



This work is sponsored by
Rolls-Royce Corporation,
Indianapolis, IN

Abstract: Nozzle Guide Vanes (NGVs), made from Nickel-based superalloys, are a key component in aircraft engines produced by Rolls-Royce. Wide Gap Brazing (WGB) is a repair method used by Rolls-Royce for NGV repair because NGVs are non-weldable and expensive to replace. Wide-gap brazing is a joining mechanism, like soldering, but occurs at temperatures above 450°C. While the basics of this practice have been studied, the limits have not been completely determined, specifically geometric effects during brazing. This project served to determine the limits of wide gap brazing with respect to angle of the part during the braze. The goal was to standardize the brazing process for Rolls-Royce, as nozzle guide vane repairs involve brazing on complex angled surfaces. During this process, we also investigated how the surface roughness of the sample surface affects the braze. While Rolls-Royce uses wide gap brazing for many different purposes, our focus was on brazing under different surface conditions to understand braze-substrate interactions, rather than any repair of cracks or deformations. The findings of this project will help to increase brazing quality, reduce costs, and establish more robust industry-wide standards.

Background and Objectives

Single-crystal nickel-based superalloys are critical materials in gas turbine engines, valued for their resistance to high temperatures, mechanical stress, and corrosive environments. Rolls-Royce relies on these alloys in turbine components such as nozzle guide vanes, which experience significant degradation over their service life.



Figure 1: Examples of braze application on a turbine vane. From left to right: dimensional restoration, crack repair, feature replacement

Wide-gap brazing is a cost-effective repair method that restores damaged surfaces without replacing entire components. A hybrid braze paste containing high melting point (HTP) and low melting point (LTP) particles is applied to the substrate before being processed in a vacuum furnace. Within the furnace, the LTP melts and densifies around the still-solid HTP before isothermal solidification bonds the materials to the substrate.

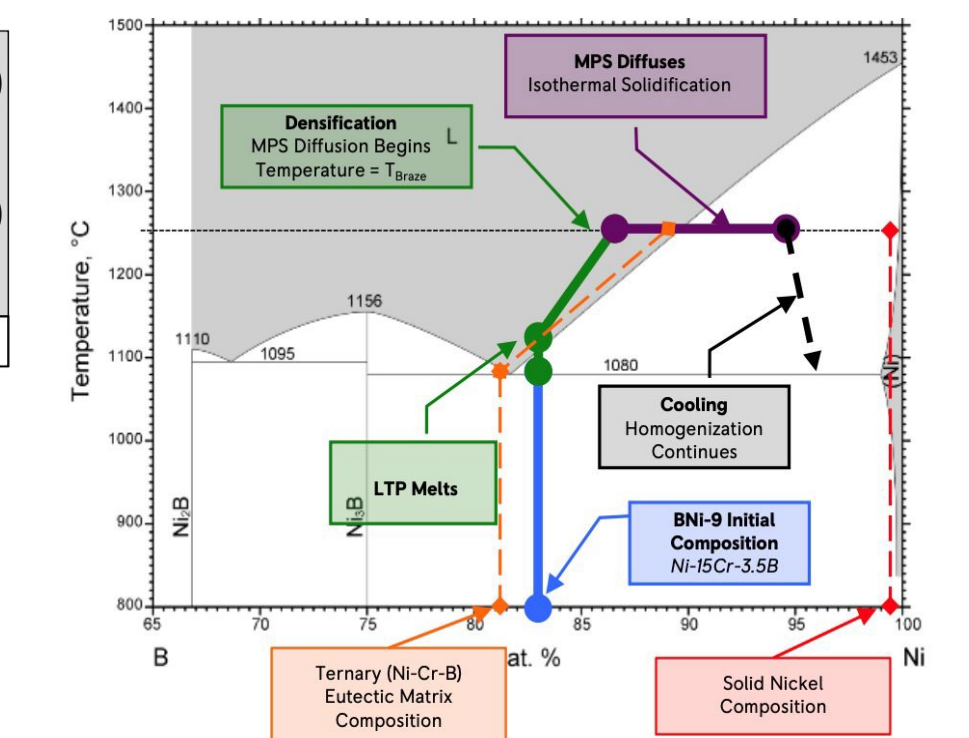
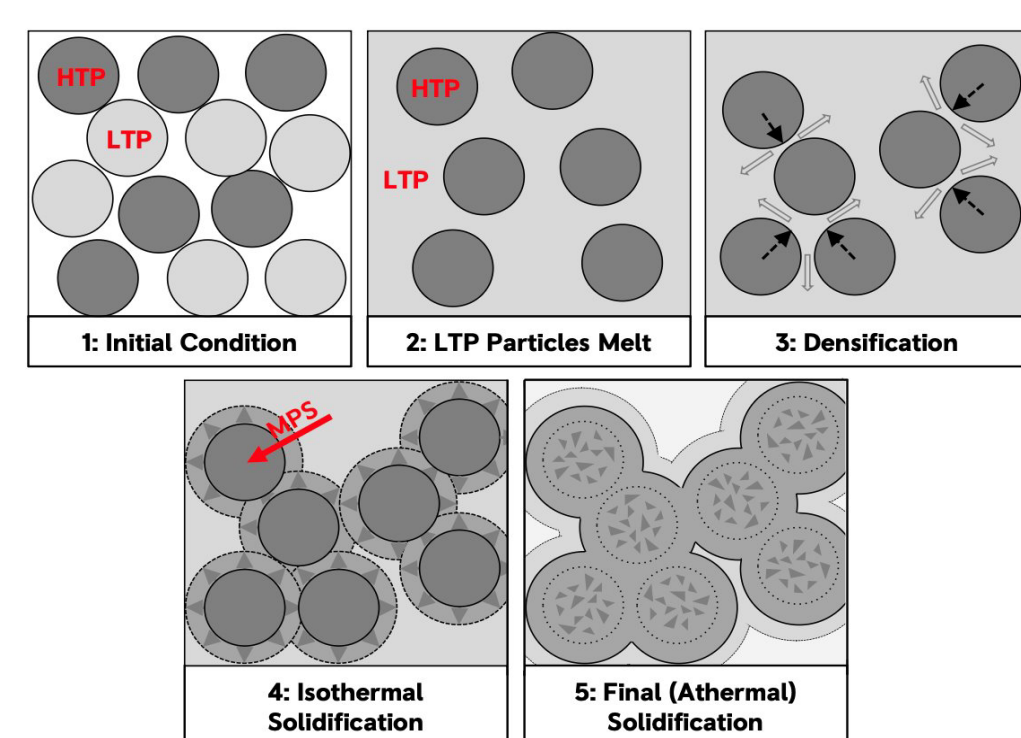


