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Thermal Expansion of Sprayed Coatings Determined by Gleeble Laser Dilatometry

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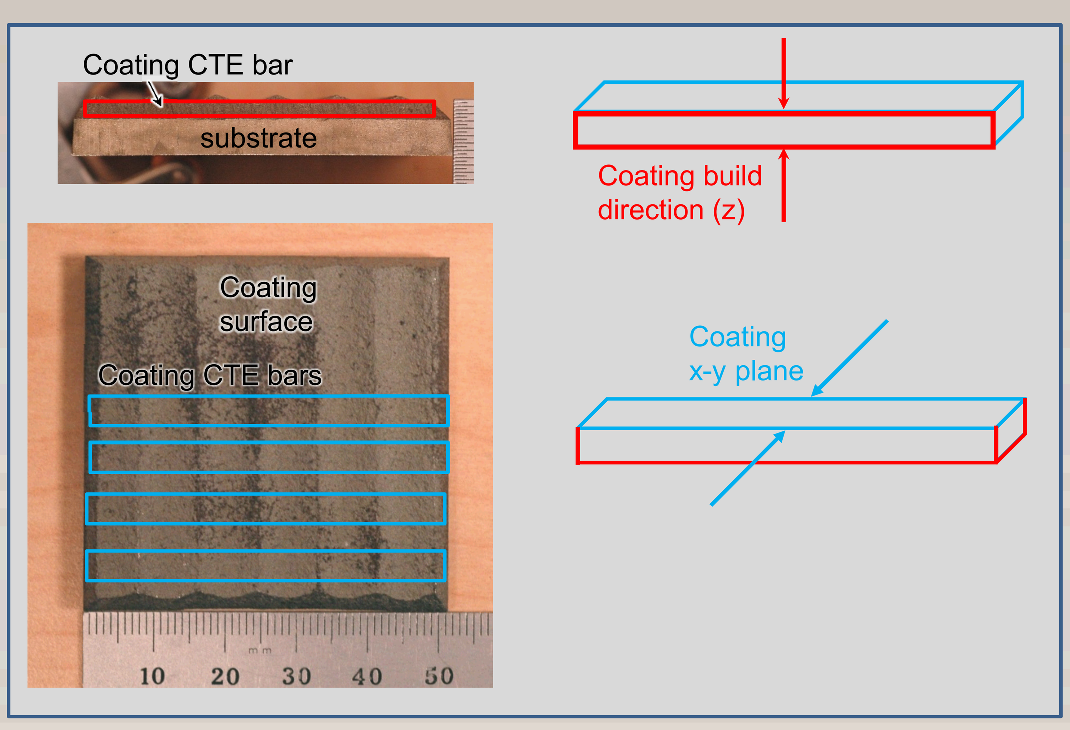
Problem Statement

Thermal spray and cold spray (CS) coatings are being considered as part of an additive manufacturing (AM) approach to building functional multi-material components. In a multi-material layered stack, thermal expansion mismatch is a concern and traditional push-rod dilatometry may not be suitable for CTE (coefficient of thermal expansion) measurement of thin coatings/layers. A non-contact laser dilatometry technique was developed using a Gleeble thermomechanical analyzer to quantify thermal expansion and contraction in the coating 'x-y' plane and in the 'z' build direction. The method was applied to cold sprayed Fe and Ti-6Al-4V coatings. Comparisons to literature data for these common materials, and to experiments on wrought versions of the alloys, demonstrated that Gleeble dilatometry is capable of collecting accurate multi-axis CTE data from metallic sprayed coatings. In addition, the effects of sintering shrinkage of porous coatings and internal stress in the deposits must be considered during CTE evaluations.

Experimental Methods

The Gleeble thermomechanical analyzer is often used for physical simulation of dynamic heating, cooling, and stress generation during a welding process. With the laser dilatometer feature, the Gleeble can also capture thermal expansion and contraction of simulated weld samples or other specimens. Unlike traditional push-rod dilatometry, Gleeble laser dilatometry is non-contact and generally measures diametral expansion of the sample rather than axial expansion. In this work, the method was used to determine the coefficient of thermal expansion (CTE) of sprayed coatings, which were machined from their substrates. With Gleeble laser dilatometry, it was possible to determine CTE in the plane of the coatings as well as the build direction by simply changing the orientation of the rectangular specimen relative to the laser, Fig. 1.



