BORGWARNER

Wire Forming Simulation for Electric Machine Stators

Andrew Dragon
Sr. Staff Engineer
Electric Machine Innovation
PowerDrive Systems

October 2023

Agenda

- About the Author
- Company Overview
- Electric Machine Components
- Types of Stators
- Hairpin Stator Forming Simulation
- Wire Insulation Simulation
- Closing Remarks

About the Author

- B.S. Mechanical Engineering, 2005, Rose-Hulman Institute of Technology
- Relevant Work experience:
  - 2006, FEA Analyst, Caterpillar Inc.
  - 2010-2017, FEA Analyst / Mechatronics Engineer, Remy Inc., Forward Development
  - 2017-Present, Staff Development Engineer, Electric Machine Innovation
    - Manufacturing Simulation
    - Structural and Thermal Analysis
    - Multiphysics Optimization
    - High Performance Computing

Our Vision:

A clean, energy-efficient world.

Our Mission:

We deliver innovative and sustainable mobility solutions.

BorgWarner In Numbers

~38k
Employees

$15.8
Billion in 2022 Sales

80
Locations

19
Countries

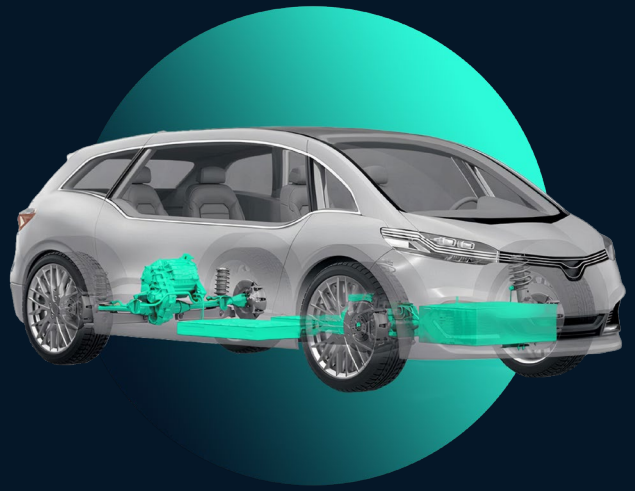
Strategic Global Operations

27 Locations in the Americas

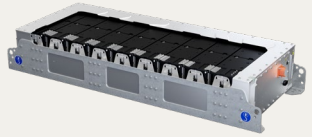
23 Locations in Europe

30 Locations in Asia

Electric Vehicle Technology*



Our growing product portfolio covers virtually all electric propulsion areas including electric motors, power transmission, power electronics, and thermal management.



Battery Systems

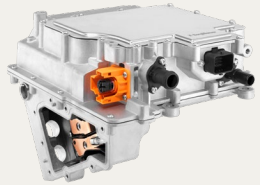
Chargers

Controllers

EV Transmissions

Electric Drive Motors

Electric Drive Modules

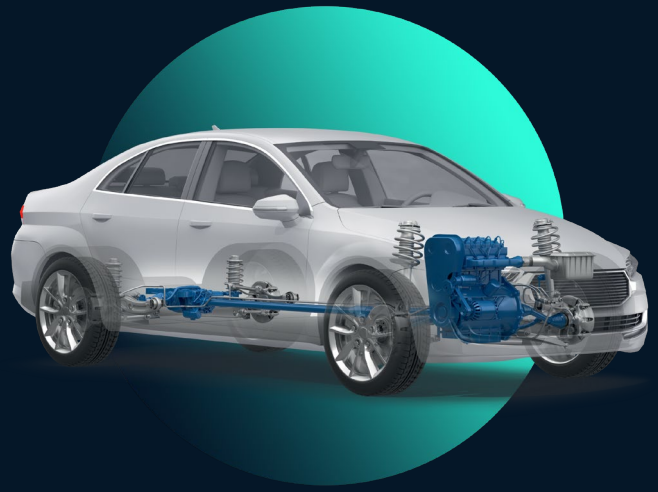


Power Electronics

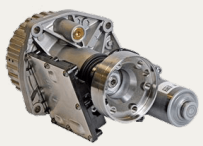
Thermal Management

*Includes battery electric vehicles, range extenders and fuel cells.

Foundational Technology*



Delivering clean, fast-to-market technology solutions to increase efficiency and performance of modern combustion and hybrid vehicles.

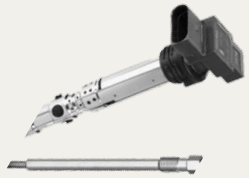


AWD + Cross Axle Systems

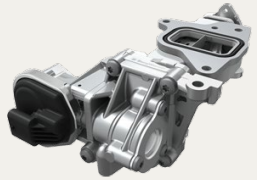
Boosting Technologies

Electric Boosting Technologies

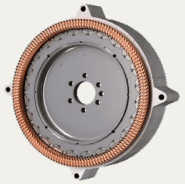
Engine Timing Systems



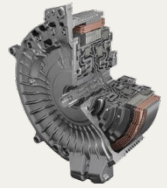
Ignition Technologies



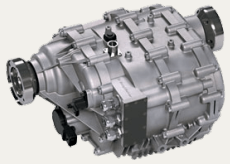
Intake and Exhaust Gas Management



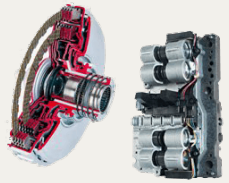
P1 Hybrid Architecture



P2 Hybrid Architecture



P4 Hybrid Architecture



Transmission Technologies

Valvetrain Systems

*Includes engines, transmissions and all-wheel drive systems, as well as mild, full and plug-in hybrid technology

Commercial Vehicle Technology

Low fuel consumption and a long service life are priorities for commercial vehicles. We offer highly efficient combustion, hybrid and electric technologies for a wide range of commercial vehicles.

