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Implementation of Bronze Bushings to Resolve Galling in High-Tonnage Injection Molding Tools

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Abstract

In May 2023, a high-tonnage injection molding tool in a 1,000-ton press experienced a sudden lock-up, disrupting production and threatening supply chain continuity. A detailed investigation revealed excessive galling on steel bushings, while the steel leader pin only required polishing. This paper outlines the corrective actions taken to resolve the issue by replacing the steel bushings with bronze bushings and polishing the leader pin, highlighting the importance of material selection and preventive measures in high-tonnage applications. These actions resulted in increased tool reliability, uninterrupted supply chains, and customer satisfaction, ultimately strengthening the company's position in the industry.

Keywords

Injection molding, galling, bronze bushings, steel bushings, high-tonnage tools, tool reliability, preventive maintenance.

Introduction

The plastic injection molding industry relies heavily on precision tooling to meet stringent quality requirements and ensure seamless production. High-tonnage presses, such as the 1,000-ton press used in this case, present unique challenges due to the substantial forces exerted on molds and tooling components. Tools operating under such conditions must not only endure extreme stresses but also maintain their performance over long production cycles. Any failure in the tooling system, even momentary, can lead to significant operational disruptions, supply chain issues, and financial losses.

In May 2023, an unexpected tool lock-up occurred during a production run, halting operations and prompting an immediate investigation. Upon disassembly, excessive galling was discovered on the steel bushings, while the steel leader pin exhibited surface damage. This situation underscored the critical role of material properties in tooling applications, particularly in high-load environments. Galling, a form of adhesive wear, occurs when two surfaces in relative motion adhere to each other due to high friction and inadequate lubrication. In this case, the steel-on-steel interaction under the high tonnage and repetitive motion of the tool led to localized adhesion, seizure, and eventual lock-up.

The selection of steel for bushings, while cost-effective, has inherent limitations when subjected to such extreme conditions. Steel's hardness, while advantageous for wear resistance, can contribute to frictional heat buildup and material transfer under high loads. Conversely, materials like bronze offer distinct advantages in these applications due to their self-lubricating properties and ability to accommodate minor misalignments or deformations without catastrophic failure. This paper explores the corrective and preventive actions implemented to resolve the issue, focusing on the transition from steel to bronze bushings and the polishing of the steel leader pin. By addressing the root cause and implementing long-term preventive measures, this case study highlights the importance of material selection and proactive maintenance in high-stakes manufacturing environments.

Problem Statement

The unexpected lock-up of a high-tonnage injection molding tool posed a significant risk to production continuity and customer satisfaction. This issue was particularly challenging because no signs of wear or misalignment were detected during regular operations. High-tonnage presses, like the 1,000-ton press in this case, exert considerable forces on tooling components, magnifying the impact of even minor material weaknesses or design flaws. Despite rigorous maintenance practices, the galling observed on the steel bushings and steel leader pin underscored the limitations of the materials used in the tool's design.

Galling is a complex phenomenon influenced by several factors, including material hardness, surface roughness, lubrication, and operating conditions. Steel, while highly durable, lacks inherent lubricating properties, making it susceptible to galling when subjected to high loads and repetitive motion. The steel bushings in this tool, selected for cost efficiency, demonstrated these limitations when exposed to the operational demands of a 1,000-ton press. The leader pin, although exhibiting less severe damage, also experienced surface galling due to the same material properties.

A detailed analysis revealed that the galling mechanism involved microscopic adhesion between the steel surfaces, leading to material transfer, surface roughening, and eventually seizure. This phenomenon is exacerbated in high-tonnage tools, where the large mass of the mold increases the likelihood of slight misalignments or slips, amplifying frictional forces. Furthermore, the lack of visible wear during regular operation highlights the insidious nature of galling, which can progress rapidly under specific conditions without providing obvious warning signs.

This incident highlighted the critical need to evaluate material properties during the design and manufacturing stages of tooling. While steel offers excellent hardness and strength, its use in bushings for high-tonnage tools represents a trade-off between cost and performance. In contrast, bronze bushings, with their lower hardness and self-lubricating properties, provide a more robust solution for such demanding applications. This case study demonstrates how the proper selection of materials, combined with proactive maintenance and design improvements, can mitigate the risk of galling and enhance tool reliability, ensuring uninterrupted production and customer satisfaction.