Figure 2: Illustrated cross section of two surfaces (Base Material) being bound via brazing [2] Figure 3: Nickel Boron phase diagram relating stages in the braze solidification sequence to the phase composition of the material (right) [2]

This project aims to:

- Determine the impact of angle (0°, 40°, 80°) on braze paste movement, wetting angle, and interface quality.
- Assess the role of surface roughness on braze effectiveness
- Compare performance between Class 2 (60% HTP / 40% LTP, low viscosity) and Class 3 (70% HTP / 30% LTP, high viscosity) pastes
- Provide Rolls-Royce with actionable best practice recommendations for wide-gap braze repair

Methods

Sample Preparation:

Eighteen 1x1in single-crystal nickel superalloy tiles were polished with 400 grit sandpaper on a polishing wheel to establish a baseline roughness for all the samples. Once brought to 400 grit, samples were separated into three groups of six using 320 grit, 150 grit, and 60 grit sandpaper to produce low, intermediate, and high roughness conditions respectively (R0, R1, R2). The surfaces were characterized at 5 locations per sample using a Zygo Optical Profilometer before normalization, after normalization, and after roughening. For each surface profile map, two line profiles were used to calculate Ra (μin) values.

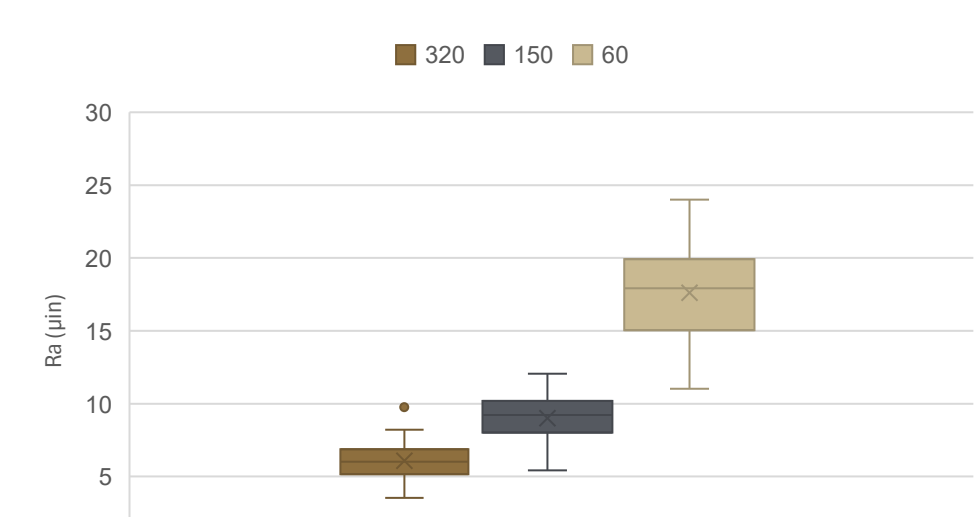


Figure 4: Roughness characterization of samples.

Brazing:

Samples were cleaned prior to brazing and arranged in alumina boats fitted with rods to hold samples at the target orientation angles of 0°, 40°, and 80°. Each batch contained six samples: half of them braze type 1 and other half braze type 2, one per roughness condition per braze type, and with two deposits per condition combination. All brazing was performed in a vacuum furnace following Rolls-Royce provided procedures.



Figure 5: 40° braze setup pre-braze.

Data Collection:

Braze movement was documented by photographing samples before and after the furnace cycle. Wetting angle, maximum height, and horizontal offset between midpoint and maximum height were extracted from 2D profiles taken parallel to braze moment using an optical profilometer, which also provided surface area measurements of the braze. For internal quality assessment, samples were sectioned and polished to 1200-grit, then imaged unetched and evaluated for interface characteristics

Image Analysis

Images were taken of the samples before and after brazing with a ruler for scale, then processed in ImageJ to measure length and width changes.

Results

Braze Movement:

- ANOVA two-way test showed:
 - Length change caused by paste type is significant at all angles
 - 80° angle is only instance of significant length change caused by substrate roughness
- Type 2 paste had greater length change than type 3 in all cases
- Greatest average length change observed at 40° with type 2 paste, **89.2%**
- Second largest was 80° type 2, **88.0%**
- By substrate roughness, **98.3%** elongation for roughest condition, **98%** for intermediate roughness

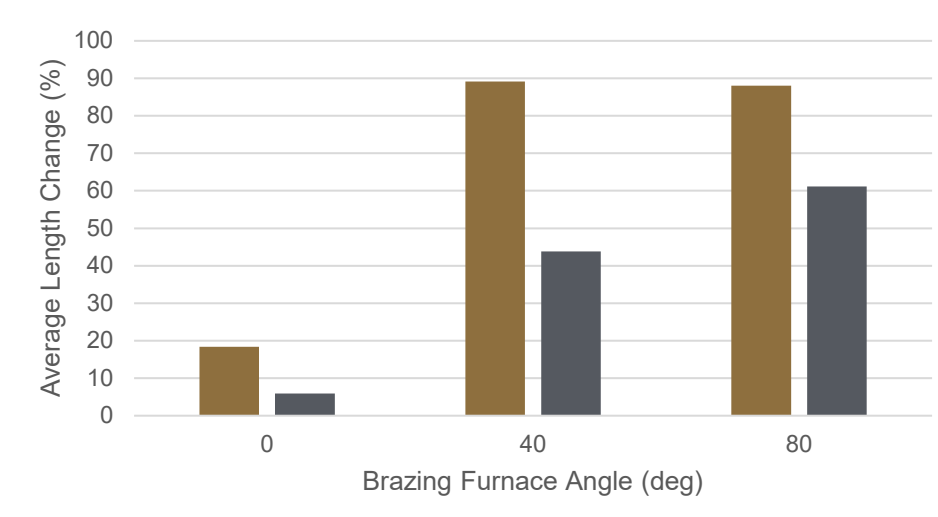


Figure 6: Study of brazing furnace angle on average length change of braze material on substrate, comparing braze type 2 and 3.



Figure 7: Comparison of substrate roughness and average length change, for 80° furnace samples only.