Photos of coating and substrate. Schematic diagrams of stand-alone coating with dilatometry measurement directions. The sample face of interest is oriented normal to the laser.

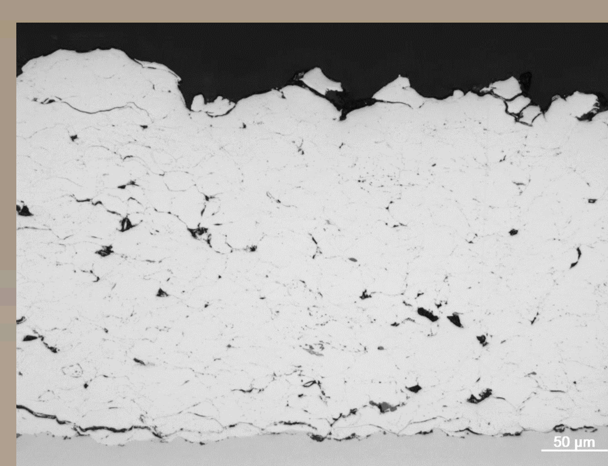
- Room temperature to 600°C and back
- Temperature ramp rate 10°C/min

- Cold sprayed pure iron
- Cold sprayed Ti-6Al-4V alloy

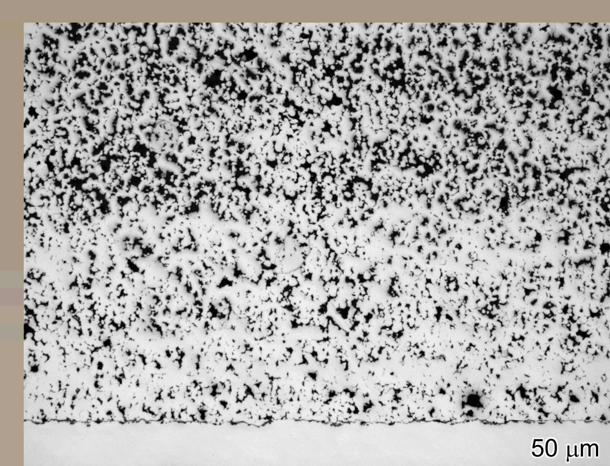
- Coatings must be conductive (metallic) to accommodate resistive heating

- Temperature is controlled in the center of the specimen by thermocouple feedback. Dilatometry is performed in the same location.