Battery Systems

Boosting Technologies

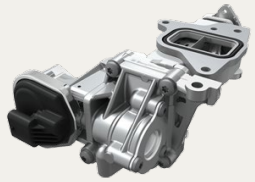
Chargers

Controllers

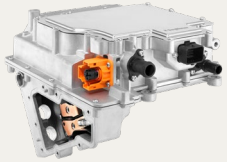
Electric Drive Modules

Electric Drive Motors

Engine Timing Systems



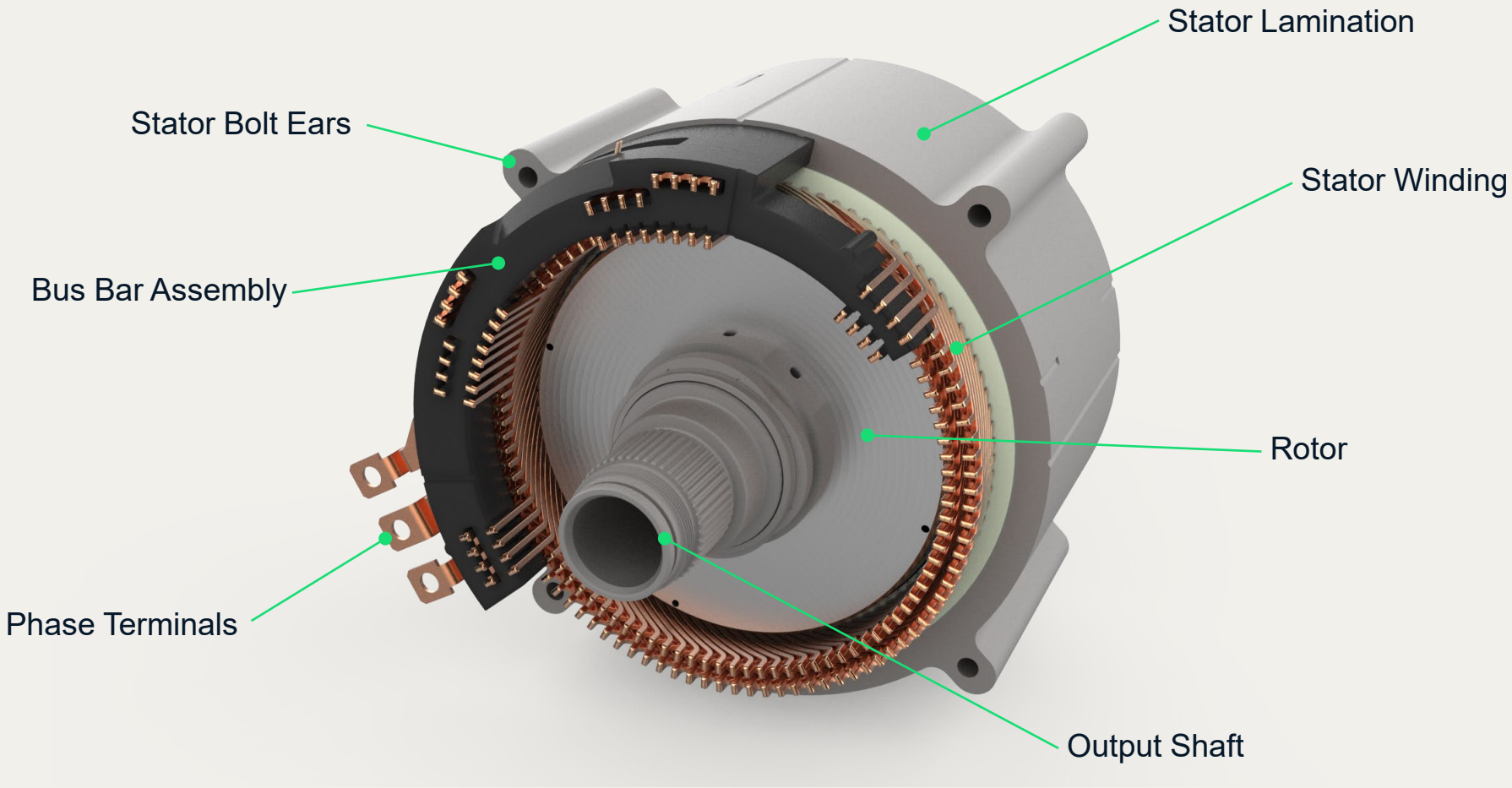
Intake and Exhaust Gas Management



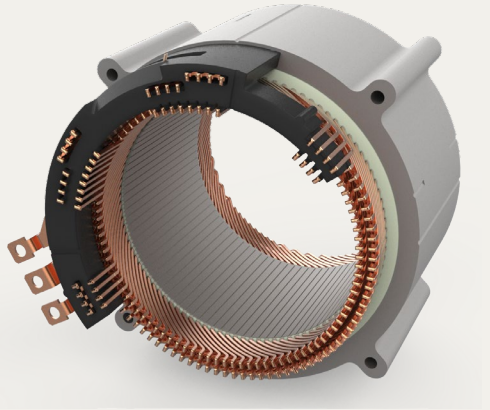
Power Electronics

Thermal Management

Electric Machine Components



What is a Stator?



- Stationary component with multiphase winding used to generate a rotating magnetic field; magnetic interaction with the rotor produces torque at the rotor output shaft
- Winding is all the electrically conducting bodies in the stator
- Generally a 3-phase winding with various connection schemes (series-parallel arrangements)
- Insulated conductor wire formed to fit within the stator slots
- Conductors must be electrically isolated from the stator (ground) and other conductors, therefore insulation coatings are used

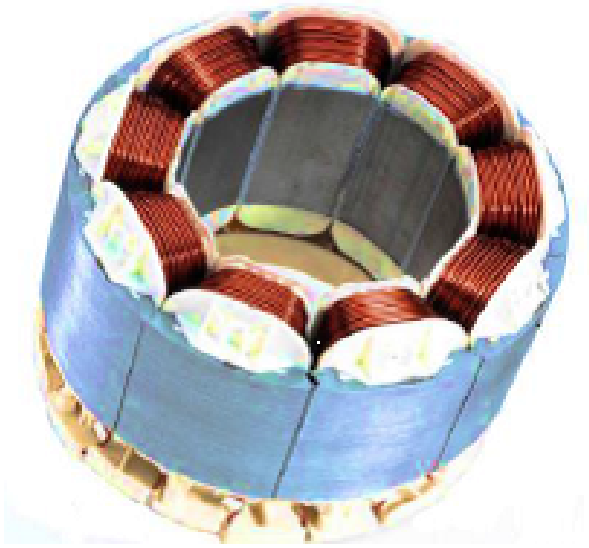
Types of Stators

- Concentrated Wound Stator
- Random Wound Round Wire Stator
- S-wind Stator
- Hairpin Stator

