A Constitutive Material Model for Simulating Texture Evolution and Anisotropy Effects in Cold Spray

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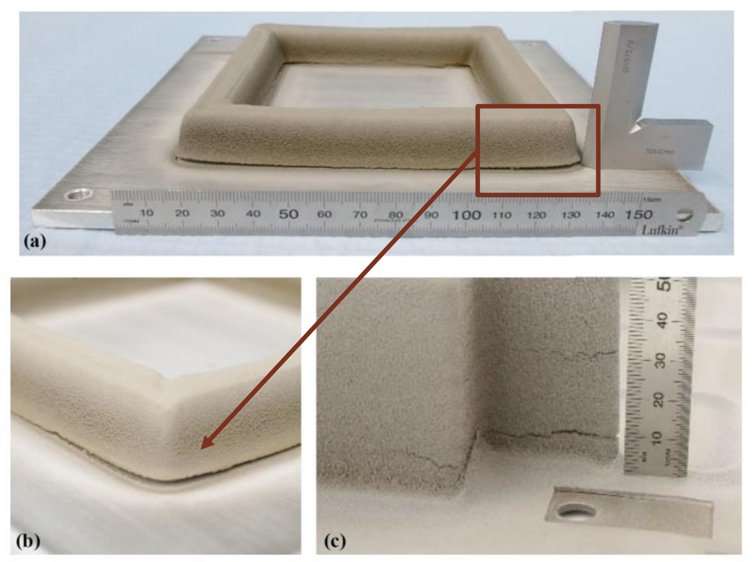
MOTIVATION

- The dynamic deformation of powder particles during cold spray produces complex textures in the finished part.
- The large strain cyclic heating and fast cooling involved in the cold spray process can cause significant residual stresses and anisotropy effects. These effects can lead to weaknesses and failures in cold spray manufactured parts that are difficult to predict in complex parts.

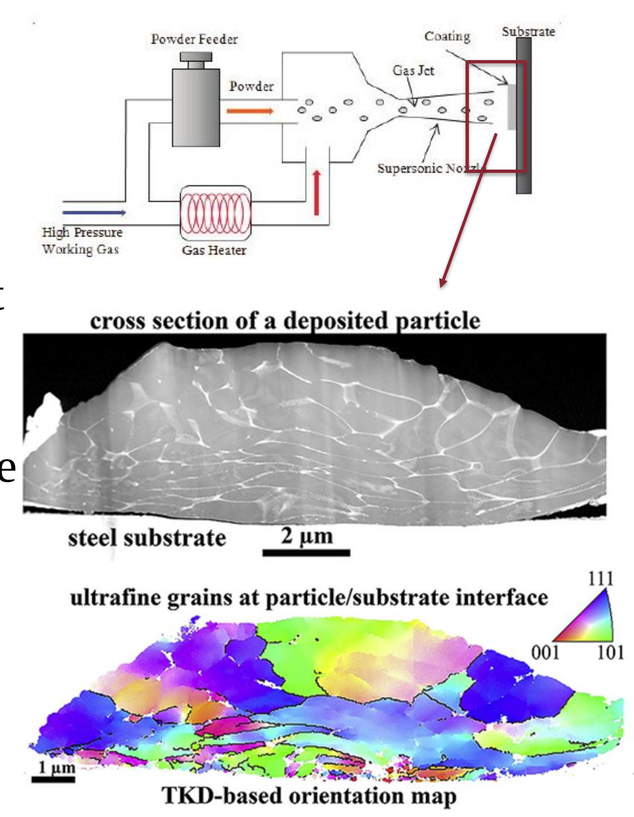


Residual stress induced geometric distortion causing detachment in cold sprayed part. (Vargas-Uscategui et al, 2020)

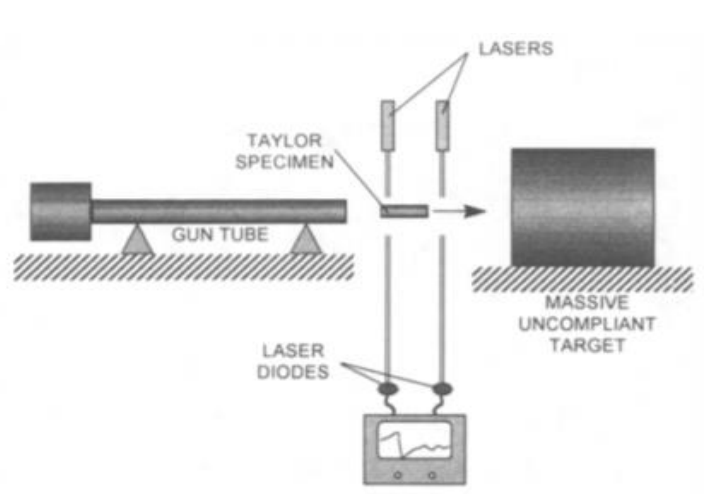
- A mathematical model that can accurately predict such stresses and texture effects can help guide optimization of developing cold spray parts

