, the Mach number was assumed to decrease linearly to zero at the substrate [19]. The shockwave location was estimated using Billig's approximation given by Equation 7 [19, 23].

$$\Delta = 0.143 D l \left[\exp \left(\frac{3.24}{M_e^2} \right) \right] \quad [7]$$

Where Δ the distance from the bow shockwave to the substrate, Dl is the nozzle diameter at the exit, and M_e is the Mach number at the nozzle exit.

The gas properties were calculated as a function of the linearly decreasing Mach number with the isentropic gas equations and reservoir conditions [19].

2.3 Numerical Integration

MATLAB version R2019a was used to program the simulation. Equation 6 was integrated using the Runge-Kutta 4 algorithm. A time step of 10^{-6} s was used from the entrance of the nozzle to the bow shockwave, and a time step of 10^{-9} s was used after the shockwave. The particle temperature partial differential equation was solved using the numerical method of lines. One hundred

temperature nodes were used for polymer particles, and 20 were used for the metal particles. The temperature equations were integrated using the ode45 function in MATLAB.

2.4 Physical Properties and Modeling

When available, data from previously simulated results or real experimental setups were used. The thermal conductivity, heat capacity, and density of each particle were assumed to be constant. Gas thermal conductivities and viscosities were assumed to be a function of only temperature except for the helium case, where the constant viscosity of $1.86 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$ from Marrocco et al. was assumed [13]. Sutherland's law was used to model the viscosity for other cases [24]. The heat transfer properties for air and nitrogen were taken from data compiled in Incropera [15]. Table 1 outlines the model setup for the conditions studied.

Table 1. Nozzle dimensions and gas conditions

Nozzle	Tr , (°C)	Pr , (kPa)	Lc , (mm)	Lt , (mm)	Ld , (mm)	De , (mm)	Dt , (mm)	DI , (mm)	Ls , (mm)	Gas
HDPE (1)	70, 100	250	23.9	26	0	9.5	1.6	1.6	15	Air
PS (2)	127	400	29.9	0	2.97	9.5	1.6	1.7	15	Air
Ti (3)	25	2900	-	-	100	-	2.9	8	-	He
Al (4)	300	3000	30	0	180	20	2	6	-	N ₂

Tr and Pr are the reservoir temperature and pressure, respectively. Lc , Ld , and Lt are the converging, diverging, and throat lengths. De , Dt , and DI are the entrance, throat, and exit diameters. The standoff distance is denoted as Ls . Figure 1 represents the simple conical nozzle geometry used in the simulation. The distance denoted in later figures is the distance from the nozzle inlet.

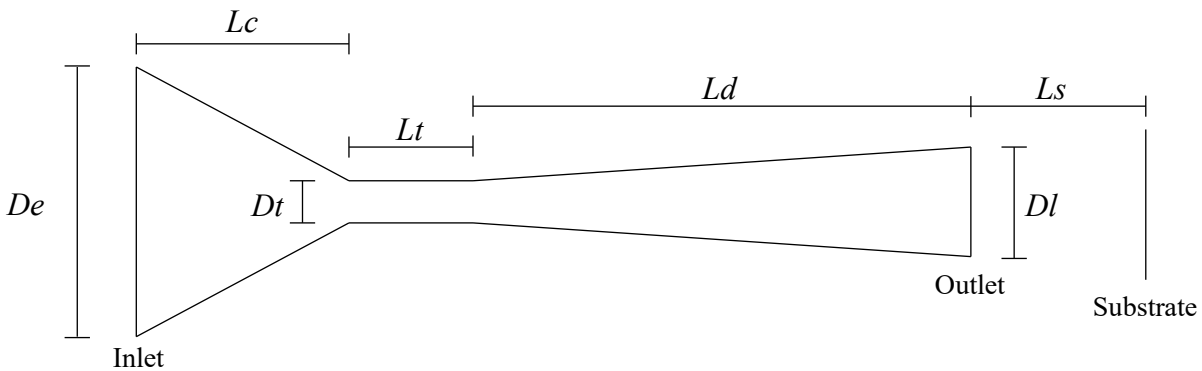


Figure 1. Representation of the simple conical nozzle geometry

Nozzle 1 is a geometry designed by Bush et al., who used the nozzle to cold spray HDPE. The spray conditions simulated included a maximum temperature condition limited by the experimental setup [5]. Several theoretical conditions with independent initial particle temperature and gas reservoir temperature were also modeled. Nozzle 2 is similar to a design used by Bush; however, the experimental conditions used for modeling were not from actual experimental

conditions [25]. The inlet pressure and temperature to achieve reasonable target particle temperatures and impact velocities from the results of Khalkali et al., who used a polystyrene particle size of 44 μm in single impact studies [6]. The larger 90 μm particle size was simulated to study the effect of changing particle size on the temperature distributions. Two metal particles were simulated from experimentally demonstrated conditions. The titanium conditions were replicated from a report by Marrocco et al., and the aluminum conditions were from Jenkins et al. [13, 26]. The material properties of the particles are given in Table 2.

