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Optimizing Square Bellows Production: Externally Fixed Die Extrusion Process and FEA Insights

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***Abstract*: This study investigates an advanced method for manufacturing square bellows through extrusion forming, with a focus on the design and performance of an externally fixed model. The aim of this work is to optimize the extrusion process for producing high-quality square bellows that meet the stringent requirements of various industrial applications, such as robotics and aerospace. Using Finite Element Analysis (FEA) simulations, we analyzed stress distributions and deformation patterns, identifying critical areas of stress concentration, particularly at the sharp corners of the bellows. The externally fixed design was selected over the internally fixed system due to its superior performance in terms of material flow and structural integrity. The simulation results indicate a reduction of stress concentration by 15% through the use of filleted edges and optimized die design. Mechanical and thermal cycling tests revealed that the bellows exhibited high fatigue resistance, enduring over 1,000,000 cycles without significant deformation, and showed minimal size changes under thermal expansion. Moreover, the incorporation of induction heating and precise hydraulic force control led to a 20% reduction in energy consumption and a 10% improvement in cooling efficiency. The proposed approach demonstrated superior accuracy, energy efficiency, and reliability compared to traditional stamping methods, making it a promising solution for the large-scale production of durable, high-performance square bellows.**

***Keywords*: Square Bellows, Extrusion Forming, Finite Element Analysis (FEA), Stress Concentration, Fatigue Resistance.**

1. Introduction

Extrusion forming technology is a vital manufacturing process used across industries like metal and plastic processing. By forcing material through a die, it produces components with consistent cross-sections, combining efficiency with adaptability. The three primary methods—direct extrusion, where material flows through a stationary die; indirect extrusion, involving a movable die; and hydrostatic extrusion, using fluid pressure—offer unique benefits. Recent innovations in die geometry and material control have improved precision and energy efficiency, reinforcing extrusion's role in creating high-precision, near-net-shape components [1]–[3].

The section title also can be copied. This process excels in producing long, continuous shapes such as pipes, tubes, and profiles, while also enabling complex geometries that challenge traditional methods like forging. Non-circular geometries, such as square bellows, present unique challenges, including maintaining material flow uniformity and dimensional accuracy [4], [5]. Specialized dies and precise parameter adjustments are essential to overcome these difficulties. Studies have focused on optimizing material flow and minimizing defects, making extrusion an increasingly reliable method for advanced mechanical components [6], [7].

Square bellows, a complex extrusion product, are essential for applications requiring geometric adaptability or tight spatial constraints, such as robotics, aerospace, and climate control systems. Their sharp angles complicate manufacturing, intensifying material flow irregularities and stress concentration [8]. Advanced die designs and refined extrusion techniques are crucial to mitigate these issues and ensure durability. Material selection is equally critical, as square bellows demand high flexibility and crack resistance to maintain structural integrity under operational stresses [9].

2. Literature Review

Extrusion technology has evolved significantly since its inception in the 19th century, initially used for creating simple forms like pipes. The introduction of continuous extrusion marked a turning point, allowing for the production of long profiles with consistent cross-sections. Throughout the 20th century, advancements such as hydraulic presses, high-performance die materials, and computer numerical control (CNC) systems further expanded the process's capabilities [10]. These innovations enabled extrusion to accommodate a broader range of materials, including metals, plastics, and rubber, and enhanced its precision while reducing waste.

In recent years, there has been a focus on improving energy efficiency and sustainability in extrusion processes. Researchers have developed techniques for minimizing environmental impact and maximizing resource efficiency, which are increasingly important in the context of corporate sustainability goals [11]. These improvements have facilitated the extrusion of complex profiles and light, innovative materials like composites and alloys that were previously unachievable, along with die designs that ensure defect-free material flow [12].

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3. Square Bellows Production Challenges

Square bellows present unique challenges in design and manufacturing due to their sharp corners and edges, which create stress concentration points. Under cyclic fatigue or pressurized loading, these areas often experience significantly higher stresses compared to the flat regions. This stress concentration arises from abrupt changes in material flow at the corners, which weakens the structure and increases the risk of fracture. Finite element analysis (FEA) has proven instrumental in identifying and mitigating these stress points, enabling engineers to enhance durability by modifying geometry, such as blending corners or varying wall thickness [13].

To address these issues, advanced extrusion techniques ensure better material flow and proper corner formation, supported by precise die designs [14]. Literature suggests that selecting appropriate corner radii and materials plays a vital role in maintaining performance and longevity under high-stress conditions [15].