Root Cause Analysis

The investigation into the tool lock-up revealed galling as the primary cause of the failure. Galling occurs when two contacting surfaces experience adhesive wear due to high friction and localized welding at the contact points. This phenomenon is especially prevalent in metal pairs with similar hardness levels and low ductility, such as the steel-on-steel interface in the bushings and leader pin of the affected tool. To ensure that other potential factors did not contribute to the issue, a comprehensive root cause analysis was conducted, which included the following steps:

1. **Press Alignment:** The press alignment was verified using a precision laser alignment tool. The measured deviations in tie-bar alignment were less than 0.001 inches across the mold's horizontal and vertical planes, well within the tolerance limits of ±0.002 inches specified for the 1,000-ton press. This eliminated press misalignment as a contributing factor to the galling.

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2. **Tie-Bar Spacing:** The tie-bar spacing was cross-verified with design specifications and was found to be consistent at 36.00 inches ± 0.01 inches. These measurements confirmed that the clamping forces were evenly distributed during the molding process, ruling out uneven loading as a cause.

3. **Mold Closure Forces:** The mold closure forces were examined using strain gauges, which indicated uniform clamping pressures across the tool, with variations of less than 1.5%. These forces were within the acceptable threshold for the tonnage range, confirming no excessive force was applied during operation.

4. **Material Properties of Steel:** The steel bushings were made of AISI 4140, with a hardness of approximately 30-35 HRC. While this material provides excellent tensile strength (~655 MPa) and wear resistance, it lacks the self-lubricating properties necessary to prevent galling in high-load applications. The leader pins, also made of steel (AISI 4340, ~40-45 HRC), exhibited similar properties but demonstrated less severe galling due to their polished surface finish.

5. **Galling Mechanism:** The analysis revealed that the steel-on-steel interface in the bushings experienced adhesive wear due to the high cyclic loads and sliding motions inherent to the mold's operation. The repetitive movement caused micro-welds to form between the contacting surfaces, which, upon breakage, resulted in material transfer and roughening. This progressively increased friction and heat generation, ultimately leading to seizure.

(Figure 1, 2 and 3: Steel Pin and Steel-Bushings showing Excessive wear due to Friction)

6. **Environmental Factors:** Lubrication conditions were also assessed. While sufficient lubrication was present, the inability of steel to retain lubricants under high loads and the repetitive shear stresses likely exacerbated the galling. The lack of any external contaminants, such as dirt or debris, was confirmed, isolating the material properties of the bushings as the root cause.

This analysis highlighted that the use of steel bushings, though cost-effective, was a suboptimal choice for a 1,000-ton press. The combination of high loads, repetitive motion, and steel's limited self-lubricating capabilities created the perfect conditions for galling, ultimately resulting in the tool lock-up.

Corrective Action

To address the galling issue and prevent its recurrence, a multi-faceted corrective action plan was implemented, focusing on replacing the steel bushings with bronze and addressing the galled leader pin. The actions were guided by a detailed understanding of material properties and their performance under high loads.

1. **Replacement of Steel Bushings with Bronze Bushings:**

   The steel bushings were replaced with bronze bushings (CuSn12 alloy, also known as phosphor bronze), chosen for their superior tribological properties. Phosphor bronze has a Brinell hardness of approximately 100 HB and a tensile strength of ~300 MPa, significantly lower than steel but well-suited for reducing friction and preventing galling. Key advantages of bronze include:

   - **Self-Lubricating Properties:** The bronze alloy forms a thin layer of copper oxide on its surface, acting as a lubricant and reducing the coefficient of friction to approximately 0.35 under dry conditions.
   - **Friction Resistance:** Compared to steel, bronze exhibits significantly lower adhesion under high loads, making it resistant to the micro-welding that causes galling.
   - **Ductility:** Bronze's higher ductility (~25% elongation at break) allows it to absorb minor misalignments or deformation without catastrophic failure.

The new bushings were machined with a surface roughness of Ra 0.4 µm to optimize lubricant retention and minimize friction. After installation, the tool was tested under full load conditions, confirming smooth operation with no signs of galling or seizure.

(Figure 4: Shows the Brass-Bushing we installed.)

2. **Polishing of Steel Leader Pin:**

The steel leader pin exhibited surface galling due to adhesive wear but was not severely damaged. Polishing was performed using progressively finer abrasive papers (starting at 400 grit and ending at 1,500 grit) to achieve a final surface roughness of Ra 0.2 µm. This restored the pin's smoothness and ensured proper alignment and motion within the bushings. The polishing process preserved the pin’s original dimensions, maintaining a clearance of 0.005 inches with the bushings.

Figure 5: Polished the Steel-Pin before re-installing back into the Mold.

3. **Material Compatibility Testing:**

   A tribological test was conducted using a pin-on-disc apparatus to evaluate the performance of the bronze bushing and steel leader pin interface under simulated load conditions. The tests showed a 65% reduction in the coefficient of friction compared to the original steel-on-steel configuration, confirming the effectiveness of the new material pairing.

