Factors affecting the failure of hot stamping molds and mold maintenance

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This article explores the influential factors leading to the failure of hot stamping molds and highlights the significance of mold maintenance. With the increasing production of electric vehicles and the adoption of lightweighting technologies, high-strength steel hot stamping forming has emerged as a pivotal approach in automotive lightweighting, underscoring the criticality of hot stamping molds. This article analyzes the hot stamping process, mold working conditions, and various factors that impact the lifespan of molds. During operation, hot stamping molds are subjected to cyclic thermal loads and stress concentration, which may result in wear, galling, cracking, honeycomb lines (micro-pits), and fracture. The failure and lifespan of molds are influenced by multiple factors, including mold design, material selection, heat treatment, manufacturing processes, surface treatment, and production processes. Proper mold maintenance plays a vital role in prolonging the lifespan of molds, ensuring part quality, controlling production costs, and mitigating the risk of accidents. The article discusses different levels of maintenance work, such as specialized maintenance, routine maintenance, and periodic maintenance, and underscores the importance of regular record-keeping, inspection, and evaluation of mold conditions. By implementing scientific management of maintenance work, the objectives of extending mold lifespan, enhancing production efficiency, and ensuring product quality stability can be achieved, thereby fostering the sustainable development of enterprises.

Keywords: Hot stamping molds, Quality stability, Production efficiency, Failure factors, Mold maintenance.

1. Hot Stamping Process and Factors Influencing Mold Failure

High-strength steel hot stamping is capable of reducing the stress and strain of materials, thereby minimizing material deformation and work hardening, as well as reducing stress during the forming process. Hot stamping enables the formation of intricate part shapes and details with lower loads, making it more adaptable to complex forming requirements and enhancing formability [1]. Through hot stamping, the structure and performance of parts can be optimized, leading to improved load-bearing capacity, tensile strength, and fatigue resistance. This technology has found extensive applications in the manufacturing of automotive body components [2].

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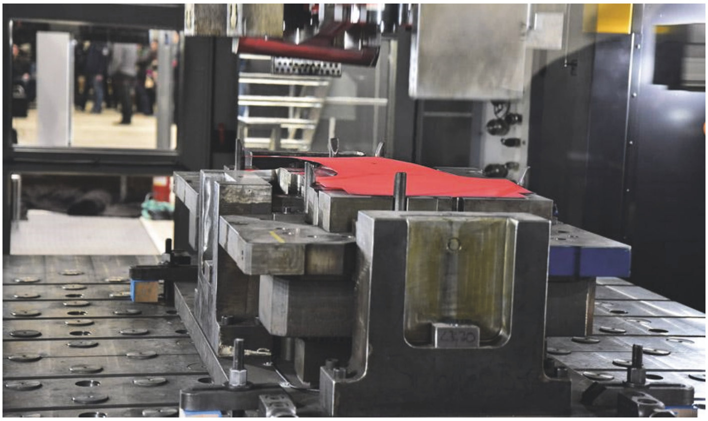

Figure 1. Hot stamping molds on the production line

1.1. *Working Conditions of Hot Stamping Molds*

Prior to hot stamping forming, the processed material is heated to the quenching temperature, and the forming and quenching processes are simultaneously conducted within the mold cavity. The cooling water channel situated beneath the surface of the mold cavity effectively dissipates the heat generated during the rapid cooling of the austenitized high-strength sheet, resulting in a swift reduction of the steel plate's temperature below the Ms point. Consequently, the material undergoes a transformation from austenite to martensite, achieving the desired strength. This process necessitates a uniform surface temperature of both the mold cavity and the material being processed, ensuring complete reduction of the temperature below the martensite formation threshold.

