



# Assessment and Model Development of Investment Shell Cracking

Laura Bartlett, MS&T  
Ben Hilgers, MS&T

Aluminum Casting Performance Initiative  
(ACPI)

AMC Technology Review

June 24-25, 2026

# Overview

- **Needs and Benefits** - Reduce shell cracking in investment casting to improve yield, lead time, and supply chain reliability for critical components
- **Approach:** Develop “smart” investment shells using distributed fiber optic sensing to measure temperature and strain during dewaxing, firing, and casting
- **Progress:** Initial laboratory trials completed demonstrating feasibility of fiber optic sensing under casting conditions
- **Transition:** Data-driven model development for integration into commercial casting simulation tools (e.g., MAGMASOFT) and adoption by industry partners
- **Cost Share Provided:** \$42,295 provided to date out of \$290,044 proposed

# Needs

- **Investment casting** is essential for complex, low-volume, mission-critical components, but is limited by long lead times and high scrap rates
- **Shell cracking** is the primary defect, with up to ~90% occurring during dewaxing/autoclave processing
- Cracking leads to runout, inclusions, and scrap, increasing cost and delaying part delivery
- **Current models are inaccurate** due to lack of real-time data on temperature and strain within the shell
- **No existing sensing capability** provides distributed, in-situ measurements during dewaxing and firing processes
- This results in trial-and-error processing, limiting scalability and reliability for DoW supply chains

# Fiber Optic Sensors for Metals Industry Applications

---

Temperature, strain and gap measurements in the metals industry are commonly performed with thermocouples, thermistors, and strain gauges

## Limitations of thermocouples and strain gauges

- Single-point measurements
- Large spacing between temperature/strain measurement points, creates measurement dead zones
- affected by electromagnetic interferences
- Strain gages are susceptible to temperature changes

A steel beam instrumented with 4 strain gauges

Thermal mapping of mold using multiple thermocouples

# Fiber Optic Sensors

- **Optical fiber:** A light pipe made of optical materials
  
- **Fiber sensors:** proven advantages for applications in hostile environments
  - Small size/lightweight
  - Immunity to electromagnetic interference (EMI)
  - Resistance to chemical corrosion
  - High temperature capability
  - High sensitivity
  - remote operation
  - Multiplexing and distributed sensing
  
  - Temperature
  - Strain
  - Slag/Flux Chemistry

# Quasi-distributed fiber-optic sensors

## Fiber Bragg Gratings

Bragg wavelength:

$$\lambda_B = 2n_{eff} \Lambda$$

Changes in temperature and strain can be measured by measuring shift in Bragg wavelength

FBG Fabrication

Multiple FBGs on a single fiber

**Fiber Bragg Grating Fibers**  
(measurement capabilities based on fiber material)

# Fiber Optic Sensing: Optical Frequency Domain Reflectometry Rayleigh Scattering Based Sensor

Distributed temperature sensing based on *Rayleigh scattering*:

- The Rayleigh backscattering shift  $\Delta\lambda$  caused by temperature variation  $\Delta T$  can be expressed as:

$$\frac{\Delta\lambda}{\lambda} = (\xi + \alpha)\Delta T$$

- $\xi$  is the thermo-optic coefficient of fiber material,  $\alpha$  is the thermal expansion coefficient.

**Optical frequency domain reflectometry  
(Typical measurement capabilities)**

# Fiber Optic Sensors for Temperature Measurement: Pouring Aluminum (A356) in a Permanent Mold

# Needs

**Objective** Develop and validate a data-driven approach to predict and mitigate shell cracking in aluminum investment casting through real-time measurement of temperature and strain using distributed fiber optic sensing.

Fiber Optic Sensors for Strain Measurement

## Technology Solution

- Deploy **distributed fiber optic sensors** to capture real-time temperature and strain fields
- Use data to **validate and improve casting process models** and enable digital twin development

**Industry Partner Statements:** “This project benefits O’Fallon Casting by allowing us to better understand our current processes ....With regards to shell cracking, we would be able to reduce the amount of cracking we see in shells as well as allow us to find possible near miss areas that experience high stress without cracking.”