Wetting Angle:

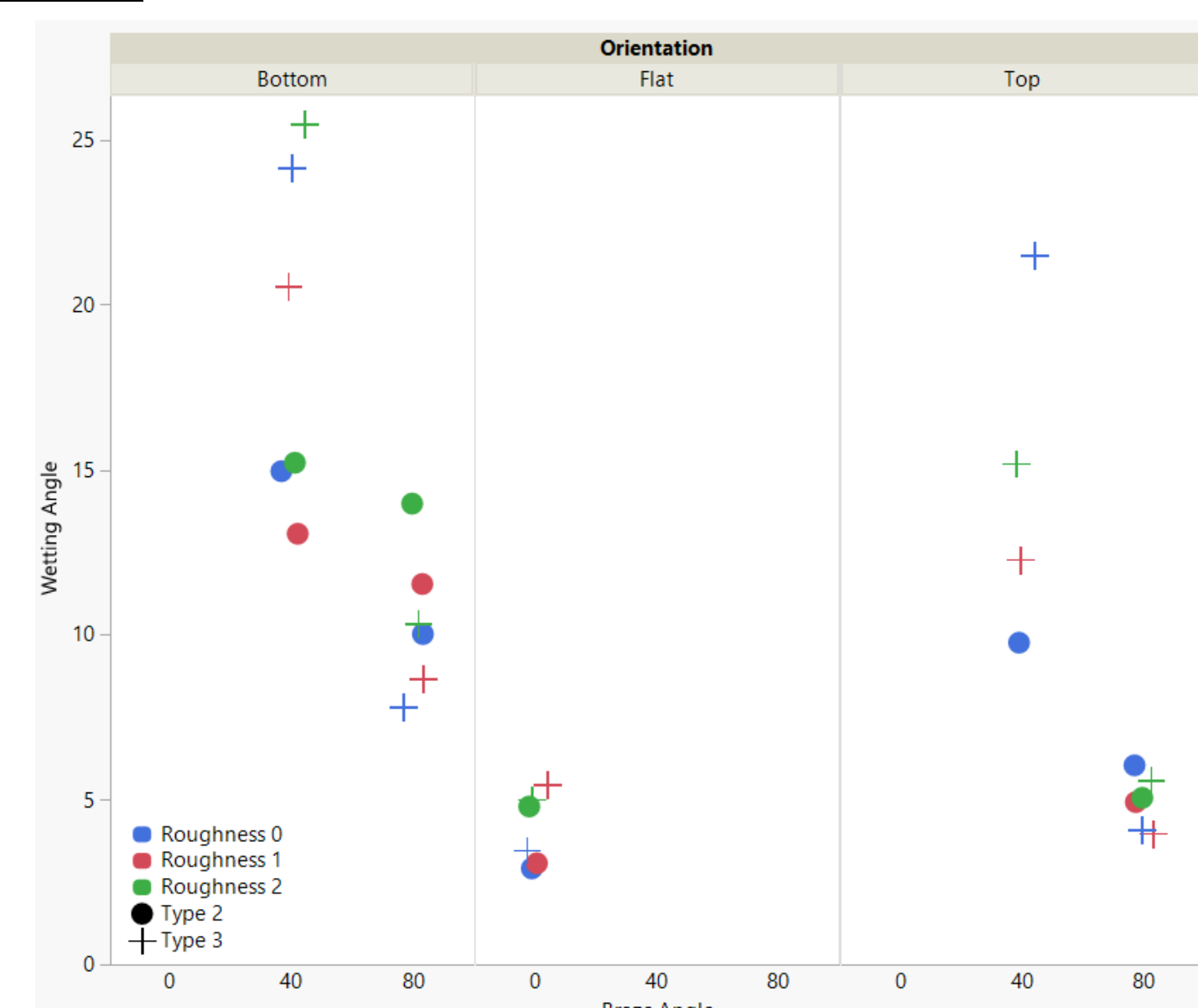


Figure 8: Graph of wetting angle across different brazes and conditions: braze angle, orientation, roughness, and braze type.

Both braze types in braze angle 0° and the bottom angle of both braze types in braze angle 80°, as the roughness of the sample increases, the wetting angle increases. Braze angle 40° has the highest wetting angles while have the most variation and missing some data of the braze type 2 top angle date due to faulty data.