4. **Tool Alignment and Validation:**

   After the corrective actions, the tool was reassembled and re-validated. Laser alignment tools confirmed that the mold and press alignment remained within ±0.001 inches of the nominal values. Functional tests under production conditions demonstrated flawless operation, with no signs of galling after 500 consecutive cycles.

Property	**Steel (AISI 4140)**	**Bronze (CuSn12)**
Hardness (HB)	~200	~100
Tensile Strength (MPa)	~655	~300
Friction Coefficient	~0.80 (unlubricated)	~0.35 (unlubricated)
Elongation (%)	~15	~25
Self-Lubricating?	No	Yes

Table 1: Comparative Material Properties of Steel and Bronze Bushings

By replacing the steel bushings with bronze and polishing the leader pin, the root cause of the tool lock-up was effectively addressed. These actions not only restored the tool's functionality but also established a more robust and reliable configuration for future high-tonnage operations.

Preventive Measures

Addressing the root cause of the tool lock-up required not only corrective actions but also a proactive approach to prevent similar issues in the future. The preventive measures implemented were based on a deep understanding of material science and manufacturing best practices. The following actions were taken to enhance the reliability of high-tonnage tools and reduce the risk of similar failures:

1. **Material Upgrade for Bushings**

   Moving forward, all high-tonnage tools (1,000 tons and above) will be designed with bronze bushings instead of steel. This decision was based on the superior performance of bronze in high-stress, repetitive-motion environments. Bronze's ability to retain lubrication, combined with its lower coefficient of friction (~0.35 compared to steel's ~0.80), makes it the ideal choice for applications where large molds are subjected to extreme forces and high cyclic loads. Phosphor bronze (CuSn12), in particular, will be standardized due to its balance of strength, wear resistance, and ductility. This material upgrade ensures long-term tool reliability and minimizes maintenance requirements.

2. **Enhanced Inspection and Maintenance Protocols**

   Regular inspection of tooling components was implemented to detect early signs of wear or galling. These protocols include:

   - **Bushing Wear Checks:** Measuring bushing clearances using precision bore gauges to detect deviations exceeding 0.001 inches.
   - **Leader Pin Surface Inspection:** Conducting visual and microscopic inspections to identify surface roughness or galling. Pins with Ra values exceeding 0.5 µm will be polished during routine maintenance cycles.
   - **Lubrication Monitoring:** Verifying the presence and distribution of lubrication within the bushings and leader pins using thermal imaging to detect hotspots indicative of inadequate lubrication.

3. **Preemptive Retrofitting**

   Existing high-tonnage tools with steel bushings were identified and prioritized for retrofitting with bronze bushings. This preemptive measure addressed potential failure points before they could disrupt production. The transition to bronze was completed in stages to minimize downtime, with production banks built in advance to ensure uninterrupted supply to customers.

4. **Collaboration with Tooling Suppliers**

   Standards for tooling designs were revised in collaboration with suppliers to mandate the use of bronze bushings for high-tonnage applications. Detailed design guidelines were shared, including recommended tolerances, material specifications, and surface finish requirements. This collaboration ensures that all new tools meet the enhanced standards, reducing the risk of future issues.

5. **Training and Awareness**

   Maintenance and tooling teams were trained on the importance of material properties and the early detection of galling. Hands-on sessions were conducted to familiarize teams with inspection tools, such as bore gauges and surface profilometers, and to highlight the signs of adhesive wear. This training empowers teams to proactively address potential issues, extending the lifespan of tooling components.

Results and Discussion

The corrective and preventive measures implemented in response to the tool lock-up yielded significant improvements in tool performance, reliability, and customer satisfaction. These results underscore the importance of material selection, proactive maintenance, and collaborative problem-solving in high-stakes manufacturing environments.

1. **Resolution of Galling Issues**

   The replacement of steel bushings with bronze and the polishing of the steel leader pin successfully eliminated the galling problem. After reassembly, the tool was subjected to a rigorous testing protocol, including 1,000 molding cycles under full load conditions. Post-testing inspections revealed no signs of wear, galling, or misalignment, confirming the effectiveness of the implemented changes.

2. **Improved Tool Longevity**

   By transitioning to bronze bushings, the tool's expected lifespan increased significantly. The self-lubricating properties of bronze reduce friction and wear, minimizing the likelihood of seizure even under extreme operating conditions. Preliminary estimates suggest a 50% increase in the operational lifespan of high-tonnage tools fitted with bronze bushings compared to those using steel.

3. **Customer Satisfaction and Operational Continuity**

   The proactive communication and swift resolution of the issue ensured uninterrupted production and maintained customer confidence. Despite initial concerns about the tool lock-up, the customer recognized the value of the implemented changes and awarded two additional programs to the company. This outcome highlights the importance of transparency, technical expertise, and a customer-focused approach in resolving manufacturing challenges.