Table 2. Material properties of simulated particles

Material	Thermal Conductivity (W/mK)	Heat Capacity (J/kgK)	Particle Density (kg/m ³)	Particle Diameter (μm)
HDPE (Nozzle 1)	0.49	2250	990	48
Polystyrene (Nozzle 2)	0.163	1460	1000	44, 90
Titanium (Nozzle 3)	21.6	528	4500	47
Aluminum (Nozzle 4)	234	1005	2700	40

The properties for HDPE are the same as Bush used for their simulations [25]. The density and thermal conductivity of polystyrene at 350 K were from Algaer and assumed to be constant [27]. The heat capacity value for polystyrene is from Incropera [15]. Titanium properties were those used by Marrocco et al. in their simulations [13]. The thermal conductivity and heat capacity values for aluminum were taken from Incropera at 250 °C, and the density at 27 °C [15].

2.4.1 Assumptions

The following assumptions apply to the nozzle model:

1. The gas flow is isentropic and frictionless
2. The particle has zero initial velocity
3. The particle does not affect gas temperature or velocity (one-way interaction)
4. The initial particle temperature distribution is uniform
5. The gas returns to reservoir conditions at the substrate

3. RESULTS

3.1 Polymeric Temperature Profiles

3.1.1 HDPE in a sonic nozzle

Four cases for the HDPE particle were modeled with varying initial particle temperature T_{po} and reservoir temperature T_r . The gas velocity, pressure, and temperature for the sonic nozzle spraying HDPE are reported in Figure 2. It was assumed that the Billigs approximation applies to this case, and the Mach number decreases linearly from 1 to 0 at the predicted location. Because the gas is sonic, there is no step change in properties at the estimated shock location. Although more complex phenomena contribute to the gas property profiles, this assumption lets us model the nozzle up to

the point of impact in a computationally inexpensive way and gain valuable insight into the heat transfer and temperature-dependent property changes experienced by the particles.

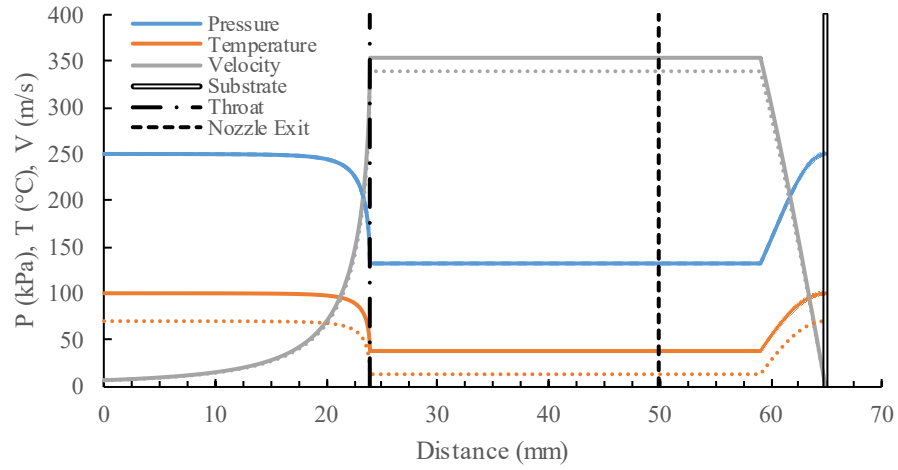


Figure 2. Gas pressure (P), temperature (T), and velocity (V) profiles through the sonic nozzle with a Tr of 100 °C (solid line) and Tr of 70 °C (dotted line).

Figure 3 presents the particle velocity profiles corresponding to these gas conditions. The higher reservoir temperature condition resulted in slightly faster particles.

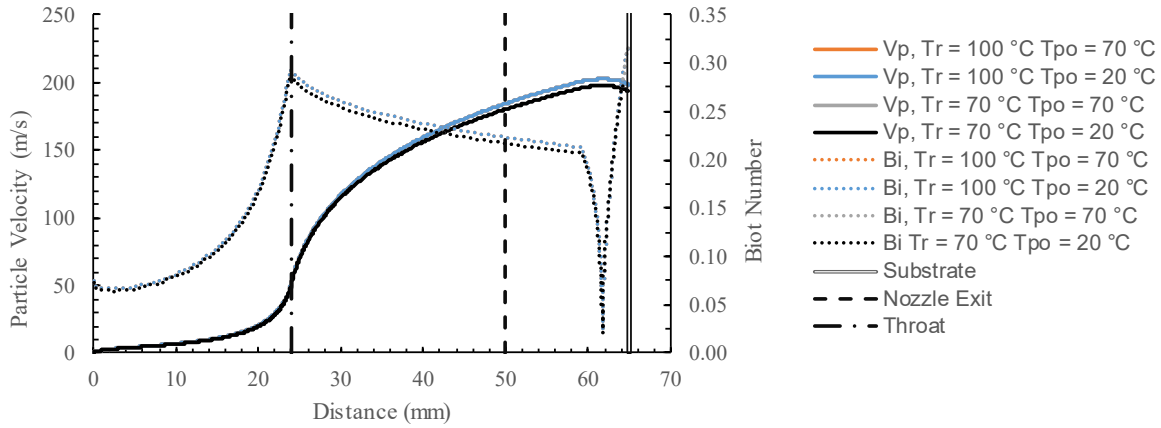


Figure 3. Particle velocity (Vp) and Biot number profiles of HDPE particles subject to the gas conditions in Figure 2.