Stator type determined by winding style

Concentrated Wound Stator

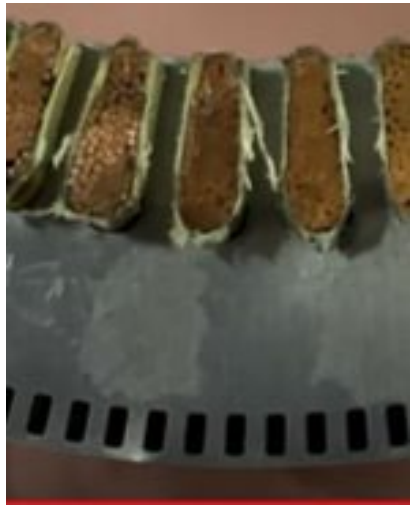
- Bobbin wound
- Concentrated coils
- Round or rectangular wire
- Radial insertion into Stator

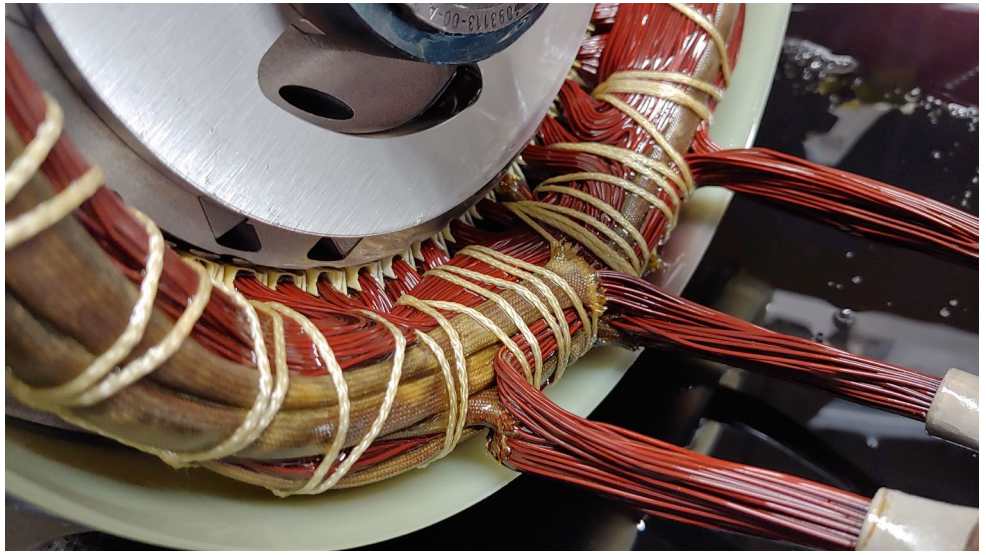


Typically used for short stack lengths in automotive applications

Random-wound Stator

- Continuous conductor
- Distributed coils
- Round wire
- Bundling
- Radial insertion into Stator