BACKGROUND

- Cold spray is an additive manufacturing process that involves powder particles projected from a supersonic de-Laval nozzle onto a solid substrate.
- Cold spray can be conducted at significantly lower temperatures than most other additive manufacturing processes, hence its name; however, the thermal effects during Cold spray are not negligible and can still result in considerable texture effects.
- High-rate deformation of particles during impact produce temperature gradients and large deformations in the particle and its vicinity.
- Due to the complex production scenario, material models need to be rigorously tested to ensure the physics are correct.



Schematic of cold spray process (Top) and texture development in cold sprayed particle (Bottom). (Liu, 2019)



Schematic drawing of Taylor test equipment (Allen, 1997)

- A simulation of a Taylor Anvil test was performed to validate the yield surface used to model the large anisotropic texture that develops during cold spray.
- The Taylor Anvil test is a dynamic impact test used to ascertain the stress response and plastic deformation of the test material under a high strain rate.
- The test involves a cylindrical specimen traveling at a high velocity impacting a rigid surface.

GOAL

Develop and validate a constitutive model to accurately predict residual stresses and anisotropic effects of cold spray manufactured parts.

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METHODS

- The Evolving Microstructural Model of Inelasticity (EMMI) constitutive material model (Martin et al, 2006) that describes the thermomechanical behavior of metals considering dislocation dynamics has been modified to include texture evolution and fast thermal effects:

$$\mathring{\boldsymbol{\sigma}} = \dot{\boldsymbol{\sigma}} - \mathbf{w}_e\boldsymbol{\sigma} + \boldsymbol{\sigma}\mathbf{w}_e = \lambda(\theta)tr\left(\mathbf{d}-\mathbf{d}_p\right)\mathbf{1} + 2\mu(\theta)\left(\mathbf{d}-\mathbf{d}_p\right) \quad \text{...elasticity}$$

$$\mathbf{d}_p = f(\theta)\,\text{Sinh}\left[\frac{|\sigma' - \alpha|}{\kappa\eta}\right]\mathbf{n}_p \;\text{...flow rule ;} \quad \mathbf{w}_p = G\lambda_g\left(\mathbf{A}\mathbf{d}_p - \mathbf{d}_p\mathbf{A}\right) \text{...plastic spin}$$

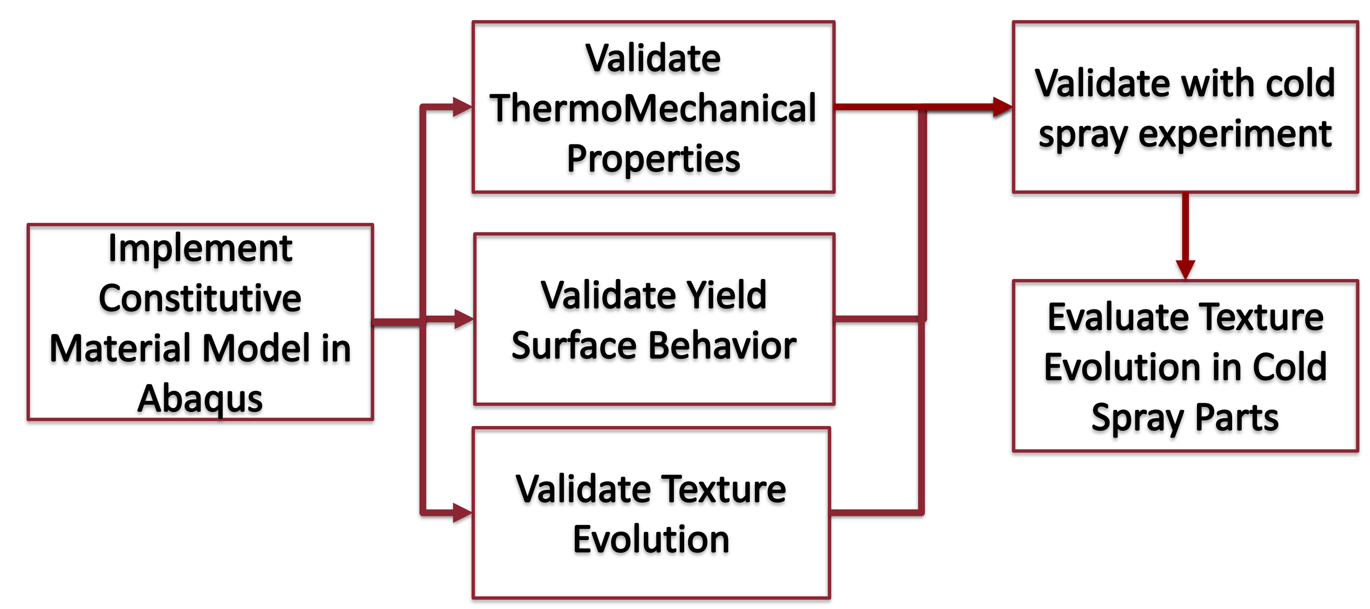
$$\eta = C_1\cos\phi + C_2\cos\phi + C_3\cos\phi + C_4\cos\phi \;\text{where}\; \cos\phi = \frac{\xi\cdot A}{|\xi||\mathbf{A}|} \text{.....coaxiality factor}$$