Particles with the same reservoir temperature condition have velocity profiles and Biot numbers that overlap. The orange and blue lines overlap, and the black and grey lines overlap. The Biot number changes along the nozzle because it is a function of the velocity difference between the particle and gas. The low Biot number observed at 62 mm is a result of the gas velocity matching the particle velocity. This matching velocity results in a minimum convective heat transfer coefficient, hence the Biot number achieves a minimum. The particle spends a considerable time at relatively large Biot numbers, indicating a potential temperature inhomogeneity within the particle. Figure 4 shows the resulting internal temperature profiles at several discrete radii.

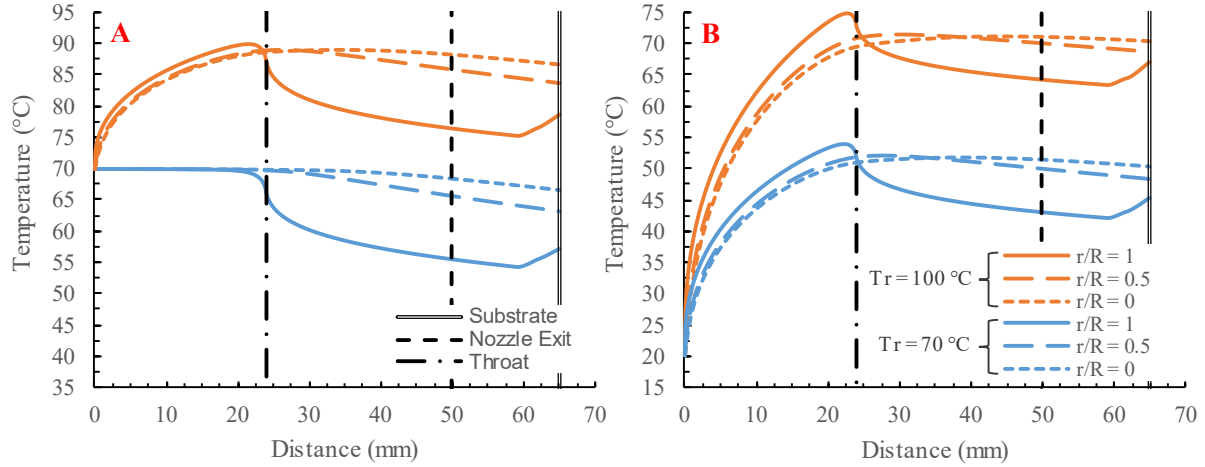


Figure 4. Particle temperature as a function of nozzle distance and dimensionless radius r/R at three discrete locations. A) 48 μm HDPE particle at $T_{po} = 70\text{ }^{\circ}\text{C}$ and B) at $T_{po} = 20\text{ }^{\circ}\text{C}$.

The particle at equal initial particle temperature and reservoir temperature ($Tr = T_{po} = 70\text{ }^{\circ}\text{C}$) is the highest temperature condition achievable by the Bush et al. cold spray apparatus [5]. In their experiments, the particle hopper is surrounded by the reservoir gas, linking the reservoir temperature and initial particle temperature. Clogging was experienced at temperatures over $70\text{ }^{\circ}\text{C}$ as particles became tacky in the hopper. The $Tr = 100\text{ }^{\circ}\text{C}$ and the $Tr = 70\text{ }^{\circ}\text{C}$, $T_{po} = 20\text{ }^{\circ}\text{C}$ conditions are outside of the operating range as they would require a different particle feeding mechanism than possible experimentally. The particles at lower temperatures than the reservoir temperature undergo heating until reaching the nozzle throat, where the gas then begins to cool them. The particle with an initial temperature equal to the reservoir only experiences cooling. For all particles, the internal temperatures appear to converge as they approach the substrate. To further investigate this, the temperature profiles just before substrate impact are discussed in Section 3.1.3.

3.1.2 Polystyrene in a converging-diverging nozzle

The polystyrene case considers a polymer particle with a much higher glass transition temperature than the HDPE case (T_g of $100\text{ }^{\circ}\text{C}$ vs. $-90\text{ }^{\circ}\text{C}$) [11, 25]. In the HDPE case, the particles were always well above the T_g . For the polystyrene simulations, two particle sizes and two initial particle temperatures were studied in a converging-diverging nozzle, unlike the purely converging nozzle for the HDPE case. The gas reservoir conditions were chosen to set the final temperature and velocity of the $44\text{ }\mu\text{m}$ polystyrene particle to values within the deposition window reported by Khalkhli et al. [6]. Figure 5 depicts the gas property profiles the polystyrene particles were simulated with.