Braze Dimensions:

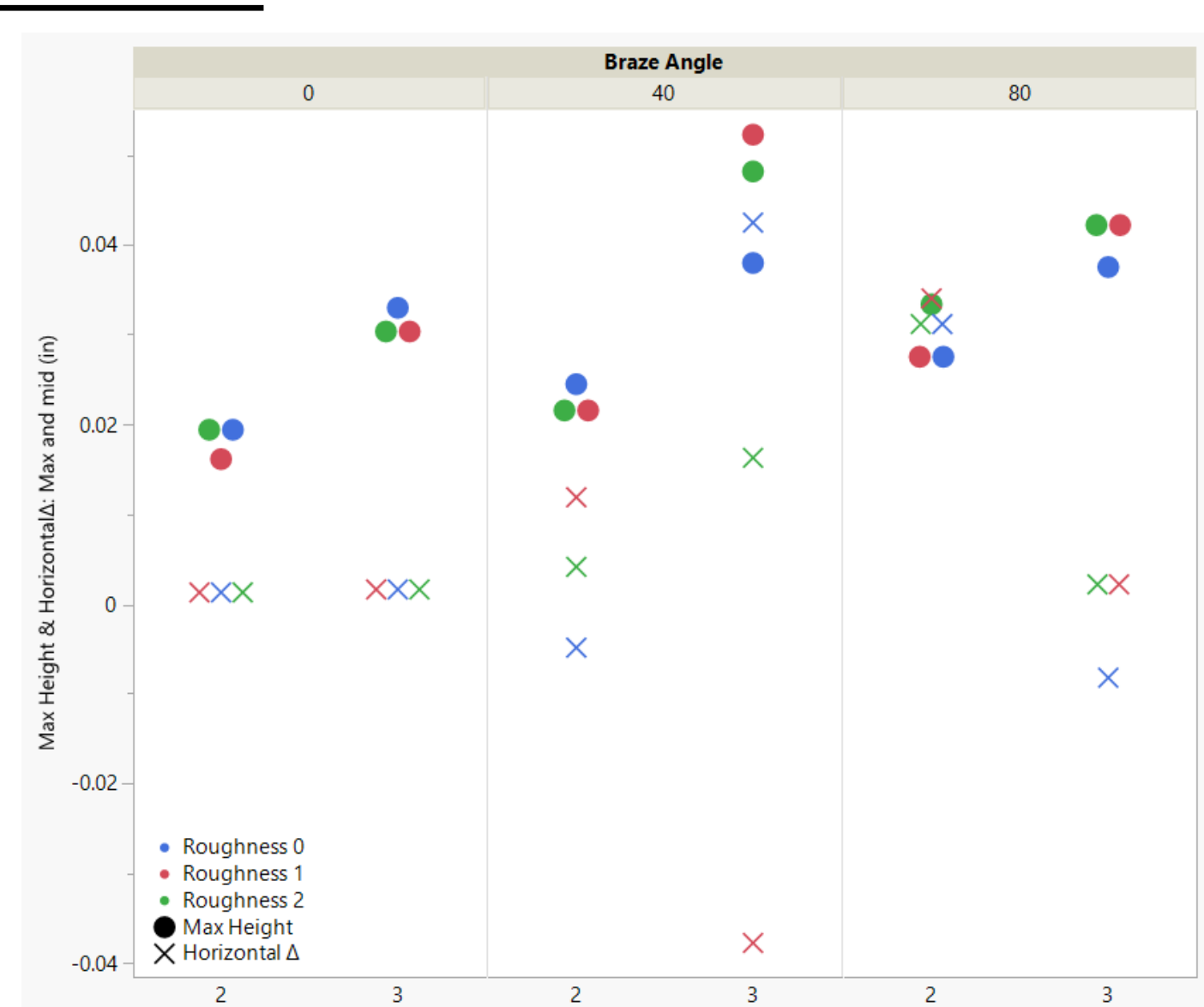


Figure 9: Graph of comparing different physical dimensions of the brazes across their different categories: showing max height and the horizontal difference of max point and midpoint.

The 0° brazes had little to no horizontal differences between max and midpoint. In general, the brazes with type 3 braze paste had a higher max height. As the braze angle and movement increased, the different between the max and midpoint shifted positive, which means the max point was up the slope compared to the midpoint.