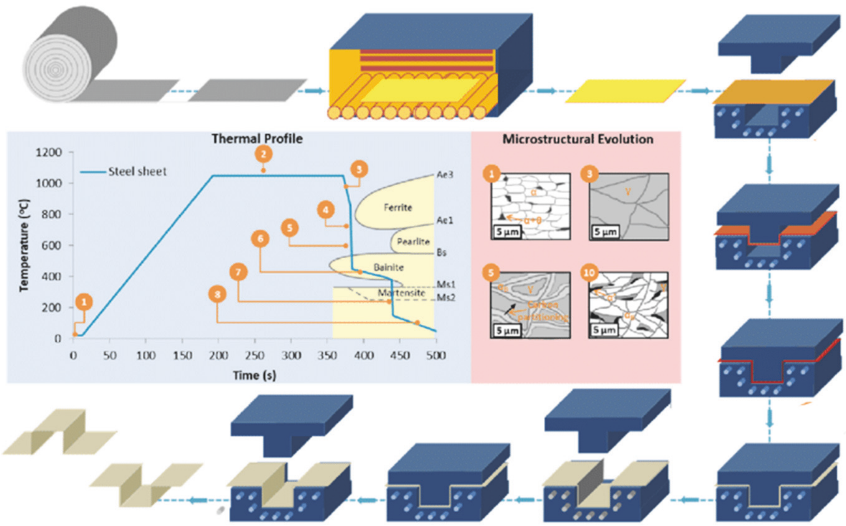

Figure 2. Schematic diagram of the hot stamping process [3]

Hot stamping molds experience cyclic thermal loads during operation as they absorb the heat from the processed metal, resulting in an elevation of the mold cavity's surface temperature. Subsequently, the heat is transferred to the cooling water or dissipated into the environment through the mold cavity surface. The temperature difference within the material gives rise to thermal stress, leading to creep and, ultimately, fatigue cracks. Moreover, the flow of solid metal across the mold cavity surface generates friction, while the presence of hard particles within the steel body, surface oxides, and externally adhered hard particles can cause surface scratches.

Simultaneously, under the influence of the molding force, areas of the mold that are prone to stress concentration, such as the corners of the insert mold, can experience the formation of thermal stress cracks and fiber cracks on the mold cavity surface during machining and surface treatment. These cracks have the potential to rapidly propagate when subjected to excessive stress concentration, ultimately leading to mold cracking a highly undesirable occurrence in the hot stamping production process.

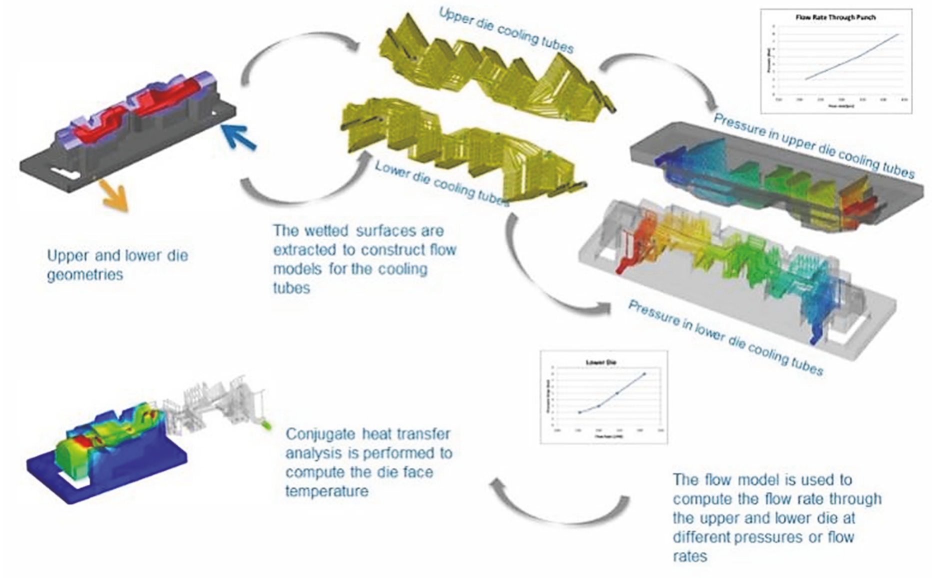

Figure 3. Schematic diagram of the hot stamping mold cooling circuit [4]

The phenomenon of wear is depicted in Figure 4 [5], which illustrates the formation of protrusions (a), scratching of the hot workpiece (b), transfer of material adhering to the mold surface (c), and the accumulation layer (abrasion) on the mold surface (d).

