PURDUE UNIVERSITY
School of Materials Engineering

Determining Best Practices for the Wide-Gap Braze Repair of Nickel-Based Superalloys

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Nozzle Guide Vanes (NGVs), made from Nickel-based superalloys, are crucial in aircraft engines but expensive to produce and replace. Wide Gap Brazing (WGB) is a widely implemented repair method in the aerospace industry, used by Rolls-Royce for NGV repair. This repair method relies on a delicate balance of numerous parameters. As the process is largely unstandardized and based in anecdotal evidence, more investigation into parameter controls would help build standards. Elements of WGB were systematically examined to enhance repair quality, reduce costs, and establish more robust industry-wide standards.

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Project Motivation

Rolls-Royce generates substantial revenue from its gas turbine engines, which operate through a process of **intake, compression, combustion, and exhaust.** A critical component in these engines is the **NGV**, made from **single-crystal superalloys** like **CMSX-4** to withstand extreme temperatures and pressures without degradation.

Due to the **high cost of replacement**, Rolls-Royce employs **WGB** as a repair solution. WGB **bridges gaps up to 2mm,** creating durable bonds that endure turbine stresses. This cost-effective process provides an efficient way to **extend the lifespan of NGVs** while maintaining their mechanical integrity. This project explored root causes that led to poor braze quality, shown in Figure 1, focusing on **Filler Storage** via **Mass Loss** and **Braze Storage**.