Optical:

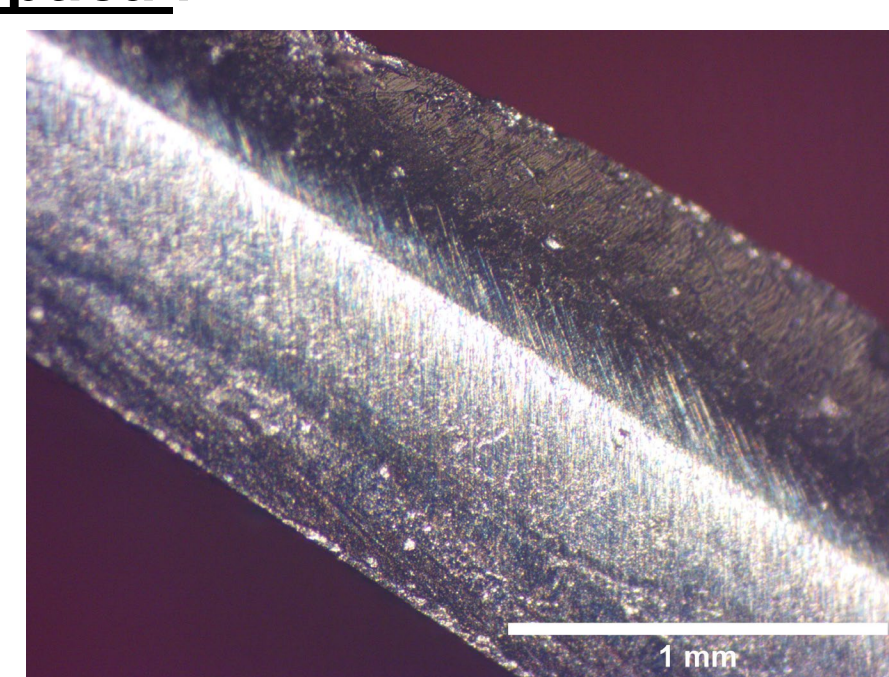


Figure 10: Optical micrograph of the type 2 braze, 40°, R2 sample

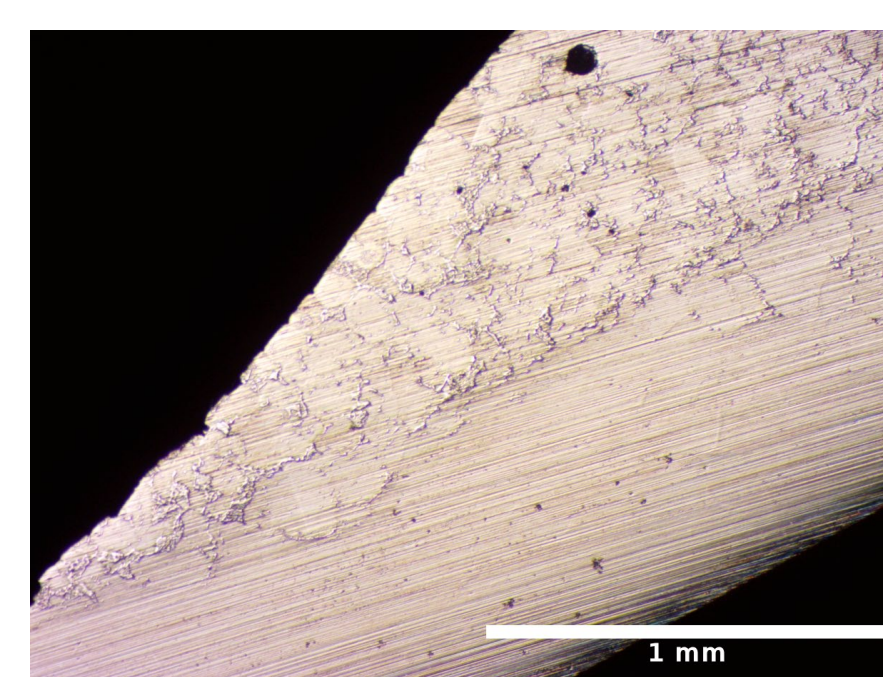


Figure 11: Optical micrograph of the type 3 braze, 80°, R2 sample

In figures 10 and 11, the quality of the braze can be observed. These figures only represent two of the eighteen samples, but the brazing quality is consistent across all the samples. The smooth area on the bottom represents the nickel substrate, with the dendrite filled top section being the braze paste. As shown in the images, there is a strong and well integrated interface.