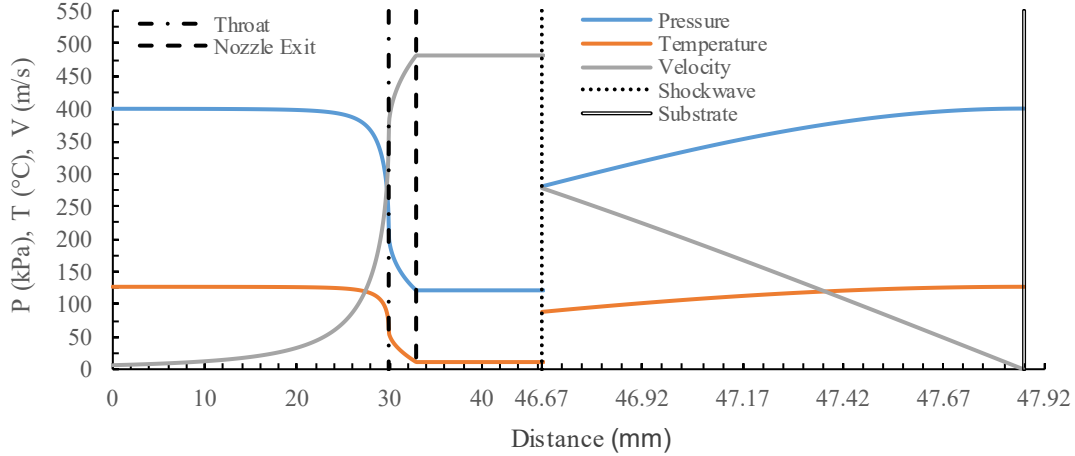


Figure 5. Pressure (P), temperature (T), and velocity (V) of the gas in the supersonic nozzle.

The Biot numbers were calculated for both particle sizes studied. The same size particles have velocities and Biot numbers independent of the initial particle temperature, exemplified by the HDPE case in Figure 3. Figure 6 shows the corresponding Biot and velocity profiles encompassing both initial particle temperatures (20 and 100 °C).

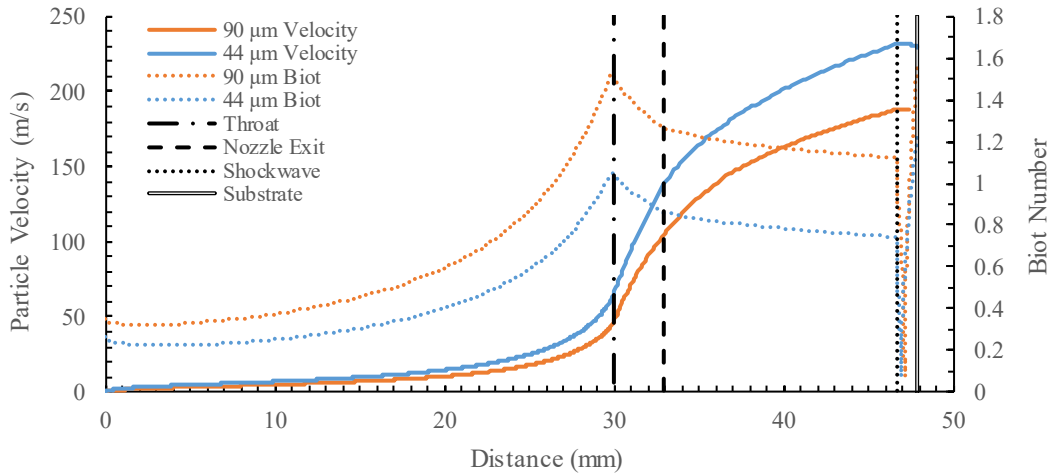


Figure 6. Polystyrene particle velocity and Biot number profiles in the supersonic nozzle.

The Biot numbers for the polystyrene system are higher than the HDPE system, and consistently above the 0.1 threshold. This is attributed to higher gas velocity and lower thermal conductivity of the particles. Because of the high Biot number, the polystyrene system cannot be adequately represented by the lumped capacitance model, and thus a temperature distribution is observed. Figure 7 reports the resulting temperature profiles as a function of distance from the particle inlet to the substrate.

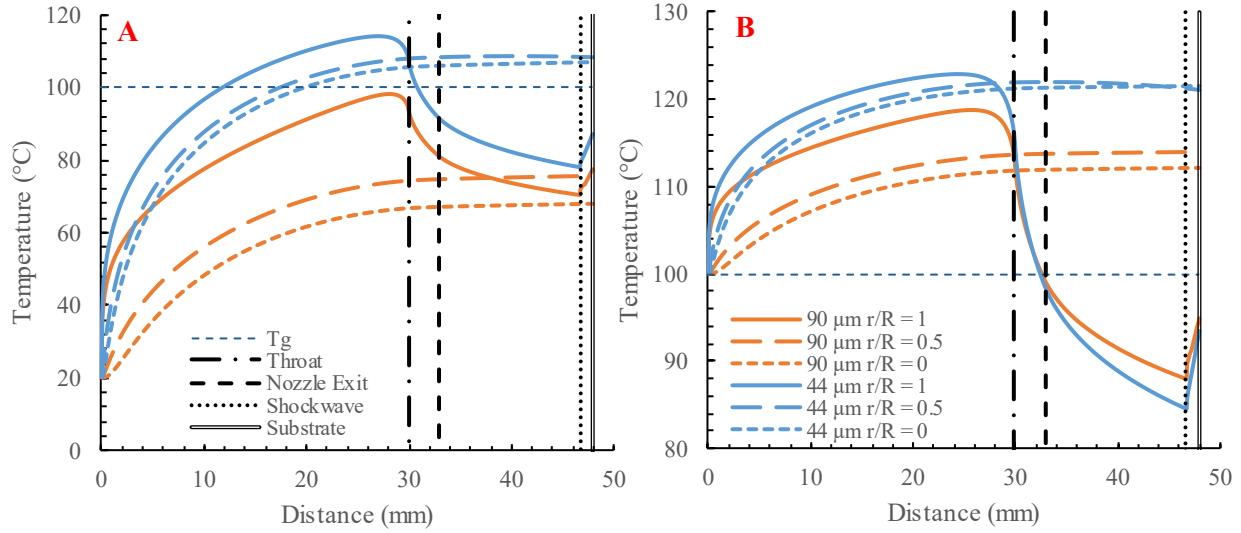


Figure 7. Temperatures of 90 and 44 μm polystyrene particles as a function of distance and dimensionless radius r/R , and at initial particle temperatures A) 20 °C and B) 100 °C. The horizontal dashed line at 100 °C represents the T_g of polystyrene. Tr and Pr are fixed at 127 °C and 400 kPa respectively.