Results



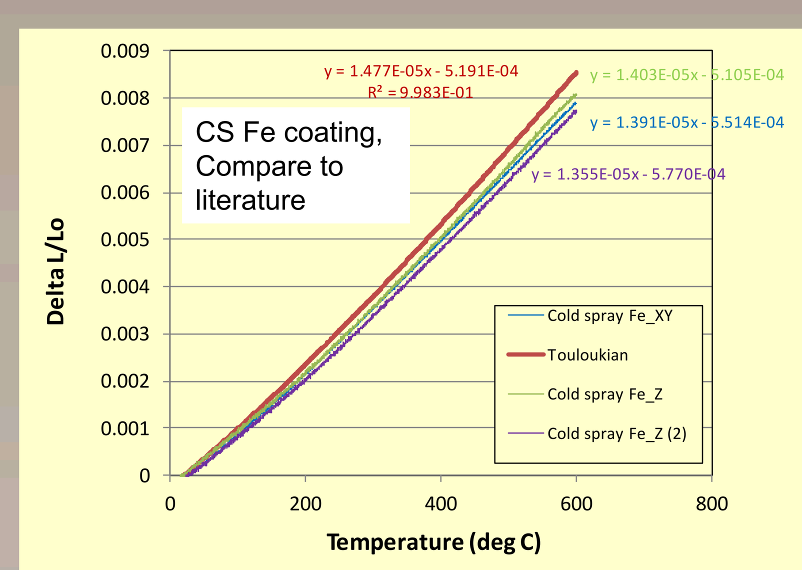
Cold-sprayed iron coating

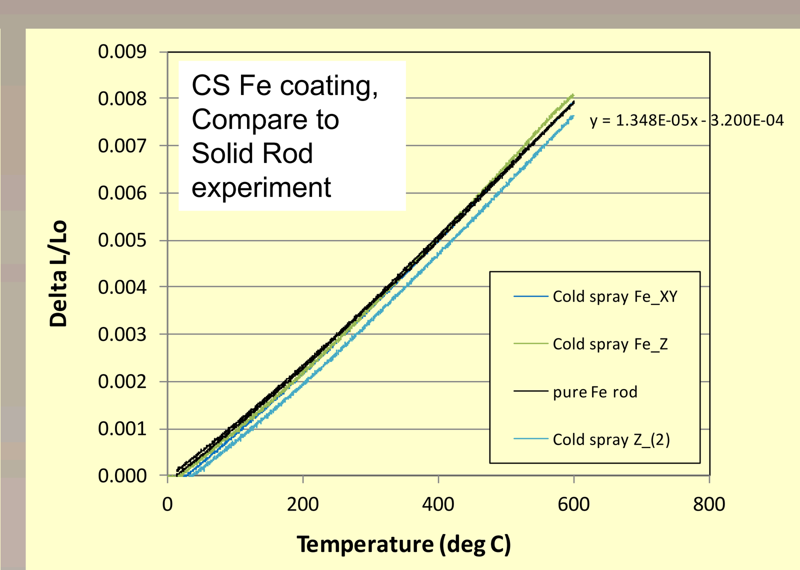


Cold-sprayed porous Ti-6Al-4V

- Cold spray coatings are built by high-velocity impact of powder particles
- CS iron microstructure is fairly dense, with "splat boundaries" between particles
- CS Ti-6Al-4V is very porous. Only slight deformation of individual particles
- Thicker coatings (0.1 in.) deposited for dilatometry

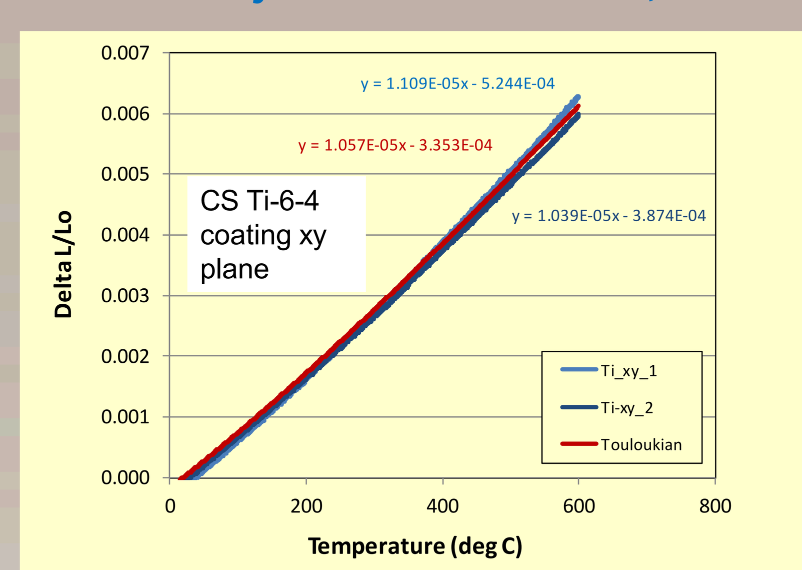
- Thermal expansion of CS iron: 13.6 – 14.0 ppm/°C, comparable to handbook value for pure Fe of 14.8 ppm/°C (Y.S. Touloukian et al., Thermal Expansion of Metallic Elements and Alloys, IFI/Plenum, New York, 1976, pp 157-172.)
- No difference between xy plane and z build direction, i.e. coating thermal expansion is isotropic