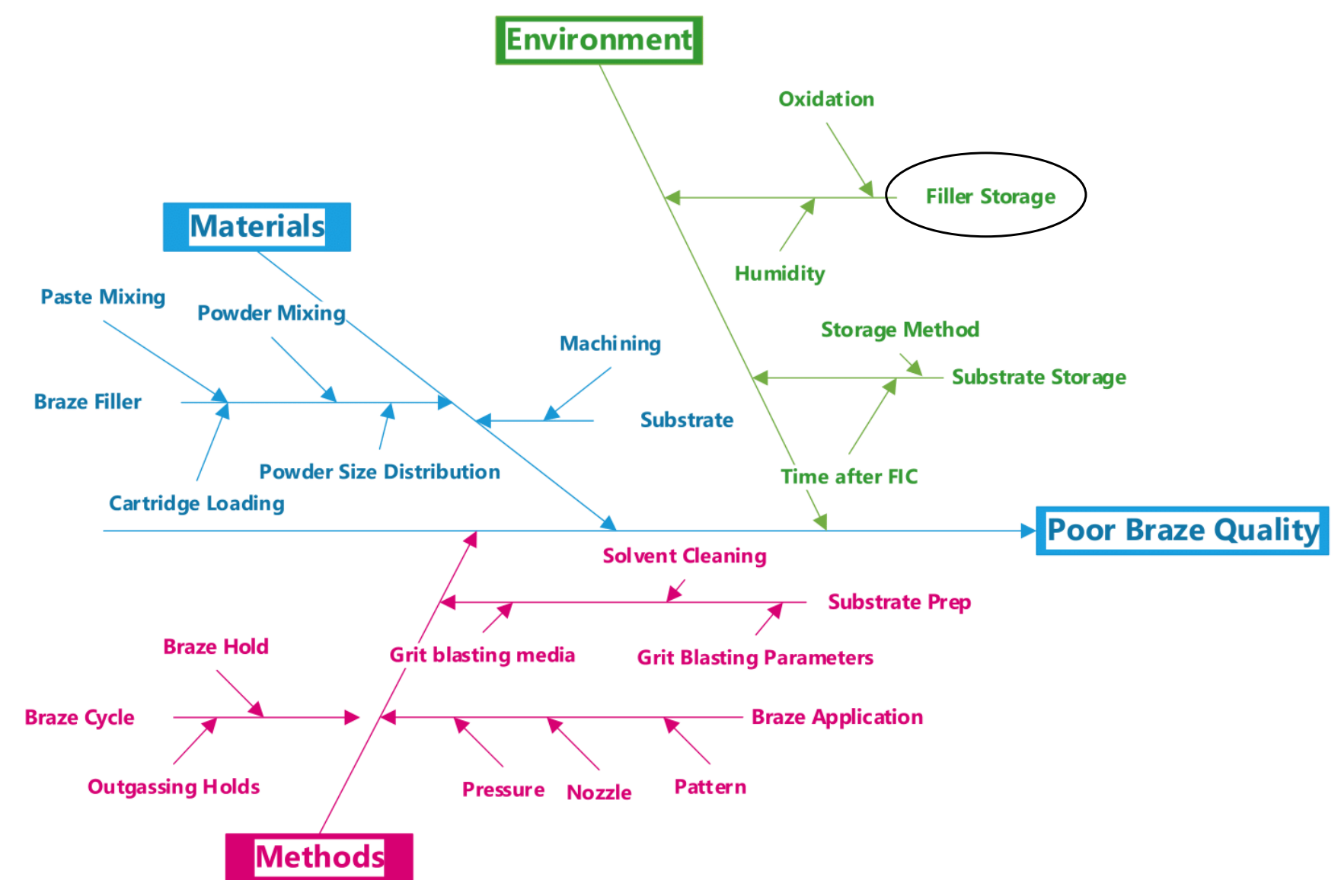

Figure 1. *A fishbone diagram presented to us by Rolls-Royce and used to identify root causes for inconsistencies in WGB.*

Background

Brazing to Fix Superalloy Components

The **brazing filler compound** consists of a **nickel-based alloy powder** mixed with a **hydrogel binder**. The alloy powder is a precisely engineered blend of many powders, each selected for its specific chemical composition and particle morphology while the binder facilitates precise application. Crack repair was studied using **combs** to observe **capillary action** and **circular buttons** were used to simulate **dimensional restoration.** All substrates were composed of CMSX-4 and underwent **Fluoride-Ion Cleaning (FIC)** to remove any deeply-embedded oxides.

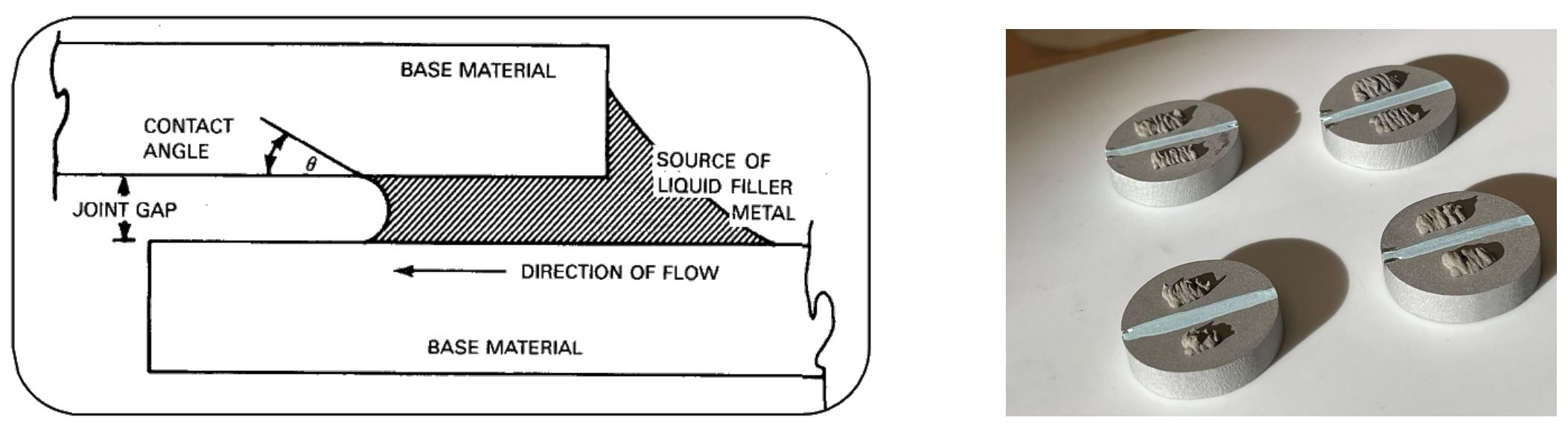

Figure 2. *A schematic view of capillary action (left) and four prepared button samples (right).*

Diffusion Brazing

This technique uses two-phase sintering powders: **High Melting Temperature Powders (HTPs)** which remain solid throughout the brazing process and **Low Melting Temperature Powders (LTPs)** that melt and form the liquid phase of the system.