Heating and cooling in the particles occur more rapidly at the surface than at the core and midpoint. The particles cool rapidly through the diverging section of the nozzle and subsequently heat again after passing through the bow shockwave. The internal temperatures however barely see this heating effect in the small region between the shockwave and the substrate, resulting in a polymer sphere with a cool shell and warm inside. The temperature profiles of the polystyrene particles upon impact with the substrate are presented in the following section.

3.1.3 Polymer particle impact temperature

The temperature profiles upon impact from the conditions in Figure 4 and Figure 7 were plotted as a function of particle radius. Figure 8 summarizes these temperature profiles. The polystyrene and HDPE particles exhibit distinct differences in the internal temperature distributions. Notably, the polystyrene particles cross the glass transition region in several cases. A 30 °C temperature differential in the region between the surface and the core implies a significant deviation in mechanical properties near the T_g . If the maximum temperature is close to the surface, we expect this deviation to cause localized deformation at the surface of the particle. The localized deformation would improve bonding, as bonding in cold spray is attributed to plastic deformation between the particle and substrate. We expect this shift in deformation localization to occur regardless of whether the bonding mechanism is shear instability or hydrodynamic deformation [28, 29].

The shear modulus profile as a function of radius for two polystyrene particles was predicted using data from Mott et al. to quantify expected mechanical property deviations in the polystyrene case [30]. Figure 9 shows the internal shear modulus profile for the denoted cases from Figure 8A, and two additional cases where all points in the respective temperature profiles are shifted a specified temperature. This shift could be achieved by adjusting initial particle temperature and nozzle

geometry. The 90 μm particle at $T_{po} = 20^\circ\text{C}$ impacts in the glassy state, and shows relatively little change in shear modulus (0.09 MPa) in a $\sim 20^\circ\text{C}$ window. The 44 μm $T_{po} = 100^\circ\text{C}$ particle straddles the glass transition upon impact, resulting in maximum 0.43 MPa difference in shear modulus (ΔG_{max}) inside the particle. Both differences are considerably increased with the specified temperature shifts, increasing to $\Delta G_{max} = 0.34$ and 0.62 for the 90 and 44 μm particles respectively. This highlights that a broad range of mechanical properties are achievable by tuning the particle temperature.

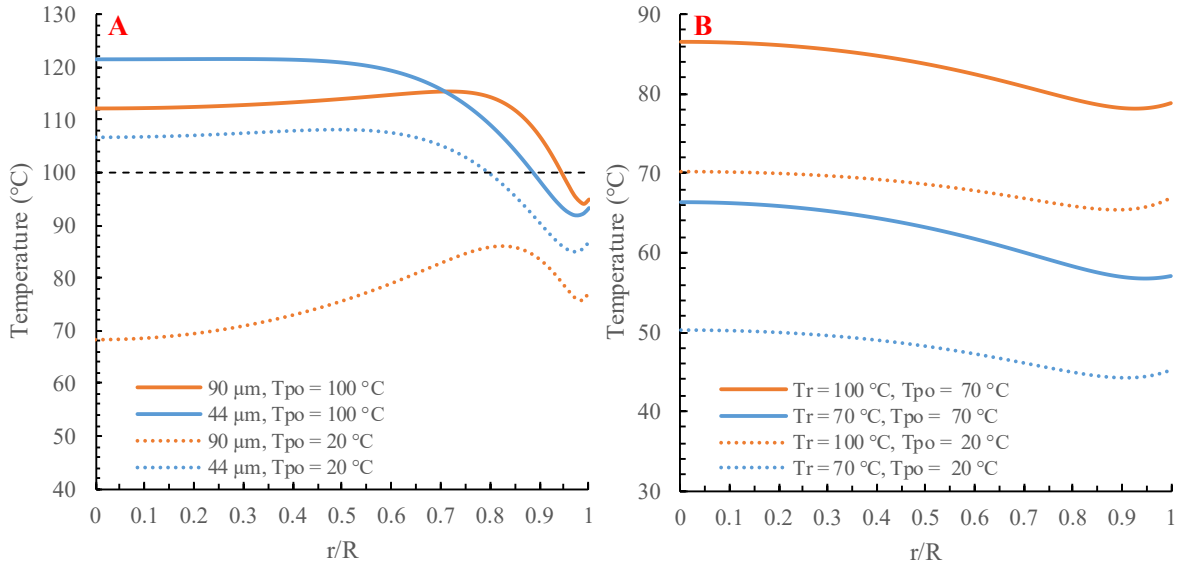


Figure 8. Temperature profiles upon impact as a function of dimensionless radius r/R in the A) polystyrene and B) HDPE particles.

