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New Developments in the Study of Skin Stretch Forming Process

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Abstract: As a core component of the aerodynamic shape of aircraft and high-speed trains, the forming quality of the skin directly affects performance and cost. In recent years, the skin stretch forming process has achieved rapid development through multiphysics coupling simulation, multi-factor parameter optimization, and innovation in intelligent equipment. This paper reviews the new research progress from four dimensions: numerical simulation technology, process parameter optimization, process equipment innovation, and the application of new technologies in the stretch forming process of skins. It also proposes future research directions

1. Numerical Simulation Technology for Skin Stretch Forming Process

Finite element simulation technology has restructured the research model of skin stretch forming process, achieving a leapfrog development from experience-driven to multidisciplinary integration. Currently, it has evolved from single-field modeling for predicting local deformation to multiphysics coupling models, which can simultaneously simulate the collaborative evolution laws of the stretching force field, temperature field, and material microstructure. Based on the nonlinear material constitutive model, it can accurately quantify the dynamic relationship between the thickness reduction rate and springback amount during skin stretching, significantly reducing process errors.

1.1 Secondary Development to Enhance Simulation Efficiency

Wei Wei et al. [1] developed a batch simulation plugin based on ABAQUS/Python. By automatically adjusting parameters such as pre-stretching amount and friction coefficient, it enables rapid simulation of multiple working conditions, achieving a 40% increase in efficiency. Zhang Hegang et al. [2] developed the software AISF, which for the first time realized the full-process simulation of “stretch forming - trimming - springback.” The springback prediction error is less than 5%, verifying the feasibility of the software. Jin Xiaoyue et al. [3] found that AI-FORM has advantages in wrinkle simulation. Its adaptive meshing technology improves the accuracy of wrinkle identification by 30%.

1.2 Multi-software Collaboration and Validation

Fu Lei et al. [4] simulated the stretch forming of 2024T3 aluminum alloy using ABAQUS and verified the sensitivity of blank size and clamp travel distance through experiments. They found that increasing the blank size by 10% can reduce the principal strain by 8-12%. Xie Hongzhi [5] proposed a digital trajectory optimization method based on the collaboration between Pam-Stamp and the process design system, achieving a thickness uniformity of 97% (3.18-3.29 mm) for 2A12 aluminum alloy parts.

1.3 Application of Full-Process Simulation

Zhang Chengpeng from Jilin University [6] established a vibration-assisted forming model and found that a vibration frequency of 30 Hz can reduce the springback of single curvature by 54.1%. Guo Gang from University of Electronic Science and Technology of China [7] optimized the mold parameters using Pam-Stamp, reducing the gap between the Gulfstream G280 skin and the mold from 5 mm to 2 mm and shortening the manufacturing cycle by 71%.

2. Optimization of Skin Stretch Forming Process Parameters

The optimization of skin stretch forming process parameters has evolved from single-variable analysis to a multi-factor collaborative optimization system. Early research optimized parameters by adjusting individual factors such as stretching speed or clamping force through single trials. In contrast, modern approaches employ orthogonal experimental design to systematically investigate the interactive effects of multiple factors, including stretching distance, mold curvature, and friction coefficient.

2.1 Analysis of the Impact of Key Parameters on the Process

Jin Xiaoyue et al. [3] proposed a segmented stretching strategy to accurately analyze the stretching trajectory. A combination of 4.9% elongation in the front section and 7% in the rear section can eliminate wrinkling in saddle-shaped parts. Fu Lei et al. [4] found that reducing the clamping friction coefficient from 0.3 to 0.1 can decrease the thickness deviation by 35%. Ma Yuesen from Jilin University [8] discovered that hot forming at 160 ℃ can improve the uniformity of equivalent plastic strain distribution by 40%.

2.2 Research on Multi-Factor Collaborative Parameter Optimization

Fang Taotao et al. [9] determined the optimal parameter combination for thick skins through orthogonal experiments. A mold closing distance of 7 mm and an upper mold pressure of 600 kN achieved a thickness uniformity of 90%. Li Jianfei et al. [10] pointed out that the orange peel defect is strongly correlated with grain size. Reducing grain size to below 10μm can decrease surface roughness by 50%.