There are five main steps to diffusion brazing:

1. Powders are suspended in the binder
2. LTPs melt to form the liquid phase
3. Capillary densification of HTPs
4. Solidification layers form
5. Full solidification is achieved

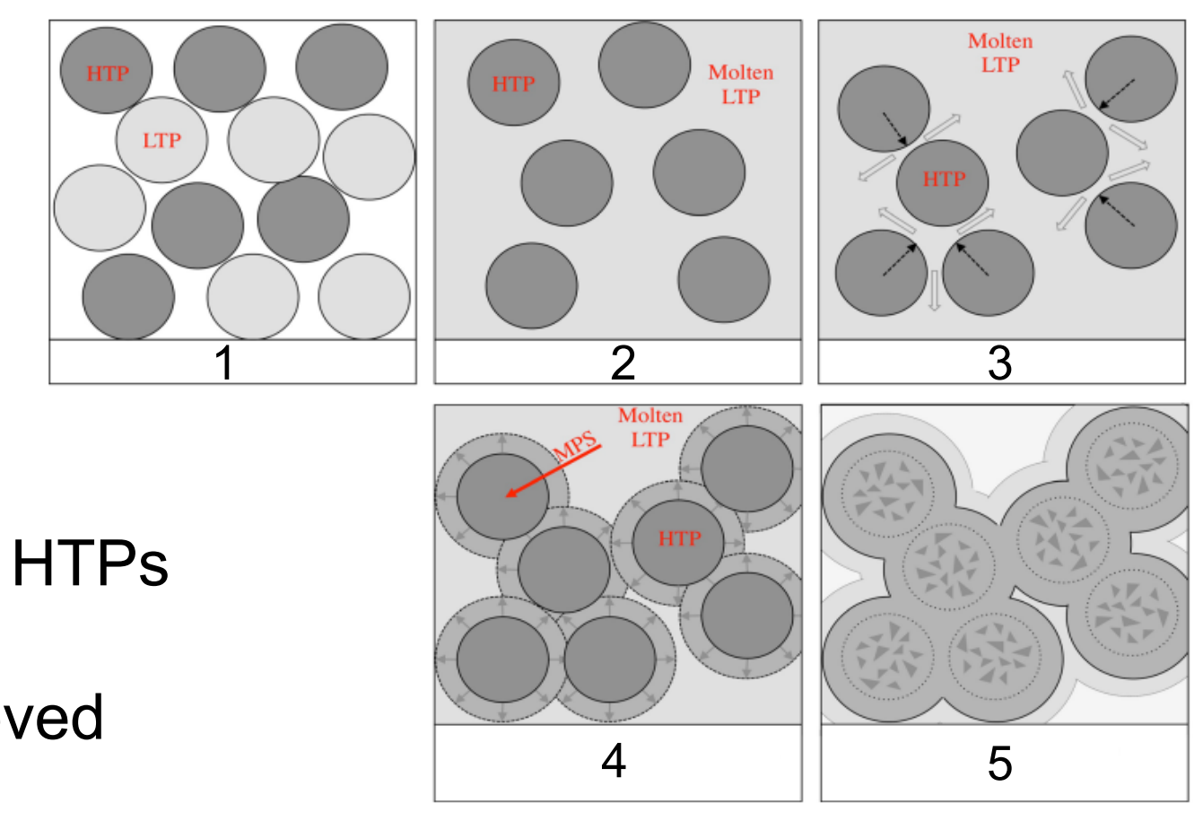

Figure 3. *Solidification sequence of the powder components, corresponding to the steps on the left of the figure.*

Defects in the Brazing Process

Defects are a key area of research, with hypotheses proposed to identify their sources. But, due to limited empirical understanding, they remain a major challenge to the widespread adoption of diffusion brazing as a reliable repair method.