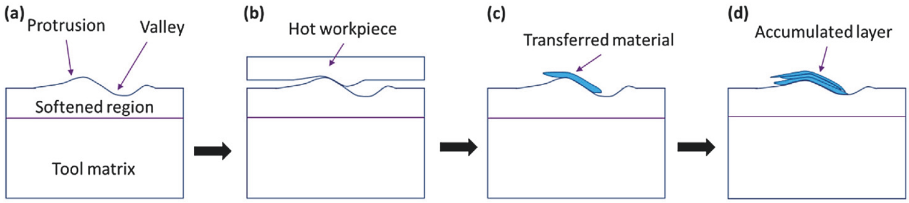

Figure 4. Illustration of wear phenomenon.

1.2. *Factors Influencing the Service Life of Hot Stamping Molds*

The failure and service life of hot stamping molds are influenced by a multitude of factors. In order to achieve the desired mold life and prevent premature mold failure, particularly catastrophic cracking, it is imperative to pay close attention to the entire process encompassing mold design, manufacturing, and maintenance. These factors encompass the following:

Mold Design: Considerations such as wall thickness, rounded transitions, distribution of cooling water channels, mold clearances, and cost limitations play a crucial role in mold design.

Mold Material: Properties such as hardenability, strength, resistance to tempering softening, red hardness, high-temperature strength, ductility, toughness, thermal conductivity, material isotropy, and expansion coefficient significantly impact the performance and lifespan of molds.

Heat Treatment: Factors including loading capacity, loading method, temperature and holding time for graded heating, austenitizing temperature and holding time, cooling medium pressure and flow rate, tempering temperature and time, uniformity and depth of hardness, and heat treatment deformation control have a profound effect on the structural integrity and longevity of molds.

Mold Manufacturing: The manufacturing processes employed, such as CNC machining, deep hole drilling, electrical discharge machining, polishing, and stress relief, directly influence the quality and durability of the molds.

Surface Treatment: Techniques like nitriding, nitrocarburizing, coating quality, bonding strength between the coating and the substrate, surface welding layer, surface boronzing, surface oxidation, blackening treatment, and laser cladding are critical in enhancing the wear resistance and performance of molds.

High-Strength Sheet: Considerations regarding the thickness, heating temperature, bare sheet, coated sheet, cutting method, surface cleanliness, and sheet specifications of high-strength sheets used in the hot stamping process are essential in ensuring optimal mold performance.

Production Process: Strict control and optimization of stamping steps, stamping temperature, mold temperature, cooling and lubrication, mold preheating, mold cooling intensity, hot stamping deformation speed, and process control parameters are essential for achieving desired product quality and prolonging the mold life.

Mold Maintenance: Proper maintenance practices, including regular cleaning of mold surfaces, welding repair, stress relief, re-nitriding and recoating, shot blasting, polishing, replacement of vulnerable parts, and avoidance of improper maintenance procedures, are crucial for preserving mold performance and extending its lifespan.

1.3. *Common Failure Modes of Hot Stamping Molds*

The common failure modes of hot stamping high-strength sheet materials mainly include wear and galling, cracking, and honeycomb lines. Once the design and forming scheme of the hot stamping mold are determined, one or several critical parts within the mold cavity, where the temperature difference or thermal stress is the highest, the deformation and flow of the processed material are the largest, and the stress concentration is the highest, are identified to a significant extent. As a result, mold failure does not occur in all inserts within the cavity, but rather in one or several inserts that experience the aforementioned issues first during service.