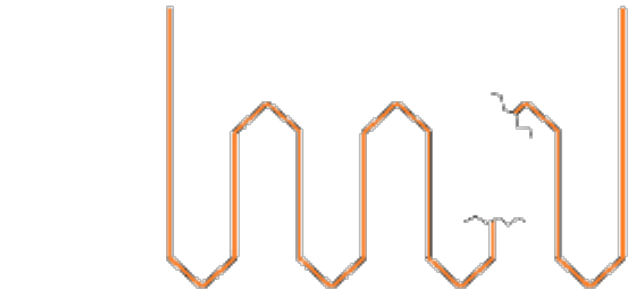


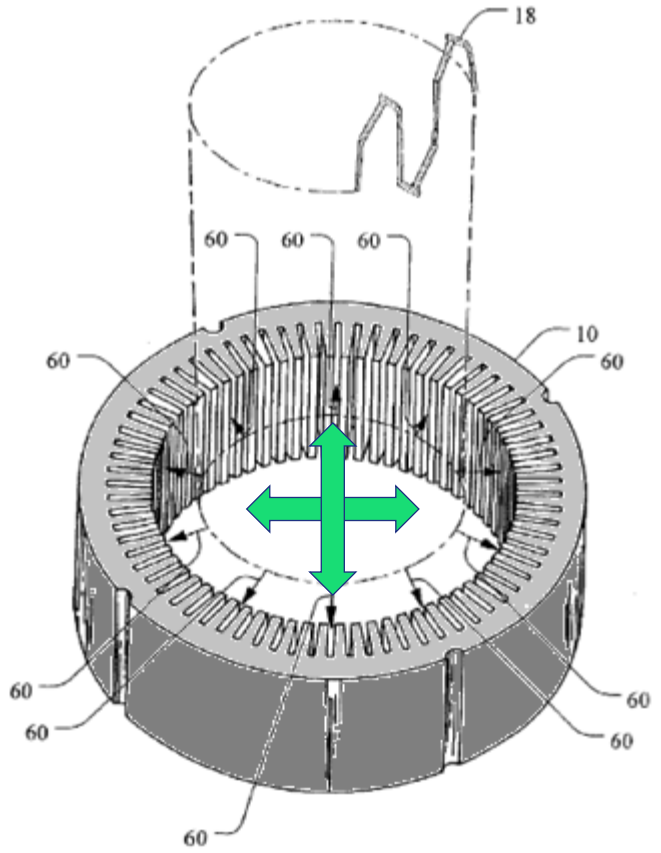


Industry moving toward distributed winding with rectangular wire

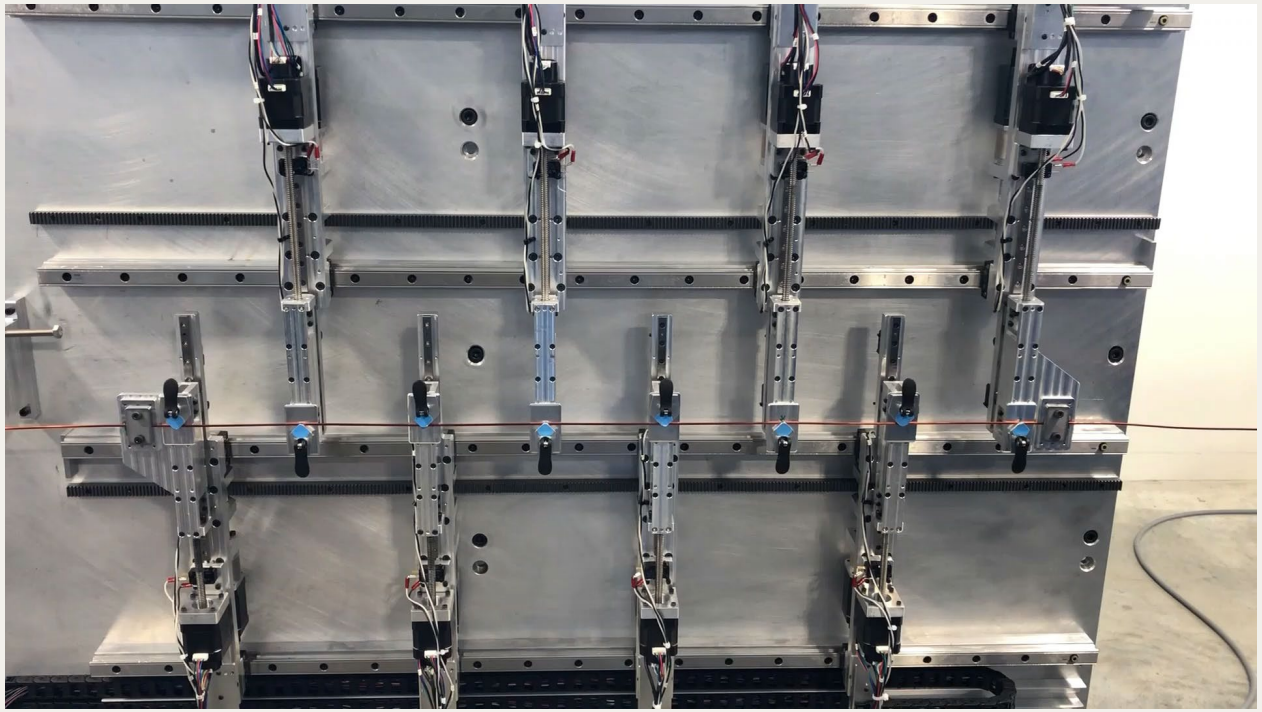
S-wind Stator

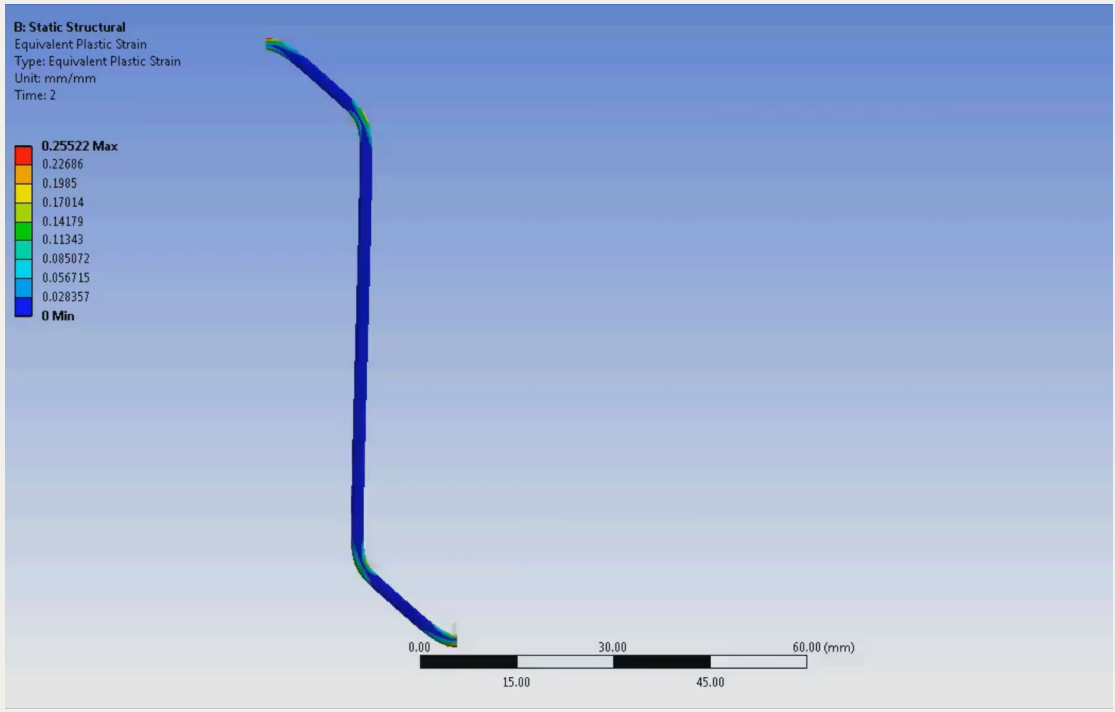
- Continuous conductor
- Distributed Coil
- Rectangular wire
- S-wind forming
- Radial insertion into Stator