Common defects include:

- Reduced joint strength
- Crack formation
- Gas leakage
- Voids

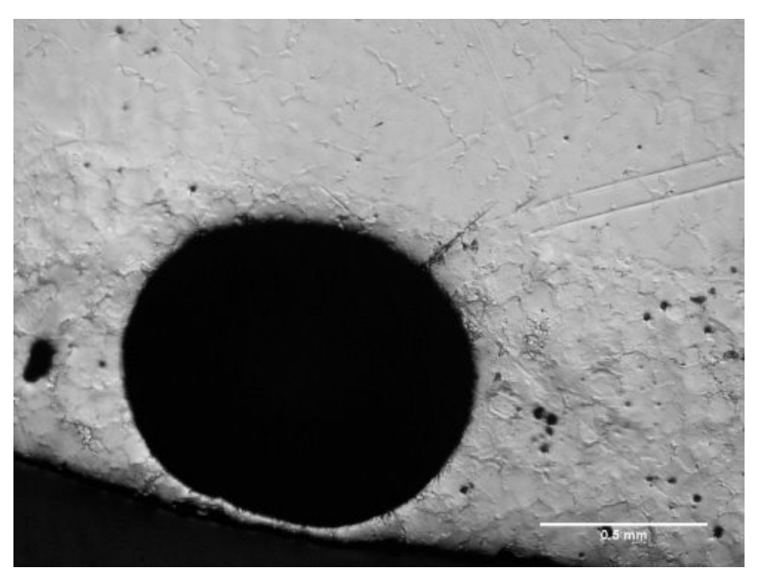

Figure 4. *An example of a large void in a brazed layer.*

Mass Loss Experiment

Procedure

Braze Preparation: The compound was extruded onto glass slides in a pattern similar to dimensional restoration applications, with a uniform layer averaging 0.16g applied to each of the eight slides. Four slides were allocated to each drying method, and images were taken of the underside of the brazing compound through the glass to compare differences in porosity.

Furnace Drying: One set of four slides was dried in a furnace for an hour at 65-70°C. Mass measurements were recorded every 5 minutes for the first 30 minutes, every 15 minutes for the remaining 30 minutes, and post-drying images were taken to assess porosity.

Vacuum Drying: The second set of four slides underwent five vacuum cycles at –20 inHg, with each cycle lasting 4 minutes. Mass measurements were taken between cycles, and post-drying images were taken to compare porosity.