“The information provided by the sensors will help us to improve our simulation software by giving us the chance to alter parameters in shell and metal to more closely match the real-world results that we see in the foundry.”

# Benefits

## Benefits to DoW / DLA

- **Improved supply chain reliability** for critical cast components by reducing shell-related failures during production
- **Reduced lead times** by minimizing trial-and-error process development and rework associated with shell cracking
- **Lower production costs** through improved yield and reduced scrap during investment casting operations
- **Enhanced part quality and consistency**, particularly for complex, thin-wall, and flight-critical aluminum components
- **Enables domestic manufacturing capability** for low-volume, high-complexity castings critical to defense systems
- **Supports transition to data-driven manufacturing (Foundry 4.0)** through integration of real-time sensing and validated process models

# Technical Progress

- Initial Trials Involving Temperature Measurement
  - The goal of this trial was to test the temperature capabilities of the fibers under investment casting conditions
  - A previously fired shell utilized
  - thermocouple and fiber optic sensors (graphite coated and stripped)

# Technical Progress: Initial Trials to Measure Temperature

- Investment shell material – zirconia shelled foam pattern
- Foam previously burned out during sintering cycle
- Shell instrumented with fiber optic sensors
  1. Polymer coating stripped
  2. Polymer *with* graphite coating
- Heated in a kiln furnace at 500°C for 2hrs
- Aluminum A356 poured at 680°C

# Technical Progress: Initial Trials to Measure Temperature

*Temperature profiles*

## Thermal Profile of Preheat, Casting, and Solidification

# Technical Progress: Initial Trials to Measure Temperature

## Thermal Profile of Preheat, Casting, and Solidification

# Technical Progress: Initial Trials to Measure Temperature

## Solidification Profile Through the Shell

- Liquidus and solidus occurred at close to expected temperatures
- Local solidification time very uniform
- Expected for low thermal gradients typical of investment casting in preheated shells

# Technical Progress: Initial Trials to Measure Temperature

- Initial Trial
  - Stripped fiber was close to the thermocouple in temperature readings
  - Graphite was further off but still followed the same temperature curve

# Technical Progress: Initial Trials to Measure Temperature

- Distributed temperature data from solidification – used to validate cooling rate effects on SDAS
- Thermal data from the shell will be coupled with solidification data to improve modeling software

# Technical Progress: Temperature monitoring using different methods

- Sand mold trials with different fiber optic sensors
- Understand effect of coating (graphite vs stripped polymer) on Rayleigh fibers and use of FBG fibers
- Sand mold instrumented at parting line
- In-line thermocouple

# Technical Progress: Temperature monitoring using different methods

# Rayleigh-based Sensing using **Graphite Coated Fiber**

# Fiber Optic Sensing using FBGs



# Rayleigh-based Sensing using **Polymer stripped fiber**

Rayleigh-  
based Sensing

## Stripped Fiber Sensor

**Polymer stripped fiber** – gave the best results  
when compared with graphite coated



# Technical Progress: Trials to Measure Strain and Temperature

- Step block pattern selected as test shell geometry
- The goal of this trial was to collect strain and temperature data of the de wax and start of firing in an investment shell
- Rayleigh-based Sensing using **Polymer stripped fibers** used
- Specially designed fixture for shelling of pattern

# Technical Progress: Trials to Measure Strain and Temperature

- Wax pattern with two stripped fiber optic sensors
  - One in stainless steel tube – temp measurement
  - One bare fiber to measure strain
- Thermocouple for single point measurement
- Heated in kiln furnace to 200°C