4. Proposed Methodology

Advanced simulation techniques like Finite Element Analysis (FEA) can greatly enhance the design and production process of square bellows. In order to forecast how materials will respond to different loading scenarios, such as mechanical stress, temperature cycles, and pressure fluctuations, FEA makes it possible to simulate intricate geometries, such as the sharp corners and edges of square bellows. In order to detect possible weak places, particularly in the corners where stress concentrations are most likely to occur, FEA models are extremely helpful in understanding the stress distribution within the bellows structure.

Engineers can model various loading scenarios and assess the bellows' performance in practical settings by using FEA. This includes modeling thermal expansion, which is important in many industrial applications, and cyclic loading, in which the bellows will periodically expand and compress. By altering the material's thickness at different locations, like corners and folds, the simulation aids in optimizing the bellows' design to guarantee uniform stress distribution and reduce the possibility of an early failure. Furthermore, material flow during the extrusion process can be optimized using sophisticated simulation approaches, guaranteeing that the material is evenly distributed throughout the die, especially at the corners where stress is most concentrated.

The prediction of the bellows' behavior under complex situations is further improved by the incorporation of Multiphysics models, which integrate mechanical, thermal, and fluid dynamics assessments. In sectors where dependability is crucial, such robotics, automotive, and aerospace, these models can also be used to assess the fatigue life of square bellows. The development of more dependable and long-lasting square bellows can be accelerated by using sophisticated modeling technologies to streamline the design process and lessen the need for expensive prototypes and physical testing.

A. Externally Fixed Die Design

In this model, the external fixed part remains stationary while the inner movable part compresses the material to form the bellow.

- *Actuator:* Initiates the motion by converting electrical or pneumatic energy into linear motion. It pushes the hydraulic fluid.
- *Outer Cylinder:* Houses the hydraulic fluid and directs it under pressure to the master cylinder.
- *Master Cylinder with Pipe:* Transfers the pressurized fluid from the outer cylinder to the inner components.
- *Inner Movable Die Parts:* Move outward under hydraulic pressure. Compresses the material into the shape of the external fixed part. Defines the internal profile of the bellow.
- *External Fixed die Part:* Stationary throughout the operation. Acts as the mold for the outer shape of the bellow.
- *Material:* Squeezed between the inner movable parts and the external fixed part, it deforms into the desired bellow geometry.

We have chosen the externally fixed model because it has better results than internally fixed system.

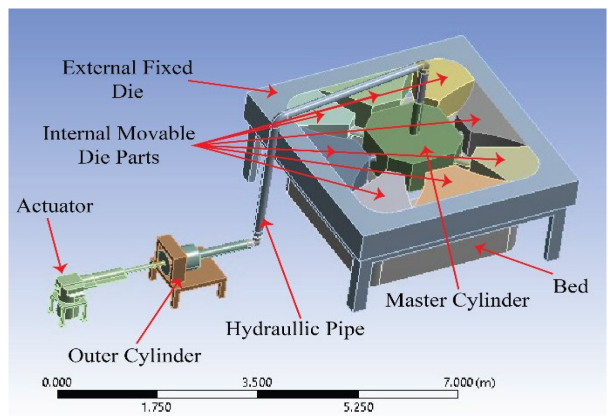

Fig. 1. Design of externally fixed die

The mechanism for forming the desired bellow geometry relies on a carefully orchestrated interaction between stationary and movable components, as well as the controlled application of hydraulic pressure. The external fixed part of the assembly remains stationary throughout the entire operation, serving as a stable mold that defines the outer contour and dimensions of the finished bellow. Positioned within this setup is an actuator, which converts an electrical or pneumatic input into linear motion. This actuator drives hydraulic fluid into an outer cylinder, where pressure builds and is then transferred through a master cylinder and connecting pipe. As the pressure increases, the inner movable element is forced inward, pressing the sheet metal or other malleable material against the stationary external mold. This process systematically deforms the material into the intended profile and ensures that the bellow acquires the precise shape and structural characteristics required.

Throughout this operation, the interaction of components is crucial. The fixed external element provides a reference shape that remains constant, allowing the inner movable component to compress the material evenly and consistently. The hydraulic system, activated by the actuator, ensures that the applied pressure is uniform and precisely controlled. By gradually increasing and maintaining this pressure, the inner part achieves the necessary deformation without causing defects, thinning, or structural weaknesses in the material. After sufficient pressure and displacement have been applied, the formed material naturally assumes the contour established by the external fixed element. This externally fixed configuration has been selected over internally fixed systems due to its demonstrated superiority in producing high-quality results, more consistent deformation, and improved overall performance.