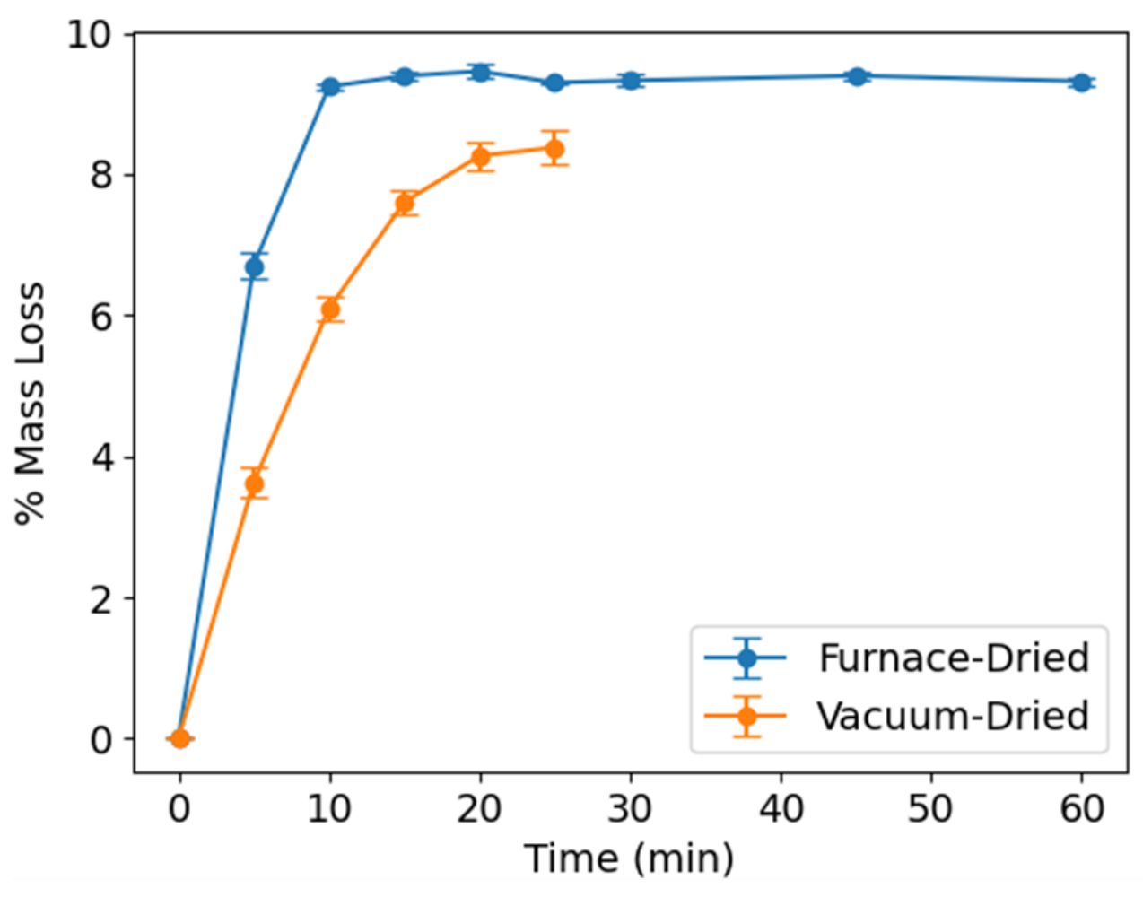

Figure 5. *Comparison of vacuum drying and furnace drying, showing mean values and standard error of the mean (SEM). Furnace drying achieves a 9% mass loss in 10 minutes, while vacuum drying reaches 8.5% mass loss over 25 minutes.*

Results

The two drying methods yielded comparable results. The furnace-dried samples experienced a more rapid mass loss in the first 10 minutes, plateauing at around 9%, while the vacuum-cycled samples showed a more gradual and consistent rate of mass loss across all five cycles.

Braze Storage Experiment

Procedure

Six syringes of compound were prepared and stored under varying time and temperature conditions. The compounds were then applied to elongated gaps in CMSX-4 comb substrates to simulate crack repair, with one comb filled using freshly mixed compound as a control and the other using aged compounds, as seen in Figure 6.