$$\mathbf{n}_p = \left(\frac{\sqrt{3/2}\,\partial|\xi|}{\partial\xi} - \frac{|\xi|}{\chi}\frac{\partial\chi}{\partial\xi}\right) \Bigg/ \left|\left(\frac{\sqrt{3/2}\,\partial|\xi|}{\partial\xi} - \frac{|\xi|}{\chi}\frac{\partial\chi}{\partial\xi}\right)\right| \quad \text{where}\; \boldsymbol{\xi} = \boldsymbol{\sigma}' - \boldsymbol{\alpha}$$

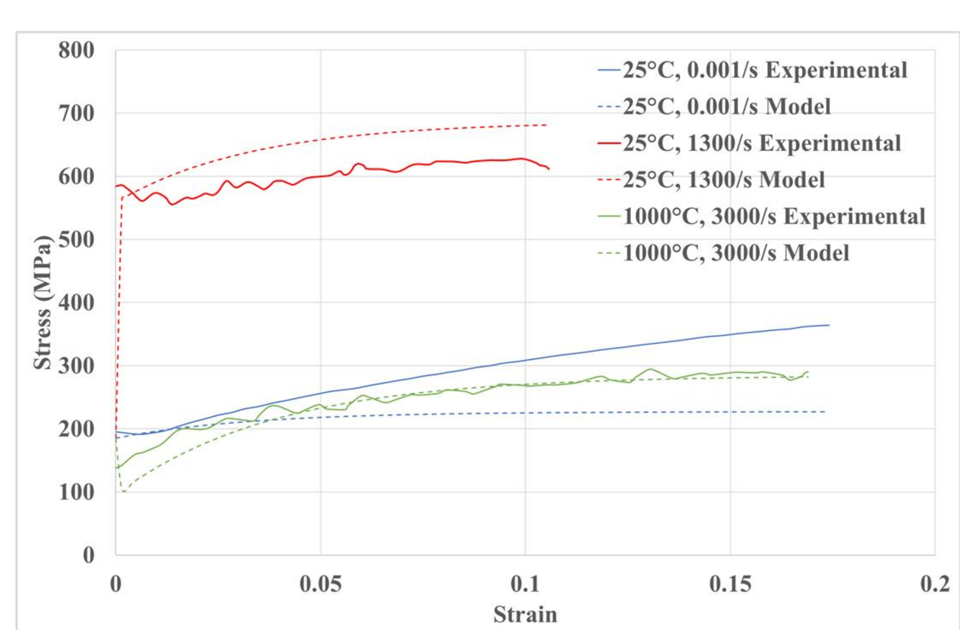
$$\frac{\partial\chi}{\partial\xi} = \frac{c_1 + 4c_2\cos\phi + 3c_3\left(4\cos^2\phi - 1\right) + 16c_4\cos\phi\left(4\cos^2\phi - 1\right)}{|\xi||\mathbf{A}|}\left[\mathbf{A} - \left(\frac{\xi\cdot\mathbf{A}}{\xi\cdot\xi}\right)\xi\right]$$

$$\dot{\kappa} = \left[H\mu(\theta) - R_d(\theta)\kappa\right]|\mathbf{d}_p| \quad \text{...evolution of isotropic hardening}$$