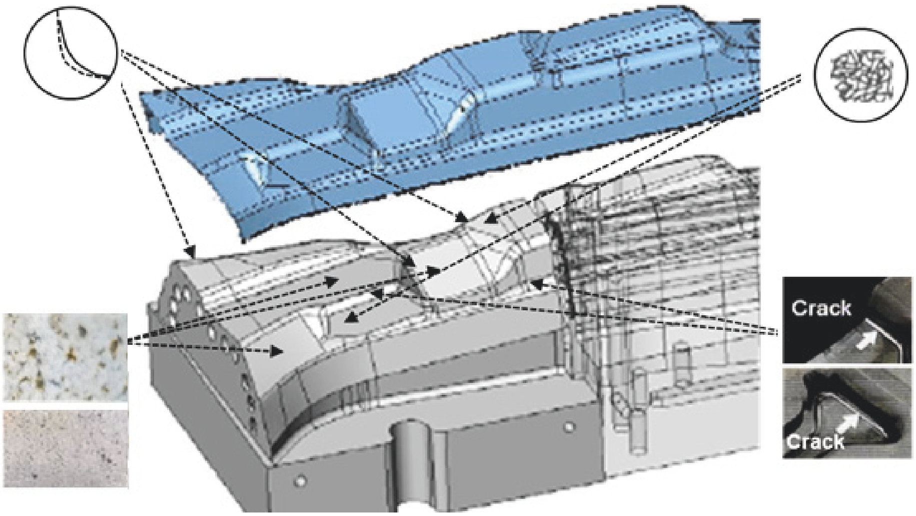

Figure 5. Illustration of failure modes and positions of hot stamping molds

Any mold or insert that fails prematurely can be regarded as a classic case, and identifying the true cause of mold failure is a challenging task. Failed molds/inserts often offer valuable insights, and with the aid of professional testing, analysis, and extensive knowledge, the underlying cause of early mold failure can potentially be uncovered. The factors contributing to early mold failure may involve a primary factor, several secondary factors, or multiple factors of equal significance. Once the primary influencing factors leading to early mold failure are identified, effective strategies can be implemented to address these issues.

2. Failure Analysis of Hot Stamping Molds

2.1. *Wear and Galling*

When wear or galling occurs in molds, the surface of the worn or galled area should be observed to see if the following phenomena exist:

- Rapid decrease in surface hardness, decarburization, low original hardness
- Failure to form nitride layer or loss of nitride layer, coating peeling
- High temperature at the worn area
- Hard particles, such as oxide particles, adhering to the surface of the processed part
- Hard particles in the mold material matrix, such as non-metallic inclusions, large carbide particles, etc.
- Insufficient cooling intensity in local areas

2.2. *Thermal Cracking*

Local high temperatures or large temperature differences in molds can cause early cracking. Observing the cooling intensity of the failed area and checking the hardness of the mold, as well as examining the heat treatment process and the furnace loading position of the failed mold, can help analyze the failure causes from multiple perspectives:

- Rapid decrease in surface hardness
- Nitride layer containing a large amount of martensite or loss of nitride layer
- High temperature at the worn area
- Coarse grains and excessive intergranular carbides in the mold material matrix, primary carbides and non-metallic inclusions
- Insufficient cooling intensity in local areas

2.3. *Mold Cracking*

Starting with the quality of the heat treatment process, combined with the mold shape and the relative positions of cooling water channels, the analysis can focus on the following aspects:

- Excessive hardness after heat treatment
- Over-nitriding at corners, nitride layer containing a large amount of martensite with initial cracks
- Excessive temperature difference stress
- Coarse grains and excessive intergranular carbides in the mold material matrix, primary carbides and non-metallic inclusions
- Excessive local cooling intensity
- Design of rounded corners, distribution of water channels

2.4. *Honeycomb Lines*

They initially appear as small cracks on the smooth surface and evolve into micro-pits that become larger over time.

– Excessive hardness after heat treatment
– Coarse grains and excessive intergranular carbides in the mold material matrix, primary carbides and non-metallic inclusions
– Excessive local cooling intensity
– Oxidizing environment on the mold cavity surface

3. Maintenance and Care of Hot Stamping Molds

When mold materials are subjected to prolonged exposure to high temperatures, the hardness of the matrix will decrease. Assuming a holding time of 10 seconds and a surface temperature of 550°C (which can be reached in certain areas), the mold material's hardness gradually decreases over time under high-temperature conditions. Table 1 presents the predicted hardness reduction for various commonly used hot stamping mold steels. The significant temperature variations on the surface of hot stamping mold cavities and the intense deformation of the processed material in specific areas make both excessive and insufficient cooling intensity impact the matrix hardness of the mold material after long-term use. The reduced hardness/strength of the mold material, under the same thermal stress conditions, accelerates the occurrence and propagation of cracks.

Under the conditions of alternating exposure to high and low temperatures, adjacent points on the surface of the mold material will undergo substantial residual stresses. If these stresses are not promptly relieved, they can result in mold deformation and stress release through the generation and propagation of cracks at stress concentration points (such as corners and crack lines).