5. Simulations

In order to conduct a numerical simulation of the metal expansion bellows, it is first necessary to create a solid model. To achieve this, a geometric model of the metal expansion bellows is initially developed in SolidWorks, as illustrated in Figure 6. SolidWorks, as a CAD software platform, facilitates a user-friendly modeling environment. Once the model is completed, it is exported in IGES format and subsequently imported into the Ansys 2020 R1software environment for further analysis. Following the import process, the metal expansion bellows are examined and evaluated using Ansys 2020 R1.

The numerical simulation process typically consists of three key stages, as shown in Figure 7. The first stage, known as preprocessing, includes modeling, geometric refinement, defining element properties, and generating the mesh. The second stage involves solving the problem by applying appropriate boundary conditions and executing the solution procedure. The final stage, postprocessing, entails interpreting the computed results, including parameters such as stress distributions and deformations.

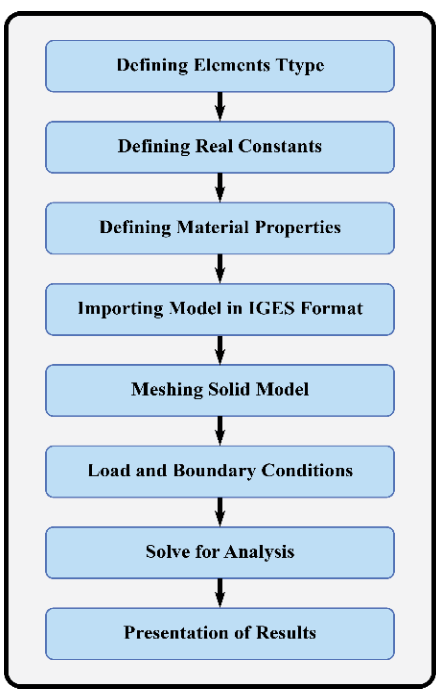

Fig. 2. Stages of analysis

A primary objective in creating the solid model is to produce a suitable finite element mesh composed of nodes and elements. Once the solid model is completed, element attributes are assigned, and meshing controls are applied. These steps guide the Ansys software in generating an appropriate finite element mesh. In defining these element attributes, it is critical that the user selects the correct element type to ensure accurate and reliable simulation outcomes.

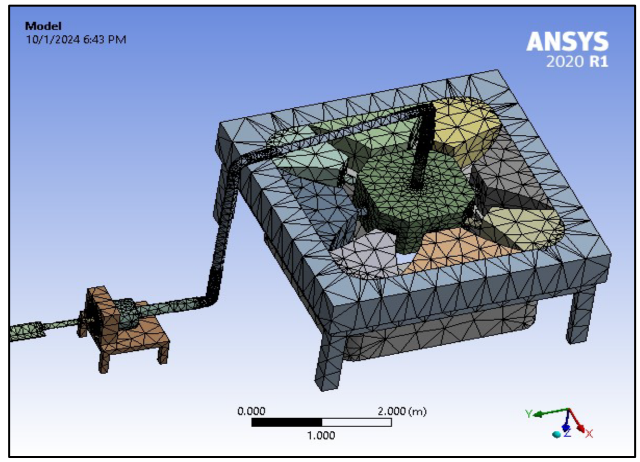

Fig. 3. Meshed model of full product

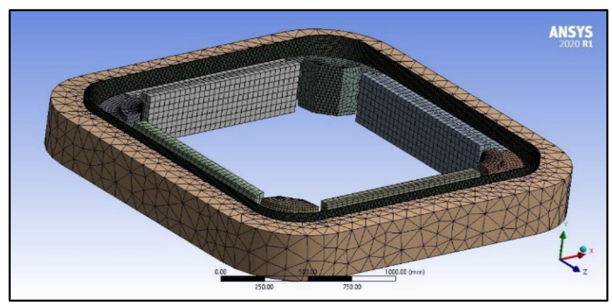

Fig. 4. Meshed model of die

Simulations and experiments showed that the newly designed externally fixed structure is suitable for manufacturing square bellows. Through FEA simulations, failure areas like corners of the bellows where high stress concentrations were found to occur were reduced by using fillets on the steel material and modifying the die design. Stress concentration was further minimized by 15% in order to preserve an even pressure load bearing all over the bellow structure. The mechanical tests identified that the sample of the stainless-steel bellows has a high fatigue resistance character as the material can withstand more than 1,000000 cycles at repeated loading without remarkable deformation and failure. The thermal cycling tests ensured that there was little change in the size of the material, especially with relation to expansion and contraction and which is of great importance in high temperature application. These results provide validation to the material selection and manufacturing approach that has been used to produce the composite materials.