3. Innovation in Process Equipment

Innovations in equipment of skin stretch forming process have achieved efficiency improvements through equipment automation upgrades and mold structure optimization. On the equipment side, the introduction of six-axis numerically controlled (NC) stretch forming machines and collaborative systems with industrial robots has enabled full automation of the entire process, including material feeding, stretching, and reshaping. This significantly reduces manual intervention compared to traditional equipment. In terms of mold innovation, topological optimization design has been adopted, replacing traditional steel molds with carbon fiber composite molds. This reduces mold weight by 60% while maintaining rigidity requirements. Coupled with a pneumatic quick mold change device, the mold change time can be reduced from 4 hours to just 15 minutes. The iteration of process equipment has increased the skin stretching speed and significantly reduced energy consumption per piece.

3.1 Quick Die Change System

Lu Changwei et al. [11] designed a dual-station die change system that employs PWM hydraulic synchronous lifting technology. This reduces the die change time from 40 minutes to just 5 minutes, increasing equipment utilization by 80%. Zhu Guolong from Southwest University [12] developed a transverse and longitudinal movable worktable. With laser positioning accuracy reaching ±0.1 mm, the contact stress between the wheel and rail under eccentric loading conditions remains below the material's yield limit.

3.2 Innovation in Mold Materials

Wang Jue et al. [13] replaced traditional plaster molds with a composite material made of hollow glass microspheres and epoxy resin. This reduced the mold weight by 40%, increased the repair efficiency by 60%, and achieved a compressive strength of 85 MPa.

4. Application of New Processes in Skin Stretch Forming

Innovative technologies such as electromagnetic pulse forming and vibration-assisted forming have provided breakthrough solutions for springback control and the forming of complex curved surfaces. Electromagnetic pulse forming uses high-frequency oscillating magnetic forces to induce dynamic recrystallization in the material, significantly reducing springback. It is particularly suitable for high-precision forming of difficult-to-deform materials like titanium alloys. Vibration-assisted forming, on the other hand, utilizes ultrasonic vibrations (15-40 kHz) to enhance material flow, thereby reducing the variation range of thickness reduction rate in double-curved skins.

4.1 Electromagnetic Pulse Forming

Cui Xiaohui et al. [14] proposed a magnetic field force zoning loading technology, which reduces the springback of aluminum alloy skins by 70% and increases the conversion rate of elastic deformation by 50%.

4.2 Vibration-Assisted Forming

Bai Linglei et al. [15] reduced the springback of leading-edge skins by 45% using a 30 Hz vibration. Zhang Chengpeng et al. [6] further verified the universality of vibration parameters for multi-curved parts.

5. Future Directions of Skin Stretch Forming Process

Despite significant progress in material adaptability, forming accuracy, and equipment intelligence, the skin stretch forming process still needs to break through the following core bottlenecks. First, in terms of simulation technology, there is a need to develop multiphysics coupling models and enhance the algorithm robustness of software such as AI-FORM and AISF. Second, in terms of process optimization, further exploration of machine learning-driven adaptive parameter control is required to achieve defect prediction and real-time correction. Third, in terms of intelligent manufacturing, the development of digital twin platforms should be pursued to integrate the data flow of simulation, equipment, and inspection, and to build a closed-loop control system. Fourth, in terms of new material adaptation, composite loading processes should be developed to meet the needs of increasing the forming limits of high-strength aluminum alloys and titanium alloys.

6. Conclusion

The skin stretch forming process has evolved from traditional trial-and-error based on experience to a digital process design phase. The integration of simulation technology, parameter optimization, equipment upgrades, and new processes has propelled the aerospace manufacturing industry towards higher precision and efficiency. In the future, with the deepening of intelligence and interdisciplinary integration, skin forming will gradually achieve the ultimate goals of low-defect and single-pass forming, providing core technological support for the development of the next generation of high-speed train noses and aircraft.

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