Therefore, conducting regular inspections of the mold surface and documenting the condition of the mold cavity surface at different mold cycles (including hardness/hardness distribution, color, smoothness, etc.) can facilitate appropriate maintenance practices (such as stress relief, re-nitriding, shot blasting, PVD, local laser cladding, or laser hardening), thereby ensuring an extended service life for the mold.

Table 1: Predicted Hardness of Hot Stamping Molds at Different Mold Cycles

Tool steel		Stamping Number					
HSB	Other grades	1,000	5,000	35,000	70,000	100,000	20,000
HSB H407	4Cr5MoSiV1/H13	-1	-5	-9	-10	-15	-20
HSB H418	4Cr5Mo2/Dievar		0	-2	-6	-8	-10
HSB H419	5Cr5Mo2V/Unimax		0	-1	-5	-7	-8
-	4Cr3Mo2V1/QRO 90			-0.5	-2	-6	-7
-	4Cr7MoV1/Cr7-V		-3	-7	-8	-13	-18

3.1. *Special Maintenance*

Special attention should be given to the treatment of hot stamping products that fail to meet customer requirements during regular production. These issues may include deviations in product size, surface scratches, excessive or insufficient strength and hardness, among others.

3.2. *Routine Maintenance*

Maintenance of the mold should be performed after every shift or approximately every 1,000 to 3,000 mold cycles. This maintenance should primarily involve polishing the mold cavity surface to remove any accumulated "built-up edges" or minor scratches. Additionally, it is essential to inspect the moving parts, clean the mold, and inspect or replace components such as oil cylinders, oil pipes, water pipes, and vulnerable parts.

3.3. *Periodic Maintenance*

Regular maintenance of hot stamping molds during production is crucial. This includes recording the mold's condition, such as wear, color, presence of cracks, crack location, crack size, hardness distribution, and more. By discussing the necessary mold maintenance, a longer mold life can be achieved. It is recommended to record and inspect the following aspects:

a) Capture infrared temperature distribution photos of the mold cavity surface within a specified time after demolding (preferably as soon as possible).

b) Take photos of the most severely worn areas and record the extent of wear.

c) Use coloring agents, magnetic powder, or other suitable methods to inspect for cracks.

d) Measure hardness at several representative locations.

e) Check for hot cracking in high-temperature areas.

It is advisable to schedule periodic maintenance based on predicted wear amounts, such as at 5,000, 10,000, 20,000, 30,000, 50,000, and 100,000 mold cycles.

Regular maintenance and care of hot stamping molds, with the collaboration of hot stamping production enterprises, mold manufacturers, material suppliers, heat treatment providers, and surface treatment providers, can yield several positive outcomes for users, including:

a) Implementation of reasonable maintenance and care methods.
b) Evaluation of material selection suitability.
c) Evaluation of heat treatment and surface treatment suitability.
d) Suggestions for improving hot stamping mold design.
e) Recommendations for enhancing the use of hot stamping molds.

4. Conclusion

This article has examined the various factors that contribute to the failure of hot stamping molds and highlighted the significance of mold maintenance. With the growing production of electric vehicles and the adoption of lightweighting technologies, high-strength steel hot stamping forming has emerged as a key approach to automotive lightweighting, underscoring the critical role of hot stamping molds. During operation, hot stamping molds are subjected to cyclic thermal loads and stress concentration, which can result in wear, galling, cracking, honeycomb lines (micro-pits), and fractures. The failure and lifespan of molds are influenced by multiple factors, including mold design, material selection, heat treatment, manufacturing processes, surface treatment, and production procedures.

Proper mold maintenance is essential for prolonging mold life, ensuring part quality, controlling production costs, and reducing the risk of accidents. By implementing scientific management of maintenance tasks, the objectives of extending mold life, enhancing production efficiency, and ensuring product quality stability can be achieved, thereby promoting the sustainable development of enterprises. It is recommended to carry out different levels of maintenance work, such as special maintenance, routine maintenance, and periodic maintenance. Emphasizing the importance of regular recording, inspection, and evaluation of mold conditions is crucial.

The periodic maintenance and care of hot stamping molds necessitate collaboration among hot stamping production enterprises, mold manufacturers, material suppliers, heat treatment providers, and surface treatment providers. This collective effort aims to achieve an extended mold life and improve production efficiency.

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