# Technical Progress: Trials to Measure Strain and Temperature

# Technical Progress: Trials to Measure Strain and Temperature



# Technical Progress: Trials to Measure Strain and Temperature



# Technical Progress: Trials to Measure Strain and Temperature

- Temperature and strain followed expected patterns (high amounts of strain before the wax reaches temperatures and melts)
- Needs further testing to verify excess strain values from wax

# Project Plans

- Design and fabricate instrumented shell geometries→ Finalize test articles and sensor integration approaches (Milestone: Month 4)
- Finish validating fiber optic sensing in laboratory shell trials→ Demonstrate reliable temperature and strain measurement during firing and dewaxing (Metric: repeatable measurements across  $\geq 3$  trials)
- Conduct laboratory-scale dewaxing, firing, and casting experiments→ Generate high-resolution thermomechanical datasets (Deliverable:  $\geq 5$  instrumented trials)
- Develop initial data-driven models for shell behavior→ Correlate temperature/strain fields with cracking events (Deliverable: preliminary model framework)
- Benchmark and calibrate simulation tools (e.g., MAGMASOFT / FE models)→ Improve prediction accuracy using experimental data (Metric: measurable improvement vs baseline predictions)
- Prepare for industrial trials with AFS partners→ Transition sensor integration to production-relevant environments (Milestone: industry trial readiness)

# Transition Plan

## Industry Partners:

Collaboration with **American Foundry Society (AFS)** and partner foundries (e.g., **O'Fallon Casting**) to implement sensor-integrated shell trials in production environments

## Near-Term Transition (0–12 months):

- Deploy fiber optic sensors in **laboratory shell builds**
- Deliver **validated temperature and strain datasets** to industry partners
- Begin **model calibration using real process data**
- Conduct **instrumented industrial casting trials** at partner foundries
- Integrate results into **commercial simulation tools (e.g., MAGMASOFT)**
- Demonstrate **improved prediction of shell cracking and process reliability**

## DoW Impact:

- Support **rapid adoption across U.S. investment casting supply base**
- Improved **availability of critical cast components**
- Reduced **lead time and scrap-related delays**
- Strengthened **domestic manufacturing capability for defense applications**

# Leveraging - Bartlett

- **Builds on prior DoE- and DLA-funded programs at Missouri S&T focused on distributed fiber optic sensing in metal casting environments**  
→ *Demonstrated real-time temperature and strain measurement in industrial processes (TRL 5–6)*
- **Leverages previous work in continuous casting and mold monitoring**  
→ Successful measurement of **air gap formation, mold temperature distribution, and thermomechanical behavior** using fiber optic systems
- **Extends validated fiber optic sensing technology from ferrous casting systems to investment casting shells**  
→ Reduces technical risk by applying **proven sensing architectures to a new application space**
- **Utilizes existing infrastructure and expertise**  
→ Wolf Research Foundry, Peaslee Steel Manufacturing Research Center, and Lightwave Technology Laboratory  
→ Established capability for **sensor fabrication, integration, and high-temperature testing**

# Leveraging - Bartlett

- **Builds on prior modeling and digital twin efforts**
  - Integration of experimental data into **FE models and commercial tools (e.g., MAGMASOFT)**
  - Enables rapid transition from **measurement** → **model validation** → **process optimization**
- **Cost share** provided through Missouri S&T facilities, personnel, and ongoing research programs
- **Synergy** with ongoing federally funded research (DoE, DoW-related efforts) reduces duplication and accelerates progress
- **Industry collaboration** through AFS and partner foundries provides in-kind support, materials, and access to production environments