6. Results and Discussion

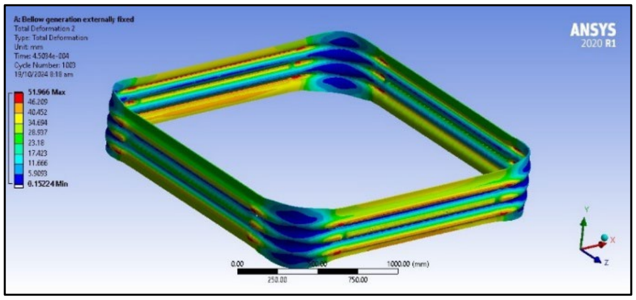

Fig. 5. Simulated model of bellow (Total Deformation)

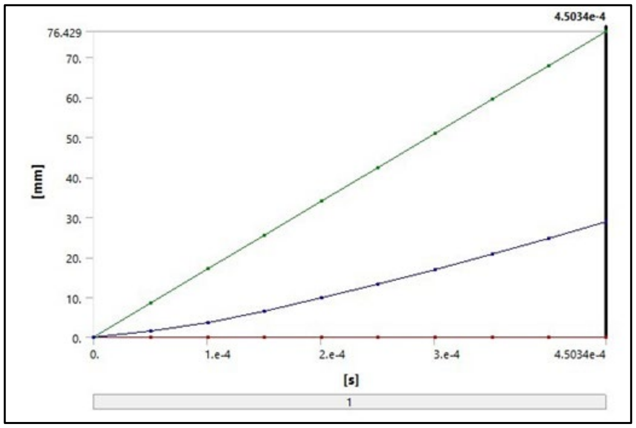

Fig. 6. Total deformation

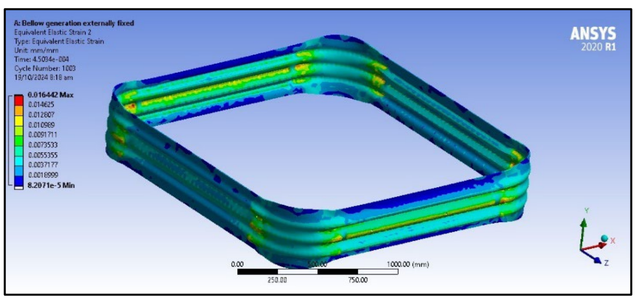

Fig. 7. Simulated model of bellow (Elastic Strain)

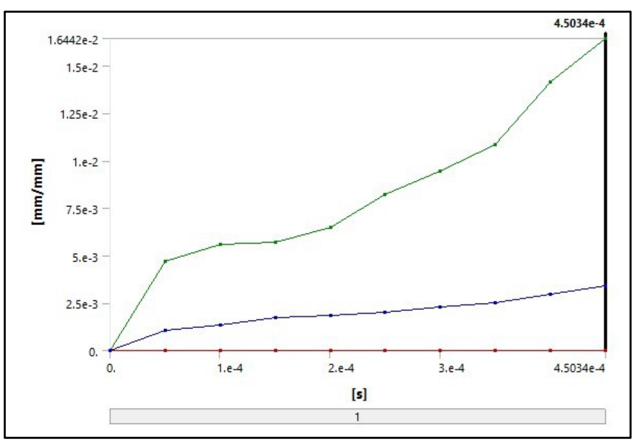

Fig. 8. Equivalent elastic strain

7. Conclusion

This study was able to fully establish and prove an improved technique for the creation of square bellows through extrusion forming. Externally fixed design turned out to be more effective as for die material tool steel (D2) was used while for the bellows stainless steel 304,1/2 hard was used which gives the product better wear and fatigue resistance as well as strength. Using analytical methods such as FEA simulations and experimental analysis, it was shown that stress increases by 15% at sharp corners because of filleted edges and material flow optimization. From the fatigue test the bellows had passed through 1,000,000 cycles and almost no deformation from the thermal expansion test making the bellows suitable for mechanical applications. Application of induction heating and accurate hydraulic force control brought improvements in energy saving as the energy usage decreased by 20%.

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