S-wind



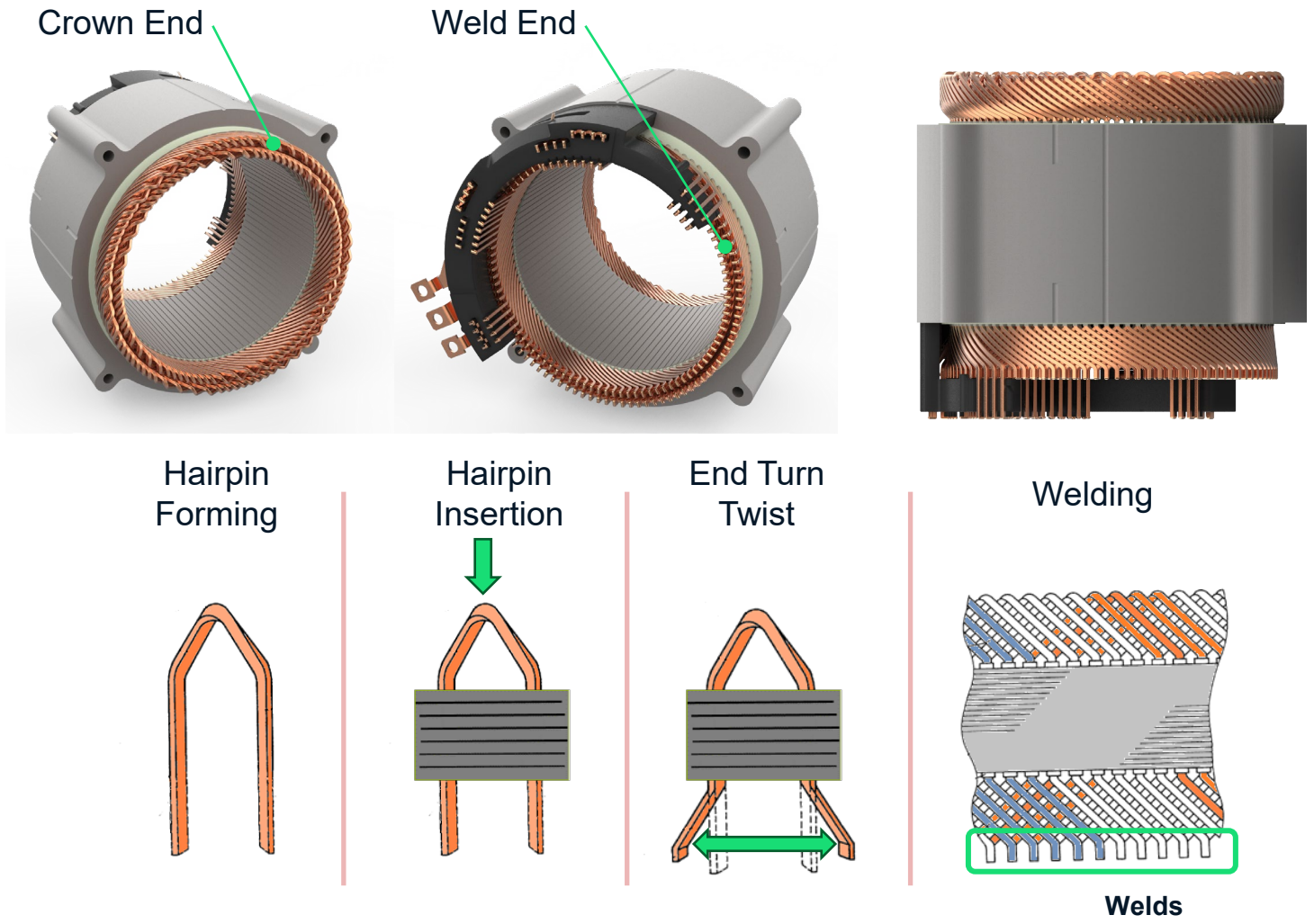


ANSYS Mechanical (Implicit) sufficient to study single wire, symmetric forming

BORGWARNER

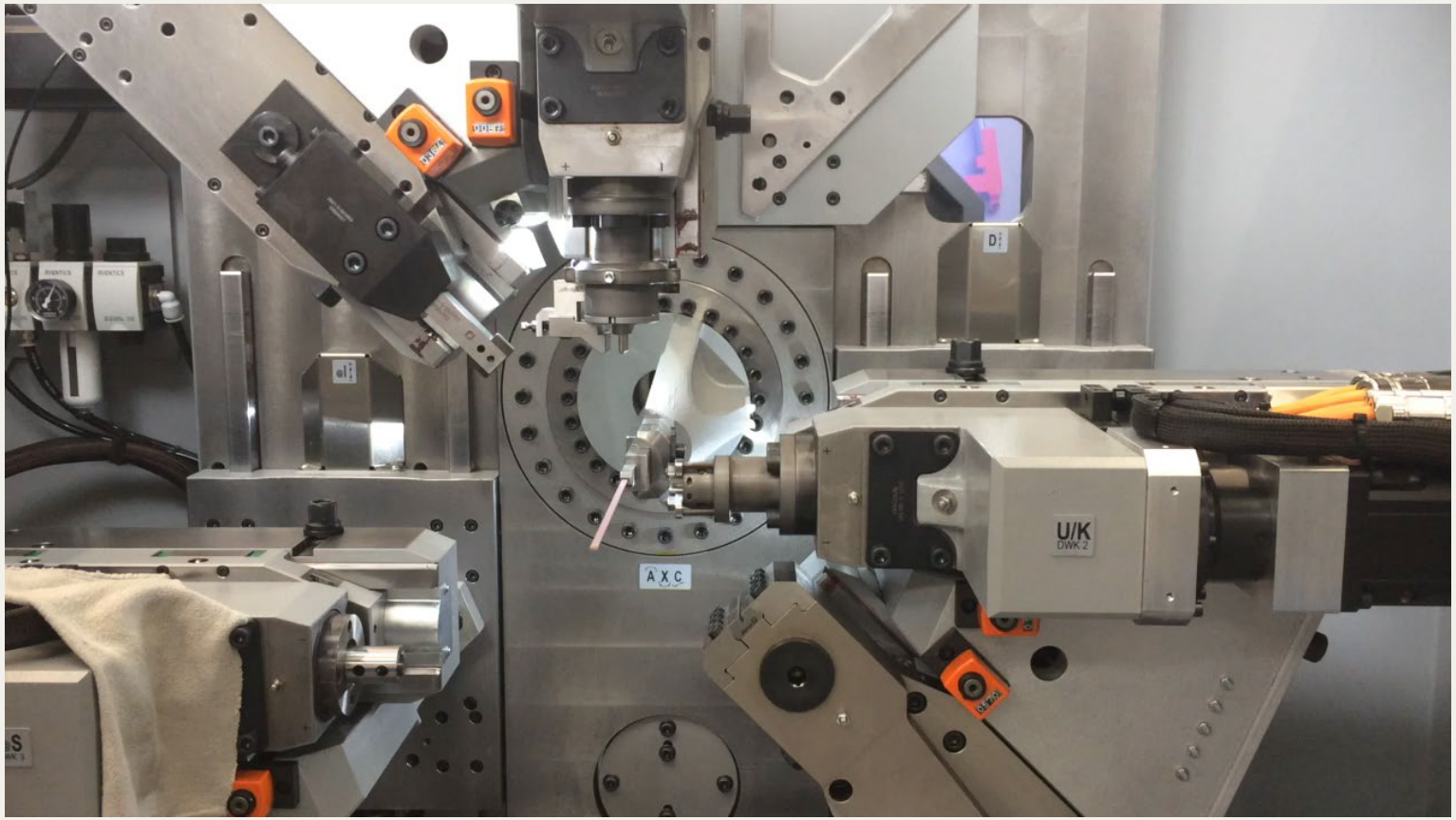
Hairpin Stator

- Hairpin Conductors
- Rectangular Wire
- CNC Bending to form Hairpins
- Axial Stator insertion
- Series Welding