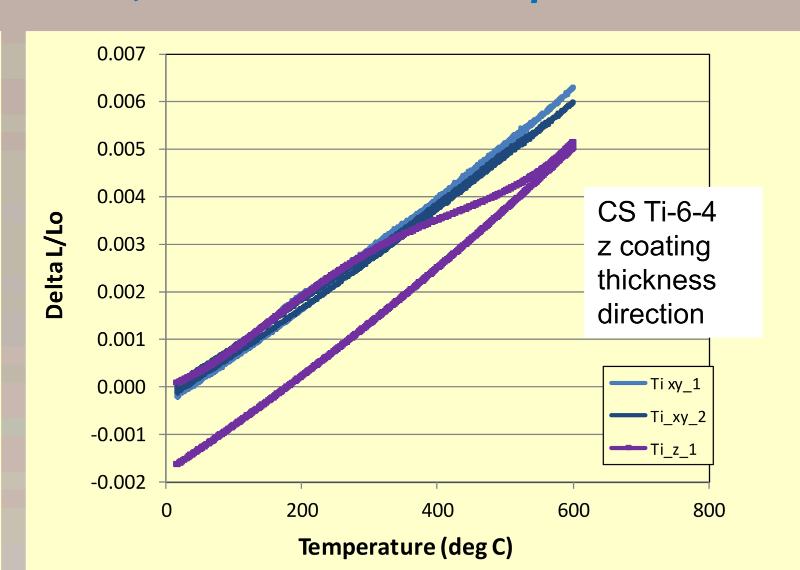


Dilatometry results for CS iron, literature data, and solid Fe bar experiment

- CTE of sprayed Ti-6Al-4V: 10.4 – 11.1 ppm/°C in the coating xy plane. Consistent with handbook value of 10.6 ppm/°C
- Anomalous behavior in the coating build direction (z). Could be due to sintering of the porous coating during initial heating and/or coating strain relief in the z-direction

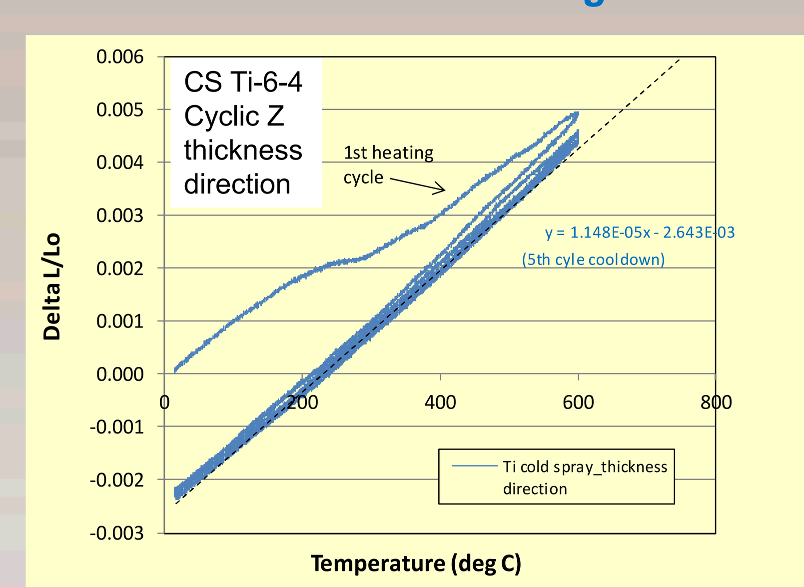


Dilatometry results for CS Ti-6Al-4V



Anomalous behavior in coating z direction

- Cyclic experiments show that sintering/strain relief effects subside after the initial temperature cycles
- Must be considered in design of material interfaces with the coating or multi-layer structures



Five thermal cycles of CS Ti-6Al-4V

Discussion

The results indicate that Gleeble non-contact laser dilatometry is capable of determining CTE of relatively thin, stand-alone coatings (machined from their substrate). In general, the cold sprayed coating materials display CTE values within about 5% of the published handbook values for bulk alloys. The thermal expansion of CS iron coatings was found to be isotropic. For CS Ti-6Al-4V, the thermal expansion behavior was more complex. The expansion in the coating xy plane matched the published handbook value of about 10.6 ppm/C. In the z build direction, the coating showed an anomalous contraction during heating. The behavior is attributed to sintering of the porous coating, possibly combined with stress relief in this direction (not actual differences in material CTE), but more work is needed to fully understand this anomalous behavior. After multiple thermal cycles, the thermal expansion behavior resumes that of typical Ti-6Al-4V alloy. The cyclic behavior supports a sintering or strain relief mechanism due to the initial condition after cold spraying.

The Gleeble dilatometry technique could be applied to other types of coatings, such as thick PVD layers, which grow in preferred crystallographic orientation. Such coatings could exhibit true anisotropy in CTE.

Conclusions

- Gleeble laser dilatometry can be used to understand the thermal expansion behavior of thin coatings. CTE can be measured in both the plane of the coating as well as the coating thickness direction by orienting a rectangular sample relative to the laser.
- For common alloy coatings, the measured CTEs correspond well to published literature values. In general, the cold-spray coatings are isotropic. The exception was porous Ti-6Al-4V in the coating thickness direction. Anomalous behavior during heating was attributed to sintering shrinkage and/or strain relief in the z direction.
- Future work is needed to fully understand the anomalous behavior of porous Ti-6Al-4V. Comparison to traditional push-rod dilatometry is underway.

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