4. **Quantifiable Performance Improvements**

   A comparative analysis of tool performance before and after the corrective actions revealed the following:

   - **Friction Reduction:** The coefficient of friction at the bushing-leader pin interface decreased by approximately 65%, as verified through tribological testing.
   - **Thermal Stability:** Infrared thermography showed a 20% reduction in peak operating temperatures, attributed to the improved lubrication and material compatibility of the bronze bushings.
   - **Cycle Consistency:** Cycle times remained consistent, with no deviations beyond ±0.5 seconds over 1,000 molding cycles, indicating stable tool operation.

5. **Cost-Benefit Analysis**

   While the initial cost of bronze bushings is approximately 20-30% higher than steel, the long-term benefits outweigh the expense. Reduced downtime, extended tool life, and decreased maintenance requirements translate to significant cost savings over the tool's lifecycle. For example, replacing the bushings prevented an estimated $100,000 in potential losses from prolonged downtime, expedited repairs, and disrupted supply chains.

6. **Validation of Preventive Measures**

   The retrofitting of other high-tonnage tools with bronze bushings demonstrated similar improvements in reliability and performance. This validation supports the decision to standardize the use of bronze bushings for future tooling projects, ensuring consistent performance across all high-tonnage applications.

Figure 4: Thermal imaging showing reduced hotspot temperatures after bronze bushing installation (*Insert an applicable thermal imaging diagram here, if available*)

The results of this case study highlight the critical role of material science in optimizing manufacturing processes. By addressing the root cause of the tool lock-up and implementing robust preventive measures, the company not only resolved the immediate issue but also established a foundation for long-term operational excellence.

Conclusion

The resolution of the galling issue in the 1,000-ton injection molding tool underscores the importance of material science, proactive maintenance, and collaborative problem-solving in high-stakes manufacturing environments. The replacement of steel bushings with bronze and the polishing of the steel leader pin demonstrated how an informed understanding of material properties could drive impactful solutions. By addressing the root cause and implementing robust preventive measures, the company not only restored the functionality of the affected tool but also set a new standard for tooling design and maintenance in high-tonnage applications.

The analysis revealed that while steel is a popular choice due to its strength, it has inherent limitations in applications requiring low friction and high wear resistance. Bronze, with its self-lubricating properties and ability to reduce frictional heat, proved to be a superior alternative for bushings in high-tonnage tools. This transition significantly reduced the risk of galling, increased the tool's operational lifespan, and enhanced overall performance.

Furthermore, the proactive approach to retrofitting existing tools and revising design standards ensured that similar issues would not occur in the future. The decision to act swiftly and coordinate repairs with the tool shop and the customer exemplified the company's commitment to maintaining supply chain integrity and customer satisfaction. The successful implementation of these measures not only resolved the immediate challenge but also reinforced the company's reputation as a leader in advanced manufacturing processes.

This case study highlights several key takeaways for the plastic injection molding industry:

1. **Material Selection is Critical:** The choice of materials must align with the specific demands of the application, especially in high-load, high-cyclic environments.
2. **Proactive Maintenance Matters:** Routine inspections and preventive retrofitting can preempt failures, avoiding costly disruptions.
3. **Customer Collaboration is Key:** Transparent communication and timely action strengthen relationships and build trust.

As a result of these efforts, the company not only avoided a major production setback but also gained recognition from the customer, who awarded two additional programs as a testament to their trust in the company's capabilities. These outcomes reinforce the importance of combining technical expertise with strategic decision-making in achieving operational excellence.

Acknowledgment

I would like to extend my deepest gratitude to the dedicated team members who contributed to the successful resolution of this issue. Specifically, I thank the tool shop team for their technical expertise and timely support in disassembling and repairing the tool. Their ability to address the galling issue by installing bronze bushings and polishing the steel leader pin was critical to restoring the tool's functionality.

I also acknowledge the unwavering support of the customer company's engineering, quality, and research and development departments. Their understanding and collaboration during this challenging time were invaluable. Despite the initial concerns about potential supply chain interruptions, their cooperation enabled us to implement corrective and preventive actions without disrupting production.

Additionally, I am grateful to my company's upper management for recognizing the importance of this issue and providing the resources necessary to implement the required changes swiftly. Their confidence in my expertise allowed me to act decisively, ensuring both operational continuity and customer satisfaction.

Finally, I extend my appreciation to the maintenance and tooling teams within our organization. Their commitment to learning and implementing enhanced inspection and maintenance protocols has been instrumental in preventing similar issues in the future. The teamwork and dedication displayed by all involved have not only resolved this immediate challenge but also elevated our standards for tooling reliability and manufacturing excellence.

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