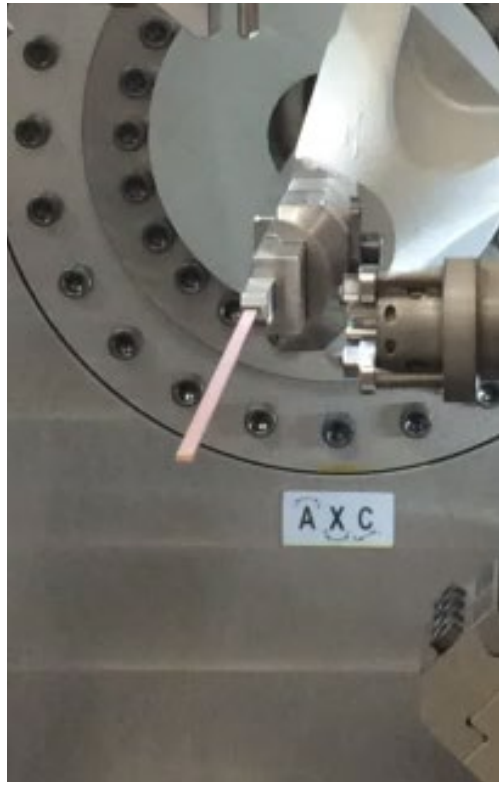
Hairpins – CNC Bending

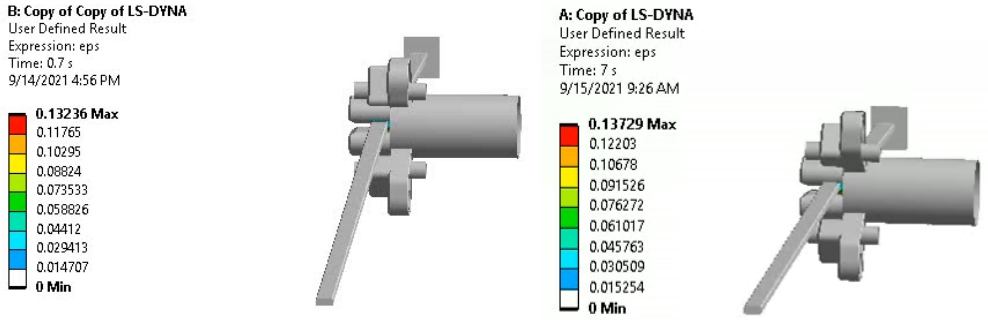
- Wafios CNC Wire Bending Machine
- Crown End bending
- Multi-axis Servos
- Specialized bending tools
- Straightening and Stripping



Hairpins – CNC Bending – Analysis

- Objectives
  - Conductor surface strains
  - Conductor shape
- Consider Explicit/Implicit Solver