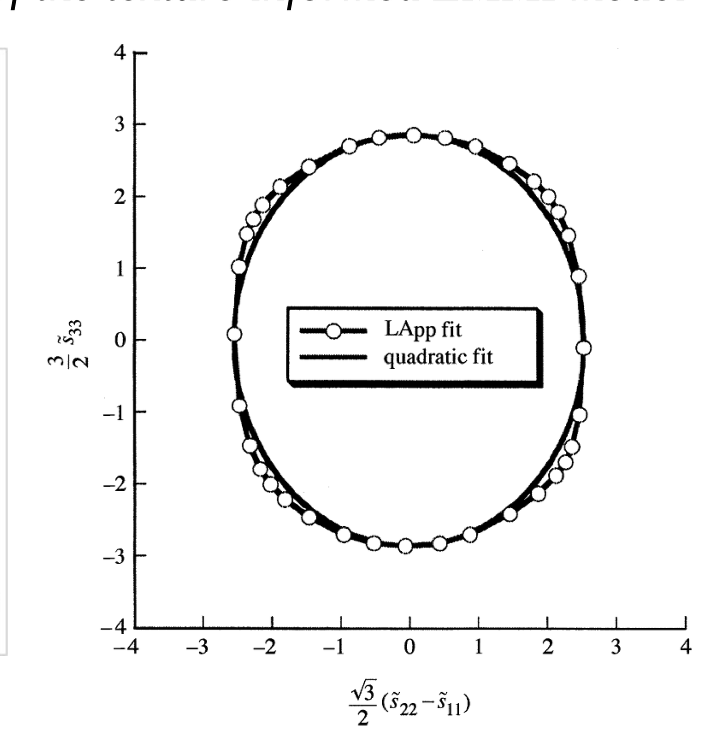
$$\dot{\boldsymbol{\alpha}} - \mathbf{w}_e\boldsymbol{\alpha} + \boldsymbol{\alpha}\mathbf{w}_e = h(\theta)\mathbf{d}_p - r_d(\theta)|\boldsymbol{\alpha}|\boldsymbol{\alpha} \quad \text{...evolution of kinematic hardening}$$



Outline for calibration and validation of the texture informed EMMI model



Calibration of constitutive material model to tensile tests for temperature and deformation rate dependence. (Maudlin, 1999)

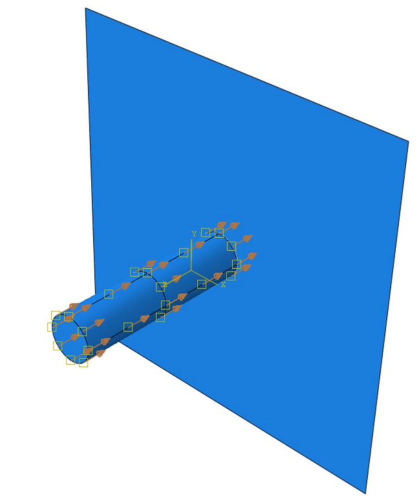


A two-dimensional π-plane subspace showing a polycrystal-generated piece-wise yield surface (line segments and points) being compared with a quadratic fit (solid curve) interpolating the piece-wise function at the horizontal and vertical axis intercepts. (Maudlin, 1999)

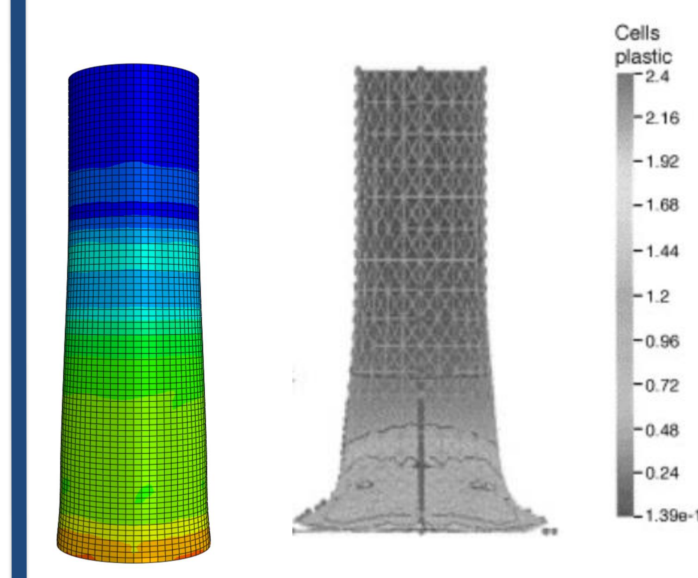
- Stress-strain data from experiments done by Maudlin, et al. was used to calibrate the material properties of refractory alloy.
- These curves shows that the stress response for this material is highly dependent on temperature and strain rate.
- Yield Surface data from these experiments was used to calibrate the Yield Function parameters using Mathematica.
- An FEA simulation of the Taylor Anvil test was used to verify the results of the EMMI model.