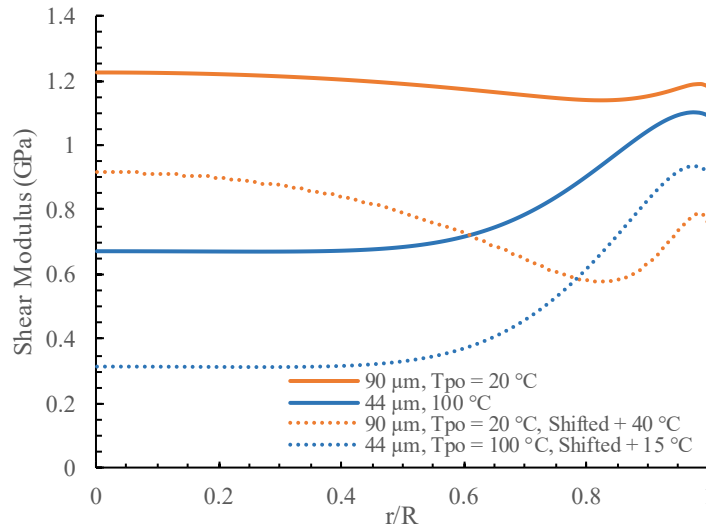


Figure 9. Shear modulus vs. dimensionless radius for two polystyrene particles. The dotted lines represent the modulus curves if the corresponding temperature profiles in Figure 8 are shifted the specified temperature increase. Shear modulus data is from Mott et al. [30].

The HDPE particles are expected to behave similarly when initially crossing the T_g . However, the HDPE particles are highly crystalline compared to polystyrene, an amorphous polymer. Amorphous polymers experience a rapid decrease in modulus with increasing temperature in the region of T_g . Semicrystalline polymers experience this decrease to a lesser degree. Additionally, a broader rubbery plateau region is observed in semicrystalline polymers all the way up to the crystal melting temperature [11]. In this region, the modulus decreases only slightly. For HDPE, this range extends from the $-90\text{ }^{\circ}\text{C}$ T_g to the $135\text{ }^{\circ}\text{C}$ melt temperature. Thus, only slight decrease in modulus is expected for the HDPE particles studied. The representative curves for HDPE would be analogous to the shear modulus profile for the glassy $90\text{ }\mu\text{m}$ $T_{po} = 20\text{ }^{\circ}\text{C}$ polystyrene particle, with minor deviations in the shear modulus.

3.2 Metal Particle Simulations

To demonstrate the substantial differences in thermal behavior between metals and polymers in cold spray, we simulated two cases for metal particles inside a cold spray nozzle from experimental spray conditions. Titanium and aluminum were chosen as representative cases for low and high conductivity metal, respectively. Figure 10A shows the predicted temperatures for the surface and core of the two particles plotted as a function of dimensionless nozzle distance (distance/total nozzle length) from the particle injection point.

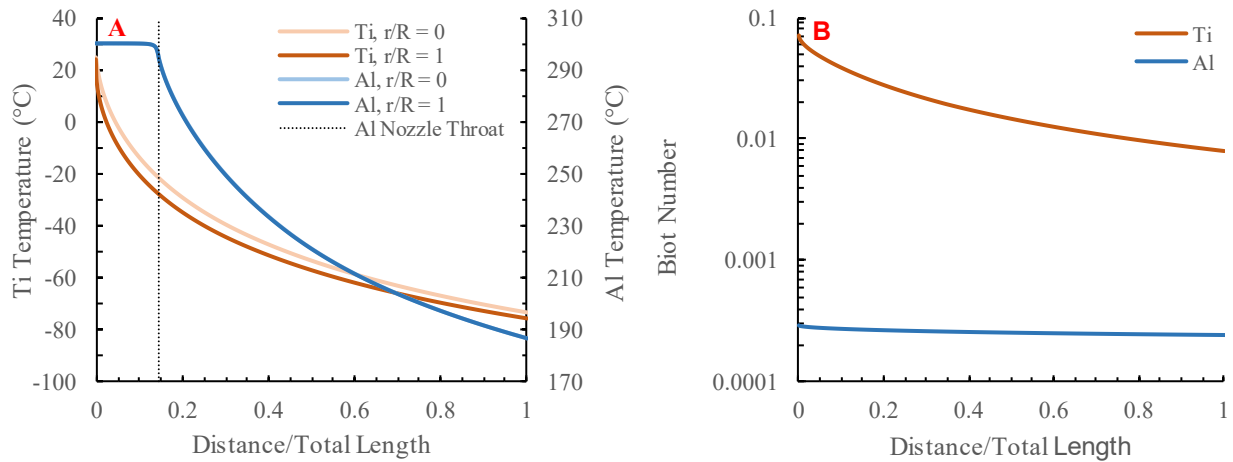


Figure 10. A) Temperature profiles in converging-diverging nozzles for the titanium and aluminum spray conditions. The values at the center and edge of the particles are plotted as a function of dimensionless length. B) Biot number profiles along the nozzles.