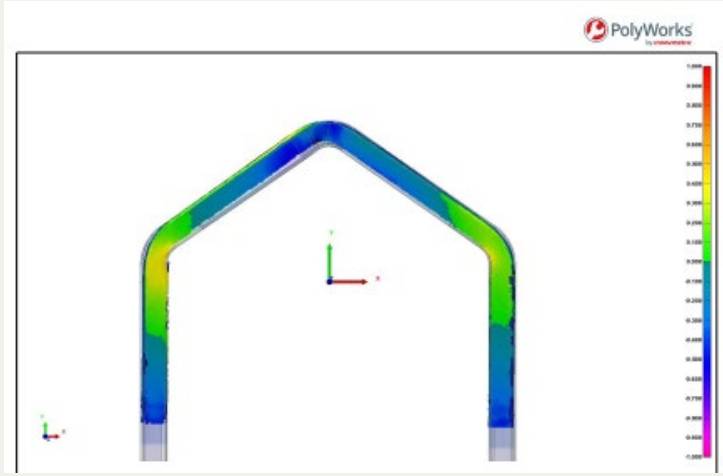
Explicit 160 cores 1h45m

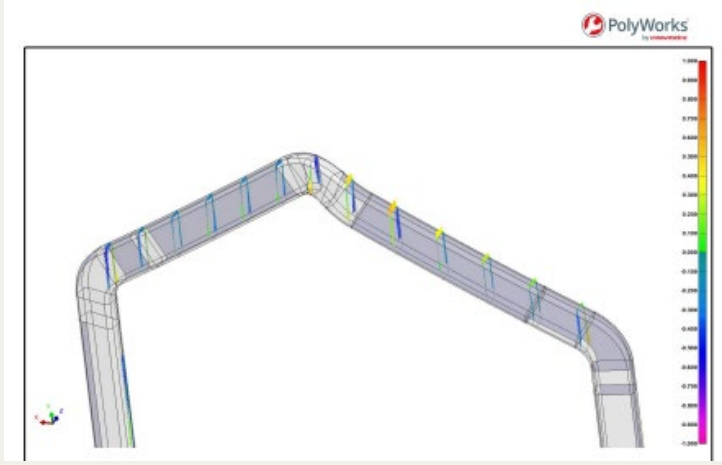
Implicit 64 cores 3h8m

Solver choice dependent on number of cores available and explicit step size

Hairpins – CNC Bending – 3D Scanning

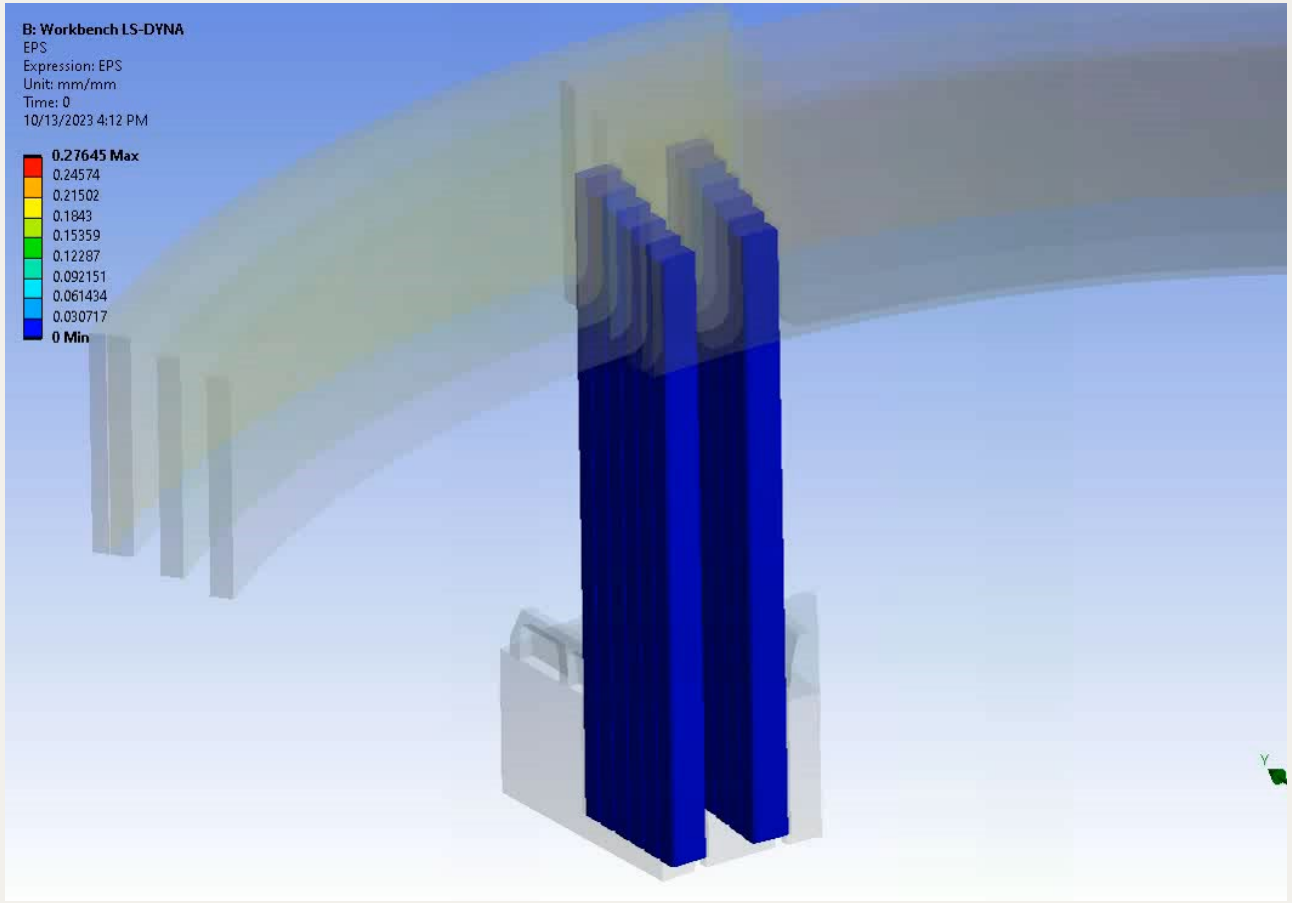
- Verification must be done with 3D Scanning
- Part gaging is of limited use for checking final shape
- Iteration between CAD Design and process capability





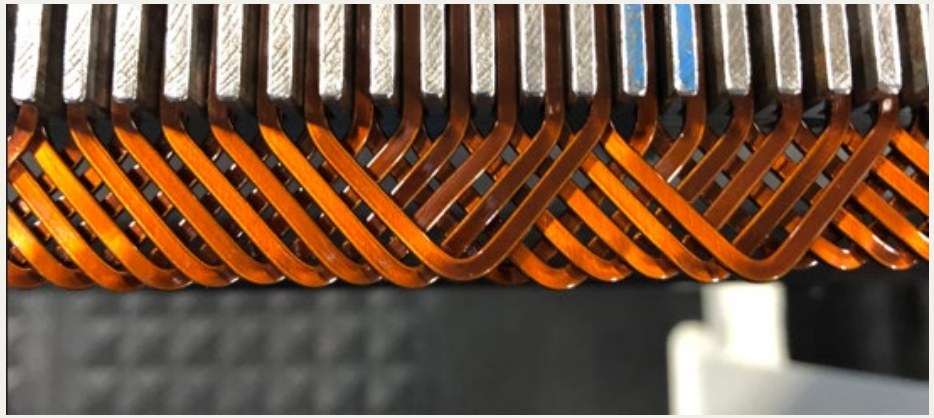
Hairpins – End Turn Twist Analysis

- Objectives
  - Conductor surface strains
  - Conductor shape
  - Conductor clearance
  - Adjacent component clearance
  - Stress levels on contacting components
  - Forming forces
- Simple contact definition – Body Interactions

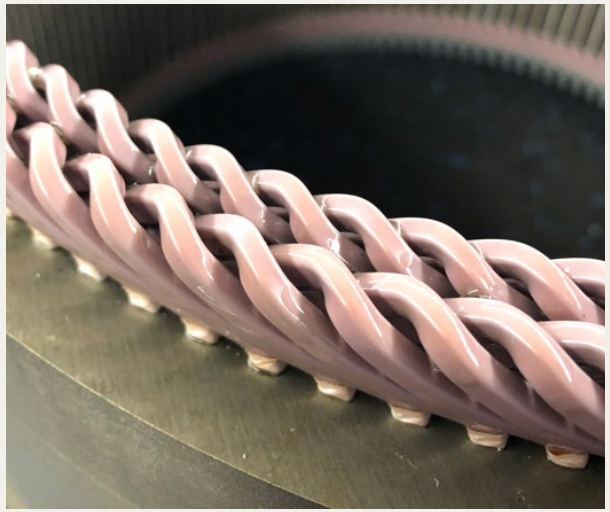


BORGWARNER

Wire Insulation

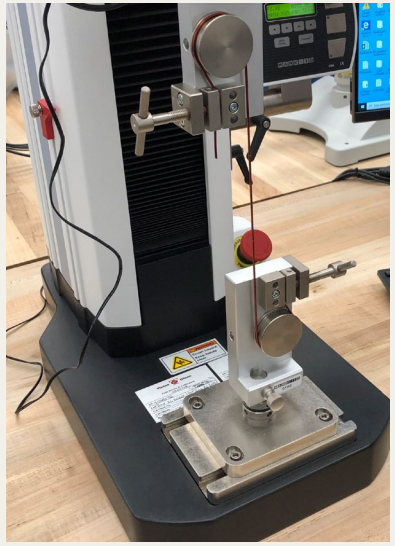


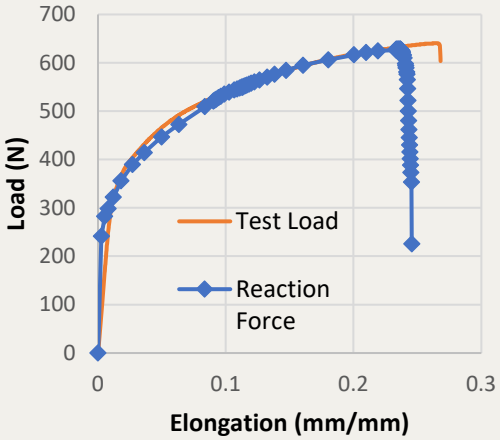
- Various insulation materials can be used:
  - PAI (enamel coating)
  - PI (enamel coating)
  - PEEK (extrusion)
  - PEEK over PAI
  - Kapton Wrap over PAI
  - …
- Insulation adhered to copper with proprietary adhesive materials