Discussion

Wetting Angle: For the 0° and bottom 80° samples, the braze angle increases with roughness for both braze types due to higher surface area, retaining more braze before spreading. This trend does not appear in top angles, where upward braze movement is driven by surface energy against gravity, producing similar wetting angles. Variation in 40° brazes due to some Type 2 brazes reaching the top of the substrate and discoloration of the LTP occurring in both Type 2 and Type 3 40° brazes from suspected contamination of the alumina boats. At 40° and 80°, the bottom wetting angle exceeds the top due to gravity and surface energy acting downward. For bottom 40° and 80° brazes, Type 3 had higher wetting angles than Type 2 due to its greater HTP content restraining LTP from spreading. This reverses at 80°, where Type 2 is higher as more movement causes more braze to pile up.

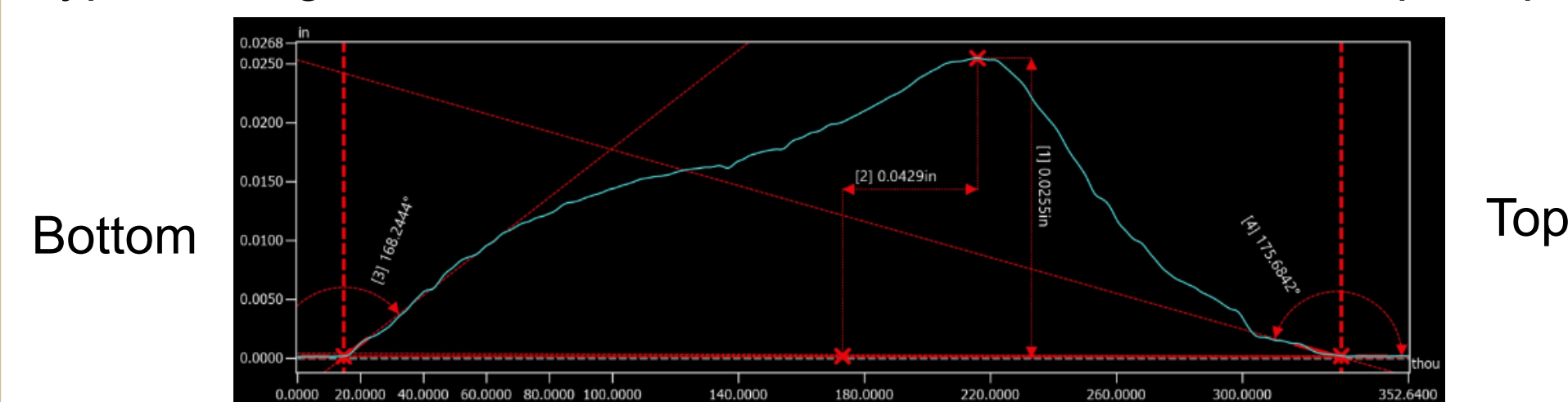


Figure 12: Profile of type 2, 80°, R1 braze with max height, braze angles, and horizontal difference in max and midpoint.

Braze Movement: The interaction between paste type and length change was significant across every sample revealing key differences:

- Type 2 paste had consistently greater length change than Type 3 due to its lower HTP content allowing the material to melt and spread more at lower temperatures.
- Surface roughness was only significant at 80° where gravity and deeper grooves in the samples drove the braze downhill. Higher roughness also increased movement via greater surface energy from unsatisfied metallic bonds.
- Length change increased from 0° to 40°, with little change between 40° and 80°, suggesting no geometric limit to braze effectiveness.
- Horizontal spread was minimal at 0° but grew with increasing angle size and braze movement as seen in Type 2 at 80°.