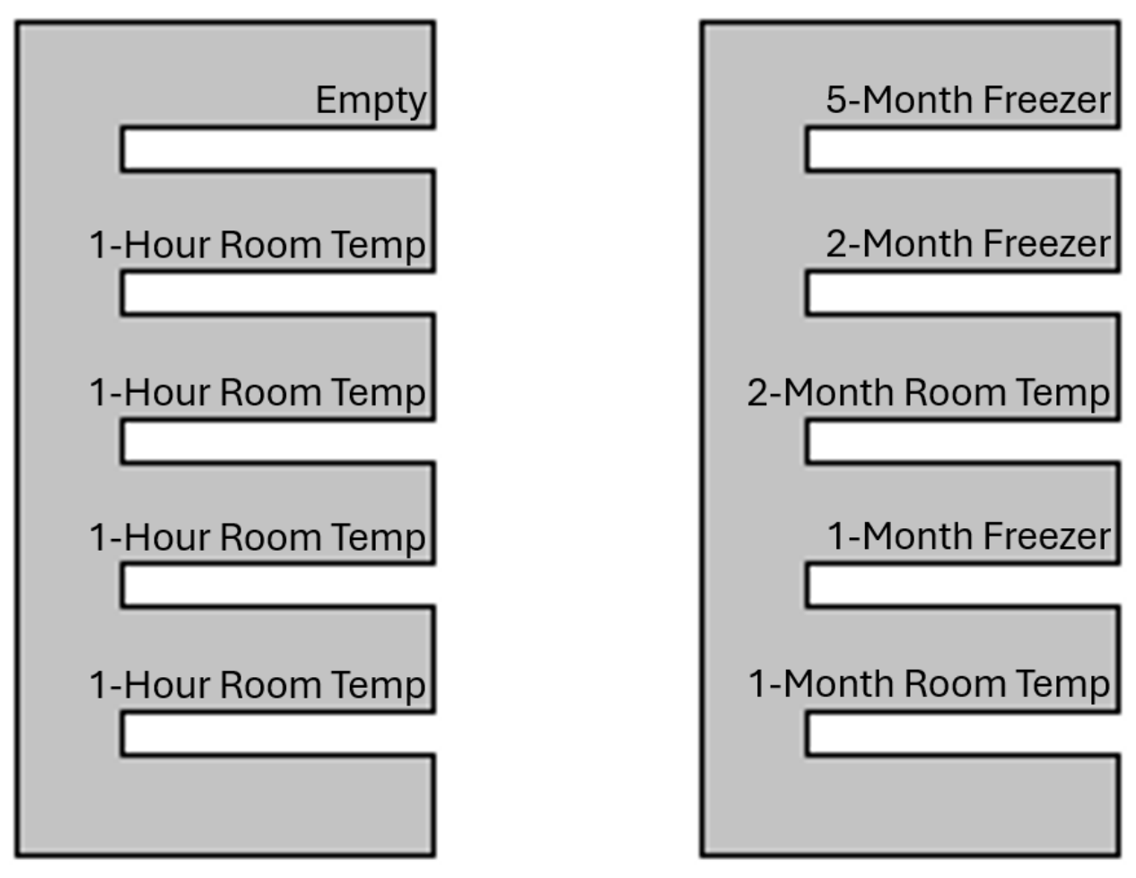

Figure 6. *CMSX-4 comb substrates with simulated cracks filled using braze compounds. The control comb (left) was filled with freshly prepared compound, while the experimental comb (right) was filled with compounds aged under different time and temperature conditions.*