The aluminum particle was injected before the nozzle throat, while the titanium particle was injected after the nozzle throat according to the experimental conditions [13, 26, 31]. Both particles show Biot numbers lower than the 0.1 lumped thermal capacitance threshold along the length of the nozzle. The aluminum case shows little temperature difference from the surface to the core of the particle at the end of the nozzle. However, the titanium case shows a greater difference, which is expected from its lower thermal conductivity, and subsequently higher Biot number. At the nozzle exit, the maximum temperature difference inside the aluminum and titanium particles is

0.53 and 4.9 °C, respectively. Unlike the polymer particles discussed in the previous section, this small difference is expected to have negligible effects on particle properties upon impact.

4. CONCLUSIONS

4.1 Discussion

The results herein emphasize that polymer particles have internal temperatures that vary considerably with location in the particle. Metal particles show relatively little temperature distribution upon impact compared to polymers. This temperature variation in polymers results in a substantial mechanical property variation within the same particle at the substrate. Not only are the temperature profiles evident in the particles, but their shape depends on the polymer properties, gas conditions, and nozzle geometry. If an amorphous polymer particle is around or above its T_g , drastic changes in mechanical properties are observed.

The various temperature distributions observed indicate that not only can the average temperature and velocity of a particle be controlled, but the temperature distribution and resulting mechanical properties are variable as well. The nozzle type, geometry, and gas conditions govern the resulting temperature profile upon impact. We plan to use this model to predict deposition temperature profiles and velocities of polymer particles upon substrate impact and target specific temperature distributions. Additionally, the heat transfer principles used herein could be applied to more complex CFD simulations that can better estimate flow properties in later studies. The resulting profiles will be analyzed in impact studies like Sagar et al. and Yildirim et al. performed to predict optimal processing conditions, and subsequently used as experimental conditions [32, 33]. Future investigations into gas properties and particle temperatures simulated with the 1D model will be validated by comparing to computational fluid dynamics (CFD) simulations and experiments.

4.2 Conclusion

The thermal histories of polymer particles inside cold spray nozzles were simulated using the 1D isentropic gas relations. Compared to metal particles, polymers are not adequately represented by the lumped capacitance assumption. The simulated radial temperature profiles at the substrate showed substantial deviation in polymer particles and were found to potentially straddle the material-dependent glass transition temperature. We expect temperature profiles and resulting mechanical property inhomogeneities to have substantial effects on deposition rate, efficiency, and bond quality. This temperature profile can be altered by changing the initial particle temperature, nozzle geometry, and gas conditions. The simulated temperature profiles on impact will be used for initial conditions in impact simulations to analyze deformation patterns. These simulations will guide experiments to optimize deposition efficiency and quality for polymer cold spray additive manufacturing.

5. REFERENCES

1. Fauchais, P., Heberlein, J., and Boulos, M., *Thermal Spray Fundamentals*. New York: Springer, 2014
2. Champagne, Victor K., *The Cold Spray Materials Deposition Process*. Cambridge England: Woodhead, 2007
3. Moridi, A., Hassani-Gangaraj, S. M., Guagliano, M., and Dao, M., "Cold spray coating: review of material systems and future perspectives," *Surface Engineering* 30 (2014): 369-395. doi: 10.1179/1743294414y.0000000270.
4. Xu, Y. and Hutchings, I. M., "Cold spray deposition of thermoplastic powder," *Surface and Coatings Technology* 201 (2006): 3044-3050. doi: 10.1016/j.surfcoat.2006.06.016.
5. Bush, T. B., Khalkhali, Z., Champagne, V., Schmidt, D. P., and Rothstein, J. P., "Optimization of Cold Spray Deposition of High-Density Polyethylene Powders," *Journal of Thermal Spray Technology* 26 (2017): 1548-1564. doi: 10.1007/s11666-017-0627-5.
6. Khalkhali, Z., Xie, W., Champagne, V. K., Lee, J.-H., and Rothstein, J. P., "A comparison of cold spray technique to single particle micro-ballistic impacts for the deposition of polymer particles on polymer substrates," *Surface and Coatings Technology* 351 (2018): 99-107. doi: 10.1016/j.surfcoat.2018.07.053.
7. Ravi, K., Ichikawa, Y., Deplancke, T., Ogawa, K., Lame, O., and Cavaille, J.-Y., "Development of Ultra-High Molecular Weight Polyethylene (UHMWPE) Coating by Cold Spray Technique," *Journal of Thermal Spray Technology* 24 (2015): 1015-1025. doi: 10.1007/s11666-015-0276-5.
8. Khalkhali, Z. and Rothstein, J. P., "Characterization of the cold spray deposition of a wide variety of polymeric powders," *Surface and Coatings Technology* 383 (2020): doi: 10.1016/j.surfcoat.2019.125251.
9. Ravi, K., Sulen, W. L., Bernard, C., Ichikawa, Y., and Ogawa, K., "Fabrication of micro-/nano-structured super-hydrophobic fluorinated polymer coatings by cold-spray," *Surface and Coatings Technology* 373 (2019): 17-24. doi: 10.1016/j.surfcoat.2019.05.078.
10. Ravi, K., Deplancke, T., Ogawa, K., Cavallé, J.-Y., and Lame, O., "Understanding deposition mechanism in cold sprayed ultra high molecular weight polyethylene coatings on metals by isolated particle deposition method," *Additive Manufacturing* 21 (2018): 191-200. doi: 10.1016/j.addma.2018.02.022.
11. Sperling, Leslie H., *Introduction to Physical Polymer Science*. Hoboken, New Jersey: Wiley, 2006
12. Champagne, V. K., Helfrich, D. J., Dinavahi, S. P. G., and Leyman, P. F., "Theoretical and Experimental Particle Velocity in Cold Spray," *Journal of Thermal Spray Technology* (2010): doi: 10.1007/s11666-010-9530-z.
13. Marrocco, T., McCartney, D. G., Shipway, P. H., and Sturgeon, A. J., "Production of titanium deposits by cold-gas dynamic spray: Numerical modeling and experimental characterization," *Journal of Thermal Spray Technology* 15 (2006): 263-272. doi: 10.1361/105996306X108219.
14. Helfrich, D. and Champagne, V. K., "Optimal Particle Size for the Cold Spray Process," in *Thermal Spray 2006*, Seattle, Washington, USA, 2006.
15. Incropera, F. P., DeWitt, D. P., Bergman, T. L., and Lavine, A. S., *Fundamentals of Heat and Mass Transfer 5th Edition*. Wiley, 2001