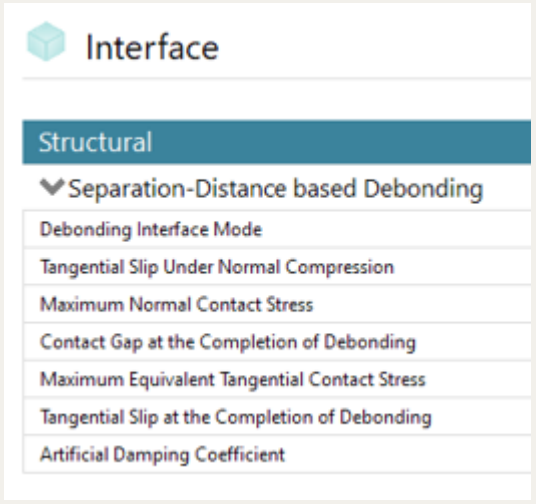


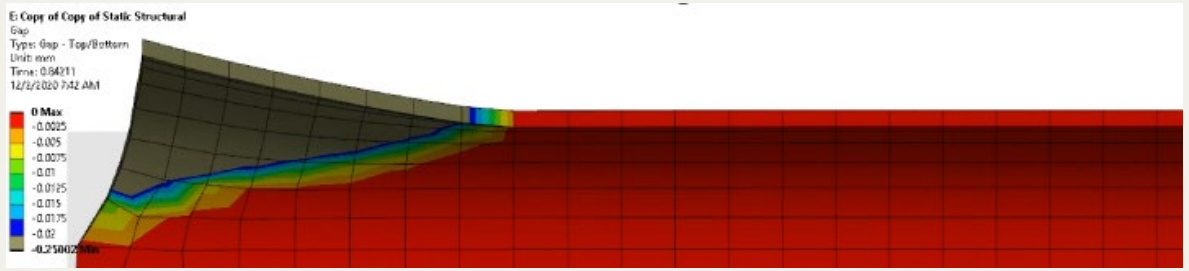
Wire Insulation – Debonding

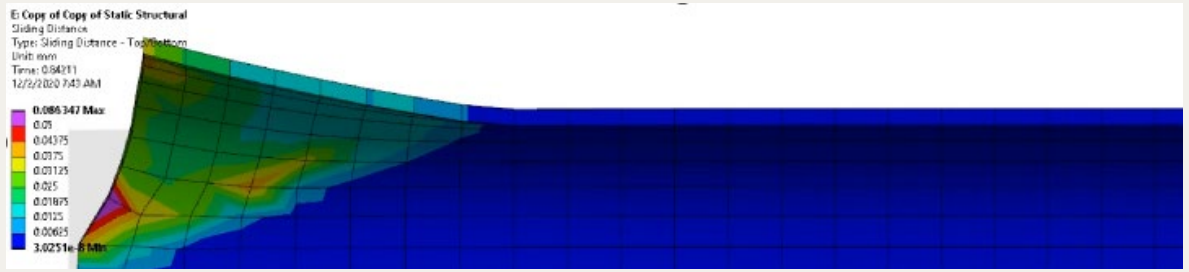
- Debonding calibrated by Ring Cut Tests
- Mixed Normal and Tangential Debonding Mode

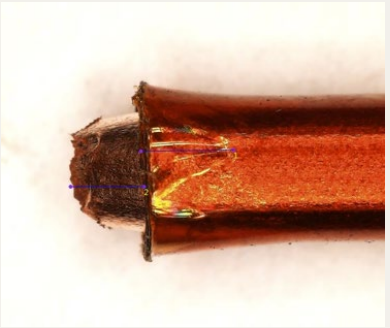


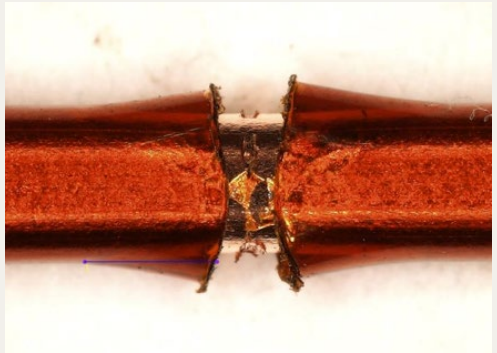








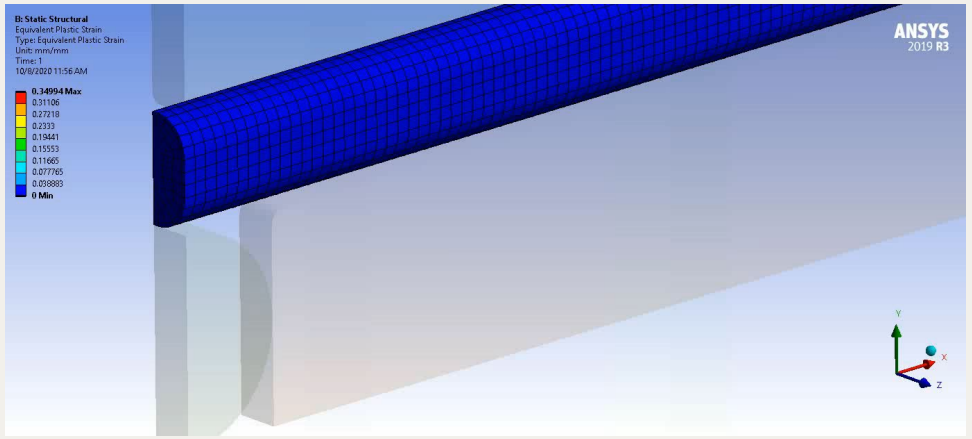




BORGWARNER

Wire Insulation – Insulation Failure

- U-Bend Simulation
  - Over-stress of insulation opposite forming tool
  - Establish strain failure criteria
  - Boundary conditions test vs. simulation important



Closing Remarks – LS-DYNA with Wire Forming Application

- Simplicity of contact definitions reduces setup time
- Explicit solver contact algorithm is robust; impossible/impractical to perform same analysis with ANSYS mechanical implicit solver
- Strain results can identify areas to improve tooling
- Physics-based wire shapes can be understood before tooling is made
- Debonding feature requires multiple inputs that must be obtained empirically

THANK YOU

Thanks to the following ANSYS team for excellent previous and continued support!

- Yi Zhang
- Adarsh Chaurasia
- Alaa Olleak
- Trent Busch

BORGWARNER