RESULTS

- The simulated test specimen was a 40 mm long refractory alloy rod with a diameter of 10 mm.
- It was given an initial velocity of 200 m/s at a set starting distance of 0.5 mm from the rigid body.

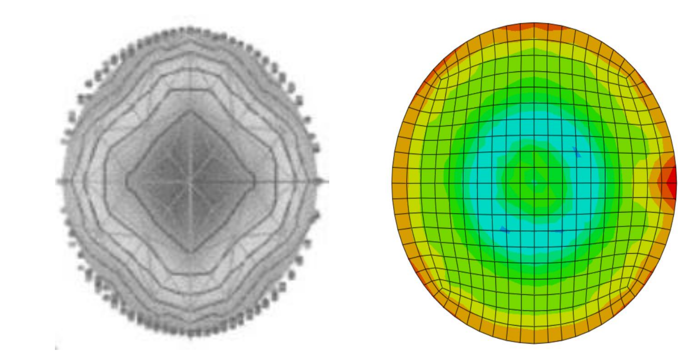


FEA model of Anvil and Rigid Body with velocity field



Experimental (Maudlin, 1999) vs computation model of Taylor anvil side view showing side view of localized plastic deformation at the base highlighting the effect of hardening.

- At collision, the impact end of the specimen deforms. This deformation is strongly affected by thermal softening.
- The high strain rates during testing result in large amounts of plastic deformation and hardening.
- The shape of this deformation, or "footprint," can be used to identify the material's anisotropic characteristics.
- A round footprint indicates that a material is isotropic, as the material deforms equally in all directions.
- An ovular footprint indicates strong anisotropy, as the material tends to deform more easily in certain directions than in others.



Experimental (Maudlin, 1999) vs computation model of Taylor anvil foot-print after high velocity impact highlighting the effect of anisotropic yield surface.

CONCLUSIONS

- We have implemented a novel constitutive material model to determine texture evolution and finalized material properties in additively manufactured parts.

ACKNOWLEDGMENTS

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BIBLIOGRAPHY

[1] Allen, D. J., Rule, W. K., & Jones, S. E. (1997). Optimizing material strength constants numerically extracted from Taylor impact data. *Experimental mechanics*, *37*(3), 333-338.

[2] Liu, T., Leazer, J.D., & Brewer, L.N. (2019) Particle deformation and microstructure evolution during cold spray of individual Al-Cu alloy powder particles. *Acta Materialia*, *168*, 13-23.

[3] Martin, E. B., Bammann, D. J., Reguerio, R. A., & Johnson, G. C. (2006). On the Formulation, Parameter Identification and Numerical Integration of the EMMI Model: Plasticity and Isotropic Damage, *Sandia Report*.

[4] Maudlin, P.J., Bingert, J.F., House, J.W., & Chen, S.R. (1999). On the modeling of the Taylor cylinder impact test for orthotropic textured materials: experiments and simulations. *International Journal of Plasticity*, *15*(2), 139-166.

[5] Maudlin, P. J., Gray, G. T., Cady, C. M., & Kaschner, G. C. (1999). High-Rate Material Modelling and Validation Using the Taylor Cylinder Impact Test. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, *357*(1756), 1707–1729.

[6] Nurul, S., Yusof, S., Manap, A., Afandi, N., Salim, M., & Misran, H. (2015). Mechanical and wear properties of aluminum coating prepared by cold spraying. *AIP Conference Proceedings*. 1669. 020044-1–020044. 10.1063/1.4919182.

[7] Vargas-Uscategui, A, King, P. C, Styles, M. J., Luzin V., Thorogood K., "Residual Stresses in Cold Spray Additively Manufactured Hollow Titanium Cylinders", Journal of Thermal Spray Technology, 2020.

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