Results

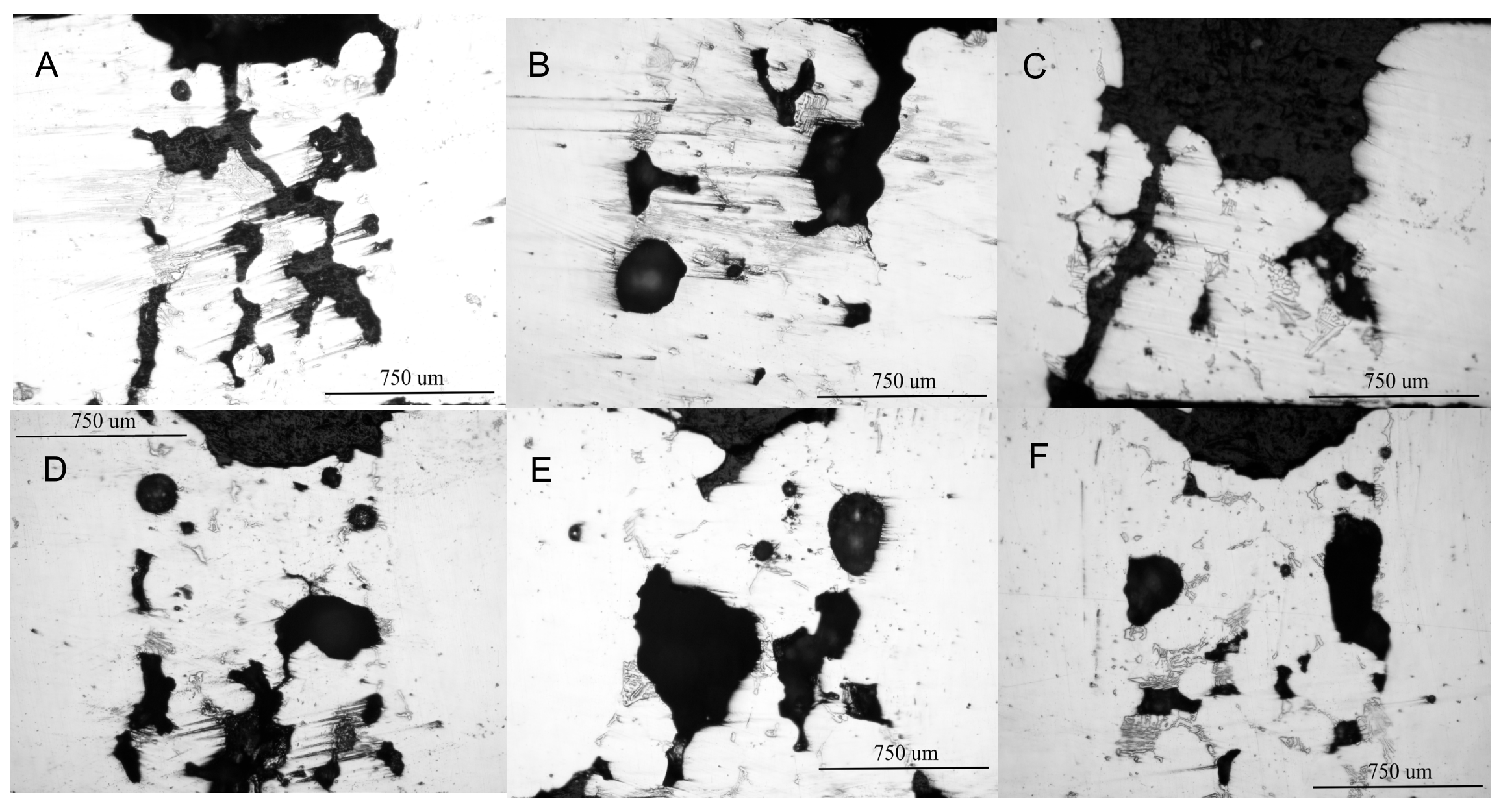

Figure 7. *Micrographs of braze compound aged under various storage conditions. Samples include (A) 1-hour room-temperature (control), (B) 1-month room-temperature, (C) 1-month freezer, (D) 2-month room-temperature, (E) 2-month freezer, and (F) 5-month freezer.*

Discussion

Mass Loss Experiment

- **Vacuum infiltration cycles** were introduced into the brazing preparation process to enhance mass loss during drying and reduce internal porosity. Under vacuum conditions of -20 inHg, water boils at 43°C, aiding in the removal of residual moisture.
- **Mass loss plateaus** differed by only half a percent when these steps were performed independently.
- **Porosity** observed before brazing could not be correlated with final porosity quality, as the brazing process involves melting under vacuum, causing pores to collapse.

Braze Storage Experiment

- **Porosity** was observed in all brazed samples, with no consistent trends across the different storage conditions. While this lack of correlation presents challenges, it highlights the need for further investigation into how storage time might influence braze quality.
- **Procedural deviation** occurred: the interval between braze paste application and the actual brazing process varied. This introduced an uncontrolled variable that may have influenced the results and could explain some of the observed inconsistencies.
- A key takeaway for our group was the significant impact that **outsourcing** procedures to third parties can have. Minor procedural inconsistencies—such as variations in timing or handling—can greatly affect final product quality.
- Despite the mixed results, the findings remain meaningful. If extended storage time does not significantly degrade braze quality, suppliers may be able to **produce and store larger batches of compound** prior to application. This could reduce costs and improve efficiency in large-scale brazing operations.

Conclusion & Recommendations

Mass Loss

The primary goal of the oven and vacuum infiltration steps is to remove water from the system before placing the NGV in the vacuum furnace. Our data indicates that mass loss occurs exclusively during the vacuum infiltration step, making the drying oven redundant, as no additional mass loss is observed after vacuum exposure. Furthermore, there was no significant difference in pre-braze porosity between oven drying and vacuum drying. However, before modifying the procedure, a validation experiment should be conducted to ensure that eliminating the drying oven does not compromise the overall process integrity.

Braze Storage

The braze storage experiment highlighted the complexity of maintaining quality in brazing processes, particularly when variables such as storage time and procedural consistency are involved. Although no clear relationship between storage conditions and porosity was established, the experiment underscored the importance of process control and consistency. The potential to store braze material for extended periods without significant quality degradation presents promising opportunities for cost and time savings in large-scale applications.

Recommendations

- Compare porosity and overall quality between furnace and vacuum brazing.
- Optimize the minimum required furnace time for effective brazing.
- Use FTIR/SEM to verify full burn-off of organic components.
- Test various vacuum pressures, durations, and cycles to improve drying efficiency
- Standardize the time between braze paste application and furnace brazing to reduce variability.
- If storage time proves to have minimal impact on braze quality, consider pre-mixing larger batches of braze material to improve production efficiency and reduce costs.

Acknowledgements & References

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Reference

1. Nelson, S.D. (2014). Spreading and solidification behavior of nickel wide-gap brazes, Weld World, 58(2), 255–271. https://doi.org/10.1007/s40194-014-0144-9

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