16. Katanoda, Hiroshi., "Numerical Simulation of Temperature Uniformity within Solid Particles in Cold Spray," *Journal of Solid Mechanics and Materials Engineering* 2 (2008): 58-69. doi: 10.1299/jmmp.2.58.
17. Ivošević, M., Cairncross, R. A., and Knight, R., "3D predictions of thermally sprayed polymer splats: Modeling particle acceleration, heating and deformation on impact with a flat substrate," *International Journal of Heat and Mass Transfer* 49 (2006): 3285-3297. doi: 10.1016/j.ijheatmasstransfer.2006.03.028.
18. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., *Transport Phenomena*. New York: Wiley, 2006
19. Helfrich, D. and Champagne Jr, V., "A Model Study of Powder Particle Size Effects in Cold Spray Deposition," in *Army Science Conference*, Florida, 2008.
20. Henderson, Charles B., "Drag Coefficients of Spheres in Continuum and Rarefied Flows," *AIAA Journal* 14 (1976): 707-708. doi: 10.2514/3.61409.
21. Ranz, W. and Marshall, W. R., "Evaporation from drops," *Chem. eng. prog* 48 (1952): 141-146.
22. Shapiro, Ascher. H., *The Dynamics and Thermodynamics of Compressible Fluid Flow*. New York: Ronald Press Company, 1953
23. Billig, Frederick S., "Shock-wave shapes around spherical-and cylindrical-nosed bodies," *Journal of Spacecraft and Rockets* 4 (1967): 822-823. doi: 10.2514/3.28969.
24. Tan, Zhongchao., *Air Pollution and Greenhouse Gases: From Basic Concepts to Engineering Applications for Air Emission Control*. Springer Singapore, 2014
25. Bush, Trenton., "Cold Gas Dynamic Spray - Polymer Deposition," Master of Science M.S., Mechanical Engineering, University of Massachusetts Amherst, 2016.
26. Jenkins, R., Aldwell, B., Yin, S., Chandra, S., Morgan, G., and Lupoi, R., "Solid state additive manufacture of highly-reflective Al coatings using cold spray," *Optics & Laser Technology* 115 (2019): 251-256. doi: 10.1016/j.optlastec.2019.02.011.
27. Algaer, Elena., "Thermal Conductivity of Polymer Materials - Reverse Nonequilibrium Molecular Dynamics Simulations," Ph.D, Physical Chemistry, Technische Universität, Darmstadt, 2010.
28. Hassani-Gangaraj, M., Veyssset, D., Champagne, V. K., Nelson, K. A., and Schuh, C. A., "Adiabatic shear instability is not necessary for adhesion in cold spray," *Acta Materialia* 158 (2018): 430-439. doi: 10.1016/j.actamat.2018.07.065.
29. Grujicic, M., Zhao, C. L., DeRosset, W. S., and Helfrich, D., "Adiabatic shear instability based mechanism for particles/substrate bonding in the cold-gas dynamic-spray process," *Materials & Design* 25 (2004): 681-688. doi: 10.1016/j.matdes.2004.03.008.
30. Mott, P. H., Dorgan, J. R., and Roland, C. M., "The bulk modulus and Poisson's ratio of "incompressible" materials," *Journal of Sound and Vibration* 312 (2008): 572-575. doi: 10.1016/j.jsv.2008.01.026.
31. Meyer, M. C., Yin, S., McDonnell, K. A., Stier, O., and Lupoi, R., "Feed rate effect on particulate acceleration in Cold Spray under low stagnation pressure conditions," *Surface and Coatings Technology* 304 (2016): 237-245. doi: 10.1016/j.surfcoat.2016.07.017.
32. Shah, S., Lee, J., and Rothstein, J. P., "Numerical Simulations of the High-Velocity Impact of a Single Polymer Particle During Cold-Spray Deposition," *Journal of Thermal Spray Technology* 26 (2017): 970-984. doi: 10.1007/s11666-017-0557-2.
33. Yildirim, B., Muftu, S., and Gouldstone, A., "Modeling of high velocity impact of spherical particles," *Wear* 270 (2011): 703-713. doi: 10.1016/j.wear.2011.02.003.