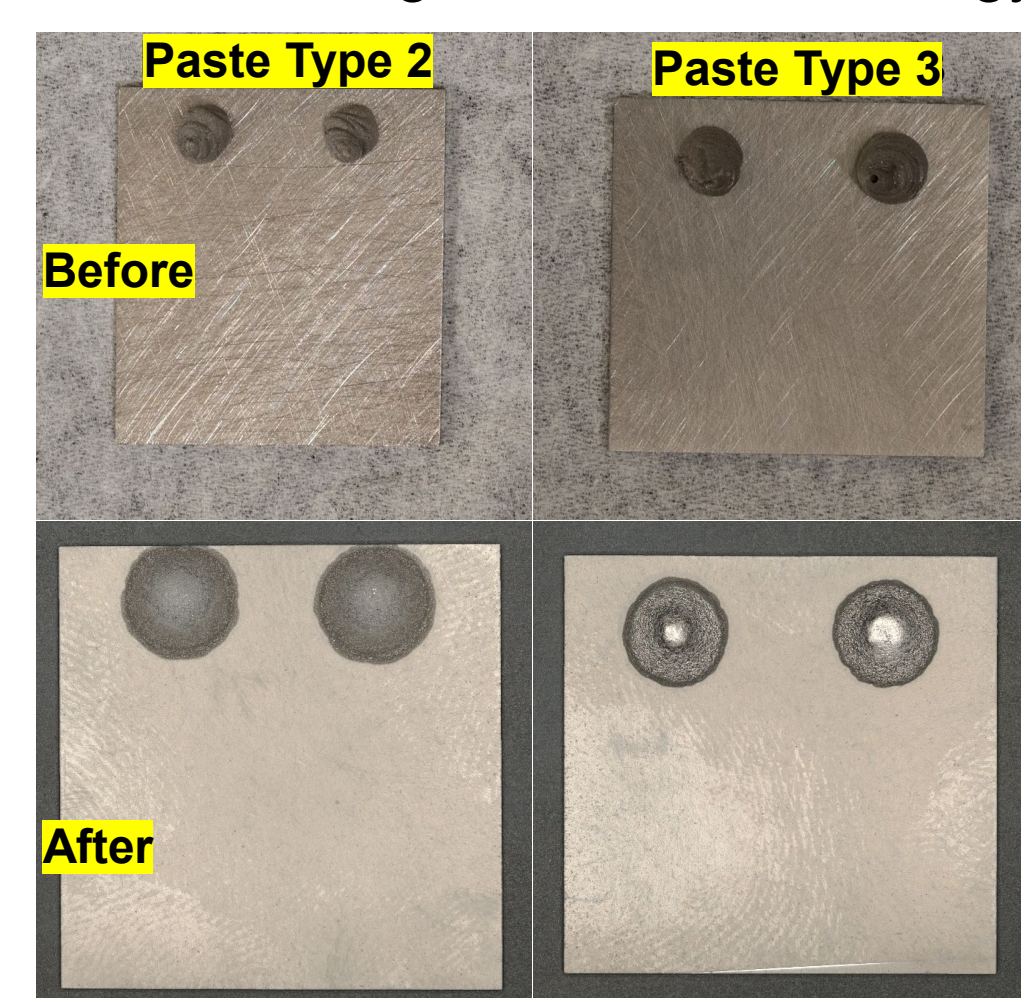


Figure 13: Before and after images of 40° type 2 and 3 braze.

Braze Quality: Optical microscopy confirmed successful brazing across all samples, with a strong substrate-paste interface throughout. Regardless of surface roughness, both materials bonded identically across the target area with no cracks, gaps, or separation, demonstrating the flexibility of this repair process.

Conclusions & Future Work

Surface roughness, braze viscosity, and angle all had minimal impact on brazing quality across all configurations, suggesting wide gap brazing operates within a wide processing window, with no limits found within the bounds of our experiment.

Further characterization of the brazing process is still necessary. A comparison between nickel blasting, chemical dealloying, and as-received surface conditions can better inform effective pre braze processes. Mechanical testing of braze joints can quantify the strength of the braze-substrate bond across conditions. Extending the study to more extreme orientation angles, with the braze on the underside of the sample, would establish the true positional limits of the process and broaden its relevance to geometrically complex components.

Acknowledgements

Thank you to all who have helped throughout this project. Our faculty advisor, Dr. Ernesto E. Marinero, and Rolls-Royce sponsor, Scott Nelson, for all their excellent technical advice and guidance provided. Thank you to Professor Michael Titus and Akhil Bejjurapu for assisting with the vacuum furnace. Finally, thanks to Sam Schmidt, Casey Peters, and Tim VanMeter for supporting our in-lab needs.

References

- Nelson, S.D. (2013) Multiphase Wide Gap Braze Alloy for the Repair of Nickel-base Superalloy Turbine Components: Development and Characterization. [Thesis, Colorado School of Mines]
- Nelson, S. D. (2025). Purdue 2025 kickoff [PowerPoint slides]. Rolls-Royce