# Project Metrics

Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Distributed temperature measurement in investment shells	No in-situ distributed data (point measurements only)	Demonstrate repeatable temperature measurement in lab shells	High-resolution distributed temperature mapping during dewaxing & casting	Comparison to thermocouples; repeatability across trials	Month 12	Initial trials completed	Lab-scale instrumented shell experiments
Distributed strain measurement in shells	No direct strain measurement capability	Demonstrate strain sensing during thermal cycling	Quantify strain evolution leading to shell cracking	Correlation of strain data with observed cracking events	Month 18	In progress	Instrumented shell firing and dewaxing trials
Model accuracy for predicting shell cracking	Low accuracy; empirical/process-based	Improved prediction vs baseline models	≥80% accuracy (stretch: >90%) in predicting cracking locations	Comparison of model predictions to experimental results	Month 24–36	Not started	Validated FE/MAGMASOFT simulations
Reduction in shell cracking / scrap	High scrap rates due to cracking	Demonstrate measurable reduction in controlled trials	≥50% reduction (stretch: 70%+) in shell cracking	Comparison of defect rates before/after implementation	Month 30–36	Not started	Lab + industrial casting trials
Transition to industry (sensor + model adoption)	No current deployment of technology	Demonstration in industrial environment	Implementation at ≥1 partner foundry	Successful industrial trial + partner feedback	Month 30–36	Planned	Industrial casting trials with AFS partners

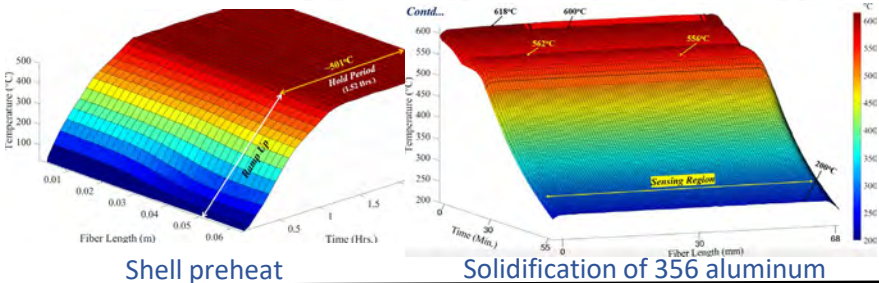
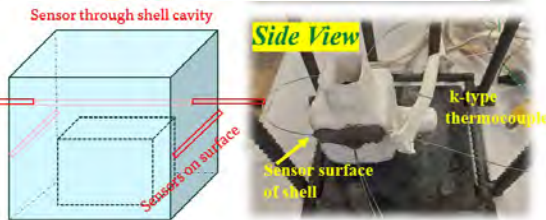
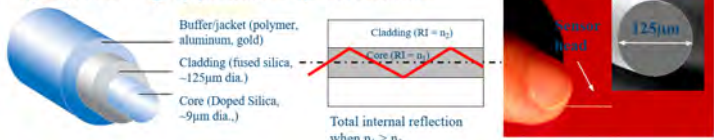
# Acknowledgements

This research is sponsored by the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, VA and DLA Troop Support, Philadelphia, PA.

# Assessment and Model Development of Investment Casting Shell Cracking

DLA - POC: DLAR.DPR@dla.mil

**Optical fiber: A light pipe made of optical materials**



## Problem

- Shell cracking is the most problematic defect for investment casters. Up to 90% of cracked investment shells are a result of improper dewaxing.

## Objectives

- This project aims to use novel fiber optic sensor techniques to measure temperature and strain in the investment shell during the dewaxing process and solidification data during pouring, then utilize the data to augment FE modeling software and develop further process control

## Benefits to Warfighter

- Increased process control and data acquisition will provide higher quality investment cast parts with less shell defects, lowering defects and costs.

## Description of Project

This project seeks to reduce investment shell cracking by utilizing fiber optic strain sensors to more accurately model shell cracking in the dewaxing, firing, and casting process.

**Team:** American Foundry Society, ATI, Missouri S&T

## Milestones / Deliverables

- Design of test shell geometries and alloy selection
- Preliminary and laboratory scale testing of shells
- Instrumented shell trials involving dewaxing, firing, and casting
- Industrial instrumented casting trials of selected shell materials
- Development of shell cracking models
- Final reporting and industrial presentations

